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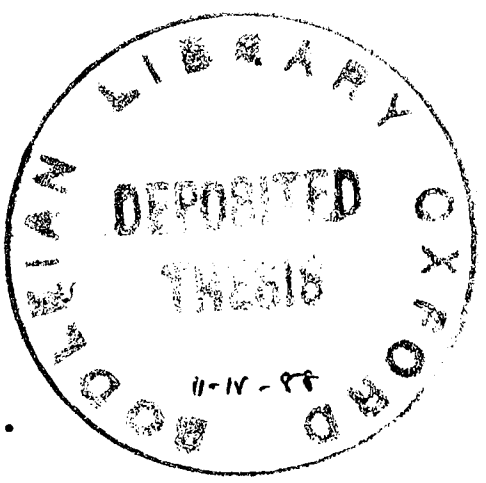
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Caledonian Tectonics From Stratigraphy and Isotope Geochemistry of Lower Palaeozoic Successions.

Volume One (Text)



by

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TO MUM AND DAD.





FRONTISPIECE. Western Brook Pond, Long Range Mountains, Newfoundland (above) and the area around Barhaskine Farm, Southern Uplands, Scotland (below).

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ABSTRACT.

The Southern Uplands of Scotland is interpreted as a Lower Palaeozoic accretionary complex which formed on the northern margin of the Iapetus Ocean. Seven conglomerates which contain detritus derived from the north-west, from sources on the Laurentian continental margin, were studied. Granite clasts in five of the conglomerates have distinct petrographic and geochemical characteristics which indicate that separate source areas supplied detritus to the Southern Uplands at different times.

The Llandeilo Corsewall Point and Caradoc Glen Afton conglomerates, which occur in Tracts 1 and 2 of the Northern Belt, contain granite clasts that yield similar Rb-Sr whole-rock isochron ages (c. 1,200 Ma, 600-660 Ma and c. 475 Ma) and similar Sm-Nd model ages. This suggests that the clasts in the two conglomerates were derived from related sources. Some of the granite clasts in the early Ashgill Shinnel Formation conglomerate, which occurs in Tract 3 of the Northern Belt, resemble those in the Corsewall Point conglomerate, but most are petrographically and geochemically distinct, and yield younger Sm-Nd model ages. The lower Llandovery Pinstane Hill conglomerate occurs in Tract 4 of the Central Belt, and contains granitic detritus which yields a Rb-Sr whole-rock isochron age of 458 ± 26 Ma and has similar characteristics to the clasts in the Shinnel Formation conglomerate.

The granite clasts in the Corsewall Point and Glen Afton conglomerates are of a different age to the granite intrusions of northern Scotland, and are unlikely to have been derived from this region. Conglomerates in the Midland Valley contain granite clasts with different petrographic and isotopic characteristics to those supplied to the Southern Uplands during the Llandeilo and Caradoc. However, north-west Newfoundland has a similar igneous history to that recorded by the Southern Uplands clasts, which could be derived from this region. The clasts supplied to the Shinnel Formation and Pinstane Hill conglomerates during the Ashgill and Llandovery have more in common with the granitic detritus in the Midland Valley. Thus, the Southern Uplands form a distinct Caledonian terrane which was south-east of Newfoundland in the Llandeilo, and was affected by sinistral strike-slip displacements during and after accretion.

LONG ABSTRACT.

The Southern Uplands of Scotland consists of a number of fault-bounded tracts which contain greywacke successions of Ordovician and Silurian age overlying pelagic shales and/or cherts and basalts. The coarse clastic sediments were deposited on the margin of the Laurentian continent, and the structure of the Southern Uplands may be interpreted as that of an accretionary complex which formed as a result of subduction of the Iapetus oceanic plate.

Palaeocurrent data from the greywacke units show a predominantly bimodal pattern. Some turbidites flowed axially along the subduction trench from the north-east, and others are associated with mass flow conglomerates which were derived from the north-west. The mass flow conglomerates contain clasts up to 1.5 m. in diameter, and clasts of this size were unlikely to have been transported great distances prior to their deposition in the subduction trench. Seven conglomerates were investigated in this study - the Corsewall Point and Glen App conglomerates in Tract 1 (N. gracilis zone age), the Glen Afton conglomerate in Tract 2 (D. clingani zone age), the Shinnel Formation conglomerate in Tract 3 (P. linearis zone age), the Pinstane Hill conglomerate in Tract 4 (C. vesiculosus zone age) and the Craigenputtock and Barhaskine conglomerates in Tract 5 (M. gregarius zone age). Tracts 1 to 3 comprise the Northern Belt of the Southern Uplands, and Tracts 4 and 5 form part of the Central Belt.

In the Northern Belt, the Corsewall Point, Glen App and Glen Afton conglomerates are associated with north-westerly derived greywackes rich in basic igneous detritus, and were deposited above north-easterly derived greywackes containing quartz-rich detritus. The Shinnel Formation conglomerate is associated with north-westerly derived quartz-

rich detritus. Some tracts in the Northern Belt also contain greywackes rich in basic igneous detritus derived from a southerly source which lay within the Iapetus Ocean. In the Central Belt, the Pinstane Hill conglomerate is also associated with north-westerly derived greywackes rich in basic igneous detritus, but the Craigenputtock and Barhaskine conglomerates, which belong to different parts of an axial fan system, contain quartz-rich detritus.

Granitic detritus occurs in five of the conglomerates studied. The granite clasts in each deposit fall into separate groups with distinct petrographic and geochemical characteristics, which suggests that they were derived from a limited number of unrelated plutons. The Corsewall Point conglomerate is dominated by granitic detritus which has mature volcanic arc characteristics, but also contains some trondhjemite and plagiogranite clasts which may have been derived from ophiolitic sources. One group of muscovite-biotite granite clasts contains abundant crustal xenoliths which show that the source area of this conglomerate contained amphibolite facies garnet-sillimanite schists. The granitic detritus in the Glen App conglomerate is more extensively altered than that in the Corsewall Point conglomerate, but the similarities between the clasts in the two deposits demonstrate that they were derived from related, but not identical source areas.

A larger proportion of the granite clasts in the Glen Afton conglomerate have trondhjemitic affinities, and the groups of granite clasts with mature arc characteristics differ petrographically from those in the Corsewall Point conglomerate. Thus, granite clasts in the Glen Afton conglomerate were probably derived from a geographically distinct source area. The granitic detritus in the Shinnel Formation conglomerate is more diverse. It contains a distinctive group of sodium- and potassium-rich granites derived from high level plutons which are not present in any of the older deposits. Plagiogranite

clasts occur in all the other conglomerates, but are not present here. However, one clast in the Shinnel Formation conglomerate is identical to the muscovite-biotite granites in the Corsewall Point conglomerate, and other clasts which show affinities with detritus in the Glen App conglomerate. The different nature of most of the detritus in the Shinnel Formation conglomerate suggests that it is derived from a separate source area, but some detritus may be reworked from older deposits.

In the Central Belt, the Pinstane Hill conglomerate is the only deposit to contain appreciable quantities of coarse granitic detritus. Clasts with similar characteristics to those in the Shinnel Formation conglomerate are present, which suggests that the two conglomerates were derived from closely related source areas. However, the Pinstane Hill conglomerate is associated with greywackes rich in basic igneous detritus, while the greywackes associated with the Shinnel Formation conglomerate are particularly quartz-rich.

The granite clasts in each petrographic group share similar characteristics and are probably cogenetic, and consequently can be used to construct Rb-Sr whole-rock isochrons. Isochrons were obtained from eight groups of clasts in three of the conglomerates studied. The muscovite-biotite granite clasts from the Corsewall Point conglomerate yield an age of 1,265 ± 130 Ma, two groups of hornblende-biotite granites yield ages of c. 600 Ma and a group of biotite granites yields an age of 475 ± 20 Ma. In addition, Rb-Sr model age determinations for a group of foliated hornblende-biotite granodiorites indicate that they are the same age as, or slightly older than, the muscovite-biotite granites.

Similar ages were obtained for three groups of granite clasts from the Glen Afton conglomerate. A group of biotite granodiorites yields a Rb-Sr whole-rock isochron age of 1,231 ± 120 Ma, a group of muscovite-

biotite granites yields an age of 660 ± 35 Ma and a group of hornblende-biotite granites yields an age of 491 ± 15 Ma. Although there are petrographic differences between the clasts in the Corsewall Point and Glen Afton conglomerates, they were derived from source areas with similar igneous histories which probably therefore belonged to related crustal segments. This conclusion is supported by the similar Sm-Nd model ages obtained from clasts in the two conglomerates which indicates that the granitic magams from which they crystallized contained similar crustal components.

No Rb-Sr whole-rock isochron ages were obtained from the granitic clasts in the Shinnel Formation conglomerate, but the perthitic biotite granites in the Pinstane Hill conglomerate, which have many features in common with the Shinnel Formation clasts, yield an age of 458 ± 26 Ma. Sm-Nd model ages obtained from clasts in the two conglomerates are younger than those obtained from clasts in the Corsewall Point and Glen Afton conglomerates. This emphasizes the close relationship between the detritus in the Shinnel Formation and Pinstane Hill conglomerates, and further distinguishes it from the detritus in the older conglomerates.

The intense deformation of granites intruded at c. 1,000 Ma precludes the northern Highlands of Scotland as a source of the older, less deformed granite clasts in the Corsewall Point and Glen Afton conglomerates. There are no granite intrusions older than 514 Ma in the Grampian Highlands, and because of the effects of the early Ordovician Grampian orogeny, it is unlikely that either the c. 1,200 Ma or the 660-600 Ma granite clasts from these conglomerate were derived from this area. The Benan conglomerate in the Midland Valley and the Corsewall Point conglomerate were both deposited during the N. gracilis zone, but contain granite clasts that have different petrographic, chemical and isotopic characteristics, which indicates that they were derived from separate source areas. Also, Sm-Nd model ages obtained from meta-

sedimentary granulite xenoliths in the Midland Valley are difficult to reconcile with the model ages obtained from Southern Uplands clasts and the presence of amphibolite facies xenoliths in the Corsewall Point muscovite-biotite granites.

An alternative source for the granitic detritus in the Corsewall Point conglomerate is found in north-west Newfoundland. The amphibolite facies gneisses in the Grenville province of the Long Range contain sillimanite schists similar to the inclusions in the Corsewall Point muscovite-biotite granite clasts, and are intruded by granites which yield ages of c. 1,100 Ma. The c. 460 Ma Burlington granodiorite has many features in common with the 475 ± 20 Ma biotite granite clasts from Corsewall Point, and potential sources for the foliated granodiorites, trondhjemites and plagiogranites are also found in north-west Newfoundland. However, a source for the 600 Ma hornblende-biotite granites is more problematic as these clasts have volcanic arc characteristics, but the only granite intrusions of this age in north-west Newfoundland are rift-related. Palaeogeographic considerations indicate that the hornblende-biotite granites are most likely to have been derived from an extension of the volcanic arc which is thought to have collided with this part of the Laurentian margin during the Middle Ordovician.

Not all the granite clasts in the Corsewall Point conglomerate precisely match the granite intrusions of north-west Newfoundland, but they are sufficiently similar to have been derived from a closely related part of the Laurentian margin. The granitic detritus in the Glen Afton conglomerate is of a similar age to that in the Corsewall Point conglomerate, but as it does not have as much in common with the Newfoundland intrusions, it is likely to have been derived from a source area further removed from this part of the continental margin. The c. 460 Ma granite clasts in the Shinnel Formation and Pinstane Hill

conglomerate have more in common with the granite clasts of a similar age in the Midland Valley conglomerates, and yield Sm-Nd model ages which are more characteristic of Midland Valley crust. Consequently, the source area of the Southern Uplands sediments changed between the Caradoc and the Ashgill to one which had a greater affinity with the Midland Valley.

As the clasts in the Southern Uplands conglomerates were deposited close to their source areas, the Corsewall Point conglomerate must have been deposited south-east of an area close to Newfoundland and accreted to this part of the Laurentian continental margin. Strike-slip displacement during the development of the accretionary complex accounts for the differences in the detritus each conglomerate contains, and reworking of detritus in the Shinnel Formation conglomerate indicates that uplift of early accreted tracts took place during the formation of the Northern Belt.

The similarity of the granitic detritus in the Shinnel Formation and Pinstane Hill conglomerates indicates that they were derived from closely related sources. However, basic igneous detritus is entirely lacking from the Shinnel Formation greywackes, but is common in the greywackes associated with the Pinstane Hill conglomerate. A basic igneous component, which lay to the south of the Southern Uplands during the early Ashgill, may have been added to the source area of the Shinnel Formation conglomerate in the 8 Ma between the deposition of the two units. The continuation of strike-slip displacements during this period would have removed the Northern Belt from this area, and the Northern and Central belts were later juxtaposed by movements on the Orlock Bridge-Kingledores Fault.

The Southern Uplands were displaced by a total of 1,500 km between the Caradoc and the Lower Devonian. Some of this movement may have taken place on other faults, such as the Highland Boundary Fault and

Great Glen Fault, but it gives an average displacement rate of between 2 and 2.5 cm y^{-1} for the Southern Uplands. These displacements resulted from the oblique closure of the Iapetus Ocean, and are related to the large scale displacements which also affected other terranes in the Caledonian-Appalachian orogen.

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Chapter 1

CHAPTER 1

INTRODUCTION

1.1 The Southern Uplands and the British Caledonides.

The Southern Uplands of Scotland form a distinct tectonic unit within the British Caledonides, separated from the Midland Valley to the north by the Southern Upland Fault and the Lake District to the south by the Iapetus suture, which is hidden beneath the Carboniferous of the Solway Basin (Fig. 1.1). It consists of three belts containing deep water successions of different ages:- Ordovician basalts, cherts and/or shales overlain by Ordovician greywackes and conglomerates in the Northern Belt, Ordovician and Silurian shales overlain by Llandovery greywackes and conglomerates in the Central Belt, and Wenlock greywackes and conglomerates in the Southern Belt. The outcrop can be traced from the Berwickshire coast to the Rhinns of Galloway, and continues across the North Channel to the Longford-Down zone of Ireland.

The existance of a "Proto-Atlantic", or Iapetus Ocean was first recognized by Wilson (1966) and subsequent models for the tectonic evolution of the Caledonides relate to the closing of this ocean. Since the Southern Uplands lie immediatly to the north of the Iapetus suture, and formed during the closure of the Iapetus Ocean, the evolution of this unit forms an important part of any Lower Palaeozoic plate tectonic model for the Caledonidan orogen.

Early interpretations of the structure of the area by Lapworth (1889) and Peach and Horne (1899) explained the repeated pattern of basalts, cherts and/or shales overlain by greywackes as the result of a series of tight isoclinal folds arranged in a broad anticlinorium and synclinorium. This was held to be the case until Craig and Walton (1959) showed that such an interpretation was inconsistent with stratigraphic

and structural relationships in the Kirkudbright area, and suggested instead that high angle thrust faults may be an important part of the structure. Early plate tectonic models (Dewey, 1969) suggested that the deformation was a climactic end-Silurian/ early-Devonian event, resulting from the final closure of the Iapetus Ocean. The importance of high angle thrust faults was confirmed by Leggett and others (McKerrow et al., 1977; Leggett, 1978; Leggett et al., 1979), but by regarding the deformation as being contemporaneous with deposition, they interpreted the structure as that of an accretionary complex. They showed that the whole area is divided into fault-bounded tracts that formed as sediments were scraped off the subducting Iapetus oceanic plate and used this model to explain the observed pattern of predominantly north-westerly directed sedimentary younging directions in a sequence that as a whole becomes stratigraphically younger to the south-east. Because sedimentation would mainly have been confined to a subduction trench (Leggett, 1980), this model also explains how sandstones of quite different age and petrography could be juxtaposed. Further, it implies that deformation was a continuous process, operating from the Caradoc to the mid-Wenlock.

This interpretation, based upon sections exposed by the excavation of a gas pipe-line across strike in the Northern Belt has been shown to hold for the Central Belt (Casey, 1983), the Southern Belt (Kemp, 1985) and along strike in Longford-Down (Anderson and Cameron, 1979; Craig, 1984). Detailed structural studies of smaller areas also support the accretionary prism model (Stringer and Treagus, 1981). Recently, some workers have expressed doubts about the now "traditional" view of the Southern Uplands as an accretionary complex, and have questioned its fore-arc setting (Murphy and Hutton, 1986; Barnes et al., 1986; Rock et al., 1986; Stone et al., 1987). The various new models which have been proposed differ in the tectonic settings that they suggest for the

Southern Uplands, and imply different timings for the deformation of this region. However, not all the new evidence on which they are based necessarily contradicts the accretionary prism model (Kemp et al., 1986; Leggett, 1987; Elders and Kemp, 1987).

Plate tectonic models have sought to relate the northwesterly directed subduction associated with the formation of the Southern Uplands to the development of other tectonic units in the Scottish Caledonides (Phillips et al., 1976; Mitchell, 1984). However, the presence of Arenig age faunas in the Dounans Limestone of the Highland Boundary Complex show that this unit must have been deformed separatly to the Dalradian Highlands as the fauna it contains post-dates the main Grampian deformation (Curry et al., 1982). Also, a 560 Ma unfoliated granite boulder in the Bennan Conglomerate at Girvan could not have been derived from an area affected by the Grampian orogeny, the climax of which was at c. 510 Ma. (Longman et al., 1979). These facts suggest that the Midland Valley had a separate history to the Grampian Highlands. Silurian conglomerates in the south of the Midland Valley contain clasts of acid igneous rocks and quartzites which are derived from the south. This area is now occupied by the Southern Uplands, and as it could not have supplied such detritus, a different terrane must have been south of the Midland Valley when these conglomerates were deposited (Bluck, 1983). The widespread occurrence of clockwise transecting cleavage in the Southern Uplands and Longford-Down has been used as evidence of sinistral shear during the closure of the Iapetus Ocean (Soper and Hutton, 1984). Consequently, more recent plate tectonic models stress the importance of large scale strike slip displacements during the evolution of the Caledonian orogen (Soper and Hutton, 1984; Dewey and Shackleton, 1984; McKerrow, 1987).

Recognition of such displacements increases the importance of understanding the evolution of the British Caledonides in the wider

context of the the whole Appalachian-Caledonian orogen, which extends from Svalbard, through Scandinavia and Greenland, the British Isles, eastern Canada and the U.S.A., as far as the southern Appalachians. This orogenic belt resulted from the convergence of three continental plates (Ziegler, 1982; Soper and Hutton, 1984); Laurentia, Baltica and the Avalon microcontinent, which rifted from Gondwana during the Ordovician (Fig 1.2; McKerrow, 1987). The plates are defined by faunal assemblages (Cocks and Fortey, 1982) - Scotland lay on the margin of Laurentia, which also included Greenland and most of north America, excluding southern Newfoundland, Nova Scotia and the eastern seaboard of the U.S.A. (Fig. 1.2).

A recent development in Appalachian geology has been the application of the terrane concept, developed in the Western Cordillera of North America, to the older Appalachian belt (Williams and Hatcher, 1982, 1983; Zen, 1983; Keppie, 1985.). Different approaches have been used; on the one hand recognizing small areas with distinct geological histories, unrelated, at least in part, to adjacent areas (Keppie, 1985), and on the other, recognizing large tracts along the length of the orogen where timing of accretion of terranes is similar (Williams and Hatcher, 1982, 1983). This also allows distinctions to be made between periods when terrane accretion resulted from obduction/accretion perpendicular to the continental margin, and other times when oblique convergence and transcurrent movements were important (Williams, 1985).

Because of the evidence of transcurrent movements in the British Caledonides discussed above, the terrane concept may be extended to this area (Gibbons and Gayer, 1985; McKerrow, 1987). The evidence for separation of the Midland Valley from the Grampian Highlands along the Highland Boundary Fault has been demonstrated by Bluck (1984). The relationship between the Southern Uplands and the Midland Valley, and

the significance of the Southern Upland Fault, is the subject of the present study.

1.2 Purpose and scope of the present study.

Although there are reasons for suspecting that the Southern Uplands has been affected by transcurrent displacements, and structural evidence exists for sinistral transpressive deformation (Soper and Hutton, 1984), there are no criteria presently available that can be used to measure absolute displacements. Consequently, plate tectonic models which include an element of sinistral displacement are poorly constrained. The aim of this thesis is to identify the source areas that were adjacent to the Southern Uplands at the time of sediment deposition, and hence to establish its position relative to Laurentia. From this the magnitude and timing of the displacements that have brought the Southern Uplands into their present position can be deduced.

Sedimentation in the subduction trench was the result of currents flowing either axially along the trench, mainly from the north-east, or laterally down the inner trench slope from the north-west (Leggett et al., 1982). The petrography of the greywackes can be used to establish the type of terrane that was being eroded (e.g. Walton, 1955; Casey, 1983) but the grain size and composite nature of the greywackes means that the source area can only be described in general terms and not specifically located. Also, it is difficult to establish how far sand grade material has been transported, or from how large a source area it was derived. Consequently, the position of the subduction trench in relation to the source area cannot be accurately assessed. However, such an approach does reveal that different source areas supplied sediment to the trench at different times (Floyd, 1975; McKerrow, 1986). Sm-Nd techniques have also been applied to Southern Uplands greywackes (O'Nions et al., 1983; Miller and O'Nions, 1984). This shows that the

crustal residence ages of the greywackes are different to those of other crustal units in Scotland, and hence that at least some component of the detritus was derived from a different crustal source. Since this approach averages the Sm-Nd characteristics of the different components of the greywackes, it is not possible to establish where this particular source is to be found.

Conglomerates are used in this study in order to obtain more detailed information about sediment source areas close to the Southern Uplands than is possible from studying greywacke detritus alone. The conglomerates occur in mass flow deposits that were derived from the north-west, and the large size of the clasts (upto 1.5m.) means that they are unlikely to have been transported far. Consequently, they were probably derived from areas that lay immediatly to the north-west of the Southern Uplands when the conglomerates were deposited.

The boulders in the conglomerates provide large discrete samples of the source area, and reveal more detailed petrographic information than the small fragments which occur in the greywackes. Although it is unlikely that petrography alone will be diagnostic of a particular source area, details of the rock types present in areas adjacent to the Southern Uplands help to characterise the source area, and have a bearing on the current debate as to its tectonic setting.

Boulders also provide samples of the source area amenable to radiometric dating. Granite clasts are common in the Southern Uplands, and have been dated in this study by Rb-Sr whole-rock isochron methods. The ages obtained provide a framework into which petroghraphic and geochemical observations can be fitted in order to establish a chronology of igneous activity and deformational events in the source areas. In addition, Sm-Nd model ages of individual clasts have also been used to determine some of the crustal characteristics of the source areas. The detailed pictures of the source areas that emerge can be

compared with the geological histories of different areas on the margins of Laurentia, and hence the position of the Southern Uplands with respect to that margin at the time of deposition of each conglomerate can be inferred. Analysis of conglomerates of different ages shows the extent to which the location of the source areas has changed with time, and the magnitude, sense and timing of displacements that have affected the Southern Uplands can thus be deduced.

1.3 Methodology.

The conglomerates investigated in this study are shown in Fig. 1.3. Table 1.1 summarizes the age and location of these outcrops. The sedimentology of the Corsewall Point, Glen App, Glen Afton and Shinnel Formation conglomerates have recently been studied in detail (Floyd, 1975; Holroyd, 1978). Consequently, sedimentological observations were concerned mainly with the Pinstane Hill, Craigenputtock and Glenluce conglomerates, which have not been described previously.

A representative collection of clasts was made at each locality for petrographic description. Larger numbers of granite clasts collected from several localities (Table 1) were described petrographically and analysed for major and trace elements and Rb-Sr isotope compositions. Some clasts were further analysed for Sm-Nd isotope compositions. All analyses were carried out using the facilities at Oxford University.

Geochemical and isotopic data for potential source areas were compiled from the literature. Additional information was obtained during a field trip in Newfoundland and the analysis of samples collected there.

TABLE 1.1

Conglomerate localities invesigated in this study.

Conglomerate	Grid Reference	Age of uderlying graptolitic shales	Tract Number (after McKerrow, 1986)	Number of clasts analysed
Corsewall Point	NX 982728	*N. gracilis*	1	30
Glen App	NX 145813	*N. gracilis*	1	12
Glen Afton	NS 628051	*C. clingani*	2b	30
Shinnell Formation	NS 790001	*P. linearis*	3d	10
Pinstane Hill	NT 017168	*C. vesiculos*	4	10
Craigenputtock	NX 783837	*M. gregarius*	5	-
Glenluce	NX 300553	*M. gregarius*	5	-

Chapter 2

CHAPTER 2

THE STRATIGRAPHY AND SEDIMENTOLOGY OF THE SOUTHERN UPLANDS CONGLOMERATES.

2.1 Introduction.

The Southern Uplands accretionary complex formed as a result of north-westerly directed subduction at the northern margin of the Iapetus Ocean, by the underthrusting of sediment packets scraped off the downgoing plate. The thrust planes on which décollement took place are preserved as high angle, strike-parallel, reverse faults which divide the area into a number of tracts containing sedimentary sequences of different ages. This provides a tectono-stratigraphic framework that can be used to classify the different greywacke formations that occur within the Southern Uplands. Ten such tracts were initially recognized (Leggett et al., 1979) but further work has shown that some may be subdivided into smaller fault-bounded units. The scheme of McKerrow (1986), which retains the original tract numbers of Leggett et al. (1979) but incorporates more recent subdivisions, is used here. Fig. 1.3 shows the geographical extent of each tract and the location of the conglomerates investigated in this study. Fig. 2.1 shows the stratigraphic sequence within each tract and the probable ages of the conglomerates they contain.

The greywackes in each tract are of a different age and have different compositions (Floyd, 1982; Casey, 1983). This implies that the sediments in each tract were deposited separately and were later juxtaposed by movements on the tract bounding faults. Most of these faults are dominated by thrust displacements, but some also contain an important strike-slip component. Consequently, the stratigraphic and structural relationships between the different conglomerates illustrated

in Fig. 2.1 are important in interpreting differences in the detritus they contain in terms of the evolution of their source areas.

The petrography of the greywackes and the full range of lithologies that occur as clasts in each conglomerate are considered in this chapter in order to determine the nature of the source areas that supplied the Southern Uplands. The granite clasts in particular are considered in more detail in Chapters 3 and 4. Although not all the rock types present in each source area form clasts that eventually become incorporated in the conglomerates, those clasts that are present have probably been derived from a small source area, proximal to the site of deposition, and reflect the geology of the continental margin adjacent to the subduction trench.

The precise extent of the area from which clasts are derived is more difficult to assess. The Southern Uplands conglomerates are mass flow deposits which form parts of submarine fan complexes. Consequently, sedimentological observations only reveal information about the final stage of transport of the clasts from the shelf into the subduction trench. However, it is probable that the clasts were transported by fluvial processes subsequent to their erosion, and because they are well rounded, there may also have been a period of residence on the continental shelf. During that time detritus from different fluvial systems may have been mixed and some long-shore transport may also have occurred. Although the extent of the earlier stages of transport cannot be accurately estimated, the large size of the clasts and the apparently restricted number of granite plutons that supplied detritus to each conglomerate indicates that the clasts were derived from small source areas and that they were not transported great distances. Palaeocurrent information contained within the conglomerates shows the direction in which the source areas lay.

2.2 The Corsewall Point and Glen App conglomerates.

2.2.a Stratigraphy.

The Corsewall Point and Glen App conglomerates occur in the nothernmost tract of the Southern Uplands, to the north of the Glen App Fault and south of the Stinchar and Dove Cove Faults (Fig. 2.2). Although the Glen App Fault, and its continuation to the south of the Corsewall Point conglomerate on the Rhinns of Galloway, has traditionally been regarded as the extension of the Southern Upland Fault in this region, Leggett et al. (1979) included this area in Tract 1 of the Southern Uplands on the basis of lithostratigraphic and biostratigraphic correlation with sections to the north-east. This implies that the Stinchar Fault, rather than the Glen App Fault, should be regarded as the continuation of the Southern Upland Fault, but this interpretation is not universally accepted (Ince, 1984).

At the northern end of the Rhinns of Galloway, to the west of Loch Ryan, the Corsewall Group outcrops north of the extension of the Glen App Fault. It is subdivided into a lower Flaggy Division and an upper Conglomeratic Division (Kelling, 1961). The Conglomeratic Division contains the rudite sequence exposed at Corsewall Point and a thicker, slightly older sequence at Milleur Point (Fig. 2.2). As the sequence is unfossiliferous, there is no direct evidence of its age at these localities, other than the reported discovery of a graptolite in a greywacke boulder which was tentatively identified as Dicellograptus, implying that the deposit is of Llandeilo age or younger (Tyrrell and Begg, 1933).

The lateral equivalent of the Corsewall Group on the east side of Loch Ryan is the Glen App Formation of Walton (1965), which includes the Glen App and Finnarts conglomerates. The latter is underlain by an equivalent of the Flaggy Division which contains Lower Glenkiln

(Llandeilo to Early Caradoc) graptolites (Walton, 1956). This implies that the Corsewall Point and Glen App conglomerates are approximately of N. gracilis zone age. Walton (1965) suggests that the Glen App Formation underlies the Dalreoch Group of the Tappins Complex, but Ince (1984) includes it within that group. The relationship of the Dalreoch Group to the Traboyack and Albany Groups, which comprise the rest of the Tappins complex, is unclear, but the Albany Group also contains a conglomerate with a fauna of N. gracilis zone age (Ince, 1984). The Traboyack Group contains red chert, sillicified mudstones and pillow lavas which form part of the Darley Formation and outcrop immediately adjacent to the Glen App Fault (Ince, 1984; see Fig. 2.2).

This succession is the same age as, and consists of similar lithologies to, that at Noblehouse, at the eastern end of Tract 1, where basalts and red cherts of Llanvirn and Llandeilo age are associated with thickly bedded greywackes overlying siltstones of N. gracilis zone age (Leggett et al., 1979). The Marchburn Fromation, which outcrops along strike in W. Nithsdale consists of a similar, but unfossiliferous, sequence of greywackes, siltstones and shales, with minor occurrences of conglomerate, spilite and chert (Floyd, 1982). The greywackes are quartz-poor, and rich in basic igneous detritus, like those at Noblehouse to the north-east, and in the Corsewall Point-Glen App tract to the south-west (Leggett et al., 1979; Floyd, 1982; Walton, 1983). This lithological correlation suggests that parts of the Tappins Complex may be related to the successions seen elsewhere in the Southern Uplands, at Noblehouse and in W. Nithsdale. In addition, because of its structure and setting, the Darley Formation can be interpreted as the topmost layers of ocean crust, overlain by sandstones deposited in a trench by axially flowing turbidity currents, which have subsequently been incorporated into the sediment pile by underthrusting (Ince, 1984). On this basis, Leggett et al. (1979) included the Corsewall Point-Glen

App tract within the Southern Uplands, as the westward continuation of Tract 1.

Although the successions to the north and south of the Stinchar Fault are quite different (Williams, 1962, p. 41), objections to including the Corsewall Point-Glen App tract in the Southern Uplands are based on the possibility that some of the detritus in the Corsewall Point and Glen App conglomerates may be derived from the Ballantrae Complex. Also, the Albany Group of the Tappins Complex contains sediments that were not deposited in an oceanic trench, and may be regarded as the more distal facies equivalents of the Barr Group sediments which occur to the north of the Stinchar Fault (Ince, 1984). Conglomerates in the Albany Group contain clasts that are identical to the 648 ± 35 Ma alkali granite clasts reported by Ince (1984) from the Kirkland conglomerate (personal field observation), north of the Stinchar Fault, which suggests that part of the Tappins Complex can be correlated with the Barr Group. However, there is evidence in this study to suggest that detritus in the Corsewall Point conglomerate was not derived from the Midland Valley, and the outcrop of the Albany Group, which occurs at the northern margin of the Glen App tract, is entirely fault-bounded (see Plate V of Williams, 1962). Thus, if the continuation of the Southern Upland Fault is considered to pass south of the Albany Group, it can be regarded as the more distal part of the Barr Group, and hence part of the Midland Valley succession, while the Traboyack and Dalreoch Groups can be regarded as the lateral continuation of Tract 1 of the Southern Uplands. The Corsewall Point and Glen App conglomerates belong to this part of the Tappins Complex, or are the lateral equivalents of it, and can be interpreted as trench deposits (see below). Consequently, they are also considered to belong to Tract 1 of the accretionary complex.

2.2.b Sedimentology.

2.2.b.i The Corsewall Point conglomerate.

The Conglomeratic Division of the Corsewall Group rests conformably on the Flaggy Division, a sequence of parallel bedded mudstones and siltstones which contain occasional coarser greywackes deposited by turbidity currents which flowed towards the south-west (Kelling, 1961; Kelling et al., 1987). The Flaggy Division is c. 750 m. thick, and towards the top of the sequence, the palaeocurrents rotate to show flow towards the south-east (Holroyd, 1978). The Conglomeratic Division contains arenites and granule grade conglomerates which pass upwards into boulder-bearing conglomerates at Corsewall Point and Milleur Point.

The coarse arenites which occur immediately beneath the conglomeratic units at Corsewall Point contain a variety of sedimentary structures. Some beds are graded and contain cross laminated and parallel laminated units. Most have sharp planar bases, but some have an erosive, channelized form (Plate 2.1). Some massive units contain isolated pockets of boulders, or individual boulders (Plate 2.2), which are probably related to the the thick rudite sequence at Milleur Point, to the north east, of which they are the lateral equivalents.

The rudaceous sequence is at least 150 m. thick at Corsewall Point; the top of the sequence is not exposed, and the lowest rudites occur at progressively higher levels in the sequence towards the south-west, part of a consistent trend across the peninsula from Milleur Point to Corsewall Point. Individual units are up to 5 m. thick, with an average thickness of 3.8 m. (Holroyd, 1978). However, the channelized nature of the rudites has resulted in lateral thickness variations, and is shown by the common occurrence of erosive bases and the presence of large rafts of finer grained laminated sandstones at the base of some rudites,

derived from the tops of the underlying units. Clast sizes vary from pebble grade material to boulders up to 1.5 m. in diameter, although most clasts have a diameter of c. 50 cms. The rudites are both clast and matrix supported and are disorganized (Plate 2.3).

The main source of palaeocurrent information for the rudites comes from the orientation of the channels in which they are contained. They show a consistent north-west - south-east orientation at Corsewall Point, and a similar but slightly less consistent orientation at Milleur Point (Holroyd, 1978; his Fig. 8.5). The mean orientation of eight readings taken from sole markings at Corsewall Point is 137° (Holroyd, 1978), which shows that the currents which caused the scour were flowing towards the south-east. All erosional structures from the rudaceous part of the Conglomeratic Division show a unidirectional pattern, with an average orientation of 151° (n=36, Holroyd, 1978; see Fig. 2.3a). The depositional features, such as cross beds and ripple laminations, which occur in arenites below and interbedded with the rudites, show much greater variation - the average orientation of all cross beds is 170° (n=13) and 190° for the ripple laminations (n=51, Holroyd, 1978). However, there is an even spread of data from south-east to west-south-west (Fig. 2.3b). This indicates that some of the currents which deposited the arenites were deflected towards the south-west, and not all were confined to the south-easterly trending channels that contained the rudites.

The features shown by the rudites indicate that they were deposited by dense cohesive debris flows that were capable of transporting boulders up to 1.5 m. in diameter and of eroding the channels in which they were confined. Laterally, the rudites pass into coarse arenites, the products of high density turbidity flows. Because these flows were not confined to channels, they were more dilute, and the palaeocurrent data obtained from them show greater variability. Consequently, they

could not transport such large clasts, although a few boulders were transported as suspended load, forming isolated pockets of conglomerate. However, the flows were still capable of localized scour (Plate 2.1). The features in the arenites are similar to those of the multiuple-scoured sandstone association described by Hein and Walker (1982) from the Cap Enragé Formation, which they interpret as deposits formed marginal to submarine channels.

Kelling et al. (1987) describe similar facies associations from the Milleur Point rudites, and also liken them to those described by Hein and Walker (1982). The Cap Enragé Formation is interpreted as a braided system of locally channellized flows within a single major submarine channel or canyon. However, at Corsewall Point the rudites appear to be stacked, rather than showing evidence of "multiple scouring and channelling with preserved bars between channels", which Hein and Walker (1982) regard as evidence of a braided system. However, the lateral relationships between the rudites and the arenites are compatible with deposition in a larger channel, but one in which the main site of deposition has shifted towards the south-west with time. Kelling et al. (1987) envisage an active channel two to three kilometres wide, which represents the most proximal part of a submarine fan complex.

The palaeocurrent information indicates that this channel was oriented north-west - south-east. The lowest part of the Corsewall Group, the Flaggy Division, consists of thinly bedded, fine grained turbidites of distal aspect, but because they contain palaeocurrents which indicate that flow was towards the south-west, they must have been deposited by a separate depositional system, the source of which lay to the north-east. The transition from the fine grained lithologies of the Flaggy Division to the coarser sediments of the Conglomeratic Division is rapid, and involves the rotation of palaeocurrents towards the south-east (Holroyd, 1978). It is not clear what proportion of the

Conglomeratic Division belongs to the submarine channel complex, but there is no coarsening upwards sequence within the unit, and the incoming of the rudaceous units is abrupt. As there is no sequence representing the intermediate parts of a submarine fan preserved between the distal and proximal facies of the Corsewall Group, it appears that there was a sudden switch to laterally derived material which was deposited on top of the earlier, axially derived and more distal sediments. Although such a pattern of sedimentation is not diagnostic of deposition in an ocean trench, it is consistent with it. Bimodal axial and lateral flow patterns develop in confined, elongate depositional basins, the shape and active tectonicism of which prevent the development of classic submarine fan sequences.

2.2.b.ii The Glen App conglomerate.

The exposures of the Glen App conglomerate are much less extensive than those of the Corsewall Point conglomerate, so the relationship of the rudite bodies to the adjacent units is not clear. However, the two conglomerates contain similar sedimentary features, which indicate that they were deposited under similar conditions.

The rudite units within the Glen App conglomerate, which outcrop on Smirton Hill (grid ref. NX 114793) and in a quarry on Leffin Donald Hill (grid ref. NX 145812), are much closer to the Glen App Fault than the Corsewall Point conglomerate is to the continuation of this fault on the Rhinns of Galloway (Fig. 2.2). Whilst siltstones and greywackes similar to the Flaggy Division of the Corsewall Group occur beneath the Finnarts Conglomerate (Fig. 2.2), such lithologies only occur at the south-western and south-eastern limits of the outcrop of the Glen App conglomerate; elsewhere coarse arenites similar to those of the Conglomeratic Division occur adjacent to the Glen App Fault (Walton, 1956). The overall shape of the rudite bodies cannot be discerned, but

they have sharp bases (Plate 2.4) and contain abundant sedimentary clasts. The conglomerates are disorganized and clast supported, and some of the coarse arenites contain isolated boulders similar to the lateral equivalents of the rudite bodies at Corsewall Point. These features allow the Glen App rudites to be interpreted in a similar manner to the Corsewall Point conglomerate - as the product of erosive high density cohesive debris flows which were confined to small channels, beyond which high density turbidity currents deposited coarse arenites containing isolated boulders.

Walton (1956) reports sedimentary structures from the coarse arenites and limited imbrication in the rudites which indicate flow from the north-west. The Glen App conglomerate is not as coarse grained as the Corsewall Point conglomerate - the largest observed clast has a diameter of 1.05 m., but most clasts have diameters in the range 30-50 cms. However, the deposits are still typical of the proximal part of a submarine fan complex, and may be interpreted in a similar manner to the Corsewall Point conglomerate, as the fill of a feeder channel or canyon.

The Glen App conglomerate is separated from the Finnarts conglomerate by finer grained facies more reminiscent of the Flaggy Division of the Corsewall Group (Walton, 1956), and although the detailed structure of the area is unknown, the Glen App conglomerate appears to occur at a slightly lower stratigraphic level. Thus it forms an earlier part of the sequence in which the feeder channel of the Glen App-Corsewall Point system shifted from north-east to south-west, depositing subsequently the Finnarts conglomerate, and then the Milleur Point and Corsewall Point conglomerates, which show this trend continuing across the Rhinns of Galloway.

2.2.c Clast assemblage.

The clast content of the Corsewall Point conglomerate has long been a source of interest. Moore (1840) first noted the presence of blocks of serpentinite, and Tyrrell and Begg (1933) commented upon the presence of "granitic gneisses and hornblendic rocks of 'Lewisoid' aspect", which led them to conclude that the Lewisian may outcrop beneath the sea not far to the west of the Rhinns of Galloway.

The Corsewall Point conglomerate contains clasts of granite, quartz-feldspar porphyry, gabbro, dolerite, basalt, chert and intraclasts of shale and greywacke (Peach and Horne, 1899; Tyrrell and Begg, 1933; Holroyd, 1978). Analyses of the clast content by Holroyd (1978) and in this study have produced comparable results (Fig. 2.4a). Both express the clast content in terms of the volume percentage of each rock type present, in order to take account of the variablity in the size of the clasts. The clast assemblage is dominated by acidic rocks - granitoid rocks account for c. 40% of the clasts, and finer grained acid igneous rocks for a further 15%. These are mainly quartz-feldspar porphyries with granophyric, crystalline groundmasses, derived from high-level intrusions, but include rare dacitic clasts of volcanic origin which contain phenocrysts of feldspar and inverted tridymite in an amorphous groundmass. The other main components are gabbro (c. 20%) and basalt and dolerite (c. 18%). The rest of the clast assemblage consists predominantly of red chert and greywacke and shale intraclasts. These figures represent an average for the whole conglomerate - 221 clast from four different rudite units were sampled in this study and 770 clasts from seven different units by Holroyd (1978). Comparison of the samples from different rudite units show that there is considerable variation in the composition of the clast populations, although some trends can be detected (Fig. 2.5). Whilst the proportion of granite remains consistently high, quartz-feldspar porphyry clasts become less

abundant towards the top of the sequence and gabbroic clasts become more abundant. The amount of basalt is more variable, but becomes slightly less common towards the top of the sequence (Fig. 2.5). This pattern indicates that erosion has reduced the volume of high level acidic porphyries exposed in the source area, but is not coupled with an increase in the amount of granitic detritus. This indicates that the granite plutons which were being eroded were unrelated to, and are therefore possibly older than, the high level intrusions. The increased abundance of gabbro towards the top of the sequence indicates that deeper levels of the basic component of the source area were exposed.

There are few clasts in the Corsewall Point conglomerate which could be interpreted as samples of older deformed crust from the source area, with the possible exception of some foliated hornblende-biotite granodiorite clasts (section 4.2.a) and rare clasts of strongly deformed quartz-feldspar rocks (sample nos. CoP 201 and 206). CoP 201 contains phenocrysts of plagioclase and alkali feldspar up to 2 cms. in length in which either the twin planes or exsolution lamellae contain kink bands (Plate 2.5). The quartz which surrounds the phenocrysts is extensively recrystallized, but due to the coarse grained nature of the sample, it does not exhibit a foliation. CoP 206 contains similar feldspar phenocrysts surrounded by recrystallized quartz, but is finer grained and also contains abundant microcline (Plate 2.6). The recrystallized quartz forms elongate stringers, as a result of which this sample has a weak foliation. Both samples are extremely quartz-rich and contain only tiny quantities of mafic minerals. Consequently, they could be the source of quartzose xenoliths that occur in muscovite-biotite granite clasts at this locality (section 3.2.a.i).

The clast population of the Glen App conglomerate contains a similar range of lithologies to the Corsewall Point conglomerate, and is again dominated by granitic clasts (Walton, 1956). However, at the base

of the sequence granitic detritus is sparse, and the most abundant clasts are basalt and dolerite (Fig. 2.4b). Chert fragments are also more common at this horizon which tends to suggest that the higher levels of an ophiolitic source were being eroded. Quartz-feldspar porphyries are also more abundant than granitic clasts, which also suggests that the Glen App conglomerate clasts are the product of higher levels of erosion. Such a relationship is consistent with the slightly younger stratigraphic position of the Glen App conglomerate. However, sedimentological sorting mechanisms may be responsible for the selective transport of certain clast types. Granites usually occur as larger, more rod-shaped clasts, while gabbros, dolerites and basalts commonly form smaller, more spherical clasts (Holroyd, 1978). Spherical clasts roll more easily than rod-shaped clasts, so weaker flows are more likely to transport small spheres (basic igneous lithologies) than large rods (granites). Granite boulders are more common higher in the sequence where the conglomerate contains larger clasts.

The source area of the Corsewall Point and Glen App conglomerates contained some old deformed granites and quartzo-feldspathic gneisses intruded by younger granites and high level intrusions. A basic component, consisting of gabbro, dolerite, basalt and chert, which may be loosely termed ophiolitic, was also present in the source area.

2.3 The Glen Afton conglomerate.

2.3.a Stratigraphy.

The Glen Afton conglomerate forms part of the Blackcraig Formation of W. Nithsdale (Floyd, 1982), and occurs in Tract 2b (McKerrow, 1986), which is bounded to the south-east by the Leadhills Line and to the north-west by the Langlee Fault (Fig. 2.6). The Leadhills Line is an

imbricated sequence of basalts, cherts and shales which yield graptolites that range in age from the N. gracilis zone to the D. clingani zone (Floyd, 1982).

The pelagic rocks associated with the Leadhills Line are succeeded by the Afton Formation, a c. 2000 m. thick succession of thinly bedded medium- to coarse-grained quartz-rich greywackes (Floyd, 1982). This is in turn overlain conformably by the Blackcraig Formation, which, by contrast, is thickly bedded, coarse grained and rich in ferromagnesian minerals. The Glen Afton conglomerate occurs close to the base of the Blackcraig Formation which is at least 1,500 m. thick (Floyd, 1982). Although unfossiliferous, the stratigraphic relationships described above indicate that the Glen Afton conglomerate is of D. clingani zone age or younger (Fig. 2.1). Quartz-rich greywackes, also assigned to the Afton Formation, occur north-west of the Langlee Fault, in Tract 2a, where they appear to be slightly older, probably of N. gracilis zone age (Floyd, 1982).

Floyd (1982) correlates the West Nithsdale succession with the succession described by Kelling (1961) from the Rhinns of Galloway, where quartz-rich greywackes of the Kirkcolm Formation are succeeded by the ferromagnesian-rich and coarser grained greywackes of the Galdenoch Group. However, the Kirkcolm Group overlies shales of N. gracilis zone age, and and could be considered part of Tract 2a. Alternatively, there may be a diachronous trend from south-west to north-east within Tract 2b (Leggett et. al., 1979), but given the similar lithostratigraphy of Tracts 2a and 2b, it is more likely to be a structural effect. Because of the presence of an additional tract in W. Nithsdale, the younger parts of the Afton Formation and the succeeding Blackcraig Formation overlie younger (D. clingani zone) shales in Tract 2b, but as this tract dies out towards the south-west, the whole succession occurs in Tract

2a, resting on older (N. gracilis zone) shales in the Rhinns of Galloway.

2.2.b Sedimentology.

The rudite units which comprise the Glen Afton conglomerate form a 170 m. thick sequence which is exposed in the bed of the Afton Water, below the Afton reservoir dam (grid ref. NX 628051), 300 m. above the base of the Blackcraig Formation (Floyd, 1982; Fig. 2.6). Although the contact with the underlying Afton Formation is poorly exposed, the contrasts in the petrographic and lithological characteristics of the greywackes which comprise the two units are marked, and the transition between them is rapid. The Afton Formation greywackes are of distal aspect and rare palaeocurrent indicators show that flow was from the north-east (Holroyd, 1978). The lower part of the Blackcraig Formation consists of coarse grained thickly bedded greywackes which become coarser towards the base of the rudite sequence.

The Glen Afton rudites differ from those at Corsewall Point in many respects, the most noticeable being that individual units are much better organized. The sequence consists of sharply-based beds up to 7 m. thick in which grading is well developed (Plate 2.7). Boulder conglomerates at the base of the beds are usually clast supported, and poorly developed inverse grading is sometimes apparent. Clasts up to one metre in diameter occur in these conglomerates, and in some instances sedimentary intraclasts are concentrated towards the the top of the conglomeratic part of the beds. The beds grade through granule grade conglomerates to coarse sands which are often massive or contain planar laminations (the "mega-graded units" of Kelling and Holroyd, 1978); large scale cross laminations are present at the tops of some units (Plate 2.8). Spectacular load features occur at the base of some beds (Plate 2.9).

There is only limited evidence from the outcrop that the rudite units were deposited in channels. The two rudite units at the base of the sequence show some cross-cutting relationships and others have irregular bases which indicates that localized scour was important; most of the beds, however, have planar bases. The abundant large intraclasts that occur in the conglomerate have the same petrography as the matrix of the conglomerate (Floyd, 1975) which provides further evidence of erosion, but as the clasts are well rounded, and are occasionally sorted, they must have been transported some distance, and may be the product of erosion elsewhere in the system. The overall shape of the rudite unit is lensoid in Glen Afton - boulder conglomerates can be traced laterally for 1 km. south-west of the Afton Water, but they die out within a few hundred metres to the north-east, where they pass into quartz pebble grits. A few conglomeratic horizons occur within the grits, but they thin laterally and are interbedded with shales and greywackes (Holroyd, 1978). These relationships indicate that although the Glen Afton conglomerate may have been deposited within a channel, it was not of great relief.

The mapped shape of the rudite unit (Floyd, 1975; Holroyd, 1978; see Fig. 2.6) indicates that the channel was probably oriented approximately north-west - south-east. This conclusion is supported by the orientation of scours at the base of three rudite units, which range from WNW-ESE to NW-SE in orientation (Fig. 8.5 of Holroyd, 1978). The average orientation of cross bedding at the base of the Blackcraig Formation indicates flow towards the east-south-east (117°, n=6), as do most current indicators within the rudite sequence (Fig. 2.7; Holroyd, 1978). However, Floyd (1975) reports that cross bedding at the top of one of the mega-graded units indicates flow towards the south-west, as do current indicators from the more thinly bedded units in the middle of the rudite sequence (Fig. 2.7). Although the rudites were derived from

the north-west, as at Corsewall Point, the greater variability in the palaeocurrent data at Glen Afton provides further evidence that channels played a less important role in confining flows.

Although there are no clearly defined vertical trends within the rudite sequence, boulder conglomerates do not occur continuously throughout it (Fig. 2.7). Two rudites near the base of the sequence are separated from the the other conglomeratic units by 30 m. of thickly bedded, coarse grained, graded arenites, and a similar succession of arenites and granule grade conglomerates occurs in the middle of the main rudite sequence. Despite this variability, there is a steady upward decline in the maximum size and proportion of extrabasinal clasts in the rudites, whilst the size of the largest clast remains constant (Fig. 2.7). This implies that although the competence of the flows is maintained, the supply of extrabasinal material declines (Kelling and Holroyd, 1978).

It is unlikely that the Glen Afton rudites were deposited by cohesive debris flows, as such a process would produce unsorted or poorly sorted deposits. The grading within the conglomerates, and the concentration of less dense intrabasinal clasts towards the top of the conglomeratic part of some units indicates a clast support mechanism and process of deposition which differentiates between clasts of different masses. In gravelly high density turbidity currents the coarsest clasts are concentrated at the base of the flow where they form a traction carpet in which the main support mechanism is dispersive grain interactions, whilst other clasts are suspended in the the lowest parts of the turbulent flow where other support mechanisms, such as fluid turbulence, also play a role. Deposition from such flows takes place when the velocity drops, which causes the traction carpet to freeze and produces an inversely graded base to the conglomerate. This is followed by direct sedimentation of the suspended clasts which are normally

graded (Lowe, 1982), producing a unit analogous to the inverse to normally graded conglomerate of Walker (1975). Removal of coarse clasts from the flow leaves a sandy high-density turbidity current, which may deposit a sequence of laminated, inversely graded and massive sands, thus forming an idealized sequence of deposits from a coarse grained turbidite (Lowe, 1982; Fig. 2.8).

Because the mechanisms of grain support are different in gravelly and sandy high density turbidity currents, sand and gravel units are unlikely to be deposited together, and a complete graded sequences (Fig. 2.8) are rarely found (Lowe, 1982). However, many of the Glen Afton rudite units are graded from coarse gravel to sand grade material, and differ from the idealized sequence (Fig. 2.8) in other respects. Consequently, it is likely that the Glen Afton rudites were deposited by some modification of the processes outlined above.

Inverse grading is present at the base of some of the rudite units, but is not well developed. This suggests that a larger proportion of the clasts were carried as suspended load rather than tractional load. The grading in the upper parts of the unit, from granule grade conglomerates to coarse sand, is also likely to be due to the gradual deposition of suspended load as velocity decreases, indicating a continuity of depositional processes which allows the large graded units to form. In addition to the grading, the presence of parallel laminations in most units, and cross laminations at the top of some, implies that suspension deposition was slow enough to allow tractional features to form at the base of the flow. Rapid suspension deposition forms poorly graded massive beds, as traction structures do not have sufficient time to develop. Consequently, it is envisaged that the Glen Afton rudites were deposited by the gradual waning of large, sustained, high-density turbid flows. The spectacular load features present at the base of some units

indicate that the coarse sands retained a high pore water content and that deposition of suceeding units was relatively rapid.

Conglomerates deposited by turbid flows are more typical than conglomerates deposited by debris flows in the less proximal parts of submarine fans (Walker, 1978). Evidence from the Glen Afton conglomerate indicates that the rudites were deposited in shallow channels, which is also a characteristic of mid-fan environments. Meandering flows are also a feature of the mid-fan, and such a process may account for the series of thinly bedded coarse arenites that separate the rudaceous parts of the sequence (Fig. 2.7). Consequently, the Glen Afton conglomerate was probably deposited in the distal part of of an upper fan or the proximal part of a mid-fan, a view shared by Kelling et al. (1987). The thickness of the units, and the rapidity with which they were emplaced, implies a high rate of sediment supply.

The more general palaeogeographic situation in which the Glen Afton conglomerate was deposited is similar to that envisaged for the Corsewall Point conglomerate. Palaeocurrent information indicates that the Glen Afton fan was supplied laterally from the north-west, but there is no evidence that it gradually prograded into the basin. The rudite sequence itself is remarkably stable, showing little variation in bed thickness or maximum clast size. Instead, the Blackcraig Formation was deposited on top of the Afton Formation which belongs to the distal part of an unrelated axially supplied system, a pattern that is consistent with sedimentation in a subduction trench.

2.3.c Clast assemblage.

The range of rock types occurring as clasts in the Glen Afton conglomerate is similar to that in the Corsewall Point and Glen App conglomerates. Granite, fine grained acidic rocks, gabbro, dolerite, basalt and chert are common to all three deposits. Sandstone intraclasts

are more abundant and more varied in the Glen Afton conglomerate, and larger shale fragments are also present. Vein quartz and quartzite are present in small quantities, and Peach and Horne (1899, p. 385) also note the occurrence of limestone clasts, not observed in this study.

The estimates of clast composition made by different workers vary considerably (Fig. 2.9). This may partly reflect the considerable variation in clast content between different beds, but may also be due to different methods of calculation. This study averages the results obtained from four different beds, whilst Floyd (1975) and Peach and Horne (1899) appear to have based their estimates on a single horizon. Both the clast size and the numbers of boulders present are taken into account in this study, which has the effect of increasing the estimated proportion of those rock types, such as granite, which predominantly occur as large clasts.

The only compositional trend shown by the Glen Afton conglomerate is the steady increase in the proportion of intrabasinal sedimentary clasts up the sequence (Fig. 2.7), which culminates in beds consisting entirely of such clasts (Plate 2.10). Most of the greywacke clasts are similar to the greywackes of the Blackcraig Formation, and are clearly the product of localized erosion, but some contain sedimentary structures which are not displayed by adjacent greywackes (Plate 2.11). These clasts may have been transported greater distances, along with shale fragments.

Even when the extrabasinal clasts are considered in isolation, they show no clear compositional trends, and unlike the clasts at Corsewall Point, do not reveal a simple erosion history of their source area. This suggests that the clast content of the Glen Afton conglomerate is influenced to a greater extent by pre-depositional sedimentary processes, which have randomly mixed the clasts derived from different components of the source area. There is some evidence that the

concentrations of chert and basic igneous clasts are linked, which may suggest that they are derived from a common ophiolitic source. As the proportion of extrabasinal clasts in the conglomerate declines, those that remain are predominantly coarse and fine grained acid igneous varieties, which may be the residual component of the detritus, left by sedimentary processes that operated in the source area.

In comparison to the Corsewall Point conglomerate, the sedimentary clasts in the Glen Afton conglomerate are more abundant and more varied. Basic igneous clasts form a smaller proportion of the detritus, and are almost equal in abundance to chert. At Corsewall Point, chert is less common, and is subordinate to basic detritus. If a similar ophiolitic source is envisaged for this component of the detritus, the greater proportion of chert in the Glen Afton conglomerate may be taken as further evidence of the effect of sedimentary processes in determining its clast composition. The chert fragments are more commonly dark grey in the Glen Afton conglomerate, in comparison to the red varieties that are prevalent at Corsewall Point. The cherts preserved in the stratigraphic sequences are usually red at the base of Tract 1 and grey at the base of Tract 2 (Leggett et al., 1979), which implies that the chert is locally derived, and that the source of the two conglomerates is separate. The basalt clasts also differ: those from Glen Afton include varieties with large feldspar phenocrysts and epidote filled amygdales (Plate 2.12), in contrast to the predominantly aphyric varieties which occur in the Corsewall Point conglomerate.

Most of the fine grained acid igneous clasts in the Corsewall Point conglomerate are quartz-feldspar porphyries, derived from high-level intrusions. Similar clasts occur in the Glen Afton conglomerate, but acid igneous clasts, which contain a few small feldspar phenocrysts in a fine grained, recrystallized groundmass, are more abundant. Some also contain rock fragments with perlitic cracks (Plate 2.13), and others

show flow banding. Their presence indicates that an extrusive rhyolitic component is more important in the source area of the Glen Afton conglomerate than the Corsewall Point conglomerate.

Deformed crustal lithologies are represented by rare quartzo-feldspathic gneisses, similar to those from Corsewall Point, and hornblende schists, some of which show a gneissic banding, but which are not present at Corsewall Point. The quartzite clasts, which form a significant proportion of the detritus, represent an additional crustal component.

The source areas of the Glen Afton and Corsewall Point conglomerates have similar characteristics - they both contain granites intruded into older deformed crust and include a basic component, which is probably ophiolitic. The differences in the nature of the clasts in the two conglomerates suggest that the source areas were not identical, which, in addition to the effects of the sedimentary processes that transported the detritus, may be responsible for contrasting clast assemblages of the two conglomerates.

2.4 The Shinnel Formation conglomerate.

2.4.a Stratigraphy.

The Shinnel Formation, which occurs in Tract 3d of McKerrow (1986), outcrops to the south-east of the Fardingmullach Fault and north-west of the Orlock Bridge-Kingledores Fault, which marks the Ordovician-Silurian boundary (Floyd, 1982; Figs. 1.3 and 2.6). There are no fossiliferous black shales exposed at the base of this tract, but shales interbedded with greywackes near the base of the sequence contain *P. linearis* zone graptolites, which give a maximum age for the Shinnel Formation (Peach and Horne, 1899; Floyd, 1982).

The Shinnel Formation consists of thinly bedded fine to medium grade greywackes which are rich in quartz and poor in ferromagnesian minerals and feldspar. This distinguishes them from the the quartz-poor, feldspar- and ferromagnesian-rich greywackes of the Scaur Formation which are also of P. linearis zone age, and occur in Tract 3c, between the Fardingmullach Fault and the Leadhills Line (Floyd, 1982; Fig. 2.6). The conglomerates form a sequence 350 m. thick which occurs near the base of the Shinnel Formation.

On petrographic grounds Floyd (1982) correlates the Shinnel Formation greywackes with the quartz-rich part of the Acid Clast Division of the Portpatrick Formation of Kelling (1961), termed the Portayew Rocks, which occur in a similar structural position, between the continuation of the Fardingmullach Fault and the Kingledores Fault, on the Rhinns of Galloway. The precise stratigraphic age of the Portayew Rocks is unclear: Kelling (1961) reports a lower Hartfell fauna from shales close to the Kingledores Fault which suggests that the Portayew Rocks are slightly older than the Shinnel Formation. Morris (1987), on the other hand, considers the Shinnel Formation to be peculiar to West Nithsdale, and without lateral equivalents.

2.4.b Sedimentology.

The best outcrops of the Shinnel Formation conglomerate are seen in Scaur Water, immediately upstream from Chanlockfoot Farm (Grid ref. NS 790001; Fig. 2.6). Although similar in some respects to the Glen Afton conglomerate, the maximum size of the extrabasinal clasts in the Shinnel Formation conglomerate is smaller, and intrabasinal clasts are more abundant throughout the sequence. In contrast to the thick graded units that are common in the Glen Afton conglomerate, the Shinnel Formation conglomerate is more thinly bedded, and grading is only occasionally

developed. The rudite units are more usually interbedded with coarse sands and granule grade conglomerates (Fig. 2.10).

Most of the rudites have sharp, erosive bases, but due to the limited outcrop, it is difficult to show any channelized relationships. The conglomerates are clast supported (Plate 2.14), and the coarsest clasts are concentrated at the base of the beds which thus exhibit a crude normal grading, although inverse grading is observed occasionally. The interbedded granule grade conglomerates and coarse sands, or, where present, the graded tops of the rudite units, are usually massive or contain both continuous and discontinuous pebbly or granule-grade laminae (Plate 2.15).

The rudites in the Shinnel Formation conglomerate have more in common than the Glen Afton rudites with the idealized sequence of Lowe (1982; Fig. 2.8), which implies that the two conglomerates were deposited by different processes. The association of coarse laminae and massive sands seen in the Shinnel Formation (Plate 2.15) results from collapse of the traction carpet of coarse material carried at the base of a flow, followed by the rapid deposition of suspended load (Lowe, 1982). This contrasts with the well developed tractional structures in the Glen Afton conglomerate, which are the product of the more gradual deposition of suspended load. The separation of conglomeratic and sandy beds implies that more conglomeratic material was transported as traction load by the flows which deposited the Shinnel Formation conglomerate (Lowe, 1982). Consequently, the continuous deposition of suspended material which produced the mega-graded units at Glen Afton could not take place. The greater proportion of detritus carried as suspended load, and the larger clast sizes, implies that the flows which deposited the Glen Afton conglomerate were more turbulent. More turbulent flows could also have supported a greater volume of suspended sediment, which explains the greater thickness of the beds in the Glen

Afton conglomerate. The absence of load structures in the Shinnel Formation indicates that the beds were deposited in less rapid succession. These characteristics suggest that the Shinnel Formation conglomerate was deposited in a more distal setting, or in a system with a lower sediment input rate, than the Glen Afton conglomerate.

The outcrop of the Shinnel Formation conglomerate is lenticular. It passes into finer grained rocks not far to the north-east of Scaur Water and the south-west of Shinnel Water (Fig. 2.6). Unlike Glen Afton, the rudite bodies are not confined to the central part of the conglomerate outcrop, and some can be traced from Scaur Water to Shinnel Water (Holroyd, 1978). This suggests that the Shinnel Formation rudites were deposited by more extensive flows in wider channels than the Glen Afton conglomerate, which is also indicative of a more distal submarine fan environment.

The channels in the Shinnel Formation conglomerate are oriented WNW-ESE (Fig. 8.5 of Holroyd, 1978), and structures within the rudites show that flow was in directions which vary between ESE and SE (Fig. 2.10). Holroyd (1978) also reports depositional structures from beds immediately above the conglomerate which consistently show flow in a south-westerly direction (213°, n=40), although rare erosive sole markings are oriented towards the south-east, indicative of meandering flows. Beds higher in the sequence contain sole markings which are consistently oriented due east (89°, n=14). Floyd (1975) likewise reports current indicators with a variety of orientations. These data suggest that, like the other deposits studied, the Shinnel Formation conglomerate was derived from the north-west or west-north-west, but occurs in a system in which turbidites transporting finer material were deflected in a variety of directions. Combined with the other sedimentological information, this indicates deposition in a mid-fan environment, beyond the confines of the main feeder channel.

Although Holroyd (1978) reaches similar conclusions about the more distal nature of the Shinnel Formation conglomerate relative to the Glen Afton conglomerate, based largely on their textural attributes, his suggestion that the two deposits belong to the same system is considered unlikely. The palaeoentological evidence summarized above suggests that the Shinnel Formation conglomerate is younger than the Glen Afton conglomerate and it is associated with greywackes which are virtually devoid of ferromagnesian minerals, whilst the Glen Afton conglomerate occurs within the Blackcraig Formation which contains abundant ferromagnesian mineral detritus. As both formations are derived from the north-west, this also implies a major change in the nature of the sediment supplied to the subduction trench.

2.4.c Clast assemblage.

Both Floyd (1975, 1982) and Holroyd (1978) consider the clast content of the Shinnel Formation conglomerate to be similar to that of the Glen Afton conglomerate, and the clast lithologies listed by Peach and Horne (1899, p. 383) have a familiar ring:-

> "acid and basic intrusive igneous rocks...diabase lavas...chert, black and grey varieties, blue and grey greywacke, grey shale, black shale, quartz etc."

Fine grained acid igneous rocks are also common, as are clasts of limestone. However, comparison of the single estimate of clast composition made by Holroyd (1978; Fig. 2.11) with similar estimates from Glen Afton (Fig. 2.9) shows significant differences in the relative proportions of the rock types present. Granite clasts are much less common in the Shinnel Formation conglomerate, but quartzite and sedimentary clasts are more abundant.

Rhyolitic clasts containing a few phenocrysts set in a recrystallized quartz-rich groundmasss occur in both conglomerates, but the Shinnel Formation conglomerate also contains more feldspar-phyric

clasts which contain abundant small feldspar laths in the groundmass and are of a trachytic composition. Quartz-feldspar porphyries occur in both conglomerates, but are considered with the granite clasts in this instance. The clasts of basic igneous rocks are mainly dolerite and basalt - gabbros are extremely rare.

The sedimentary clasts in the Shinnel Formation conglomerate include a significant proportion of limestone, some bioclastic, which is extensively recrystallized. Consequently, the original faunal content cannot be identified. However Peach and Horne (1899, p. 384) report the presence of Orthis and crinoid stems in such clasts. These fauna also occur in the Wrae Limestone and other fossiliferous conglomerates in the Lowther Beds which are of the same age and occur along strike from the Shinnel Formation conglomerates. In this instance the limestone clasts are derived from the shelf lying to the north-west, rather than from a seamount as suggested by Leggett (1980b) for the Wrae Limestone. Peach and Horne (1899, p. 384) also report the presence of Diplograptus and Climacograptus fragments from black shale clasts.

The range of older deformed lithologies that are present in the Corsewall Point and Glen Afton conglomerates do not occur in the Shinnel Formation conglomerate, although quartzite clasts are more common. Two varieties occur - weakly foliated pure quartzites and less deformed more granular quartzites which also contain appreciable quantities of feldspar. Whether the contrasting composition of the detritus in the Shinnel Formation conglomerate reflects the operation of different sedimentary processes, rather than changes in the source area, is difficult to assess. A greater degree of sedimentary reworking may explain some features, such as the relative rarity of gabbroic clasts in the Shinnel Formation conglomerate. However, the presence of more varied detritus of volcanic origin, the lower abundance of granite clasts as compared to fine grained acid igneous clasts and the more

common limestone clasts are difficult to explain in terms of sediment reworking or the evolution of a single source area. The srikingly different composition of the associated greywackes also implies that there was a more fundamental change in the nature of the source area that lay to the north-west of the Southern Uplands in the early Ashgill.

2.5 The Pinstane Hill conglomerate.

2.5.a Stratigraphy.

The Pinstane Hill conglomerate outcrops north of Moffat, 3½ km. south-west of the Orlock Bridge-Kingledores Fault, which divides the Ordovician greywackes of the Northern Belt from the Silurian greywackes of the Central Belt (Fig. 2.12). The main conglomerate occurs as a patchy band of loose blocks just south of the summit of Pinstane Hill, but further bands of conglomerate are exposed in stream sections on the northern slopes. Fossiliferous black shales do not occur in this region and there is no obvious fault which delineates the tract to which this deposit belongs. However, the proximity of the conglomerate to the Kingledores Fault indicates that it probably occurs in Tract 4, and a zone of highly deformed greywackes and shales which occur in the British Gas pipeline 1½ km. south-west of Pinstane Hill (BGS unpublished data), marked on the 1-inch Geological Survey map of Moffat (sheet 16) as "greywackes and shales cleaved and rendered schistose", may mark the base of Tract 4 in this region (Fig. 2.12).

The greywackes associated with the Pinstane Hill conglomerate have a greenish hue, which indicates that they contain a high concentration of ferromagnesian mineral detritus. This is also a characteristic of other Tract 4 sediments, such as the Pyroxenous Group of Walton (1955),

which occurs to the north-west in the Peebles area, and the Kilfillan Formation of Gordon (1962) which occurs to the south-west around Glenluce (Leggett et al., 1979). The Pyroxenous Group overlies shales of the M. acuminatus or C. vesiculosus zone, and is interbedded with shales of the M. gregarius and M. sedgwickii zones (Casey, 1983). Likewise, the Kilfillan Formation is associated with graptolites of the M. acuminatus, C. vesiculosus and M. gregarius zones. Thus it is likely that the Pinstane Hill conglomerate is also of M. acuminatus or C. vesiculosus zone age, or younger.

2.5.b Sedimentology.

As the outcrop of the Pinstane Hill conglomerate consists of dispersed blocks and poorly exposed stream sections, it yields sedimentological data of only limited quality. However, the features displayed by the separate blocks reveal the sedimentological processes which operated, and the general relationships of the conglomeratic units to the surrounding lithologies allow the environment of deposition to be deduced.

Clasts up to 30 cms. in diameter occur in what are predominantly clast supported conglomerates. Most of the conglomerates are chaotic, but some show inverse grading at the base. Massive or poorly graded granule grade conglomerates and coarse sands often cap the conglomeratic units; some also contain discontinuous laminae of pebbly and granule grade material, or large isolated boulders (Plate 2.16).

The concentration of the coarsest clasts at the base of the depositional units, and their chaotic nature, indicates that most of the material was probably carried as tractional load, supported as grain dispersions, the freezing of which produced the inverse-graded parts of the beds. However, isolated boulders in the sandy layers indicate that some of the coarse material was also carried as suspended load, and that

fluid turbulence was not the only support mechanism operative in this part of the flow. Rapid deposition of the suspended load must have taken place to prevent such large clasts from settling out, and to produce the massive sands in which they are set. Where deposition was more gradual, textural features such as pebbly laminae could form. Such processe are typical of gravelly high density turbid flows (Lowe, 1982), and this indicates that the Pinstane Hill conglomerate was the product of similar depositional mechanisms to those which formed the Glen Afton and Shinnel Formation conglomerates.

The Pinsatne Hill conglomerate differs from the other conglomerates studied as it is not associated with coarse arenites, but occurs in a sequence of fine sands and silty lithologies. Siltstones outcrop between the conglomerate bands, and the bases of some conglomeratic units contain abundant siltstone clasts derived from the underlying beds. The conglomerates also have highly irregular bases, which suggests that they are erosive into the siltstones.

The strike-wise continuation of the conglomerate is not entirely clear, due to the paucity of the outcrop. The section exposed by the British Gas pipeline to the southwest consists largely of thinly bedded siltstones and shales and massive fine to medium grained greywackes. However, the greywackes are coarser and contain graded conglomerates along strike from one of the conglomerate bands exposed in the stream section to the north of Pinstane Hill (BGS unpublished data, Fig. 2.12). Further to the south-east, a roadcut adjacent to the A74 reveals a sequence of graded coarse grained units containing granule grade conglomerates which are separated from a sequence of massive sands by c. 40 m. of laminated fine grained sands and silts (Fig. 2.13). This may represent the lateral equivalent of the sequence seen at Pinstane Hill, where there is a similar relationship between coarse and fine grained facies. Likewise, to the north-west, in Dodd's Brae (Fig. 2.12), two

granule grade conglomerate beds occur in a sequence of well bedded, laminated fine grained sands and silts.

The relationship between the different conglomeratic and coarse sandy units cannot be determined precisely, but it appears that they form a number of lenticular bodies separated by fine sands and silts. The shape of these units, and the clear contrast in grain size with the adjacent lithologies implies that they were deposited in channels, oriented north-west - south-east, which were of sufficient relief to contain the turbulent flows, and which shifted position from time to time. No palaeocurrnet indicators were found in the Pinstane Hill conglomerate, but elsewhere the Pyroxenous Group shows derivation from the north-west (Casey, 1983). Thus it is concluded that in common with the other conglomerates investigated in this study, the Pinstane Hill conglomerate forms part of a submarine fan which was supplied from the north-west. The lateral extent of the separate lenses is less than the width of other conglomerate outcrops, which implies that the Pinstane Hill conglomerate was deposited in channels associated with a smaller scale submarine fan. The incised nature of the channels implies deposition in an upper fan environment, but the absence of cohesive debris flows and the shifting position of the channels are more typical of the lower parts of an upper fan.

2.5.c Clast assemblage.

The Pinstane Hill conglomerate contains clasts of granite, fine grained acid igneous rocks, quartzite, vein quartz, basalt, chert, rare boulders of coarser grained basic igneous rocks, greywacke and shale; an assemblage which closely resembles that of the Shinnel Formation conglomerate, although it lacks limestone clasts.

Detailed clast counts were not carried out at this locality because of the poor quality of the outcrop, but as in the Shinnel Formation

conglomerate, the most prominent members of the clast assemblage are fine grained acid igneous rocks and quartzites. The former group consists mainly of dacitic fragments, which contain abundant phenocrysts of quartz and feldspar and rarer phenocrysts of biotite, but also includes some rhyolitic clasts which contain small inverted tridymite phenocrysts and abundant lithic fragments of volcanic origin. Trachytic varieties, which are present in the Shinnel Formation conglomerate, do not occur here. Quartz-feldspar porphyries, in which the groundmass consists of delicate micrographic intergrowths, are also present. The quartzites are similar to the granular feldspar-bearing clasts that occur in the Shinnel Formation conglomerate, but are coarser grained.

Basalts are a more prominent component of the clast assemblage in the Pinstane Hill conglomerate, and sedimentary clasts are less common than in the Shinnel Formation conglomerate. The greywacke clasts are more indurated than the matrix which implies that they may be derived from a pre-lithified source, but thin section examination shows that they contain abundant feldspar fragments, occasional ferromagnesian minerals such as pyroxene, hornblende and biotite, and very little quartz. Such features are characteristic of the Pyroxenous Group (Walton, 1955), of which the Pinstane Hill conglomerate is the along-strike equivalent.

Because the greywacke clasts in the Pinstane Hill conglomerate could not be derived from the quartz-rich greywackes of the Shinnel Formation, and because of the petrographic differences between the various types of clast that occur in the two deposits, the Pinstane Hill conglomerate could not be derived by the reworking of the Shinnel Formation conglomerate. There must have been an input of fresh detritus during the Early Silurian, but it was derived from a source area with similar characteristics to that which supplied the Shinnel Formation conglomerate.

2.6 The Craigenputtock and Barhaskine conglomerates.

2.6.a Stratigraphy.

The Craigenputtock conglomerate outcrops on Castramon Hill (formerly Craigenputtock Hill), 7½ km. due south of Moniaive (grid ref. NX 777835). The Barhaskine conglomerate occurs 55 km. along strike to the south-west, and forms a laterally extensive outcrop 8 km. south-east of Glenluce (grid ref. NX 258539 - see Fig. 1.3). Both conglomerates are assigned to Tract 5a of McKerrow (1986).

Black shales of the M. gregarius zone, which mark the base of Tract 5a, occur immediately beneath the greywackes associated with the Craigenputtock conglomerate (Peach and Horne, 1899, p. 156-158). The Intermediate Group of Walton (1955), which occurs along strike to the north-east, consists of quartz-rich greywackes of similar composition to those at Craigenputtock, and also succeeds shales of the M. gregarius zone. The Craigenputtock conglomerate is considered to to be the lateral equivalent of, and the same age as, the Intermediate Group.

The Barhaskine conglomerate occurs towards the top of the Garheugh Formation of Gordon (1962), which also succeeds shales of the M. gregarius zone, and contains greywackes of a similar quartz-rich petrography (Casey, 1983). Kelling et al. (1987) subdivide the Garheugh Formation on sedimentological grounds, and assign the two parts to separate tracts. Their Tract 5a, in which the Barhaskine conglomerate occurs, is unfossiliferous, but as the greywackes of the two parts of the Garheugh Formation are of the same composition, they are considered here to belong to the same unit and are therefore all post-M. gregarius zone in age.

2.6.b Sedimentology

2.6.b.i The Craigenputtock conglomerate.

The Craigenputtock conglomerate forms a spectacular outcrop of poorly bedded, chaotic boulder conglomerate, which has a lensoid shape and is associated with massive, poorly bedded coarse sand and granule grade greywackes. Despite the disorganized nature of the deposit, there is a crude coarsening upwards sequence from black graptolitic shales, through massive silts to finer grained sands interbedded with silts. These are succeeded by the various coarse grained units described above, which are randomly interbedded with one another. However, the finer grained facies comprise only a small part of the succession which represents a rapid transition from fine grained pelagic deposition to coarse grained clastic deposition.

Massive sandstones dominate the lower part of the sequence, and are interpreted as the rapidly deposited suspended load of sandy high density turbid flows. They are structureless and ungraded, as a result of which it is difficult to determine the thickness of individual units. Thin discontinuous silty bands are occasionally present, and pass laterally into strings of clasts of the same material. These represent the remnants of the fine grained tops which may have originally capped each sandstone unit, but were removed as a result of erosion by the subsequent flow. The thick sequence of amalgamated massive sandstones probably result from the deposition of individual units in rapid succession: incomplete lithification of units between depositional events would have facilitiated the removal by erosion of the finer grained tops of sandstone units, and material of similar grain size from separate depositional units could have become homogenized, thereby obscuring bedding.

Bedding is also poorly developed in the rudite units. Although individual rudite units are up to 5 m. thick, it is difficult to trace them laterally, which implies that they are lenticular. Although they lack sharp or regular bases, the rudites contain a high proportion of intraformational sandstone clasts which testifies to the erosive nature of the flows from which they were deposited. Extrabasinal clasts up to 25 cms. in diameter occur within the rudite units which are disorganized and are either clast or matrix supported (Plate 2.17). Some rudite units consist entirely of sandstone clasts up to 50 cms. in diameter which are either supported by a matrix of granule grade material (Plate 2.18), or are apparently in contact with one another, although each clast is surrounded by a rim of granule grade material. It is unlikely that the clasts in the latter group of intraformational conglomerates have been transported far, as little mixing has taken place with the granule grade matrix; instead they may have been entrained as a tractional carpet in flows less turbulent than those which deposited the extrabasinal conglomerates. The rudites are randomly interbedded with, and pass laterally into, massive coarse sand and granule grade greywackes, some of which contain isolated boulders. Some rudite units also contain discontinuous sandy lenses (Plate 2.17).

Because of the chaotic nature of the rudites, their lenticular shape, and the random nature of their interbedding with other lithiologies, they are interpreted as the deposits of erosive, high density cohesive debris flows. Evidence that channels were eroded into poorly consolidated massive sands comes from the poorly developed bedding, the large number of intraclasts, and from a small conglomeratic lens which occurs below the main rudite units. It is distinguished from them by containing dispersed extrabasinal clasts supported by a silty matrix (Plate 2.19). Because of the contrast in grain size, it is possible to see considerable intermixing between the fine grained matrix

and coarser sand from adjacent beds, which suggests that they were incompletely lithified when the small rudite unit was deposited.

The channelized nature of the rudites, the rapidity with which they were deposited and the sedimentary transport processes that operated are consistent with the deposition of the rudites in a proximal submarine fan environment. Because of the amalgamated nature of the beds and the absence of tractional bedforms, there are no palaeocurrent indicators, but the lack of along-strike continuity of the rudite units indicates that they were deposited in channels oriented approximately north-west - south-east, at a high angle to the strike. A similar, but less well developed rudite sequence on the adjacent hill of Knockure indicates a lateral shift in the site of deposition. However, these proximal facies were deposited on top of pelagic shales, which precludes the presence of a classic prograding submarine fan sequence. The lack of structure within the coarse arenites and the thickness of the units implies that the load carried by individual flows was rapidly deposited, possibly as a result of a sudden change in gradient. The Craigenputtock conglomerate is therefore interpreted as having formed at the mouth of a submarine canyon where it debouched onto oceanic crust, with its covering of pelagic shales, shortly after it entered the subduction trench. The succeeding beds, although still massive, show better developed grading and more clearly defined bedding which indicates that the sediment load was deposited more slowly, possibly as a result of a reduction in the gradient as the sediment pile built up.

2.6.b.ii The Barhaskine conglomerate.

The outcrop of the Barhaskine conglomerate can be traced laterally for 7 km. from Craigeach Fell (grid ref. NX 318565) to west of Barhaskine Farm (grid ref. NX 256538), south-east of Glenluce (see Fig. 1.3). Outcrops of black graptolitc shales in Gillespie Burn, immediately

to the north-west of the conglomerate outcrops at Barhaskine, mark the base of Tract 4; thus the conglomerate occurs at the top of the sequence of sediments which comprise Tract 5 in this region.

The lower part of the sequence is dominated by coarse sand and granule grade greywackes, some of which are reminiscent of those that underlie the conglomerate at Craigenputtock - massive structureless sandstones, capped by thin discontinuous bands of finer grained sand and silt which pass laterally into clasts of the same material, and conglomerates consisting entirely of sandstone clasts surrounded by a thin layer of granule grade matrix. Granule grade conglomerates, which have highly irregular, convoluted bases, some of which show spectacular loading (Plate 2.20), are associated with these lithologies. The sedimentological features of this part of the sequence indicate rapid deposition of suspended material from coarse grained, high density turbid flows, emplaced in rapid succession.

The poorly bedded facies alternate with units in which bedding is better developed (Plate 2.21). Grading and tractional features such as parallel laminations, convolute laminations and, less commonly, low angle cross bedding are also observed in these units. They represent the product of the more gradual deposition of suspended load from flows emplaced in less rapid succession than the poorly bedded units. Where grading is better developed, it is possible to show that the units have erosive bases, as it is rarely possible to trace the boundary of a particular unit for any great distance.

The conglomeratic part of the sequence contrasts strongly with that at Craigenputtock. The individual rudite units are usually c. 1 m. thick, well bedded, often inverse-to-normally graded and together comprise a sequence less than 10 m. thick (Plate 2.22). The rudites contain extrabasinal clasts up to 30 cms. in diameter, and where the long axes show a preferred orientation, they are oriented north-east -

south-west (Fig. 2.14). Cross cutting relationships illustrate the erosive nature of the flows. The rudites are often succeeded by, and occasionally passes laterally into, a thinly bedded, finer grained silty facies. Because of this marked differentiation of grain size, the conglomeratic flows were probably confined to incised channels. The size of the units indicates that they were transported by smaller flows and that they were deposited in smaller channels than the rudite units in the Craigenputtock conglomerate. The development of inverse-to-normal grading indicates that they represent deposition of the tractional and suspended load of conglomeratic turbid flows (Lowe, 1982), in contrast to the rudites in the Craigenputtock conglomerate, which formed by the freezing of cohesive debris flows.

The more organized nature of the rudites in the Barhaskine conglomerate indicates that they were deposited in a less proximal part of a submarine fan complex. Periodically advancing and laterally shifting sedimentary lobes are characteristic of mid-fan environments and could produce the observed alternation between sequences of coarser, less well bedded sands and granule grade conglomerates, and the finer grained units in which bedding and grading are better developed. Such features correspond to the axial channel facies association described by Underwood and Bachman (1982) from modern subduction trenches. The alternation of coarse conglomerates and thinly bedded silts in the rudaceous part of the sequence provides evidence that the conglomerates conglomerates were deposited in meandering channels; thus the sequence associated with the Barhaskine conglomerate may mark the transition from a mid fan environment to the distal part of a proximal fan.

The orientation of clasts in the Barhaskine conglomerate and the lateral extent of its outcrop suggests that the channels were oriented north-east - south-west. This supports the palaeocurrent data reported by Kelling et al. (1987) which indicate that the sediments in this part

of the Garheugh Formation were derived from the north-east, and raises the possibility that the Craigenputtock and Barhaskine conglomerates belong a related axial fan system, developed within the subduction trench. If the input to the trench was in the vicinity of Craigenputtock, the Barhaskine sequence may be the product of the progradation of an axial fan towards the south-west.

2.6.c Clast assemblage.

The clast content of the Craigenputtock and Barhaskine conglomerate is distinguished from the other conglomerates by the absence of granite clasts and basic igneous detritus. A small amount of chert and fine grained acid igneous rock is present, but the extrabasinal clast assemblage is dominated by vein quartz and quartzite. However, sedimentary material forms the largest proportion of the clast population, and includes greywacke, shale and limestone clasts. The strong similarity between the clast assemblage of the Craigenputtock and Barhaskine conglomerates provides further evidence that they belong to the same depositional system.

Detailed clast counts were not undertaken at either locality because clasts have been removed from weathered exposures, leaving a strongly biased sample. However, it is clear that the clast population represents a much more "mature" assemblage than that in other conglomerates. Some of the quartzites in the Craigenputtock and Barhaskine conglomerates are similar to clasts that occur in the Pinstane Hill and Shinnel Formation conglomerates, which suggests that they may have been derived from similar sources, and more extensive sedimentary reworking may account for the dominance of such clasts in these deposits. However, the Pinstane Hill conglomerate, which contains a diverse clast assemblage, occurs in the tract immediately to the north-west, and is only two or three graptolite zones older than the

Craigenputtock and Barhaskine conglomerates. The marked change in clast content may indicate that other processes were also controlling sediment supply.

The granodiorite clasts reported by Gordon (1962) from the Barhaskine conglomerate were not found, but a small number of clasts of silicified oolite are present in this deposit (Plate 2.23).

Chapter 3

CHAPTER 3

THE PETROGRAPHY AND GEOCHEMISTRY OF THE GRANITE CLASTS.

3.1 Introduction.

The range of detritus present in each of the conglomerates investigated in this study reveals the characteristics of the source areas that supplied detritus to the Southern Uplands and allows some assumptions to be made about the relationships between them. The granite clasts contain more detailed information about the tectonic regimes in which the granitic magmas were generated and the conditions under which the original plutons were intruded. The comparison of such information from different conglomerates illustrates more precisely the relationships between the different sediment sources.

The granite clasts fall into a number of distinct petrographic and geochemical groups. The variation in the characteristics shown by the clasts within each group can used to show which samples are likely to be cogenetic, information which forms the basis of the selection of samples used to construct Rb-Sr whole-rock isochrons (Chapter 4).

3.2 Petrography.

The granite clasts in each conglomerate are divided into a number of groups on the basis of their mineralogy. The interpretation of their petrographic features provides information about the processes involved in the formation of the original plutons and illustrates the independence of the different groups of granite clasts. Many granitic rocks are emplaced in a partially solidified state, and sub-solidus recrystallization during the cooling of large plutons is common. These processes complicate the interpretation of textures in terms of simple

crystallization sequences, but the contrasts between the textural features of the groups of granite clasts are sufficient that the different conditions under which each group formed can be recognized.

The general features of the petrographically defined groups of clasts are described in this section. Additional petrographic information for the granite clasts in the Corsewall Point and Glen Afton conglomerates is contained in Appendix 1. Each group of clasts is identified by a letter and a number, in addition to its petrgraphic name, in order to facilitate easy reference between different parts of the text, and between the text, tables and diagrams. The letter and number correspond to the section of the chapter in which the group is described, and consequently the letter also refers to the conglomerate in which the clasts occur. (A = Corsewall Point, B = Glen App, C= Glen Afton, D = Shinnel Formation, E = Pinstane Hill.)

3.2.a Corsewall Point.

The granite clasts in the Corsewall Point conglomerate are the most numerous and varied of all the conglomerates studied. Table 3.1 summarizes the features of the seven different groups that have been recognized, and shows which samples belong to each group. The granite clasts in the adjacent Glen App conglomerate are less diverse, more weathered and form a lower proportion of the total clast assemblage. As there are also some differences between the petrography and geochemistry of the granite clasts from the two localities, they are considered separately.

3.2.a.i Corsewall Point muscovite-biotite granites (Group A1).

The muscovite-biotite granites form the largest single group amongst the clasts sampled at Corsewall Point, although they are not the most abundant granite type in this deposit. The mineralogy of this

TABLE 3.1 THE GROUPS OF GRANITE CLASTS RECOGNIZED IN THE CORSEWALL POINT CONGLOMERATE.

GRANITE TYPE	SAMPLE NUMBERS	DISTINGUISHING MINERALOGICAL FEATURES	DISTINGUISHING CHEMICAL FEATURES	COMMENTS
Muscovite-biotite granites. (Group A1)	CoP 3 CoP 119 CoP 24 CoP 120 CoP 27 CoP 121 CoP 101 CoP 122 CoP 117 CoP 123 CoP 118 CoP 124	Equigranular texture, primary muscovite, abundant zircon and monazite.	K_2O (4.11→2.64%) > Na_2O (2.46→1.81%) ≃ MgO (2.69→1.19%) > CaO (1.56→0.70%)	Common quartz and garnet-sillimanite xenoliths.
Unfoliated hornblende-biotite granites. (Group A2a)	CoP 13 CoP 106 CoP 102 CoP 110 CoP 105	Some interstitial alkali feldspar, unstrained quartz, skeletal hornblende.	CaO (3.43→2.34%) >/= K_2O (3.87→2.61%) >/= Na_2O (3.21→2.78%) >/= MgO (3.87→2.61%)	
(Group A2b)	CoP 22 CoP 104 CoP 109	Poikilitic alkali feldspar, strained quartz, euhedral hornblende.	CaO (3.40→3.21%) > Na_2O (2.61→2.58%) ≃ K_2O (2.70→2.60%) ≃ MgO (2.67→2.49%)	
Foliated hornblende-biotite granodiorites. (Group A3)	CoP 2 CoP 23 CoP 107	Extensively recrystallized quartz, elongate bent hornblende, bent plagioclase twins.	CaO (3.89→3.22%) ≃ MgO (3.29→2.33%) > Na_2O (2.56→2.32%) > K_2O (1.95→1.60%)	
Biotite granites (Group A4)	CoP 6 CoP 103 CoP 11 CoP 108	Equigranular texture, small mafic inclusions.	Na_2O (4.44→3.13%) > K_2O (2.87→2.79%) > CaO (1.67→0.76%) > MgO (2.44→0.34%)	Garnet and muscovite-bearing phases also present.
	CoP 25	Weak foliation, extensive quartz recrystallization.	Na_2O ≃ K_2O > CaO > MgO	
Trondhjemite (Group A5)	CoP 28	Zoned plagioclase and alkali feldspar.	Na_2O(4.39%) >> MgO(1.64%)≃ CaO(1.30%) ≃ K_2O(0.93%)	
Plagiogranite (Group A6)	CoP 29	Sodic plagioclase and quartz, only fine grained alkali feldspar present in interstices.	Na_2O(6.52%) >> CaO(0.70%)> MgO(0.39%) > K_2O(0.09%)	

group is quartz + plagioclase feldspar + alkali feldspar + biotite + muscovite + zircon + opaque minerals ± garnet ± sillimanite ± apatite ± monazite.

The medium grain size and equigranular texture of these clasts is apparent in hand specimen (Plate 3.1). Most samples display a weak foliation which is more strongly developed in a few clasts. Rounded quartz xenoliths up to 3 cms. in diameter, and more diffuse biotite-rich mafic xenoliths, often concordant with the foliation, are common in all specimens (Plate 3.1).

In thin section (Plate 3.2) anhedral quartz grains show varying degrees of strain (see below). Limited granophyric intergrowths with alkali feldspar occur between larger individual grains of the two minerals. The alkali feldspar occurs as large anhedral crystals which enclose euhedral plagioclase grains, and also as smaller subhedral grains. Strings of perthite are developed and some microcline is present. Plagioclase occurs as large euhedral crystals up to 2 mm. in length, and smaller subhedral crystals about 0.5 mm. long. Some are strongly zoned, but most are of constant composition (c. An_5 - determined optically). Thin overgrowths of quartz occur on some of the larger grains where they are in contact with potassium feldspar.

Biotite grains are generally tabular and no more than 1 mm. in length, although some interstitial grains are anhedral. They show a deeply coloured orange-brown - red-brown - fawn pleochroism, which suggests a high Ti content. Tabular muscovite is less common; it also occurs in complex intergrowths with quartz and alkali feldspar, associated with biotite, or in veinlets which bisect potassium feldspar crystals. These textures suggest that while some muscovite is primary, it also occurs as a later, sub-solidus phase.

Zircon is the most abundant accessory mineral phase, and commonly occurs in biotite, where it is associated with dark brown to black

pleochroic haloes. Isolated grains, up to 0.2 mm. in size, occur as well formed, short stubby prisms dispersed throughout all specimens. A few grains of monazite, which typically have less well developed pleochroic haloes, are also present in some samples. Opaque phases occur both as inclusions in biotite and as isolated grains. The abundance of apatite is variable, occurring as small isolated grains in some samples, but absent in others.

Both sets of xenoliths are crustally derived, and provide evidence of the nature of the country rock into which the granite was intruded. The quartzose xenoliths consist almost entirely of large interlocking quartz crystals which show comparable degrees of strain to the quartz in the host rock. The xenoliths have sharp boundaries and may represent the residue from the melting of inclusions similar to the deformed quartzo-feldspathic clasts that occur in the Corsewall Point conglomerate. Because of the quartz-rich nature of these clasts, quartz and feldspar would have melted at temperatures above the granite minimum, leaving a residue of pure quartz which would remain as a solid phase in the magma.

The basic inclusions are more varied. Although dominated by biotite, they also contain plagioclase feldspar, sillimanite, garnet, muscovite, chlorite and small amounts of alkali feldspar, zircon and opaque minerals (Plate 3.3). Such an assemblage is indicative of a pelitic protolith, although its precise nature is difficult to establish because of the reactions associated with the incorporation of such a rock into a granitic magma. However, alternating plagioclase- and biotite-sillimanite-rich bands may represent a relict foliation, and the arcuate arrangement of biotite grains in some of the plagioclase-rich bands may indicate that this fabric is a crenulation cleavage. In addition, some biotite and plagioclase grains are more deformed than

those in the immediately adjacent host rock, which indicates that the inclusions had an earlier tectonic history.

Some quartz and alkali feldspar may have been lost as a result of partial melting of the pellitic inclusion. Garnet is almost certainly an original part of the mineralogy, although its association with biotite, muscovite and plagioclase indicates that it has been involved in break-down reactions. Biotite grains are smaller and darker brown than in the host rock, and usually lie parallel to the foliation. The presence of larger grains discordant to the fabric indicates that some recrystallization has taken place. Likewise, some of the muscovite may be primary, while some is the product of later reactions. The plagioclase grains within the xenoliths are only slightly zoned and are of a more calcic composition (andesine - optically determined) than the plagioclase in the host rock. At the edge of the inclusions plagioclase grains in contact with quartz of igneous origin are strongly zoned and have albitic rims, which indicates that the plagioclase grains derived from the xenolith were not in equilibrium with the melt. The presence of sillimanite is more problematic, as it is the high temperature polymorph of Al_2SiO_5, and would be expected to form in a pelitic xenolith included in a granite melt. However, it could also be an original component of a sillimanite schist. It occurs both as elongate needles of a variety of sizes, and as larger, more blocky grains. Some of the longer needles lie parallel to the foliation and are folded with it (Plate 3.3), which indicates that the sillimanite pre-dates the intrusion of the granite. The larger blocky grains consist of an aggregate of finer grained sillimanite which appears to be breaking up, leaving a trail of stubby prisms, a texture that indicates the replacement of another mineral. Although some of the sillimanite is an original component of the pelite, some of it may have formed after the incorporation of the xenolith into the melt.

The presence of xenoliths raises the question of the extent of crustal contamination of the magma. The partial assimilation of larger xenoliths can be seen from their diffuse boundaries and the reaction textures described above. Small discontinuous laminae of finer grained dark brown biotite may represent the remnants of more completely digested xenoliths in some cases, and fragments of garnet are the only evidence of a pre-existing xenolith in other samples. Zircons are abundant in both the xenoliths and the granite, and many of them may be inherited. However, their common occurrence in the larger lighter brown biotites indicates that some biotite growth post-dates the assimilation of the xenoliths and is therefore of igneous origin.

The subsequent deformation suffered by this suite of rocks is indicated by the degree of strain shown by quartz grains and the foliation seen in hand specimen. CoP 123 and CoP 124 show the strongest foliation. Quartz grains in these specimens show sutured boundaries, clearly developed subgrains and minor recrystallization. The deformation has also affected plagioclase grains, which conain offset twin lamellae, and biotite and muscovite, which show kinked cleavage.

The remarkable uniformity of the samples in this group indicates that they have a common origin. The granite magma was intruded into country rock that included garnet-sillimanite grade pelites and a quartzo-feldspathic rock. Some of this material was incorporated into the melt and xenoliths remain where melting was incomplete. Fresh biotite and plagioclase crystallized producing large unzoned crystals of uniform, if quite sodic, composition. This crystallizing assemblage was later joined by quartz, alkali feldspar and muscovite, which formed intergrowths in the final stages of crystallization. Muscovite continued to form as a sub-solidus phase. Subsequent deformation produced a foliation, which affected some samples more strongly than others.

3.2.a.ii Corsewall Point unfoliated hornblende-biotite granites (Group A2a and A2b).

Unfoliated hornblende-biotite granites are the most abundant type of granite clast found at Corsewall Point. They are medium to coarse grained and weather to a pink colour. The mineralogy of the group is quartz + plagioclase + alkali feldspar + biotite + hornblende ± apatite ± zircon ± opaque oxides. Chlorite and epidote are present as alteration products of biotite. Although all the specimens appear to be similar in hand specimen, their details petrographic characteristics allow two separate groups to be distinguished (Table 3.1, Plates 3.4 and 3.5).

The first group (Group A2a - Plate 3.4) contains euhedral grains of orthoclase, some of which are zoned, and plagioclase of constant composition (An_{12} - optically determined). Interstitial grains of quartz, and less commonly alkali feldspar, partially enclose the euhedral grains. Quartz shows little evidence of strain, other than sweeping extinction. Hornblende shows pale green - blue green - olive green pleochroism and forms subhedral crystals in which hexagonal and prism sections can be recognized, but which have a skeletal appearance due to intergrowth with adjacent quartz and alkali feldspar (Plate 3.4). Biotite forms large tabular crystals which show a pale brown - dark brown - yellow brown pleochroism. Apatite forms hexagonal prisms which are often included in biotite, and larger grains which are dispersed throughout the specimens. Small amounts of zircon and opaque oxides are also present.

The second group of clasts (Group A2b - Plate 3.5) also contain euhedral plagioclase and orthoclase grains, although plagioclase is more abundant in these samples. Both feldspars show evidence of zonation: plagioclase has moderately calcic cores (An_{40}) and rims of albite or oligoclase. In addition, large anhedral alkali feldspar grains, upto

0.5 cms. in length, poikilitically enclose earlier formed euhedral feldspars. These crystals commonly contain fine perthitic exsolution lamellae and some show tartan twinning. Quartz grains less commonly enclose euhedral feldspars, but in contrast to the first group of clasts, show subgrain formation and sutured boundaries, which indicates they were subjected to higher degrees of strain. Hornblende and biotite show similar pleochroic schemes to crystals in the first group of clasts, which indicates that they are of a similar composition, but the hornblende crystals are euhedral. Zircon is more common and often occurs as inclusions in hornblende, while apatite is less abundant in thes clasts.

The close relationship between the two groups of unfoliated hornblende-biotite granites is shown by their similar mineralogy, the similar composition of the biotite and hornblende they contain, and is reflected by their chemical composition (see section 3.3.a). Consequently, the different textures probably reflect different cooling histories, rather than major compositional differences. Experimental studies predict that textures similar to those displayed by the the second group of hornblende-biotite granites are likely to form during the final stages of crystallization of a melt of granodioritic composition as a result of the rapid growth of a small number of large alkali feldspar crystals which poikilitically enclose earlier formed euhedral crystals (Swanson, 1977). The zoned nature of the feldspars indicates the importance of fractional crystallization in this group, and the sequence of crystallization is illustrated by the albite-anorthite-orthoclase phase diagram (Fig. 3.1b). Plagioclase, and then plagioclase and alkali feldspar crystallize as the liquid moves across the plagioclase field and down the two-feldspar boundary curve. Both feldspars evolve to more albite-rich compositions, so that during the late stages of crystallization, when conditions favour the rapid growth

of large alkali feldspar crystals, they are of a more albitic composition, and hence develop microperthitic textures. This probably took place at relatively high pressures (> 5kb.), as low pressure fractionation would have resulted in the development of more extensive perthite (Fig. 3.1a).

By contrast, the first group of hornblende-biotite granites (Group A2a) lack large, late stage alkali feldspars. The early formed euhedral feldspars are not zoned, which indicates that fractional crystallization was a less important process. A greater degree of equilibrium crystallization causes the rock to solidify at higher temperatures, as a result of which a larger proportion of the magma is crystalline when conditions favour the rapid growth of alkali feldspar. The late stage alkali feldspar also contains a smaller albite component under such conditions (Fig. 3.1b), which has the effect of reducing the crystal growth rate (Swanson, 1977). Consequently, the rock contains interstitial, non-perthitic alkali feldspar.

In addition, euhedral crystals of hornblende in the second group of clasts indicate that crystallization of this phase ceased before quartz and alkali feldspar began to form, while in the first group there was an overlap in the crystallization of these phases, which resulted in the development of skeletal intergrowths. The presence of microcline in the second group of clasts indicates that the pluton from which they were derived cooled more slowly, and the more markedly deformed quartz fabrics indicate that the pluton was subject to greater degrees of strain.

The contrasting petrographic features of the two groups of clasts suggest that they were derived from separate plutons which crystallized under different conditions. There are slight chemical differences between the two groups, and the minor phases occur in different proportions, which indicates that the original magmas were distinct.

Consequently the two groups are used to construct separate Rb-Sr whole-rock isochrons.

3.2.a.iii Corsewall Point foliated hornblende-biotite granodiorites (Group A3).

The strong foliation evident in hand specimen distinguishes this group of clasts from the unfoliated hornblende-biotite granites (Group A2). Their mineralogy consists of quartz + plagioclase feldspar + alkali feldspar + biotite + hornblende + opaque oxides ± apatite ± zircon. Some chlorite and epidote are present as alteration products. Textures are dominated by deformational fabrics (Plate 3.6).

The quartz is extensively recrystallized and now forms discontinuous laminae which partly define the foliation. Euhedral plagioclase grains, 1-2 mm. in size, are moderately calcic (c. An_{40}-optically determined) and show minor zonation. Twin lamellae are often slightly curved and in some cases are dislocated. Occasional euhedral grains of alkali feldspar are strongly zoned, and larger unzoned anhedral grains enclose plagioclase crystals. Both feldspars have slightly altered cores.

Biotite and hornblende crystals are also arranged in laminae, sub-parallel to one another. Biotite is more abundant, and has a greenish brown - dull brown - fawn pleochroism. The cleavage planes are often folded. Hornblende shows a deep green - blue green - green yellow pleochroism and is present as needles up to 4 mm. long, and also as elongate hexagonal sections up to 4 mm. wide which enclose small plates of biotite. Some of the larger needles which lie parallel to the foliation are slightly bent (Plate 3.6). The biotite is generally well preserved, although in places it is associated with chlorite and epidote. In one specimen (CoP 107) it appears to replace hornblende.

Opaque oxides are often associated with biotite. Isolated zircon and apatite crystals are scattered throughout the rock.

The mineralogy of this group resembles that of the unfoliated hornblende-biotite granites described above (Group A2 - section 3.2.a.ii), and the textural relationships indicate that similar fractionatal crystallization processes took place in both groups. However, plagioclase forms a much higher proportion of the feldspars in the foliated granodiorites, and the detailed mineralogy of the main phases is different. This group of clasts has also suffered a much higher degree of deformation which means that it is unlikely that they are related to the unfoliated hornblende-biotite granites (Group A2) described above. Consequently, they are considered as a separately derived group.

3.2.a.iv Corsewall Point biotite granites (Group A4).

The biotite bearing granites in the Corsewall Point conglomerate are medium to coarse grained and leucocratic (Plate 3.7). Their mineralogy is dominated by quartz, plagioclase and orthoclase. Biotite occurs in all specimens, and small amounts of hornblende are present in some. One specimen also contains garnet and muscovite. Small amounts of apatite, zircon and opaque oxides are present as trace minerals. Small rounded mafic inclusions up to 4 cms. in diameter are common. In some specimens a weak foliation is evident in hand specimen.

The rock has a hypidiomorphic granular texture. Some smaller quartz grains are interstitial to subhedral feldspars, but there are also coarse intergrowths between quartz and plagioclase feldspar (Plate 3.7). The feldspars are only slightly zoned, and some alkali feldspars show the development of a moderately coarse blocky perthitic texture, with twin planes apparent in the exsolved plagioclase.

Biotite occurs as small independent grains dispersed throughout the sample, interstitial to, or partially enclosed by, quartz and feldspar crystals. The biotite is often altered to chlorite, but the original deep brown - light brown pleochroism is still evident. Garnet and muscovite also occur in one sample (CoP 6, see Plate 3.8). The garnets are subhedral, up to 2 mm. in size, pale brown in plane polarized light and have a fractured appearance. Smaller grains are enclosed in alkali feldspar, while larger ones are interstitial to quartz. Their irregular appearance and their occurrence within other phases suggests that they are inherited and that they have been partially resorbed before being enclosed by other crystals. Muscovite occurs as small grains associated with garnet and in thin irregular lamellae of biotite.

The mafic inclusions consist of small euhedral crystals of hornblende and plagioclase, and some alkali feldspar. Larger subhedral crystals of plagioclase and alkali feldspar containing trails of small hornblende fragments are also present. Optical continuity between the hornblende fragments indicates that the feldspars have replaced or overgrown the original texture. Quartz occurs as an interstitial mineral. Large biotite crystals occur towards the edge of the inclusions, which in hand specimen have sharp boundaries, but which appear to grade into the host rock in thin section. The inclusions probably represent segregations of an earlier, more basic igneous source which have been included in the granite melt, and partially mixed with it.

The common development of sub-grains in quartz crystals indicates that these clasts have been subject to strain. In CoP 6 some of the quartz is recrystallized, and the segregation of biotite into discontinuous stringers has produced a weak foliation. The biotite is finer grained in this sample which indicates that recrystallization was associated with formation of the foliation, and hence that the fabric

formed subsequent to intrusion. CoP 25 is more extensively deformed and has a better developed foliation; large feldspars crystals have retained their original shape, but extensively recrystallized quartz and biotite define the foliation which wraps around these porphyroblasts. Because of the extent of deformation and the loss of original textures it is not clear whether this sample should be regarded as a more deformed equivalent of the other biotite granites, or considered separately.

The presence of basic inclusions of an igneous character suggest that this granite evolved from a more basic precursor. However, intrusion of the magma probably involved the incorporation of some country rock which was largely digested to produce more aluminous phases containing garnet and muscovite. Early crystallization of alkali and plagioclase feldspar produced subhedral crystals. Both phases continued to crystallize in the presence of quartz, forming coarse intergrowths, which indicates that fractionation took place under conditions of high pressure (> 5kb. - see Fig. 3.2). The moderately coarse perthitic texture may indicate a relatively vapour-rich magma. Subsequent deformation involved recrystallization of some phases and produced a weak foliation in the more deformed samples.

3.2.a.v Corsewall Point trondhjemites and plagiogranites (Groups A5 and A6).

Trondhjemites are defined as rocks that contain at least 20% quartz, and plagioclase that is more sodic than andesine. Alkali feldspars and mafic minerals each comprise less than 10% of the rock, and K_2O concentrations are generally less than 2.5 wt.% (Barker, F., 1979; Barker, D.S., 1983). Plagiogranites also conform to this definition, but are distinguished from trondhjemites by the virtual absence of alkali feldspar, which is only present in trace amounts,

usually as an interstitial mineral, and by K_2O concentrations less than 1 wt.% (Barker, D.S., 1983).

The two samples of coarse grained leucocratic rock collected from Corsewall Point illustrate these differences. CoP 28 contains subhedral crystals of plagioclase and alkali feldspar, both of which are strongly zoned (Plate 3.9), although plagioclase is much more abundant (the outer rims have the composition of oligoclase - An_{13}, optically determined). The interstices are filled by perthitic alkali feldspar, and in some instances, biotite. Quartz forms interlocking crystals which show some evidence of strain. These textures indicate that both alkali feldspar and plagioclase fractionation took place, and the rock is classified as a trondhjemite (Group A5), rather than a plagiogranite.

CoP 29 consists of large subhedral crystals of plagioclase and quartz. The plagioclase shows some zonation, and is of albitic composition. Quartz crystals are unstrained, and where they are not interlocking, are rounded and slightly embayed. The interstices are occasionally filled by alkali feldspar, but more usually by fine grained quartz, plagioclase and alkali feldspar (Plate 3.10). Epidote and chlorite are present as the alteration products of mafic minerals. Fractionation of plagioclase feldspar alone has produced a mineralogy that is typical of oceanic plagiogranites (Coleman and Peterman, 1975). This distinguishes it from the trondhjemite clast, CoP 28, and it is classified separately (Group A6).

3.2.b Glen App

The Glen App and Corsewall Point conglomerates are both of *N. gracilis* zone age and outcrop 15 km. apart along strike. Sedimentological investigations indicate that they belong to the same depositional system, and the clast content of the two conglomerates is

similar. This suggests that they were supplied by similar source areas, but differences between the granite clasts in the two deposits indicate that their sources were not identical. Table 3.2 summarizes the distinguishing features of the different types of granite clasts found at Glen App and compares them to the groups recognized at Corsewall Point.

Due to the less extensive outcrop and the lower proportion of granite clasts in some horizons of the Glen App conglomerate, fewer clasts were sampled here than at Corsewall Point. No muscovite-biotite granite clasts were found in this deposit, but they form a sufficiently prominent part of the clast assemblage at Corsewall Point that their absence from the Glen App conglomerate must be related to the differences between the detritus supplied to the two deposits.

3.2.b.i Glen App hornblende-biotite granites (Group B1).

The textures shown by four of the five samples which comprise this group of granite clasts are identical to those described from the second group of unfoliated hornblende biotite granite clasts from the Corsewall Point conglomerate (Group A2b). Zoned euhedral crystals of plagioclase and orthoclase are poikilitically enclosed by large anhedral orthoclase grains which have developed perthitic textures, and sub-grains are extensively developed in quartz crystals. Euhedral hornblende crystals show a similar blue-green - green pleochroism to the hornblende in the Corsewall Point clasts, which indicates that it is of a similar composition. However, biotite is more extensively altered to chlorite and epidote and some feldspars contain cores of sericite and/or epidote. The Glen App clasts are more extensive altered than the Corsewall Point hornblende-biotite granites, but were derived from a closely related pluton that crystallized under similar conditions and was subjected to similar degrees of strain.

TABLE 3.2 THE GROUPS OF GRANITE CLASTS RECOGNIZED IN THE GLEN APP CONGLOMERATE

GRANITE TYPE	SAMPLE NUMBERS	DISTINGUISHING MINERALOGICAL FEATURES	DISTINGUISHING CHEMICAL FEATURES	COMMENTS
Unfoliated hornblende-biotite granites. (Group B1)	AP 5 AP 7 AP 6 AP 10	Poikilitc alkali feldspar, unstrained quartz, euhedral hornblende	Na_2O (3.81→3.25%) > CaO (3.54→2.56%) >/= MgO (2.62→2.14%) >/= K_2O (2.28→1.35%)	Petrogaphically like Group A2b, some chemical differences due to weathering.
	AP 15			extensively altered
Foliated granodiorite (Group B2)	AP 13	Strained quartz, Hornblende replaced by biotite.	CaO(3.62%) > Na_2O(2.49%)≈ MgO(2.33%) > K_2O(0.23%)	As CoP 107.
Biotite granites (Group B3)	AP 8 AP 17	Inequigranular texture, some hornblende also present. Small mafic inclusions.	Na_2O (4.20→4.05%) ≈ K_2O (3.96→2.21%) > CaO (2.38→1.53%) > MgO (1.60→0.77%)	Affinity with Corsewall Point biotite granites.
Foliated biotite granites (Group B4)	AP 11 AP 14 AP 16	Extensively recrystallized quartz, microcline present, elongate aggregates of biotite.	Na_2O (3.60→3.18%) ≈ K_2O (3.96→2.21%) > CaO (2.38→1.53%) > MgO (1.60→0.77%)	As CoP 25.
Plagiogranite (Group B5)	AP 2	Albitic plagioclase and unstrained quartz.	Na_2O(6.02%) >> CaO(1.56%)> MgO(0.96%) > K_2O(0.23%)	

The precise affinities of AP 15 are more difficult to establish. It shows some mineralogical and textural similarities to the other members of this group, but is cut by calcite veins which obscure many petrographic details. No clasts were found in the Glen App conglomerate which correspond to the first group of hornblende-biotite granite clasts from Corsewall Point (Group A2a), which are more abundant in that deposit.

3.2.b.ii Glen App Foliated Granodiorite (Group B2).

A single specimen which closely resembles the foliated hornblende-biotite granodiorites from Corsewall Point (Group A3) was found at Glen App (AP 13). It displays a slightly less intense foliation, and in thin section quartz is less extensively deformed, although plagioclase crystals still contain curved twin lamellae. Much of the hornblende has been replaced by fine grained aggregates of biotite, as is the case in one of the samples in the equivalent group of clasts from Corsewall Point (CoP 107). Other aggregates mimic original large biotite grains. The strong similarity between the deformational fabrics and mineralogical characteristics shown by AP 13 and the Corsewall Point clasts suggests that they were derived from closely related sources.

3.2.b.iii Glen App biotite granites (Group B3).

There are some similarities between the two samples of unfoliated leucocratic biotite-bearing granite from Glen App and their counterparts from Corsewall Point (Group A4), but the Glen App clasts display a less equigranular texture and are finer grained. They contain small euhedral crystals of plagioclase and orthoclase which are occasionally enclosed by larger anhedral grains of orthoclase and quartz. Biotite occurs as small tabular crystals and hornblende, which form a more prominent

component of the mineralogy of the Glen App clasts, occurs as small euhedral crystals (Plate 3.11).

The Glen App clasts have a broadly similar chemistry to the Corsewall Point biotite granites (section 3.3.b), and both groups of clasts contain small mafic inclusions consisting of plagioclase and hornblende, which indicates that they evolved from similar, more basic sources. Quartz grains in both groups of clasts show similar degrees of strain. However, mineralogical differences between the two groups indicate that they have slightly different compositions, and the more aluminous phases that are present in the Corsewall Point clasts were not found in the Glen App clasts. Thus, the two sets of clasts may be derived from related, but not identical plutons, or possibly from different parts of the same pluton. As with other samples from Glen App, calcite veins occur in these clasts.

3.2.b.iv Glen App foliated biotite granites (Group B4).

The presence of a distinct foliation in hand specimen distinguishes this group from the other biotite-bearing granite clasts in the Glen App conglomerate. In thin section (Plate 3.12) quartz is extensively recrystallized and forms elongate stringers which wrap around large euhedral and subhedral plagioclase grains. The original form of the plagioclase has been retained but it contains dislocated twin planes. Alkali feldspar has recrystallized as microcline which forms small anhedral crystals of a similar size to, and within aggregates of, recrystallized quartz. Biotite is not abundant and is largely altered. However, relict textures indicate that it formed elongate fine grained aggregates sub-parallel to the foliation.

The mineralogy of these samples and the deformational textures they dispaly are very similar to those shown by CoP 25, the foliated biotite granite clast from Corsewall Point. The clasts in both conglomerates

were probably derived from similar sources, but deformed biotite granites are more abundant than the undeformed biotite granites in the Glen App conglomerate, and there is a strong mineralogical contrast between the two groups in this deposit. Consequently, the foliated clasts are likely to have had a separate origin to the unfoliated biotite granites. Because of the similariities between the clasts in the Corsewall Point and Glen App conglomerates, it is likely that CoP 25 also had an origin independent of the undeformed clasts in that deposit.

3.2.b.v Glen App plagiogranite (Group B5).

A single plagiogranite clast was found at Glen App. Like the sample from Corsewall Point (CoP 29 - Group A6) it consists almost entirely of large subhedral crystals of plagioclase and quartz. The plagioclase has a similar albitic composition to that in the Corsewall Point clast, but is unzoned. Some alkali feldspar occurs as an interstitial phase. The small amount of biotite that was originally present has been altered to chlorite. The presence of biotite is less typical of true oceanic plagiogranites (Coleman and Peterman, 1975), which normally contain small quantities of hornblende, but this sample could have been derived from a source similar to that of the Corsewall Point clast.

3.2.c Glen Afton.

The Glen Afton conglomerate is at least three graptolite zones younger than the Corsewall Point and Glen App conglomerates, and contains detritus which differs from that in the older deposits (Chapter 2). The petrography and geochemistry of the granite clasts in the Glen Afton conglomerate can be used to show whether they were derived from plutons related to those which supplied the Corsewall Point and Glen App

conglomerates, and hence whether the differences in detritus are due to the evolution of their source areas, or whether there was a change in the source of the sediments supplied to the Southern Uplands between the Llandeilo and Caradoc. Table 3.3 shows the different types of granite that were identified in the Glen Afton conglomerate, and the samples which belong to each group.

3.2.c.i Glen Afton muscovite-biotite granites (Group C1).

Granites containing biotite and muscovite bearing form the most abundant group of granite clasts in the Glen Afton conglomerate. Their mineralogy is quartz + plagioclase feldspar + alkali feldspar + biotite + muscovite ± zircon ± apatite. Chlorite, epidote and clinozoisite are also present. The rock is coarse grained and three of the eleven samples (GA 45, GA 173 and GA 226) display a weak foliation in hand specimen.

Plagioclase occurs as euhedral crystals up to 3 mm. in size which are frequently zoned and range from oligoclase to albite in composition. Alkali feldspar occurs as large anhedral crystals which poikilitically enclose plagioclase, biotite and muscovite. Some well formed plagioclase crystals have irregular and indistinct boundaries with alkali feldspar, and occasional intergrowths have formed between the two minerals. Perthitic textures are well developed in the alkali feldspar grains, with exsolution lamellae forming elongate stringers, although in some instances they are short and blocky. These textures are consistent with feldspar fractionation at low pressures (Fig. 3.1a). Quartz forms large anhedral crystals up to 1 cm. in size which show strain extinction. There are some very limited intergrowths between quartz and alkali feldspar. Biotite forms platy crystals up to 1 mm. in size which are partially or wholly enclosed by alkali feldspar. Muscovite is less common, but also forms platy crystals up to 0.5 mm. in length which are

TABLE 3.3 THE GROUPS OF GRANITE CLASTS RECOGNIZED IN THE GLEN AFTON CONGLOMERATE.

GRANITE TYPE	SAMPLE NUMBERS	DISTINGUISHING MINERALOGICAL FEATURES	DISTINGUISHING CHEMICAL FEATURES	COMMENTS
Muscovite-biotite granites (Group C1)	GA 1 GA 223 GA 21 GA 224 GA 39 GA 226 GA 45 GA 231 GA 170 GA 232 GA 173	Zoned euhedral plagiocalse, large poikilitic alkali feldspar, secondary muscovite and clinozoisite.	K_2O (4.19:2.76%) > /= Na_2O (3.83→2.82%) > CaO (2.54→1.41%) > MgO (1.11→0.56%)	Unrelated to Corsewall Point muscovite-biotite granites.
Biotite granodiorite (Group C2)	GA 2 GA 165 GA 11 GA 168 GA 46 GA 225	Moderately calcic plagioclase, interstitial alkali feldspar, large biotite crystals.	CaO (3.74→2.59%) > Na_2O (3.02→2.17%) ≈ K_2O (2.62→1.32%) > MgO (2.01→0.90%)	
Hornblende-biotite granites (Group C3)	GA 51 GA 172 GA 171 GA 221	Plagioclase mantled by perthitic alkali feldspar. Intergrowths between quartz and both feldspars.	Na_2O (5.47→4.98%) > K_2O (3.48→1.63%) > CaO (1.84→0.61%) > MgO (0.63→0.09%)	Some affinities with Corsewall Point biotite granites.
Granophyric and acicular hornblende granites (Group C4)	GA 15 GA 222* GA 25 GA 227 GA 27 GA 229	Separate radiating granophyric intergrowths with both feldspars. Acicular hornblende and tabular plagioclase.	Na_2O (5.47→4.98%) > CaO (3.84→1.63%) > MgO (1.34→0.35%) > K_2O (0.87→0.24%)	
Trondhjemites (Group C5)	GA 24 GA 36	Large zoned albitic plagioclase with thin rims of perthite. Few mafic minerals.	Na_2O (5.22→5.14%) > CaO (2.64→1.49%) > MgO (0.58→0.47%) ≈ K_2O (0.43→0.34%)	
Plagiogranites (Group C6)	GA 169 GA 228	Albitic plagioclase and quartz with some alkali feldspar.	Na_2O (6.57→6.19%) >> CaO (0.58%) > MgO (0.34→0.22%) > K_2O (0.06%)	Some affinity with Glen App plagiogranites.

* = no chemical analysis, thin section only

enclosed by alkali feldspar or are interstitial to alkali feldspar and quartz grains. Finer grained crystals of muscovite are often associated with biotite, which it may be replacing.

Muscovite can only crystallize from granitic melts at pressures greater than 1.5 kb. (Yoder and Eugster, 1955), but the presence of a single late stage perthitic feldspar indicates that fractionation took place at pressures less than that at which the solvus-solidus intersection meets the Ab-Or join in the system An-Ab-Or (Fig. 3.1). This occurs between 2 and 5 kb. (Yoder et al., 1957). Consequently, if muscovite formed as a primary mineral, the granite must have crystallized at pressures of about 2 kb. However, isolated grains of clinozoisite are present in all samples, usually occurring as small euhedral grains, interstitial to plagioclase and quartz (Plate 3.13). This indicates that an alternative, more probable explanation for the presence of muscovite is that it formed with clinozoisite as a result of the hydrothermal alteration of plagioclase by potassium-rich fluids. The conversion of the anorthite component of the plagioclase to clinozoisite would leave a more sodic feldspar and would also liberate aluminium, silicon and oxygen. Additional potassium would be required to form muscovite, but if this was introduced by potassium-rich fluids it may also account for the unaltered nature of the alkali feldspars. Muscovite and clinozoisite are dispersed throughout these samples and are rarely found within the altered plagioclase crystals, which may also be due to the involvement of a fluid phase. It is likely that such hydrothermal alteration occurred shortly after the formation of the granite. The in-situ partial alteration of biotite to chlorite and a more iron-rich epidote, and the further turbid alteration of plagioclase feldspars may have been a later event associated with the uplift and erosion of the original granite prior to the erosion of the clasts.

One sample from this group, GA 224, contains both the usual coarse grained granite, similar to the other members of this group, and a fine grained equivalent. The mineralogical and textural features of the two types of granite are similar, but they are separated by a sharp boundary. Because of the size of the boulder it is not possible to determine whether this is an intrusive contact, or whether the finer grained granite is an inclusion. However, it indicates that there were at least two phases of intrusion of magmas of a similar composition.

The marked sweeping extinction shown by the quartz grains in all samples indicates that the granite was subjected to some strain. The weakly foliated samples (GA 45, GA 173 and GA 226) also show the formation of sub-grains, and the boundaries between quartz grains are sutured, features which probably developed subsequent to crystallization.

The petrographic characteristics of this group of granite clasts clearly distinguishes them from the Corsewall Point muscovite-biotite granites (Group A1). The Corsewall Point clasts were derived from a pluton that crystallized muscovite and two feldspars at high pressure. The effects of later alteration are minimal, and the clasts are characterized by abundant quartzose and pelitic xenoliths. In contrast, the pluton that supplied the muscovite-biotite granite clasts to the Glen Afton conglomerate crystallized at low pressure, and muscovite formed as a result of sub-solidus hydrothermal processes. No xenoliths are found in these clasts. However, both groups of clasts contain foliated samples and have been subject to similar degrees of strain. It is unlikely the the two groups of clast were derived from different levels of the same pluton as the clasts which crystallized at lower pressures, and were derived from higher levels, occur in the younger deposit. Separate plutons supplied the muscovite-biotite granite clasts to the Corsewall Point and Glen Afton conglomerates.

3.2.c.ii Glen Afton biotite granodiorites (Group C2).

The clasts of biotite-bearing granodiorite from the Glen Afton conglomerate are coarse grained and some samples display a weak foliation in hand specimen. Their mineralogy is quartz + plagioclase + alkali feldspar + biotite + hornblende + apatite ± zircon. Chlorite and epidote are present as alteration products.

This rock is characterized by clusters of euhedral feldspar crystals separated by large anhedral quartz grains. Unzoned euhedral crystals of andesine (An_{35} - optically determined) are much more abundant than euhedral alkali feldspar crystals, but the interstices between plagioclase grains are more commonly filled by non-perthitic anhedral alkali feldspar than by anhedral plagioclase, which is intergrown with quartz. The interstitial plagioclase is of a similar moderately calcic composition to the euhedral plagioclase. The large quartz grains show strain extinction. Biotite occurs as large isolated grains dispersed throughout the rock, and also as smaller grains associated with the euhedral feldspars. The biotite is largely altered to chlorite, with some epidote. The unaltered crystals show a deep brown pleochroism. Apatite occurs as small euhedral inclusions in most phases, and small amounts of zircon are present as inclusions in biotite. GA 2 is similar to other members of this group, but contains abundant hornblende in addition to biotite.

An early phase of crystallization of two feldspars and biotite, in which plagioclase was the most important phase, was followed by the crystallization of two feldspars and quartz, in which alkali feldspar was the more important phase. The occurrence of coarse intergrowths of quartz and plagioclase indicate that they crystallized simultaneously, along with alkali feldspar, during the late stages of crystallization of these samples. This may be a result of crystallization at the eutectic in the system Ab-Or-Qz at pressures greater than 5 kb. (Fig. 3.2), but

it could also be caused by the high An component of the melt (Fig. 3.3; James and Hamilton, 1969). The non-perthitic nature of the alkali feldspar favours crystallization at high pressure. The high proportion of alkali feldspar in the interstitial phases may be a result of rapid crystal growth during the final stages of crystallization of the melt (Swanson, 1977). There are no equivalents of these granodiorite clasts in the Corsewall Point conglomerate.

3.2.c.iii Glen Afton hornblende-biotite granites (Group C3).

The hornblende-biotite granite clasts in the Glen Afton conglomerate have a similar sodium-rich chemistry to the biotite leucogranites from Corsewall Point (Group A4). Like those from Glen App (Group B3), they also contain appreciable quantities of hornblende, but the Glen Afton clasts show more mineralogical and textural variation. Their mineralogy consists of quartz + plagioclase feldspar + alkali feldspar + biotite + hornblende. The rock is medium to coarse grained and unfoliated.

Plagioclase forms subhedral crystals up to 2 mm. in length that are clearly zoned and have sodic compositions (oligoclase → albite). Alkali feldspar forms some similar sized subhedral crystals, but also occurs as smaller anhedral crystals which partially mantle plagioclase (Plate 3.14). Very fine grained myrmekitic intergrowths occur in the plagioclase where it abuts against alkali feldspar. Unlike the subhedral crystals, the anhedral alkali feldspars are strongly perthitic. Quartz forms large anhedral grains which show little evidence of strain. Intergrowths between quartz and both alkali and plagioclase feldspar are extensively developed in one clast, GA 51, but are of more limited extent in other samples. Biotite forms isolated platy crystals and also fills the interstices between subhedral plagioclase crystals. It has a pale green-brown pleochroism, which may indicates a high iron content,

but could also be the result of alteration due to weathering. Hornblende, which forms short stubby prisms distributed throughout these clasts, shows a pale green - olive green - light green pleochroism. Sample GA 172 is almost totally devoid of ferromagnesian minerals, apart from a few long thin needles of hornblende, but otherwise displays textures that are very similar to the other members of this group.

The zoned nature of plagioclase indicates that fractional crystallization was important in this group of clasts, and the well developed perthitic textures in the anhedral alkali feldspars suggest that it took place at relatively low pressures. The complex textural relationships may be explained by reference to the system Ab-Or-An-Qz (Fig 3.4). Plagioclase may have formed first, but the liquid would have descended towards the two feldspar surface where alkali feldspar with a low Ab component would also have crystallized. The fairly low normative An content of this rock would mean that the liquid would move across this surface close to its lower edge (which is above the Ab-Qz-Or surface), and would meet the quartz-feldspar surface near the end of the line formed by the intersection of the two feldspar and the feldspar-quartz surfaces. Two feldspars and quartz would crystallize as the liquid moved down this line, allowing quartz-plagioclase intergrowths to form. Once the liquid reached the end of this line, plagioclase crystallization would cease and the liquid would move across the quartz-feldspar surface towards the granite minimum, crystallizing quartz and a single perthitic feldspar, which would mantle the pre-existing plagioclase and form intergrowths with quartz. Sub-solidus reactions include the formation of perthite and myrmekitic intergrowths.

The hornblende-biotite granite clasts show some similarities to the sodium-rich biotite granite clasts from Corsewall Point (Group A4) and the biotite and hornblende bearing granite clasts from Glen App (Group

B3). All three groups contain small rounded inclusions of hornblende and plagioclase, which indicates that they were derived from similar basic sources. The Corsewall Point clasts lack perthitic alkali feldspar and probably crystallized at high pressure (see section 3.2.a.iv). Hornblende is less common in the Corsewall Point clasts which also show evidence of strain and contain more aluminous phases. The Glen Afton clasts lack these features, but have more in common with the Glen App biotite granites which contain some hornblende, and which may also have crystallized at low pressures. The petrological evidence suggests that all three groups of clasts were derived from similar sources.

3.2.c.iv Glen Afton granophyric and acicular hornblende granites (Group C4).

Spectacular granophyric textures are shown by three clasts from the Glen Afton conglomerate (Plate 3.15). Amalgamated quartz-feldspar intergrowths are separated by more regularly crystallized material which gives the rock a blotchy appearance in hand specimen. Quartz forms separate intergrowths with alkali feldspar and with plagioclase of albitic composition. Some of the quartz-plagioclase intergrowths have nucleated about subhedral plagioclase crystals, but the quartz-alkali feldspar intergrowths lack such cores. Individual intergrowths are up to 0.5 cm. in diameter.

The crystalline areas between the intergrowths contain millimetre sized subhedral crystals of alkali feldspar and plagioclase of similar albitic composition to that in the intergrowths, and interstitial anhedral quartz grains. There are some limited intergrowths between the quartz and feldspar in these regions, but there is no continuity with the adjacent granophyric intergrowths against which they sharply abut. Small amounts of green-brown pleochroic hornblende are present as small

subhedral grains within the crystalline areas and as long needles which grow across the granophyric intergrowths (Plate 3.15). Some interstices between quartz and feldspar grains are filled with fine grained epidote and chlorite which may have replaced anhedral hornblende or biotite grains.

Acicular hornblende crystals are the dominant feature of two non-granophyric granite clasts, only one of which provided enough material for chemical analysis (GA 15; GA 222 - thin section only). They contain green-brown pleochroic hornblende needles up to 0.5 cm in length, similar to those in the granophyric granite clasts. Plagioclase and alkali feldspar form euhedral and subhedral crystals, many of which are also elongate. The needles of hornblende and feldspar lie across one another, indicating simultaneous growth (Plate 3.16). Needles of apatite are also present, up to 1.5 mm. in length. Quartz occurs as anhedral grains which partially enclose some early feldspars and form limited coarse intergrowths with others. Chlorite has replaced some small anhedral biotite grains, and fine grained chlorite and epidote fill the interstices between some subhedral grains.

Although it lacks acicular hornblende, GA 27 is also considered to be a member of this group. It consists mainly of regularly crystalline material, and also contains some small radiating granophyric intergrowths up to 1 mm. in diameter. Hornblende is present as small subhedral crystals, but some of the feldspar forms elongate crystals typical of other members of the group.

The similar textures displayed by the acicular hornblende granite clasts and the granophyric granite clasts indicate that they may be related. A gradation exists from purely granophyric granites through those with more prominent crystalline areas to acicular hornblende granites. Barker (1970) interprets granophyric textures as the result of rapid crystallization at the granite minimum in the Ab-Or-Qz system,

at low pressures. This produces an intergrowth between quartz and a single feldspar, and subsequent unmixing may result in a zoned intergrowth with quartz and plagioclase at the core, and quartz and alkali feldspar towards the edge. However, in the Glen Afton samples the intergrowths between quartz and alkali feldspar and between quartz and plagioclase are separate. It is also clear from the more coarsely crystalline samples that two feldspars and quartz crystallized together. The albitic nature of the plagioclase indicates that this took place close to the Ab-Or-Qz plane in the Ab-Or-An-Qz system (Fig. 3.4). Consequently, crystallization must have taken place at the eutectic point, at pressures greater than ≃ 5 kb., rather than at the granite minimum, at lower pressures (Fig. 3.2). Rapid crystallization at depth may be related to changes in the volatile content of the magma (see Fig 3.5). Liberation of vapour would cause the magma to drop below the solidus and would produce conditions favourable for rapid crystal growth, resulting in the formation of delicate intergrowths and acicular crystals. Rapid crystallization may also produce a residual fluid phase (Barker, 1970) which may be responsible for the extensive alteration seen in these samples.

Clasts showing such textures do not occur in the Corsewall Point or Glen App conglomerates and this group represents a rock type that was present only in the source area of the Glen Afton conglomerate.

3.2.c.v Glen Afton trondhjemites (Group C5).

Two samples of a hypidiomorphic granular leucogranite with the mineralogical and chemical composition of trondhjemite as defined by Barker (1979) were found at Glen Afton. They consist of large euhedral crystals of plagioclase up to 0.5 cms. in length, and smaller subhedral crystals of plagioclase and minor alkali feldspar. Most of the feldspar crystals are of albitic composition, are strongly zoned and often

contain thin overgrowths of perthite (Plate 3.17). Occasionally perthite fills the interstices between crystals. The feldspars form loose clusters separated by anhedral quartz grains. Small amounts of subhedral hornblende, now altered to epidote and chlorite, and anhedral interstitial grains of biotite, now altered to chlorite, are also present.

The overgrowths of perthite on the zoned feldspar crystals could be the result of low pressure fractional crystallization of feldspar. However, the boundaries between the perthite and non-pethitic feldspars are sharp, and probably represent a distinct change in conditions, rather than a gradual change in the crystallizing assemblage. Also, it is difficult to see how, at low pressure, such sodic plagioclase and orthoclase could crystallize together (Fig. 3.1a). It is more probable that much of the fractionation took place at higher pressures, with most of the plagioclase forming as the liquid moved towards the two feldspar boundary curve. The fractionation path followed by a sodium-rich melt crystallizing albitic plagioclase would meet this curve close to the eutectic point, where alkali feldspar would join the crystallizing assemblage. The crystallization of a single feldspar must have taken place at lower pressures and may have occured once the granite was emplaced at a higher level, possibly as a sub-solidus phase. Subsequent unmixing during cooling would produce the perthitic textures.

These textures differ from those of the Corsewall Point trondhjemite clast (CoP 28 - Group A5) which contains more prominent large zoned alkali feldspar crystals and less sodic plagioclase. The liquid from which this clast crystallized would have met the two feldspar boundary curve further from the eutectic point, and the entire fractionation process could have taken place at low pressure. It appears that the sources of the two groups of clasts are similar, but unrelated.

3.2.c.vi Glen Afton plagiogranites (Group C6).

Two samples of plagiogranite similar to those found at Corsewall Point and Glen App are present in this deposit. They consist almost entirely of anhedral and subhedral crystals of unzoned albitic plagioclase and anhedral crystals of quartz which show no evidence of strain. These samples differ from typical plagiogranites in that a few large suhedral crystals of alkali feldspar which show well developed perthitic textures are also present. Mafic minerals are rare - altered remnants of hornblende can be recognized, but more often isolated radiating needles of epidote occur. Some opaque minerals are also present.

These clasts have some features in common with the single plagiogranite clast from Glen App (Group B5) and may be derived from a similar source.

3.2.d Shinnel Formation.

Only a limited number of granite clasts occur in the Shinnel Formation conglomerate; consequently a smaller number of samples were collected at this locality. However, a wide variety of different granite types are present, some of which show affinities with the groups of granite clasts recognized in other conglomerates. The samples are generally heavily altered and do not fall into such clearly defined groups as they do elsewhere. Table 3.4 shows the different groups of granite clast that were recognized in the Shinnel Formation conglomerate.

3.2.d.i Shinnel Formation deformed leucogranites (Group D1).

Two samples of coarsely crystalline leucogranite consisting almost entirely of quartz, alkali feldspar and plagioclase feldspar in

TABLE 3.4 THE GROUPS OF GRANITE CLASTS RECOGNIZED IN THE SHINNEL FORMATION CONGLOMERATE

GRANITE TYPE	SAMPLE NUMBERS	DISTINGUISHING MINERALOGICAL FEATURES	DISTINGUISHING CHEMICAL FEATURES	COMMENTS
Deformed leucogranite (Group D1)	SW 14 SW 18	Unfoliated, strained quartz, bent plagioclase twin lamellae. Partially annealed textures.	$Na_2O \simeq K_2O > CaO \simeq MgO$ (affected by calcite and chlorite veins.)	
Muscovite-biotite granite (Group D2)	SW 12	Equigranular texture, primary muscovite, abundant zircon, biotite-rich inclusions.	$K_2O > Na_2O > MgO > CaO$ (see Table 3.7)	Identical to Corsewall Point muscovite-biotite granite.
Biotite-bearing granites (Group D3)	SW 16a SW 16b ShW 10	Diverse features.	Diverse features	No genetic relationships between members of this group.
Granophyres and porphyries (Group D4)	SW 8 ShW 5 SW 9* ShW 8 SW 17	Granophyric intergrowths with a single perthitic feldspar. Some samples are also porphyritic.	Na_2O (5.54→4.17%) K_2O (2.70→1.77%) CaO (1.63→0.20%) MgO (0.90→0.45%)	Unrelated to Glen Afton granophyres.

* = no chemical analysis, thin section only

approximately equal proportions were collected from the Shinnel Formation (Plate 3.18). They contain some chlorite and opaque minerals which may be replacing minerals such as biotite. The rock is cut by chlorite and calcite veins. Fine grained epidote and sericite occur in saussuritized feldspars.

Individual grains are usually 2 to 3 mm. in size and are anhedral. Quartz shows distinct extinction domains, but recrystallization is limited to the contacts between grains. There are some limited diffuse intergrowths of quartz with alkali feldspar. The alkali feldspar is commonly perthitic, in places sufficiently coarse for the exsolved plagioclase to show multiple twins. In places it appears partially to enclose subhedral plagioclase grains. The plagioclase is andesine (An_{35} - optically determined) and contains twin lamellae that are frequently bent.

Although deformation has modified the original textures, features such as the poikilitically enclosed subhedral plagiocalse crystals indicate that the rock had an igneous origin. Only a weak foliation is evident in hand specimen due to the lack of mafic minerals and the limited recrystallization of quartz. Deformed granites occur at other localities, but they have a different composition and contain different textures.

3.2.d.ii Shinnel Formation muscovite-biotite granite (Group D2).

A single sample of muscovite-biotite granite, petrographically identical to those described from Corsewall Point (Group A1), was found in the Shinnel Formation conglomerate. It has a medium grained equigranular texture and contains strained quartz which shows limited intergrowths with alkali feldspar, platy biotite and muscovite, and large zircons crystals, features which are characteristic of the Corsewall Point muscovite-biotite granites. The strongest evidence that

this clast is related to those from Corsewall Point comes from the presence of a distinctive centimetre sized biotite-rich inclusion derived from a partially molten pelitic xenolith. No quartz xenoliths were present in this sample, but they are less common than the pelitic xenoliths in the Corsewall Point clasts, and may be absent because of the small size of this clast.

Chlorite is more common in this sample than in the Corsewall Point clasts: it partially or wholly replaces biotite and is associated with muscovite. Although this could be because the clast was derived from a more severely altered part of the pluton, it more probably reflects the more intense weathering suffered by this clast since erosion. This may also explain the different colour of the hand specimen - the Corsewall Point clasts are iron stained and have a reddish tinge, while the sample from the Shinnel Formation is whiter, as a result of the leeching of iron.

The significance of the occurrence of identical clasts in the Corsewall Point and Shinnel Formation conglomerates will be discussed later.

3.2.d.iii Shinnel Formation biotite-bearing granites (Group D3).

Three samples of biotite-bearing granite were collected from the Shinnel Formation. They are petrographically distinct from one another and also differ chemically (section 3.3.d). Consequently, there is no genetic relationship between the different members of this group and they are described separately.

SW 16b is a leucocratic rock consisting of quartz, alkali feldspar and plagioclase feldspar with some large altered biotite crystals. The feldspars range in size from 1 mm. to 4 mm. and are subhedral. The plagioclase is of albitic composition and the alkali feldspar is anhedral and encloses quartz and plagioclase grains. The quartz is

entirely unstrained. Platy biotite crystals occur throughout the sample, but are strongly altered, particularly along cleavage planes. Chlorite veins disrupt the sample. Although it shows some affinity with the deformed leucogranites (Group D1), SW 16b is unstrained and is richer in biotite.

SW 16a is extensively altered, and its original mineralogy is largely obscured. Heavily saussuritized feldspars form euhedral and subhedral crystals which are partially or totally enclosed by anhedral quartz grains. Fine grained epidote and chlorite may be replacing euhedral hornblende grains, while biotite is pseudomorphed by chlorite alone. These textures do not correspond to those of any of the groups of clasts described from other conglomerates.

ShW 10 contains clusters of small subhedral and euhedral plagioclase and alkali feldspar crystals, and occasional larger euhedral alkali feldspar crystals, separated by areas of anhedral quartz grains with smaller amounts of anhedral feldspars. Mafic minerals are not abundant, but generally fine grained biotite, now largely altered to chlorite is dispersed throughout this sample. ShW 10 is similar in some respects to the Glen Afton trondhjemites, but is distinguished from them by more abundant alkali feldspar and by the absence of hornblende.

3.2.d.iv Shinnel Formation granophyres and porphyries (Group D4).

Granites showing granophyric and porphyritic textures form the most abundant group of clasts in the Shinnel Formation conglomerate. They share a similar chemistry and have some textural features in common, but it is unlikely that the relationship between the individual members of this group is as close as it is between the clasts that comprise the groups described at other localities.

SW 8 and SW 9 show the best developed granophyric textures. Both contain subhedral crystals of plagioclase and alkali feldspar and

anhedral crystals of quartz which pass laterally into intergrowths with a single perthitic feldspar. The intergrowths are delicate and radiating in SW 8, and form a large proportion of the the rock, but they are coarser and of more limited extent in SW 9, where they usually mantle subhedral crystals. The interstices in this sample are filled with either granophyric intergrowths or with perthitic feldspar. The textures shown by both clasts are consistent with feldspar fractionation and the development of intergrowths at low pressure. Crystallization appears to have been regular at first, but a change to more rapid crystal growth resulted in the development of intricate intergrowths. Small amounts of chloritized biotite are present in both specimens.

ShW 8 and SW 17 are more porphyritic. They both contain large euhedral crystals of plagioclase and alkali feldspar which are often mantled by fine grained granophyric intergrowths. The groundmass consists of blocky fine grained intergrowths between quartz and a single perthitic feldspar. SW 17 also contains quartz phenocrysts and has a finer grained groundmass. ShW 5 contains small phenocrysts of plagioclase, alkali feldspar and quartz at the core of spherulitic fine grained intergrowths of feldspar and quartz.

The Shinnel Formation granophyres differ from those described from Glen Afton as they clearly formed at shallow depths while the Glen Afton samples formed at pressures > 5kb. The Shinnel Formation clasts do not contain acicular hornblende. Porphyritic rocks occur in other conglomerates, but were not studied in detail as they are not obviously related to any group of granite clasts.

3.2.e Pinstane Hill.

Granites form only a small proportion of the total clast assemblage of the Pinstane Hill conglomerate, as a result of which fewer

samples were collected at this locality. The granite clasts are all leucocratic and have a sodium-rich chemistry, but a number of distinct groups can be recognized, as shown in Table 3.5.

3.2.e.i Pinstane Hill foliated biotite granites (Group E1).

Three foliated biotite-bearing granite clasts were found in the Pinstane Hill conglomerate. Two of the samples are equigranular (PS 41 and PS 17) and one has a porphyritic texture. Biotite is too dispersed to form continuous laminae, but along with elongate quartz grains, it defines a weak foliation in all specimens.

Only one of the equigranular clasts provided a specimen large enough for chemical analysis (PS 41; PS 17 - thin section only). Most of the quartz grains are recrystallized in PS 17, but in PS 41 recrystallization is limited to grain contacts. Both samples contain subhedral alkali and plagioclase feldspar grains, which in PS 17 display deformed twin lamellae.

The more porphyritic rock, PS 22, contains euhedral crystals of plagioclase and alkali feldspar and some subhedral crystals of quartz set in a finer grained groundmass which consists mainly of quartz, feldspar and biotite (Plate 3.19). The quartz phenocrysts show sub-grain formation, and the quartz in the groundmass shows sweeping extinction. The subhedral nature of the quartz phenocrysts is probably a result of deformational processes, but the original texture indicates that this clast was derived from a high level intrusion.

The equigranular clasts may be compared to the foliated biotite granite clasts from the Corsewall Point and Glen App conglomerates (Group B4) and the clasts of deformed leucogranite in the Shinnel Formation (Group D1). They differ mineralogically from the Corsewall Point and Glen App samples, in which biotite is more abundant and microcline is also present. The Shinnel Formation clasts have more in

TABLE 3.5 THE GROUPS OF GRANITE CLASTS RECOGNIZED IN THE PINSTANE HILL CONGLOMERATE

GRANITE TYPE	SAMPLE NUMBERS	DISTINGUISHING MINERALOGICAL FEATURES	DISTINGUISHING CHEMICAL FEATURES	COMMENTS
Foliated biotite granite (Group E1)	PS 41 PS 17*	Recrystallized quartz, bent plagioclase twin lamellae, discontinuous biotite laminae.	Na_2O(4.58%) > CaO(1.51%) ≈ K_2O(1.24%) > MgO(0.7%)	Some affinity with Shinnel Formation leucogranites (D1).
	PS 22	As above, but with porphyritic texture.	similar to Group E2	
Perthitic biotite granites (Group E2)	PS 3 PS 38 PS 13 PS 43	Euhedral feldspars with separate thick perthite overgrowths.	Na_2O (5.16→4.16%) > K_2O (3.35→2.22%) > CaO (1.24→0.26%) >/= MgO (0.75→0.26%)	Some similarities with Shinnel Formation granophyres (D4).
Granophyric granites (Group E3)	PS 1	Separate intergrowths between quartz and two feldspars.	Na_2O(6.14%) >> CaO(0.54%)= MgO(0.59%) > K_2O (0.22%)	Some affinity with Glen Afton granophyric granites.
	PS 44	Intergrowths between quartz and a single perthitic feldspar.	similar to Group E2	
Trondhjemites (Group E4)	PS 2 PS 34	Mainly plagioclase and quartz, some alkali feldspar in PS 34.	Na_2O (5.83→5.69%) >> CaO (1.64→1.58%) > MgO (0.53→0.46%) > K_2O (0.47→0.24%)	

* = no chemical analysis, thin section only

common mineralogically with the Pinstane Hill clasts, but are not as strongly deformed. Deformed porphyritic granites do not occur in the other conglomerates. Although some of the clasts in the different conglomerates may have been derived from similar sources, there is little evidence to suggest that their source areas were closely linked.

3.2.e.ii Pinstane Hill perthitic biotite granites (Group E2).

The most common granite type amongst the clasts in the Pinstane Hill conglomerate is characterized by spectacular perthitic overgrowths which have formed around euhedral feldspar crystals (Plate 3.20).

The euhedral feldspars commonly occur as unzoned tabular plagioclase crystals of albitic composition, 1-2 mm. in length. They are occasionally clustered, and a few euhedral alkali feldspar crystals are also present. Each crystal is partially or wholly surrounded by separate overgrowths of perthite, usually about 0.5 mm. thick. The exsolution lamellae are stringy, but when they are more coarsely developed the exsolved plagioclase is in optical continuity with the plagioclase crystal around which the overgrowth has developed. In some instances the perthite itself is partially mantled by plagioclase that is likewise in optical continuity with the exolved plagioclase in the intergrowth (Plate 3.20).

Quartz forms large anhedral crystals that are generally rounded and slightly embayed. They are often partially surrounded by perthite and give the appearance of being loosely intergrown with it. Biotite, and less commonly hornblende form scattered subhedral interstitial grains.

These textures result from the low pressure fractional crystallization of feldspar (Fig 3.1a). Euhedral plagioclase crystals are much more abundant than alkali feldspar which indicates that the liquid moved across the the plagioclase field, crystallizing increasingly sodic plagioclase, until it reached the two feldspar

boundary curve not far from its termination. Some alkali feldspar would also have formed as the liquid moved the short way down the boundary curve towards this point, where the two feldspars were replaced by a single feldspar as the crystallizing phase. Perthitic textures developed as a result of sub-solidus unmixing of the single feldspar. This accounts for the transition from non-perthitic to perthitic feldspar and for the fact that each crystal has a separate overgrowth with which it is in optical continuity.

However, not all the observed textural features can be explained by this process. If feldspar fractionation was important the euhedral plagioclase crystals should be zoned, and fractional crystallization at low pressure would be unlikely to produce such sodic plagioclase (see section 3.2.c.v). Also, the crystallization sequence described above does not account for the occasional overgrowths of plagioclase on perthite. It is difficult to explain this particular feature in terms of any fractionation process, and it seems more likely that it is the result of sub-solidus recrystallization. As the plagioclase overgrowths are in optical continuity with exsolved lamellae in the perthite, which in turn are in optical continuity with the euhedral plagioclase crystals, the sub-solidus recrystallization associated with the formation of the perthite must have been more extensive and affected all the feldspars, resulting in plagioclase of a constant, more sodic composition.

The extensive development of perthite provides clear evidence that crystallization took place at low pressures (< 5kb.). The Glen Afton trondhjemites also contain euhedral feldspars rimmed by perthite, but the rims are much thinner and are interpreted as later features that did not grow in continuity with the euhedral crystals. Although the two groups of clasts share a common textural feature, they do not appear to have a common origin.

3.2.e.iii Pinstane Hill granophyric granites (Group E3).

Two unrelated granophyric granite clasts were found in the Pinstane Hill conglomerate. One sample, PS 1, contains separate intergrowths of quartz with alkali feldspar and with plagioclase. Euhedral crystals of both feldspars are also present and are in optical continuity with the feldspar in the intergrowths. The intergrowths are rounded and become finer towards the edge (Plate 3.21), which suggests that they formed at an early stage in the crystallization of this rock. Fine grained intergrowths also occur interstitially to the euhedral crystals. The presence of separate intergroths of quartz with plagioclase and alkali feldspar indicates that this clast formed at high pressures, in a manner similar to the Glen Afton granophyric granite clasts.

The other sample, PS 44, is similar to the granophyric granite clasts from the Shinnel Formation conglomerate and contains intergrowths between quartz and a single perthitic feldspar, which indicate that it also crystallized at low pressures. Both samples in the Pinstane Hill conglomerate contain large anhedral quartz grains which are not intergrown with feldspar, and small amounts of mafic minerals, which are altered to epidote and chlorite.

Although there are some similarities between PS 1 and the Glen Afton granophyres, they are not identical. Acicular hornblende crystals, which are characteristic of the Glen Afton granophyres, do not occur in this sample, and the Glen Afton samples lack large anhedral quartz grains and more delicate late stage intergrwoths. The sources of the clasts in the two conglomerates are similar, but not the same. There are greater similarities between PS 44 and the Shinnel Formation clasts, which may be derived from related sources.

3.2.e.iv Pinstane Hill trondhjemites (Group E4).

Two samples of trondhjemite were found at Pinstane Hill, but they are not identical. PS 2 is coarser grained and contains unzoned euhedral and subhedral plagioclase crystals (oligoclase) up to 0.5 cm. in size. Alkali feldspar forms rare subhedral grains, but occurs more commonly as an interstitial mineral. Quartz forms large anhedral grains which show minor intergrowths with some feldspars. A few patches of chlorite and epidote indicate the former presence of mafic minerals.

PS 34 is finer grained. It contains a few large zoned crystals of alkali feldspar and plagioclase, but most of the plagioclase occurs as small euhedral tabular crystals. The interstices betwen these crystals are filled by quartz and occasional alkali feldspar. Small amounts of opaque minerals and altered biotite are also present.

The presence of zoned alkali feldspars in PS 34 indicates that fractionation of alkali feldspar played an important role in the early stages of formation of this sample and it is classified as a trondhjemite rather than a plagiogranite. The mineralogy of PS 2 is similar to the plagiogranites that occur in other conglomerates, and it may be derived from a similar source.

3.3 Chemistry.

The classification of the granite clasts on the basis of petrography is qualitative, as is the inference of different petrogenetic processes which indicate that the different groups of clasts were derived from unrelated plutons. Major and trace element analyses show the relationships between the members of each group of granite clasts more clearly, and illustrate the independence of the different groups in each conglomerate. Chemical data can also be used

to test the relationship between similar groups of clasts from different conglomerates.

The chemical features of the granite clasts can also be used as indicators of the tectonic settings in which the original plutons were intruded. Major element analyses have been used to distinguish between granites intruded under convergent and divergent plate tectonic regimes (Petro et al., 1979), while Pearce et al. (1984) have developed trace element discrimination diagrams which distinguish between ocean ridge, volcanic arc, within plate and syn-collisional environments. In convergent settings, Brown (1982) has described the features of intrusive granitic rocks from different types of volcanic arc. The distinction between I- and S-type granites (Chappel and White, 1974), which reflects igneous and sedimentary source rocks, is widely used. This classification has been extended to include A-type granites (anorogenic - Loiselle and Wones, 1979) and M-type granites (mantle derived - White, 1979). Pitcher (1983) relates the different granite types to different settings within convergent zones (Table 3.6), and draws a further distinction between Cordilleran and Caledonian I-type granites, which he regards as subduction related and post-collisional respectively. The characteristics of the different types of granite are listed in Table 3.6. The use of trace elements as tectonic discriminants has also been extended to distinguish between granites intruded during the different stages of continental collision (Harris et al., 1986). These different approaches can be used to interpret the chemical data from the groups of granite clasts that occur in the Southern Uplands conglomerates and to deduce the tectonic conditions that prevailed in the sediment source areas.

Tables of chemical data are contained in Appendix 2. Major and trace element analyses were carried out using a Phillips PW 1400 XRF spectrometer, following the method outlined by Devey (1986). Further

TABLE 3.6. CHARACTERISTICS OF DIFFERENT GRANITE TYPES AND THEIR RELATIONSHIP TO PLATE TECTONIC SETTING (FROM PITCHER, 1983).

M-type	I- (Cordilleran) type	I- (Caledonian) type	S-type	A-type
Plagiogranite subordinate to gabbro	Tonalite dominant but broad compositional spectrum — diorite to monzogranite — with wide SiO_2-range. Major association with gabbro	Granodiorite-granite in *constrasted* association with minor bodies of hornblende diorite and gabbro	Granites with high but narrow range of SiO_2. Leucocratic monzogranites predominate but granitoids with high biotite content locally important	Biotite granite in evolving series with alkalic granite and syenite. Highly contrasted acid–basic relationship
Hornblende and biotite; pyroxene	Hornblende and biotite; magnetite, sphene	Biotite predominates; ilmenite and magnetite	Muscovite and red biotite; ilmenite, monazite, garnet, cordierite.	Green biotite. Alkali amphiboles and pyroxenes in alkalic types, astrophyllite.
K-feldspar interstitial micrographic	K-feldspar interstitial and xenomorphic	K-feldspar generally interstitial and invasive. Often quartz-rich	K-feldspar often as megacrysts with protracted history. Autometasomatic variants	Perthites
Basic igneous xenoliths	Dioritic xenoliths; may represent restitic material	Mixed xenolith populations	Metasedimentary xenoliths predominant	Cognate xenoliths, also basic magma blebs
Typical initial $^{87}Sr/^{86}Sr$ ratios $<0{\cdot}704$	$Al/\left(Na+K+\frac{Ca}{2}\right)<1{\cdot}1$ (often <1) $<0{\cdot}706$	$Al/\left(Na+K+\frac{Ca}{2}\right)$ *ca.* 1 $>0{\cdot}705$ $<0{\cdot}709$	$Al/\left(Na+K+\frac{Ca}{2}\right)>1{\cdot}05$ $>0{\cdot}708$	Peralkaline, relatively rich in F. Considerable range, 0·703–0·712
Small, quartz diorite-gabbro composite plutons	Great multiple, linear batholiths with arrays of composite cauldrons	Dispersed, isolated complexes of multiple plutons and sheets	Multiple batholiths, plutons and sheets, less voluminous and more commonly diapiric than I-types	Multiple, centred, cauldron-complexes of relatively small volume
Associated island-arc volcanism	Associated with great volumes andesite and dacite	Sometimes associated basalt–andesite lava "plateaux"	Can be associated with cordierite-bearing lavas but characteristically lacking in voluminous volcanic equivalents	Associated with caldera centred alkalic lavas
Short, sustained plutonism	Very long-duration episodic plutonism	Short, sustained plutonism; postkinematic	Sustained plutonism of moderate duration; syn- and post-kinematic	Short-lived plutonism
Oceanic island arc	Andinotype marginal continental arc	Caledonian-type post-closure uplift	Hercynotype continental collision. Also encratonic ductile shear-belts	Post-orogenic or anorogenic situations
Open folding; burial-type metamorphism	Vertical movements, little lateral shortening; burial-type metamorphism	Dip-slip and strike-slip faulting; retrograde metamorphism	Much shortening; low-pressure metamorphism in slate belts; part of a *Granite Series*	Doming and rifting
Porphyry-Cu, Au, mineralization	Porphyry-Cu, Mo, mineralization	Rarely strongly mineralized	Sn and W-greisen and vein-type mineralization	Columbite, cassiterite and fluorite

details are given in Appendix 4. In order to reduce errors due to weighing, and to facilitate comparisons between samples and with data from possible source areas, major element analyses were normalized to 100%. Devey (1986) has shown that the values obtained for major element analyses are accurate to ~1%, which is sufficiently small to allow compositional differences to be easily recognized.

3.3.a Corsewall Point.

The major element characteristics of the different groups of granite clasts (Table 3.1) are most conveniently represented by the Na_2O-K_2O-CaO diagram (Fig. 3.6) which shows that the petrographically defined groups of clasts also have distinct chemical characteristics. There are no clear relationships between the different groups of clasts which supports the view they were derived from separate and possibly unrelated granite plutons. The majority of clasts lie close to the calc-alkali trend of Nockolds and Allen (1953), although they are not always parallel to it. This diagram also distinguishes rocks of trondhjemitic affinity, which differ from other calc-alkali rocks by having low Na/K ratios (Barker, 1979). This is illustrated by the trend defined by trondhjemites from south-western Finland (Barker and Arth, 1976), with which the samples of plagiogranite and trondhjemite from Corsewall Point show a greater affinity.

The affinity of the granite clasts with calc-alkali rocks is also shown by the AFM plot (Fig. 3.7). Intrusive and extrusive rocks from volcanic arcs show similar ranges in composition and follow similar trends of arc maturity (Brown, 1982). It can be seen that most of the granite clasts lie within the range of compositions shown by extrusive arc rocks and lie sub-parallel to the trends that they define. The biotite granites (Group A4) lie on a separate trend to the muscovite-

biotite granites (Group A1) and the foliated hornblende-biotite granites (Group A3), which again suggests that they are unrelated.

The trace element data are also consistent with a volcanic arc origin for most of the granite clasts (Fig. 3.8). The only sample to plot outside the field of volcanic arc granites is the plagiogranite, CoP 29. The chemistry of this clast, in addition to its mineralogy, is consistent with an origin at an ocean ridge (section 3.2.a.v., Coleman and Peterman, 1975). This confirms the distinction between it and the other trondhjemitic clast, CoP 28, which plots in the field of volcanic arc granites. Trondhjemites are typical of oceanic island arcs, but small volumes also occur in subduction-related settings at continental margins, associated with larger volumes of more typical calc-alkali granites. This clast plots on the trend defined by more "mature" volcanic arcs (such as the Cascades of North America or the North Chile margin) on the AFM diagram (Fig 3.7), a trend that is also followed by the Sierra Nevada batholith (Brown, 1982). CoP 28 also plots in the continental trondhjemite field on the K_2O-SiO_2 diagram (see Fig. 5.11), so it is more likely it was derived from a continental setting, rather than an oceanic island arc.

The majority of clasts fall in an area of the Rb v. Y+Nb diagram (Fig. 3.8) where it is impossible to distinguish between volcanic arc granites and post-collisional granites (Pearce et al., 1984). Such a distinction may be acheived using Hf and Ta in addition to Rb (Harris et al., 1986), but no such data is available in this study. However, the muscovite-biotite granites (Group A1) show chemical and mineralogical characteristics typical of S-type granites - they contain muscovite, biotite, monazite and garnet, metasedimentary xenoliths are common and they have molecular $\frac{Al_2O_3}{Na_2O+K_2O+CaO}$ ratios in the range 1.32 to 1.65. On

the other hand, the low initial $^{87}Sr/^{86}Sr$ ratio of this group (0.705 ± 0.002 - see Chapter 4) is more typical of I-type granites, and the clasts follow calc-alkali trends (Figs. 3.6 and 3.7). S-type granites (sensu stricto) typically form in syn-collisional environments and represent the melts generated during thrusting related to continental collision (the group II granites of Harris et al., 1986). The muscovite-biotite granite clasts differ from syn-collisional granites in having low Rb/Zr ratios and lower Rb concentrations, as well as a low initial $^{87}Sr/^{86}Sr$ ratio (Harris et al., 1986). This apparent conflict may be resolved if the clasts are regarded as post-collisional granites (the group III granites of Harris et al., 1986), which form as a result of slow uplift and thermal relaxation in the crust following continental collisional. Such magmas have both crustal- and mantle-derived components and as they are associated with subduction systems, they are often chemically indistinguishable from volcanic arc rocks, while having an S-type mineralogy.

The two groups of unfoliated hornblende-biotite granites (Groups A2a and A2b) that were distinguished on petrological grounds have slightly different chemical characteristics (Table 3.1). The samples in Group A2b, which contain poikilitic alkali feldspar crystals, have equal proportions of MgO, Na_2O and K_2O, in the range 2.5 to 2.7%, and CaO in the range 3.2 to 3.4%, while the Group A2a granites contain more variable proportions of MgO, Na_2O and K_2O and generally have lower concentrations of CaO. These differences are reflected by the Na_2O-K_2O-CaO and AFM diagrams (Figs. 3.6 and 3.7), but are not apparent in the trace element data (Fig. 3.8). The two groups lie on the same trend on the AFM plot (Fig. 3.7), which further suggests that they are closely related (section 3.2.a.ii). However, this trend lies sub-parallel to the AF side of the diagram, and is at a high angle to the trends defined by modern volcanic arcs. Scatter parallel to the AF

side of the diagram is considered by Petro et al. (1979) to be a characteristic of granites from extensional rather than compressional environments. Granites intruded into attenuated continental crust may show calc-alkali affinities (Pearce et al., 1984), but on the basis of Peacock's alkali-lime index, these clasts are calcic and are also peraluminous, features that are more typical of granites from compressional environments (Petro et al., 1979). The trace element data plots in the volcanic arc field, rather than in the within plate granite field (Fig. 3.8), where granites from extensional environments would be expected to plot. Thus, it appears most likely that the clasts of unfoliated hornblende-biotite granite (Group A2) were derived from a volcanic arc setting.

The foliated hornblende-biotite granites (Group A3) show features that are typical of volcanic arc intrusions. However, they always plot separately from the unfoliated hornblende-biotite granites (Group A2), and are distinguished from them by containing slightly less Na_2O (2.3→2.5%), less K_2O (1.6→2.0%) and more MgO (2.3→3.3%). This supports the petrographic evidence that this group is not the deformed equivalent of Group A2. Similarly, the biotite granites (Group A4) show island arc characteristics, but the most deformed sample, CoP 25, always plots separately from the other members of the group, which confirms the view that it had a separate origin, and is not the deformed equivalent of the other biotite granites (section 3.2.a.iv).

3.3.b Glen App.

Comparisons between the Na_2O-K_2O-CaO diagrams for the granite clasts from Glen App and Corsewall Point (Figs. 3.9 and 3.6) show that similar types of granite are present in both deposits. The differences between the two diagrams reflect the differing proportions in which the various clasts occur, and the greater degree of alteration that has

affected the samples from Glen App. The alteration of biotite and hornblende has the greatest effect on the chemical composition and resuls in a relative decrease in the potassium content and a relative increase in the iron content of these clasts. Some of the potassium may be used in the formation of sericite which accompanies the conversion of anorthite to clinozoiste during the albitization of plagioclase feldspar (section 3.2.c.i). The reduction in potassium is seen by comparing Figs. 3.6 and 3.9 - in both cases most of the clasts lie sub-parallel to the calc-alkali trend, but the Glen App samples fall on the potassium-poor side of this line. The presence of calcite veins in some samples also causes the translation of points towards the CaO apex. Apart from a single clast of plagiogranite (sample AP 2), there are no clasts of trondhjemitic affinity in this deposit.

On the AFM plot all the clasts fall within the compositional range shown by extrusive rocks from volcanic arcs, with the exception of the foliated biotite granites, which still follow a calc-alkali trend (Fig. 3.10). All the clasts fall within the volcanic arc field on the Rb v. Y+Nb diagram (Fig. 3.11), with the exception of the plagiogranite clast. Comparison with the data from Corsewall Point (Fig. 3.8) shows that Rb is depleted in most groups, a reflection of the reduction in potassium discussed above. Y and Nb are little affected by such alteration (Pearce et al., 1984). Despite the effects of alteration, these clasts retain chemical characteristics that are consistent with a volcanic arc origin.

The similarity between the detritus in the Corsewall Point and Glen App cconglomerates is also apparent in the chemical data. On the AFM diagram (Fig. 3.10) the unfoliated hornblende-biotite granites from Glen App (Group B1) plot between the two groups of unfoliated hornblende-biotite granite from Corsewall Point (Group A2), on a trend sub-parallel to the AF side of the diagram. The same relationship does not occur on

the Na_2O-K_2O-CaO and trace element diagrams as a result of the potassium and rubidium depletion discussed above. The much altered clast, AP 15, shows a greater affinity with the foliated granodiorites (Group B2) on the Na_2O-K_2O-CaO plot, but with the unfoliated hornblende-biotite granites (Group B1) on the AFM plot, whic reflects the presence of calcite veins in this sample. The clast of foliated granodiorite, AP 13, has a very similar chemistry to CoP 107 (see Appendix 2) and always plots close to the field of foliated hornblende-biotite granodiorites from Corsewall Point (Group A3), although there is some potassium and rubidium depletion due to alteration.

The biotite granites from Glen App (Group B3) lie on the trend defined by the biotite granites from Corsewall Point (Group A4) in the AFM diagram, and the two groups occupy fields that overlap on the trace element diagram. The foliated biotite granites (Group B4) form a separate group and are distinguished from the unfoliated biotite granites (Group B3) by having more equal proportions of sodium and potassium. This also distinguishes the foliated biotite granite clast at Corsewall Point (CoP 25) from the less deformed biotite granites in that deposit. CoP 25 falls within the field defined by foliated biotite granites from Glen App on the Na_2O-K_2O-CaO plot, but plots separately from the the Glen App samples on the AFM and trace element diagrams, which, together with petrographic differences between the foliated biotite granite clasts in the Glen App and Corsewall Point conglomerates, suggests that they were derived from similar, rather than identical, sources. The same argument applies to the plagiogranite samples from the two localities, which are not petrographically identical and which have only generally similar chemical characteristics.

The Glen App granite clasts are derived from a similar volcanic arc source to the Corsewall Point granite clasts. The close similarities

between some groups of clasts suggest that parts of the source area were common to both conglomerates, but the differences in the composition of the clast assemblages show that they were derived separately.

3.3.c Glen Afton.

The Na_2O-K_2O-CaO diagram for granite clasts from the Glen Afton conglomerate (Fig. 3.12) shows that it contains a similar range of detritus to the Corsewall Point and Glen App conglomerates (Figs. 3.6 and 3.9). Most of the granite clasts fall within the volcanic arc field on the Rb v. Y+Nb diagram (Fig. 3.14) and within the compositional range shown by extrusive rocks from modern volcanic arcs on the AFM diagram (Fig. 3.13). This indicates that most of the clasts in the Glen Afton conglomerate were also derived from granite plutons that formed within volcanic arcs.

However, there are significant differences between the data obtained from the Glen Afton conglomerate and from the Corsewall Point and Glen App conglomerates. This reflects more general changes in the nature of the detritus that was supplied to the Southern Uplands during the Caradoc (Chapter 2) and is best illustrated by the Na_2O-K_2O-CaO diagrams for the three deposits (Figs. 3.6, 3.9 and 3.12), which shows that granite clasts of trondhjemitic affinity are more abundant in the Glen Afton conglomerate. Only two groups of clasts lie on the calc-alkali trend - the muscovite-biotite granites (Group C1) and the biotite granodiorites (Group C2). Although the muscovite-biotite granites from Corsewall Point (Group A1) and Glen Afton occupy similar positions on the Na_2O-K_2O-CaO diagrams (Figs. 3.6 and 3.12), they are clearly separated by the AFM diagram (Figs. 3.7 and 3.13), which provides further support for the conclusion that they were derived from unrelated sources (section 3.2.c.i). The Glen Afton muscovite-biotite granites have chemical characteristics more typical of I-type granites

($\frac{Al_2O_3}{Na_2O+K_2O+CaO}$ in the range 1 to 1.2, initial $^{87}Sr/^{86}Sr$ = 0.7061 - see Chapter 4) which indicates that they are derived from an igneous source, probably within a volcanic arc. This contrasts with the Corsewall Point muscovite-biotite granites which contain a significant crustal component and which may have formed in a post-collisional setting.

The unfoliated biotite granodiorites from Glen Afton (Group C2) have a similar composition to the foliated hornblende-biotite granodiorites from Corsewall Point (Group A3), and they follow similar trends on the AFM diagram. However, the strong petrographic differences between the two groups of clasts means that it is unlikely that they were derived from closely related sources.

The hornblende-biotite granites (Group C3) lie closer to the trondhjemitic trend than the calc-alkali trend on the Na_2O-K_2O-CaO diagram (Fig. 3.12), although they are not trondhjemites as defined by Barker (1979). However, this does distinguish them from the Corsewall Point biotite granite clasts (Group A4), which lie closer to the calc-alkai trend (Fig. 3.6), but not from the Glen App biotite granites (Group B3), which are also mineralogically similar to the Glen Afton hornblende-biotite granites (Fig. 3.9; section 3.2.c.iii). The AFM diagram (Fig. 3.13) shows that the Glen Afton clasts are more evolved and follow a trend that is closer to those defined by less mature volcanic arcs. The Corsewall Point biotite granites (Group A4) and the Glen App biotite granites (Group B3) are less evolved and follow trends that are parallel to those defined by more mature volcanic arcs (Figs. 3.7 and 3.10). Primitive arcs are developed on oceanic crust, whilst mature arcs are typical of continental settings (Brown, 1982). Consequently, granites from mature arcs are more likely to contain a crustal component, and some may show S-type characteristics. Although both the Corsewall Point biotite granites (Group A4) and the Glen Afton

horneblende-biotite granites (Group C3) have relatively low initial $^{87}Sr/^{86}Sr$ (0.7056 and 0.7064 respectively - see Chapter 4), which indicates that the magmas were derived from igneous sources, the Corsewall Point clasts also show evidence of a crustal component in the melt. The Corsewall Point clasts contain both igneous xenoliths and garnets that may be derived from assimilated crustal material (section 3.2.a.iv) and have $\frac{Al_2O_3}{Na_2O+K_2O+CaO}$ ratios that range from 1.1 to 1.2. The Glen Afton samples contain only igneous xenoliths and have lower $\frac{Al_2O_3}{Na_2O+K_2O+CaO}$ ratios, which range from 1.0 to 1.05. The Glen App biotite granites (Group B3) show I-type characteristics similar to the Glen Afton clasts but they follow the same trend as the Corsewall Point clasts on the AFM diagram, which suggests that they are derived from a similar mature volcanic arc (section 3.3.b), rather than the less mature source of the Glen Afton clasts. Although similar granites of volcanic arc origin have supplied detritus to the Corsewall Point-Glen App and Glen Afton conglomerates, the sources are not identical.

The acicular hornblende granites and granophyres (Group C4) are not easily distinguished from the trondhjemites (Group C5) by either the Na_2O-K_2O-CaO diagram (Fig. 3.12) or the Rb v. Y+Nb diagram (Fig. 3.14). However, they plot separately on the AFM diagram (Fig. 3.13), but like the hornblende-biotite granites (Group C3), they follow trends that are typical of less mature volcanic arcs. The main chemical difference between the two groups is that the trondhjemites contain more Al_2O_3 and less Fe_2O_3 than the granophyric granites of similar silica content, which reflects the lower concentration of ferromagnesian minerals and the greater abundance of feldspar in the trondhjemites. The chemical evidence suggests that the two groups of granite clasts have a similar origin, but petrographic differences indicate they formed under different conditions (sections 3.2.c.iv and 3.2.c.v). Both groups have

$\frac{Al_2O_3}{Na_2O+K_2O+CaO}$ ratios in the range 0.9 to 1.07 and they probably also had low initial $^{87}Sr/^{86}Sr$ (Chapter 4), which is consistent with an igneous source for the granitic magma. Low potassium trondhjemitic magmas are typical of island arcs, and because the clasts follow the trends defined by less mature arcs (such as the Aleutians and the Lesser Antilles), it is likely that both groups of clasts were derived from such a source. This is in contrast to the trondhjemitic clast collected from Corsewall Point (Group A5) which has a broadly similar major element chemistry but different trace element characteristics (the Corsewall Point clast is much richer in Rb and Sr and poorer in Y and Nb - see Figs. 3.8 and 3.14). The Corsewall Point clast was derived from a volcanic arc in a more mature continental setting, and its source is unlikely to be related to that of the Glen Afton trondhjemites.

The two plagiogranite clasts (Group C6) plot in the field of ocean ridge granites on Fig. 3.14. Although they have formed in a similar setting to the Corsewall Point and Glen App plagiogranites (Groups A6 and B5), chemical and petrographic differences indicate that they were not derived from identical sources.

Both the chemical and petrographic data suggest that the granite clasts in the Corsewall Point-Glen App conglomerates and the Glen Afton conglomerate were derived from distinct sources. Calc-alkali granites derived from mature volcanic arcs dominate the clast assemblage at Corsewall Point, while the granitic detritus in the Glen Afton conglomerate includes a variety of trondhjemitic clasts derived from less mature arcs. The granites of calc-alkaline affinity that occur in the Glen Afton conglomerate do not correspond to those from Corsewall Point, and many of the granite types present at Corsewall Point do not occur in the Glen Afton conglomerate. This suggests that the source area for the Southern Uplands sediments changed from one dominated by

mature continental volcanic arcs during the N. gracilis zone to one which also included less mature oceanic island arcs in the D. clingani zone.

3.3.d The Shinnel Formation.

The chemical data for the granite clasts collected from the Shinnel Formation conglomerate show considerable scatter which reflects their more diverse origins. Although granite clasts form a smaller proportion of the detritus, they appear to be derived from a wider variety of sources. Some of the scatter may also be due to the effects of weathering, which is considerable in some cases.

One of the clasts, a muscovite-biotite granite (SW 12 - Group D2), is petrographically identical to the large group of muscovite-biotite granites that occur in the Corsewall Point conglomerate (Group A1 - see section 3.2.d.ii). Table 3.7 compares the analysis of SW 12 with the range in values and the average of the analyses of the suite of petrographically similar clasts collected from Corsewall Point. All the major element data fall within the range of values shown by the Corsewall Point clasts with the exception of TiO_2 and P_2O_5 which occur in minor phases that are likely to be present in variable amounts. In addition, Al_2O_3, MgO, CaO, Na_2O and K_2O fall within 1σ of the average analyses. There is also a close correspondence between the trace element data for SW 12 and the Corsewall Point clasts: only Nb is present in greater concentrations. Although this clast is more weathered than its counterparts from Corsewall Point (section 3.2.d.ii), the Rb and Sr values are both close to the average for the Corsewall Point suite which suggests that the Rb and Sr isotopic composition of SW 12 may have been little affected by the additional weathering that it has suffered. SW 12 plots within the field defined by the Corsewall Point muscovite-biotite granites on the Na_2O-K_2O-CaO diagram (Fig. 3.15) and on the Rb

TABLE 3.7

A comparison of the chemistry of the Corsewall Point muscovite-biotite granites and sample SW 12 from the Shinnel Formation conglomerate.

	Corsewall Point data		SW 12
	Range	Average (±1σ)	
SiO_2	75.47→67.07	72.40±2.18	69.41
TiO_2	1.01→0.44	0.74±0.16	1.08
Al_2O_3	15.57→11.16	13.51±1.01	13.56
Fe_2O_3	6.77→3.71	4.82±0.88	6.63
MnO	0.11→0.06	0.07±0.01	0.11
MgO	2.69→1.19	1.81±0.44	1.88
CaO	1.56→0.70	1.16±0.25	1.40
Na_2O	2.46→1.81	2.04±0.19	2.07
K_2O	4.11→2.64	3.39±0.42	3.63
P_2O_5	0.11→0.06	0.08±0.02	0.23
Rb ppm	123.4→55.2	82.5±17.3	103.2
Sr	311.1→188.4	217.8±32.8	219.6
Y	29.3→14.0	19.2± 4.4	23.0
Zr	279.8→134.4	206.3±37.1	243.7
Nb	13.8→8.0	10.8± 1.7	15.1
Pb	27.5→16.9	19.2± 3.3	16.6

v. Y+Nb diagram (Fig. 3.17), but slightly away from the trend that they define on the AFM diagram (Fig. 3.16). However, the general chemical and petrographic characteristics of this clast indicate that it has the same origin as the Corsewall Point muscovite-biotite granites.

The two samples of deformed leucogranite (SW 14 and SW 18 - Group D1) have similar petrographic features, and are broadly similar chemically. The main differences between them lie in the different proportions of K_2O and CaO they contain, with associated contrasts in Rb and Sr, and to a lesser extent, Na_2O and MgO. This explains why the two points plot close together on the AFM diagram (Fig. 3.16) but apart on the Na_2O- K_2O-CaO and the Rb v. Y+Nb diagrams (Figs. 3.15 and 3.17). Such differences are likely to be due to the efects of alteration, and reflect the presence of calcite and chlorite veins and saussuritized feldspars (section 3.2.d.i). Although the leucogranites are petrographically distinct from the Glen App foliated biotite granites (Group B4), they are chemically similar, and plot on the same trend on the AFM diagram, which appears to be the diagram least affected by the alteration processes described above. It is possible that the deformed leucogranites present in the Shinnel Formation conglomerate and the foliated biotite granites present in the Glen App conglomerate are derived from a similar source.

The biotite-bearing granites (Group D3) are a diverse group which show unrelated petrographic features (section 3.2.d.iii). The variable chemistry of the clasts, evident in all the plots, confirms their independent origins, but is further complicated by extensive weathering. SW 16a is so strongly altered that its chemistry is unlikely to be of any use. ShW 10 is a low potassium granite and is chemically similar to the Glen Afton trondhjemites (Group C5), although differences in MgO and Fe_2O_3 concentrations are due to the more extensive alteration of biotite to chlorite in this sample. There are also some mineralogical

differences between this clast and the Glen Afton trondhjemites (section 3.2.d.iii), and ShW 10 never falls within the field defined by the Glen Afton clasts, although it may be derived from a related source.

SW 16b is as potassium rich as the muscovite-bearing granites from Corsewall Point (Group A1) and Glen Afton (Group B1) but contains only relatively small amounts of biotite which is rarely altered to muscovite. Most of the potassium is present in sericite, which occurs in the altered cores of plagioclase. Extensive calcite veins have also affected the chemical composition, but this clast may originally have been more like the biotite and hornblende-biotite granite clasts from other localities which it resembles petrographically.

The granophyres and porphyries (Group D4) form the most coherent group of granitic clasts in the Shinnel Formation conglomerate. They are chemically distinct from the Glen Afton granophyres (Group C4), which supports the petrographic evidence of their separate origins (section 3.2.d.iv). The Shinnel Formation granophyres are much more potassic, and comparison of the Na_2O-K_2O-CaO diagrams (Figs. 3.15 and 3.12) and the Rb v. Y+Nb diagrams (Figs. 3.17 and 3.14) for the two conglomerates shows that there is no relationship between the separate groups of granophyric granite clasts they contain. The two groups of clasts also plot on separate trends on the AFM diagrams (Figs. 3.16 and 3.13) and most of the Shinnel Formation granophyres plot in the field of within plate granites on the trace element diagram (Fig. 3.17). However, they are calcic in terms of Peacock's alkali-lime index, and metaluminous to peraluminous, features that are more typical of granites derived from volcanic arcs. Alteration by alkali-rich fluids, which has the effect of increasing Y and Nb (Pearce et al., 1984), may account for this discrepancy. This group of clasts is chemically and petrographically distinct from any of the groups previously described, and represents a new component of the detritus.

In addition to the freshly derived detritus, some of the clasts in the Shinnel Formation conglomerate are similar to clasts found in older deposits which raises the possibility that some detritus was reworked from other conglomerates. Such a variety of origins may account for the diversity that is present amongst the granite clasts in the Shinnel Formation conglomerate.

3.3.e Pinstane Hill.

There is a more complex relationship between the chemical characteristics of the granite clasts in the Pinstane Hill conglomerate and the petrographic groups they define. The four samples of perthitic biotite granites (Group E2), which form a petrographically distinct group, have similar chemical features, but some of the clasts belonging to other petrographic groups are chemically indistinguishable from them.

The perthitic biotite granite clasts were derived from high level intrusions (section 3.2.e.iii). Figure 3.18 shows their sodium- and potassium-rich nature, but because of their high SiO_2 contents they are calc-alkali in terms of Peacock's alkali-lime index. Also, they are metaluminous to peraluminous and although some of them fall in the within-plate granite field on the Rb v. Y+Nb diagram (Fig. 3.20), they are not sufficiently alkaline to be interpreted as within-plate granites. Their position on the trace element discrimination diagram may be the result of alteration by alkali-rich fluids (see section 3.3.d), and their major element chemical characteristics are more typical of granites derived from volcanic arcs. These features are very similar to those shown by the granophyric and porphyritic granite clasts in the Shinnel Formation conglomerate (Group D4 - section 3.3.d), which were also derived from high level intrusions. They occupy similar positions on the Na2O-K2O-CaO diagrams (Figs. 3.15 and 3.18), the AFM

diagrams (Figs 3.16 and 3.19) and the Rb v. Y+Nb diagrams (Figs 3.17 and 3.20), but the Pinstane Hill clasts are generally more potassic and contain more Al_2O_3 and less Fe_2O_3. Although they have different petrographic features, the Pinstane Hill perthitic biotite granites and the Shinnel Formation granophyres appear to have been derived from closely related sources.

The two granophyric granite clasts (Group E3) have contrasting petrographic features which suggests that they were derived from granite plutons intruded at different depths (section 3.2.e.iii). The chemical characteristics of the two clasts are differ. PS 44 has a similar chemistry to the perthitic biotite granites (Group E2) described above, and like them, was also derived from a high level pluton. It plots close to the fields defined by the perthitic biotite granites in all three diagrams used in this study, and is distinguished from the Shinnel Formation granophyres (Group D4) by the same features that distinguish them from the Pinstane Hill perthitic biotite granites (higher K_2O and Al_2O_3, lower Fe_2O_3). Although the source of PS 44 was also very similar to that of the granophyres in the Shinnel Formation conglomerate, it was probably derived from a source more closely related to that of the perthitc biotite granites in the Pinstane Hill conglomerate.

The other granophyric clast, PS 1, is petrographically similar to the granophyric clasts from Glen Afton (Group C4), and like them, formed at higher pressures. Both clasts have a similar low-potassium, trondhjemitic chemistry, but PS 1 is distinguished from the Glen Afton clasts by much higher Na_2O and lower CaO and Fe_2O_3. Consequently, it does not plot within the fields defined by the Glen Afton granophyres on any of the diagrams. PS 1 is therefore unlikely to have been reworked from the Glen Afton conglomerate, but may have been derived from a similar source.

Of the three samples of foliated biotite granites (Group E1), only two were analysed. Although they are both strongly deformed, they show different petrographic features, and this is reflected by their different chemical compositions. PS 22 has a relict porphyritic texture, which indicates that it was intruded at shallow depths. It plots within the field defined by the perthitic biotite granites (Group E2) on the Na_2O-K_2O-CaO diagram (Fig. 3.18) and the Rb v. Y+Nb diagram (Fig. 3.20), which are also derived from a high level pluton. This clast was probably derived from a similar source to the perthitic biotite granites, but one that has also suffered deformation. The other deformed biotite granite, PS 41, has a similar sodium-rich chemistry to the deformed leucogranites in the Shinnel Formation (Group D1). However, the correspondence is not particularly close and there are petrographic differences between the two groups. It is probable that these clasts are derived from similar, but not identical sources.

Despite their petrographic differences, the two trondhjemite clasts (Group E4) have similar chemical compositions, which correspond to the composition of the Glen Afton trondhjemites (Group C5). They lie close to the boundary between the fields of volcanic arc granites and oceanic plagiogranites on the Rb v. Y+Nb diagram (Fig. 3.20), but they are more potassic and richer in Rb than the other plagiogranite clasts. Also, the presence of alkali feldspar (section 3.2.e.iv) in both of the Pinstane Hill clasts suggests that they are more properly considered as trondhjemites, and consequently it is likely that they were derived from a volcanic arc source. Although they do not have identical petrographic features to the Glen Afton trondhjemites, they may have been derived from similar sources.

The similarities between the granitic detritus in the Pinstane Hill conglomerate and some of the detritus in the Shinnel Formation conglomerate suggest that there was little change in the character of

the sediment source areas between the end of the Caradoc and the Lower Llandovery.

3.4 Conclusions.

Most of the granite clasts in the Southern Uplands conglomerates have a chemical signature which is consistent with their derivation from a volcanic arc source. Given the interpretation of the Southern Uplands as an accretionary complex, such a source would be expected for any contemporary granitic detritus. However, some of the clasts give older radiometric ages (see Chapter 4), and the deformation of others suggests that they were derived from source areas with a more complex tectonic history.

Detailed interpretation of the geochemical data shows that the granite clasts were derived from different types of volcanic arcs at different times, which indicates that changes occurred in the source of the Southern Uplands sediments during the formation of the accretionary complex. Table 3.8 summarizes the petrographic and geochemical relationships between the groups of granite clasts that occur in different conglomerates, which allows the relationships between the different source areas to be established.

There is a close relationship between the the granitic detritus in the Corsewall Point and Glen App conglomerates, which reflects their spatial and temporal proximity. Similar source areas, dominated by plutons with mature continental volcanic arc characteristics, supplied detritus to both conglomerates. The presence of rare plagiogranite clasts indicates that this source area also contained an ophiolitic component.

The source of the granite clasts in the Glen Afton conglomerate is distinctly different. Although slightly more than 50% of the granite

TABLE 3.8 A SUMMARY OF THE RELATIONSHIPS BETWEEN GRANITE CLASTS FROM DIFFERENT LOCALITIES.

CORSEWALL POINT	GLEN APP	GLEN AFTON	SHINNEL FORMATION	PINSTANE HILL
Muscovite-biotite granites (Group A1) high P ? post-collisional			Muscovite-biotite granite (Group D2) high P ?post-collisional	
		Muscovite-biotite granites (Group C1) ?low P ?mature arc, hydrothermally altered		
Hornblende-biotite granites (Group A2a) high P ?equilibrium crystallization mature arc				
Hornblende-biotite granites (Group A2b) high P fractional crystallization. mature arc	Hornblende-biotite granites (Group B1) high P fractional crystallization mature arc			
		Biotite granodiorites (Group C2) mature arc undeformed		
Foliated hornblende-biotite granodiorites (Group A3) post-crystallization deformation mature arc	Foliated granodiorite (Group B2) post-crystallization deformation			
Biotite granites (Group A4) high P fractional crystallization mature arc	Biotite granites (Group B3) mature arc	Hornblende-biotite granites (Group C3) low P fractionation immature arc.		
Foliated biotite granite (CoP 25) post-crystallization deformation	Foliated biotite granites (Group B4) post-crystallization deformation		Deformed leucogranites (Group D1) post-crystallization deformation	Foliated biotite granites (Group E1) post-crystallization deformation.
		Granophyric and acicular hornblende granites (Group C4) rapid crystallization at high P immature arc characteristics		Granophyric granites (Group E3) evidence of rapid crystallization at high P in PS1. immature arc characteristics
			Granophyres and porphyries (Group D4) rapid crystallization at low P mature arc characteristics	Perthitic biotite granites (Group E2) low P fractional crystallization
Trondhjemite (Group A5) low P fractionation mature arc affinities		Trondhjemites (Group C5) high P fractional crystallization immature arc affinities	Biotite-bearing granites (Group D3) diverse group, ShW 10 shows trondhjemitic affinities.	Trondhjemites (Group E2) immature arc characteristics
Plagiogranite (Group A6) oceanic affinities	Plagiogranite (Group B5) oceanic affinities	Plagiogranites (Group C6) oceanic affinities		

Chemically and/or petrographically similar granites occur at the same horizontal level. Solid lines connect granite clasts that are closely related and probably derived from the same source. Dashed lines connect granite clasts that have similar characteristics, but are not identical.

clasts sampled were derived from a mature continental volcanic arc source, they account for only two of the six groups of granite clasts that are present in this conglomerate (Groups C1 and C2); the other four groups of granite clasts have characteristics that are more typical of less mature oceanic island arcs. This suggests that the source area of the Glen Afton conglomerate contained a few large plutons associated with a mature arc and a greater variety of smaller plutons associated with the less mature arcs which must have been accreted to the continental margin before subduction-accretion commenced. The mature arc granites are unlike those that occur in the Corsewall Point and Glen App conglomerates, which suggests that the location of the source area changed between the N. gracilis and C. clingani zones.

The Shinnel Formation conglomerate, which was deposited during or shortly after the P. linearis zone, contains granitic detritus that is also present in the Corsewall Point conglomerate (muscovite-biotite granites, Groups D2 and A1). It is unlikely that the source area of the Shinnel Formation and Corswewall Point conglomerates was the same given the change in the location of the source area of the intervening Glen Afton conglomerate and the presence of distinctive granophyric granite clast in the Shinnel Formation conglomerate (Group D4). It is more likely that a new source area was being eroded, and that additional detritus was derived from older, reworked conglomerates. The Pinstane Hill conglomerate, which is of Lower Llandovery age, contains petrographically distinct granite clasts derived from high level plutons (Group E2) which are chemically very similar to the granite clasts derived from high level plutons that occur in the Shinnel Formation conglomerate (Group D4). This suggests that a similar or closely related source area continued to supply detritus to the Southern Uplands during the Llandovery.

Chapter 4

CHAPTER 4

THE ISOTOPE GEOCHEMISTRY OF THE GRANITE CLASTS.

4.1 Introduction.

As granite plutons occur throughout the Caledonian-Appalachian orogen (see Fig. 6 of Pitcher, 1983), there are many areas that could have supplied granitic detritus to the Southern Uplands. The petrographic and geochemical features of the granite clasts collected from the Southern Uplands conglomerates reveal the types of plutons that were present in the source areas and the environments in which they were intruded, but this is not sufficient to uniquely identify a particular source area as similar processes have produced similar granites in various locations on the margins of Laurentia. However, granites were intruded at different times in different places, so dating the granite clasts should show the location of the source areas more precisely.

In order to determine the age of the granitic detritus the Rb-Sr whole-rock isochron method was applied to the suites of granite clasts described in the previous chapter. The age and initial $^{87}Sr/^{86}Sr$ ratios obtained from the isochrons, together with Sm-Nd model ages, provide an isotopic fingerprint which can be used to compare the suites of granite clasts with plutons from which they may have been derived. Not all the petrographically defined groups of granite clasts yield isochrons, but in some cases model age calculations demonstrate the relationships between groups of granite clasts from the same conglomerate and provide a further basis for comparison with other groups of granite clasts from different conglomerates.

4.2 Rb-Sr Geochemistry.

In order to determine the Rb-Sr whole-rock isochron age for a suite of granite clasts it is necessary to plot the data from a number of different samples on the same isochron. However, a Rb-Sr whole-rock isochron will only be meaningful if the different samples used to construct it are cogenetic. Each group of clasts described in Chapter 3 consists of samples which have petrographic and geochemical features similar to one another, but distinct from the samples which form the other groups of granite clasts in the same conglomerate. The individual members of a particular group are, therefore, likely to have formed under similar conditions, and are sufficiently closely related for the data from them to be used to construct a Rb-Sr whole-rock isochron. However, the problem remains that because the clasts in a conglomerate are not in situ, there is no absolute guarantee that all the members of a particular group were derived from the same pluton. The risk of introducing errors through using clasts that are not cogenetic on the same isochron is reduced by excluding those samples that differ from the rest of the group in the details of their petrography and/or geochemistry. Clasts showing evidence of significant alteration are also excluded.

The MSWD (mean squares of weighted deviates) of an isochron provides a useful check on the assumption that the samples used to construct it are cogenetic. The MSWD measures the scatter of data points about the best-fit straight line, and a value less than one indicates that all the data points lie on that line, within analytical error. MSWD values greater than one imply that analytical errors may not be sufficient to account for the scatter of points about the best-fit straight line, and when the MSWD rises above 2.5, there must be some additional geological reason for the distribution of the data. A suite of samples that are cogenetic, had the same initial $^{87}Sr/^{86}Sr$ ratio and

have suffered no subsequent isotopic disturbance should yield an isochron with an MSWD of less than one. Although higher MSWD's may indicate that the samples used to construct an isochron are not cogenetic, other factors could produce a similar result. Magmas that were originally isotopically heterogeneous, or that have been subject to open system behaviour, which may be caused by a processes such as alteration or deformation subsequent to crystallization, would produce plutons in which the isotopic systems were not in equilibrium, and would yield isochrons with high MSWD's.

Where the isochron constructed from a suite of clasts has an MSWD of less than one, the assumption based on petrographic and geochemical criteria that the samples are cogenetic is clearly justified, and is also likely to be valid in cases where the MSWD is between one and 2.5. In cases where the MSWD is greater than 2.5, consideration of the possible causes of the scatter of the data are required in order to determine whether or not the clasts which form the suite are cogenetic. Of the twenty-seven groups of clasts recognized in in Table 3.8, only fourteen contain more than two samples and could therefore be used to construct whole-rock isochrons. Using the criteria outlined above, eight of the groups yielded isochrons which could be interpreted as the age of the plutons which supplied the clasts. Of these, three have MSWD's less than one, two have MSWD's between one and 2.5, and the remaining three have MSWD's greater than 2.5.

A high value for the MSWD of an isochron reduces confidence in the age determined from it. For those isochrons with an MSWD greater than one, the errors on individual analyses were expanded in order to reduce the MSWD to one. This procedure increases the errors on the age and initial ratio determinations, and reflects the greater uncertainties associated with them. The MSWD is an additional feature of the isotopic

characteristics of a suite of clasts that can also be used when comparing them to potential sources.

The Rb-Sr whole-rock isochron method has been successfully used to determine the age and provenance of granite clasts in a Pleistocene beach deposit in South Wales (Jenkins et al., 1985). Three clasts yielded an isochron with the same age as the nearby Lundy granite, which they match petrographically. This points to the validity of using petrographically and geochemically similar granite clasts to determine Rb-Sr whole-rock isochrons.

Sr isotope determinations were carried out using a VG Micromass 30 thermal ionization mass spectrometer, following standard techniques. Rb/Sr ratios were determined either by an X.R.F. method similar to that of Pankhurst and O'Nions (1973), or by mass spectrometric isotope dilution analysis using an ^{87}Rb-^{84}Sr mixed spike. Full details of the analytical techniques and statistical procedures are contained in Appendix 4. A decay constant for ^{87}Rb of 1.42×10^{-11} $years^{-1}$ was used to calculate ages from isochrons. All ages and initial ratios are quoted with 2σ errors (95% confidence). The isotope data are presented in Appendix 3.

4.2.a. Corsewall Point.

4.2.a.i Whole-rock isochrons.

Four of the eight different types of granite clast from Corsewall Point recognized in Table 3.8 yielded Rb-Sr whole-rock isochron ages. The muscovite-biotite granites (Group A1) yielded the oldest age; of the twelve clasts in this group, nine define an isochron with an age of 1,265 ± 130 Ma, an initial $^{87}Sr/^{86}Sr$ ratio of 0.7046 ± 0.0020 and an MSWD of 10.78 (Fig. 4.1). The three samples excluded from the isochron

determination are CoP 117, CoP 120 and CoP 121.* Fig. 4.1 shows that they all contain strontium more radiogenic the other clasts in this group with similar Rb/Sr ratios. The heavy alteration of CoP 121 has resulted in aggregates of muscovite and epidote completely pseudomorphing plagioclase feldspar crystals, a process which may have altered the Rb-Sr isotopic composition of this clast. CoP 120 is more strongly deformed than the other clasts, and the replacement of large biotite crystals by finer grained aggregates may have caused isotopic disturbance. It also differs chemically from the other clasts in having Na_2O/K_2O close to one, and may be only loosely related to the other members of the group. There is less to distinguish CoP 117, although it lacks the large euhedral plagioiclase crystals which are common in other samples. All three samples contain the pelitic xenoliths which characterize this group of clasts, showing that they were derived from plutons intruded into similar crust as the pluton that supplied the other samples. However the petrographic differences shown by these clasts indicates that they had a separate origin and justifies their exclusion from the isochron suite.

The isochron defined by the remaining clasts has a high MSWD (10.78), the likely cause of which is the ubiquitous presence of pelitic xenoliths. As they are only partially assimilated, it is improbable that the magma from which the pluton crystallized was isotopically homogeneous. Initial variations in $^{87}Sr/^{86}Sr$ isotope ratio are reflected by the scatter of points about the isochron, and are the cause of the high MSWD. In the extreme case, the isochron could be interpreted as a mixing line between a pelitic and an igneous end member, but as there is no simple linear relationship between $^{87}Sr/^{86}Sr$ and the inverse of strontium concentration for the samples which comprise the isochron suite (Fig. 4.2), this is unlikely to be the case. The pelitic inclusions are mostly small and are evenly distributed throught the

*see Appendix 7 (inside back cover)

sample, so the effect of the original heterogeneities on the determination of the age of these clasts will be minimal, and is further reduced by the removal of any larger xenoliths during sample preparation.* The marked petrographic and geochemical similarity of the clasts in this group means that the high value of the MSWD is unlikely to be the result of mixing samples from different plutons, and as they appear fresh in thin section, alteration processes are unlikely to have contributed much to the scatter of points on the isochron diagram. Consequently, 1,265 ± 130 Ma is regarded as a reasonable estimate of the age of intrusion of these clasts.

The two groups of hornblende-biotite granites (Groups A2a and A2b) define separate isochrons which yield the same age (Fig. 4.3). The larger group (Group A2a), which is chemically and petrographically the more diverse, yields a 4-point isochron with an age of 600 ± 30 Ma, an initial $^{87}Sr/^{86}Sr$ ratio of 0.7059 ± 0.0003, and an MSWD of 1.86 (Fig. 4.3a). One sample belonging to this group, CoP 105, is excluded from the isochron suite because it contains biotite that has been completely altered to chlorite and epidote, and feldspar which is heavily saussuritized.* Such alteration is likely to cause a loss of potassium, and a concomitant loss of Rb (section 3.3.b). CoP 105 contains less Rb than the other members of the group (see Appendix 3), which causes the sample to plot above the isochron defined by the four remaining clasts. Although the other clasts are less altered, similar processes may account for the slight scatter of points about the isochron.

The second group of hornblende-biotite granites (Group A2b) forms a much more compact group, both chemically and petrographically, as a result of which the three samples define a good isochron, with an MSWD of 0.12 (Fig. 4.3b). The age of this group of clasts, 603 ± 40 Ma, is similar to that of the other hornblende-biotite granites, but as the samples cover a smaller range of Rb/Sr ratios, the errors on both the

*see Appendix 7 (inside back cover)

age and initial ratio determinations are larger. The similarity in age between the two groups of hornblende-biotite granites supports the chemical evidence that they are closely related (section 3.3.a), but the different initial $^{87}Sr/^{86}Sr$ ratios (0.7068 ± 0.0004 for Group A2b) supports the petrographic evidence that the two groups of clasts were derived from separate plutons (Section 3.2.a.ii).

Four samples of biotite granite from Corsewall Point (Group A4) also define a good isochron, with an MSWD of 0.53. It yields an age of 475 ± 20 Ma and an initial ratio of 0.7056 ± 0.0003 (Fig. 4.4). The most radiogenic sample in this suite is CoP 6, which although chemically similar to the other clasts, also contains garnet and muscovite (section 3.2.a.iv.). If it is excluded from the isochron, the three remaining clasts yield an age of 478 ± 38 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7056 ± 0.0004 (MSWD = 1.03). As this isochron is indistinguishable from the one that includes CoP 6, it is reasonable to assume that this clast has the same origin as the other members of the group. The more accurate four point isochron is used to determine the age of intrusion and initial $^{87}Sr/^{86}Sr$ ratio of the biotite granites. CoP 25 is more strongly deformed than the other members of the group and it contains strontium of a more radiogenic composition (Fig. 4.5), which supports the conclusion that it is unrelated to the other biotite granites (section 3.2.b.iv). Consequently, it is excluded from the isochron suite.*

The three foliated hornblende-biotite granodiorites (Group A3) do not define a meaningful isochron, which, because of the petrographic differences between CoP 107 and the two other clasts, indicates that the samples are unlikely to be cogenetic. However, it is possible to compare the Rb-Sr isotope characteristics of the three clasts with those of the other groups of granite clasts from Corsewall Point by means of a Sr isotope evolution diagram (Fig. 4.5) and model age calculations. The

*see Appendix 7 (inside back cover)

present day Rb/Sr ratios of the clasts are used to project their Sr isotope composition back through time, which can then be compared to the initial $^{87}Sr/^{86}Sr$ ratio of the clasts which define the whole-rock isochrons described above, and with the Sr isotope composition of the bulk earth (BE) and the depleted mantle (DM). However, open system behaviour, which results from processes such as weathering, hydrothermal alteration, deformation and metamorphism, alters the Rb/Sr ratio and, in some cases, the $^{87}Sr/^{86}Sr$ ratio of a sample; consequently the Sr isotopic composition cannot be projected back beyond such an event.

Similar constraints apply to the calculation of Rb-Sr model ages. Using the present day $^{87}Rb/^{86}Sr$ ratio, the time at which the sample had some assumed initial $^{87}Sr/^{86}Sr$ ratio can be calculated, provided that the sample has suffered no open system behaviour subsequent to its formation. Thus the time at which the Sr isotope evolution line intersects one of the mantle reservoir lines gives a model age for that sample, but one that only has any chronological significance if the magma from which it formed was derived directly from such a source. This is rarely the case with granites, which usually have higher initial $^{87}Sr/^{86}Sr$ ratios than mantle values, but such a model age does provide an upper limit for the absolute age of a granite clast.

The Sr isotope evolution lines for the foliated hornblende-biotite granodiorites show that they contained strontium of a more radiogenic composition than the unfoliated hornblende-biotite granites (Groups A2a and A2b) at 600 Ma, which is when the unfoliated granites were intruded (Fig. 4.5). It is therefore unlikely that the two groups are related. However, the evolution lines for all three granodiorite clasts pass through the error polygon for the age and initial $^{87}Sr/^{86}Sr$ ratio of the 1,265 ± 130 Ma muscovite- biotite granites (Group A1), which indicates that they had a similar $^{87}Sr/^{86}Sr$ ratio to the magma which formed the muscovite-biotite granites at c. 1,265 Ma, and that they would plot on,

or close to, the isochron defined by the muscovite-biotite granite clasts. This could be taken as evidence that the magmas which formed the foliated hornblende-biotite granites and the muscovite-biotite granites were derived from a similar source at a similar time. However, as the deformation of the granodiorites is more intense, the possibility exists that they were intruded and deformed prior to the intrusion of the muscovite-biotite granites, in which case another possible interpretation of the data is that the granodiorites could be the source from which the muscovite-biotite granites were derived.

The foliated granodiorites have I-type characteristics, and such magmas typically have initial $^{87}Sr/^{86}Sr$ ratios in the range 0.704 to 0.706 (Chappel and White, 1974). They also show affinities with granites intruded in mature volcanic arc settings (section 3.3.a), such as the Mesozoic batholiths of California, which have initial $^{87}Sr/^{86}Sr$ ratios which range from 0.7031 to 0.7082 (Kistler and Peterman, 1973). Although the initial ratio depends to a certain extent upon the type of crust into which the plutons were intruded, the granodiorites tend to have initial $^{87}Sr/^{86}Sr$ ratios in the range 0.704 to 0.706 (Faure, 1986). Using these values as an estimate of their initial ratios, the foliated hornblende-biotite granodiorites yield Rb-Sr whole-rock model ages in the range 1,000 to 1,200 Ma for an initial ratio of 0.706 and 1,340 to 1,500 Ma for an initial ratio of 0.704. Thus it is likely that these clasts are of a similar age or slightly older than the muscovite-biotite granites.

The Sr isotope evolution line for the foliated biotite granite clast (CoP 25) shows no clear relationship to any of the other groups of granite clasts (Fig. 4.5). This sample is more extensively recrystallized than the foliated hornblende-biotite granodiorites and deformational processes may have had a more significant effect on the Rb/Sr ratio. However, the high $^{87}Sr/^{86}Sr$ ratio and the present day

$^{87}Rb/^{86}Sr$ ratio yield older model ages than the foliated granodiorites, assuming a similar initial $^{87}Sr/^{86}Sr$ ratio, although the maximum possible age for the two groups of foliated clasts, given by the depleted mantle model age, is similar (1,950 Ma for the biotite granite, 1,800 to 1,940 Ma for the granodiorites - see Fig. 4.5). These model ages have little geological significance, but in order to obtain a realistic model age for the foliated biotite granites, similar to that of the foliated granodiorites, it would be necessary to assume a higher initial $^{87}Sr/^{86}Sr$ ratio. If deformational processes have had only a small effect on the Rb/Sr ratio, the model age calculations indicate that the foliated biotite granite is either older than the foliated hornblende-biotite granites, or that the magma was derived from an older source in which the strontium was more radiogenic.

The two remaining clasts from Corsewall Point, a trondhjemite (CoP 28 - Group A5) and a plagiogranite (CoP 29 - Group A6), both have low $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios. Consequently, model age determinations are subject to large errors. The trondhjemite clast would have had a similar $^{87}Sr/^{86}Sr$ ratio to the biotite granites (Group A4) at 475 Ma, the time at which they formed, and so could have been derived from a similar source. The plagiogranite has such a low $^{87}Rb/^{86}Sr$ ratio (0.0289) that the $^{87}Sr/^{86}Sr$ ratio (0.70663) will have changed very little and will approximate to the initial value. This is only slightly higher than the range in initial $^{87}Sr/^{86}Sr$ ratios reported by Coleman and Peterman (1975) for the plagiogranites from the Troodos Complex, and significantly higher than mantle values. $^{87}Sr/^{86}Sr$ ratios of plagiogranites are generally increased above mantle values as a result of interaction with seawater (Coleman and Donato, 1979), and the $^{87}Sr/^{86}Sr$ ratio of this sample is consistent with derivation from an ophiolitic source.

4.2.a.ii Mineral Isochrons.

The determination of a Rb-Sr mineral isochron from a single clast provides an alternative method of dating granite boulders which avoids the necessity of making assumptions concerning the cogenesis of samples used to construct whole-rock isochrons. Although the data from mineral isochrons may, therefore, be used as a further check on the validity of the whole-rock isochrons, the information obtained from the two methods, and its interpretation, may differ, as a result of which direct comparisons cannot always be made. Prolonged cooling of a pluton may result in the delayed closure of isotopic systems within a mineral phase, relative to the whole-rock, as a result of which the mineral isochron will yield a younger age than the whole-rock isochron. Similarly, a thermal event or metamorphic reaction subsequent to the intrusion of a pluton may may cause isotopic re-equilibration between mineral phases, but not on a whole-rock scale, as a result of which the mineral isochron would record the age of the younger event, rather than the age of crystallization. The younger mineral isochrons would also have higher initial $^{87}Sr/^{86}Sr$ ratios than the corresponding whole-rock isochron.

Longman (1980) reports mineral isochrons from five granite clasts in the Corsewall Point conglomerate obtained by separating feldspar fractions of different densities. The chemical analyses of the five clasts are shown on an Na_2O-CaO-K_2O diagram (Fig. 4.6), in relation to the groups of granite clasts recognized in this study. Although there is not a direct correspondence, petrographic descriptions and the general chemical characteristics of the clasts from which the mineral isochrons were obtained can be used to correlate them with the groups which form whole-rock isochron suites. The results obtained by the two methods are compared in Table 4.1.

TABLE 4.1 A comparison of whole-rock and mineral isochron ages obtained from granite clasts in the Corsewall Point conglomerate.

Whole-rock isochron suites from this study.	Whole-rock isochron data	Sample No.'s of corresponding clasts from Longman (1980)	Mineral isochron data from Longman (op. cit.)
Muscovite-biotite granites (Group A1)	1,265 ± 130 Ma. I.R. = 0.7046±21 MSWD = 10.78	988	798 ± 84 Ma. I.R. = 0.7152±11 MSWD = 21.93
Hornblende-biotite granites (Group A2a)	600 ± 30 Ma. I.R. = 0.7059±3 MSWD = 1.86	993	577 ± 27 Ma. I.R. = 0.7063±7 MSWD = 15.42
		982	564 ± 23 Ma. I.R. = 0.7062±1 MSWD = 15.29
Biotite granites (Group A4)	475 ± 20 Ma. I.R. = 0.7056±3 MSWD = 1.86	996	525 ± 22 Ma. I.R = 0.7056±3 MSWD = 17.54
Trondhjemites (Group A5)	no isochron (present day $^{87}Sr/^{86}Sr$ = 0.70681)	985	463 ± 62 Ma. I.R. = 0.7085±1 MSWD = 0.07

The closest agreement between the mineral and whole-rock isochrons occurs in the case of the hornblende-biotite granites (Table 4.1). Both of the clasts for which mineral isochrons were determined (samples 993 and 982) equate with the first group of hornblende-biotite granites (Group A2a), and the whole-rock analyses of both clasts plot on the whole-rock isochron determined in this study. Sample 982 is chemically more similar to the other members of this group (Fig. 4.6), and when the Rb-Sr whole-rock analysis of this clast is included in the isochron suite it yields an identical, more accurate isochron (age = 600 ± 24 Ma., initial ratio = 0.7059 ± 0.0002, MSWD = 1.27). When the whole-rock analysis of sample 993 is included, there is only a slight change in the slope of the isochron, which has a similar MSWD (age = 597 ± 27 Ma., initial ratio = 0.7059 ± 0.0003, MSWD = 1.75). This indicates that both clasts were derived from the same source as the clasts which comprise Group A2a.

The mineral isochrons yielded by the two clasts are indistinguishable and record an age of about 570 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7063. Both have MSWD's of about 15. This age is slightly younger than that recorded by the whole-rock isochron, and the initial ratio is slightly higher, but the values lie just beyond the limit of the errors on the whole-rock isochron determinations. As the whole-rock analyses of all the clasts lie on the same isochron, which has a low MSWD, it is reasonable to interpret the whole-rock age of 600 Ma as the age of intrusion of the granite plutons which supplied these clasts, and the slightly younger mineral isochron ages as the time of closure of the feldspars to Rb and Sr. The mineral isochrons have much higher MSWD's than the whole-rock isochron, which may be attributable to the saussuritization of feldspars. Such a process would produce more scatter on the mineral isochrons than on the whole-rock isochron and may reduce the significance of the mineral isochron age. However, the

younger mineral ages indicate prolonged cooling of the pluton, which is consistent with the petrographic observations that the granite crystallized at high pressures (section 3.2.a.ii).

The single muscovite-biotite granite clast analysed by Longman (1980; sample 988) has a very similar chemistry to the muscovite-biotite granites which comprise Group A1 of this study, and plots on the whole-rock isochron which they define. When included in the data set, the slope and the intercept of the isochron are unchanged, but the MSWD and errors are reduced (age = 1,265 ± 121 Ma, initial ratio = 0.7046 ± 0.0019, MSWD = 9.62). This clearly indicates that sample 988 is cogenetic with the other members of this group, but a mineral isochron based on four feldspar fractions from this clast yields a younger age (798 ± 84 Ma) and a higher initial $^{87}Sr/^{86}Sr$ ratio (0.7152 ± 0.0011 - Longman, 1980). However, the whole rock analysis of this clast does not lie on the mineral isochron, and its MSWD is high (21.93), which implies non-equilibrium behaviour. This may be caused by two factors. Firstly, the effect of heterogeneities in the original magma caused by the presence of pelitic xenoliths may be enhanced if feldspar fractions of different density separated feldspars of igneous origin from those derived from the pelitic xenoliths. This may produce a pseudo-isochron with an "age" different to that of the whole-rock isochron, but mass balance considerations require the whole-rock analysis to plot on the mineral isochron. Alternatively, the mineral isochron may represent a younger thermal event, during which there was incomplete re-homogenization of the Rb-Sr isotope system, resulting in a mineral isochron with a high MSWD which does not contain the whole-rock analysis. Because of the uncertainties associated with the mineral isochron for sample 988, 798 ± 84 Ma does not necessarily represent the age of this event.

Sample 996 is petrographically similar to the group of biotite granite clasts identified in this study (Group A4), but it is chemically distinct (Fig. 4.6). The whole-rock analysis of sample 996 does not plot on the whole-rock isochron defined by the samples in Group A4, and it yields a mineral isochron with a slightly older age (Table 4.1). This indicates that not all the biotite granite clasts in the Corsewall Point conglomerate were supplied by the same pluton, but as the different isochrons have the same initial $^{87}Sr/^{86}Sr$ ratios it is possible that the magamas from which they formed were derived from similar sources. Consequently, the clasts may record the same period of emplacement of more sodic granites at about 500 Ma.

Sample 985 has a trondhjemitic chemistry very similar to CoP 28 (Group A5), and is only distinguished from it by being less potassic; consequently the two samples plot apart on the Na_2O–CaO–K_2O diagram (Fig. 4.6). Sample 985 contains strontium more radiogenic than CoP 28, and as it also has a lower $^{87}Rb/^{86}Sr$ ratio (0.1272 as compared to 0.2152), this must always have been the case, assuming that the Rb/Sr ratio has remained constant. This indicates that the two trondhjemitic clasts were derived from separate sources, but the age of 463 ± 62 Ma yielded by the mineral isochron from sample 985 is consistent with the probable age of CoP 28, based on considerations of $^{87}Sr/^{86}Sr$ evolution (section 4.2.a.i). The absence of alkali feldspar from these clasts results in a narrow range of $^{87}Rb/^{86}Sr$ values for the feldspar fractions, as a consequence of which there is a large error associated with the age determined from the mineral isochron. However, it yields an age close to the depositional age of the Corsewall Point conglomerate (N. gracilis zone - c. 455 Ma, McKerrow et al., 1985), which indicates the presence of a contemporary arc.

Although the two methods that have been used to determine the age of the granite clasts in the Corsewall Point conglomerate do not always

produce comparable results, there is no aspect of the mineral isochron data which contradicts the interpretation of the whole-rock data. The whole-rock isochrons have lower MSWD's, and where the clasts from the two studies can be shown to be cogenetic, older ages and lower initial ratios. This suggests that the whole-rock isochrons provide a more reliable estimate of the age of intrusion of the granite clasts. However, the mineral isochron data does reveal that there is a greater diversity amongst the younger clasts which suggests that the source area contained a greater variety of plutons of Early to Middle Ordovician age. The combined whole-rock and mineral isochron data reveal the igneous history of the source area for the Corsewall Point conglomerate, which includes old foliated granodiorites and biotite granites, muscovite-biotite granites intruded at 1,265 ± 130 Ma, hornblende-biotite granites intruded at 600 ± 40 Ma, biotite granites intruded between 525 and 475 Ma, a contemporary trondhjemitic source and plagiogranites from an ophiolitic source.

4.2.b Glen App.

The petrographic and chemical correlation between the granite clasts in the Corsewall Point and Glen App conglomerates indicates that they are derived from related sources (section 3.4). If this is the case, the clasts in the Glen App conglomerate should have similar ages and isotopic characteristics to those in the Corsewall Point conglomerate. However, no whole-rock isochrons were obtained from the the Glen App clasts - only two of the five petrographic groups contain more than two clasts, and the isotopic analyses of these samples show considerable scatter because of intense alteration (section 3.3.b), which has reduced the Rb/Sr ratios of these clasts.

The reasons for the reduction in Rb/Sr ratio are twofold. Firstly, the major element chemistry shows that the more altered clasts are poorer in potassium as a result of the chloritization of biotite and hornblende (section 3.3.b). The loss of potassium is mirrored by a loss of rubidium, an effect that can be seen by comparing the position of clasts of similar petrography from Corsewall Point and Glen App on the Rb v. Y+Nb diagrams (Figs. 3.8 and 3.11), and is most noticeable in those clasts in which mafic minerals are more abundant. However, a comparison of the analyses of petrographically similar clasts from the two conglomerates shows that while most major and trace elements are present in comparable concentrations, strontium concentrations are much higher in the Glen App clasts (Appendices 2 and 3). This indicates that the calcite veins which are present in some samples contain strontium that has been added during alteration. Such a process not only reduces the Rb/Sr ratio, but also affects the strontium isotopic composition of a clast.

This explains why the Glen App clasts do not plot on the isochrons defined by clasts of similar petrography from Corsewall Point. Also, model age calculations are suspect in cases where it can be shown that alteration processes have affected the Rb-Sr isotope geochemistry, as it is impossible to project the Sr isotope composition back beyond the alteration event. On the Sr isotope evolution diagram (Fig. 4.5), the composition of certain clasts is projected back only as far as the depositional age of the sediments (N. gracilis zone - c. 455 Ma, McKerrow et al., 1985), which is when the most significant alteration is likely to have taken place.

In general, the Glen App granite clasts contain Sr which is less radiogenic than that in their counterparts from Corsewall Point. The hornblende-biotite granites (Group B1) form a cluster below the 600 Ma isochrons defined by the equivalent clasts from Corsewall Point, which

is possibly an effect of their alteration. The foliated granodiorite clast (AP 13 - Group B2) contains strontium more radiogenic than in the unfoliated clasts of similar composition (Group B1), but less radiogenic than in the foliated clasts at Corsewall Point. The Sr isotope evolution diagram (Fig. 4.5) shows that if the clasts from both conglomerates were derived from the same source and had a similar $^{87}Sr/^{86}Sr$ ratio at c. 1,300 Ma, the differences in the present day $^{87}Sr/^{86}Sr$ ratio could be accounted for by a slight reduction in the Rb/Sr ratio, and/or a small change in the $^{87}Sr/^{86}Sr$ ratio, at the time of deposition. AP 13 contains 60% more strontium than CoP 107, the foliated granodiorite whose major element chemistry it matches most closely, which indicates that the addition of Sr at the time at which the clast was eroded may be sufficient to account for its different Sr isotope composition.

The differences between the foliated biotite granite clasts in the two conglomerates are more marked, and cannot be explained by such a simple model. The Sr in the Glen App foliated biotite granites (Group B4) is much less radiogenic than that in CoP 25, the only foliated biotite granite clast from Corsewall Point, and requires a large input of strontium of less radiogenic composition at the time of deposition, as the difference cannot be explained in terms of a change in the Rb/Sr ratio alone. Two of the clasts have strontium concentrations at least twice that of CoP 25, but one clast (AP 11) has a closely similar strontium concentration, and a higher, rather than a lower, Rb/Sr ratio. Although the replacement, rather than the addition of strontium may alter the $^{87}Sr/^{86}Sr$ ratio, the differences between the clasts may not be entirely an effect of alteration. The depleted mantle model age for AP 11, which gives the maximum possible age of the clast, assuming the effects of the alteration are negligible, is 760 Ma, compared to 1,950 Ma for CoP 25. This may indicate that there is also a younger source of

foliated biotite granites that have supplied clasts to the Glen App conglomerate.

There are no obvious similarities between the isotopic characteristics of the biotite granites in the two conglomerates (Groups A4 and B3). This may reflect the chemical and petrographic differences between the two groups of clasts, and demonstrates the lithological diversity that exixts in the detritus of Ordovician age. The plagiogranite clast from Glen App (Group B5) has a low $^{87}Sr/^{86}Sr$ ratio (0.70566) and a low $^{87}Rb/^{86}Sr$ ratio (0.0781), consistent with derivation from an ophiolitic source.

Because of the poor quality of the Rb-Sr isotopic data for the granite clasts in the Glen App conglomerate, correlations with clasts in the Corsewall Point conglomerate are best based upon petrographic and geochemical features. Most of the clasts in the two conglomerates have similar characteristics, but although the original isotopic composition of the Glen App granite clasts has been obscured by alteration processes, the possibility still exists that some components of the detritus in the two conglomerates are different.

4.2.c Glen Afton.

Of the six groups of granite clasts recognized in the Glen Afton conglomerate, three yielded whole-rock isochrons, two contain only two clasts, and the samples in the remaining group contain too little rubidium to form a meaningful Rb-Sr whole-rock isochron. The geochronological information that the clasts contain can be compared with that obtained from Corsewall Point to determine the extent of the differences between the source areas that supplied the two conglomerates.

The Glen Afton muscovite-biotite granites (Group C1) are distinguished from those that occur at Corsewall Point because they contain muscovite of secondary origin. The subsolidus reaction of which it is a product might have caused isotopic re-equilibration, and if it is the result of hydrothermal alteration, contamination may also have occurred. As such processes usually occur shortly after the intrusion of a granite, and if they do not result in isotopic disequilibrium between different samples, a whole-rock isochron may still be obtained which records the age of intrusion of the original pluton, although some scatter of the data might be expected.

Three samples in this group are foliated (GA 45, GA 173 and GA 226; section 3.2.c.i), and as they may have suffered additional isotopic disturbance, they are excluded from the isochron suite.* The remaining eight clasts yield a whole-rock isochron with an age of 661 ± 35 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7069 ± 0.0006 (Fig. 4.7). This isochron has an MSWD of 1.67, which indicates some scatter of the data, but is within acceptable limits. The five clasts which show the greatest chemical and petrographic similarity, and in which clinozoisite is clearly developed (GA 1, GA 39, GA 170, GA 223, GA 232), plot on a straight line (MSWD = 0.19) with an age of 702 ± 86 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7061 ± 0.0015. The large errors on this isochron are due to the narrow range of $^{87}Rb/^{86}Sr$ values shown by these samples, but are in agreement with the values determined from the eight point isochron. Despite the clear evidence of alteration, the isochron does not represent a mixing line between an igneous end member and a hydrothermal contaminant, as there is no correlation of $^{87}Sr/^{86}Sr$ with 1/Sr in these samples. This indicates that the most altered samples have been in isotopic equilibrium from about this time, which is probably when post-magmatic hydrothermal alteration occurred. As the less altered clasts also plot on a similar isochron, the degree of

*see Appendix 7 (inside back cover)

alteration does not appear to affect the isotopic composition of the samples. Alteration may account for the slight scatter of data about this isochron, but the age of 661 ± 35 Ma that it yields is a reasonable estimate of the age of intrusion of the original granite.

Five biotite granodiorite samples from Glen Afton (Group C2) define an isochron which yields an age of 1,231 ± 120 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7039 ± 0.0013 (MSWD = 5.89, see Fig. 4.8). GA 2, which differs petrographically from the other members of the group in that it contains appreciable quantities of hornblende (section 3.2.c.ii), is excluded from the isochron suite.* Including it with the other data does not significantly change the slope of the isochron, but increases the MSWD, which indicates that while it may be of a similar age to the other clasts, it probably had a separate origin.

This isochron has an MSWD with a value greater than 2.5, as does the isochron of a similar age yielded by the Corsewall Point muscovite-biotite granites. However, there is no obvious evidence of isotopic heterogeneity in the magma from which the Glen Afton biotite granodiorites were derived, as was so clearly the case for the Corsewall Point muscovite-biotite granites. However, biotite is extensively altered to chlorite and epidote and as such alteration is bound to effect the Rb/Sr ratio of the clasts, it probably accounts for the scatter of data about the isochron. This may reduce the reliability of the age determined from it, but the expansion of the errors on individual analyses to reduce the MSWD to one increases the 2σ errors on the age and initial ratio. Provided that the alteration process scatters the points to both sides of the isochron, rather than shifting them all to lower $^{87}Rb/^{86}Sr$ values, which would steepen the isochron, the increased errors on the age determination should account for the uncertainties introduced by the effects of alteration.

*see Appendix 7 (inside back cover)

The four hornblende-biotite granite clasts (Group C3) define a good whole-rock isochron with an age of 491 ± 14 Ma, an initial $^{87}Sr/^{86}Sr$ ratio of 0.7064 ± 0.0002 and an MSWD of 0.67 (Fig. 4.9). It is reasonable to assume that this represents the age of intrusion of the pluton that supplied these clasts.

The granophyric and acicular hornblende granites (Group C4) have low Rb concentrations, and, with the exception of GA 15, show little variation in $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ values. It is difficult to fit a meaningful isochron to these data because the slope of the isochron and the scatter of points about it are more susceptible to uncertainties in Rb/Sr ratios where these values are low and cover a narrow range. In addition, the determination of Rb/Sr ratios by XRF methods is less precise in low-Rb samples. Because GA 15 has a distinctly different isotopic composition to the other clasts in this suite, it has a strong influence on the slope of the isochron. The best fit straight line for all the data yields an age of 768 ± 168 Ma, but has an MSWD of 13.43. If GA 15 is excluded from the suite the remaining four clasts scatter about a line that yields an age of 251 Ma, but with an error almost as large as the value itself. This illustrates the unreliability of dating low-Rb rocks by this method and, combined with the high MSWD of the isochron that includes GA 15, indicates that 768 ± 168 Ma is unlikely to be a reasonable estimate of the age of these clasts. The $^{87}Sr/^{86}Sr$ evolution lines for these clasts do not pass through the error polygons for the age and initial $^{87}Sr/^{86}Sr$ ratios of the isochrons derived from other groups of clasts in this conglomerate, which suggests that they have a separate origin.

The two trondhjemite samples (Group C5) also have low $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios, only slightly higher than those of the granophyric and aciciular hornblende granites (Group C4). The low ratios make model age determinations imprecise, but the two groups are likely to have had

similar $^{87}Sr/^{86}Sr$ ratios in the past. However, because the magmas from which these granites formed must also have been derived from sources with low $^{87}Sr/^{86}Sr$ ratios, and hence low $^{87}Rb/^{86}Sr$ ratios, the strontium isotope composition of the sources will have been slow to change, and the different granites need not necessarily be of the same age.

The two plagiogranite clasts (Group C6) have even lower $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios (0.70676 and 0.70686), comparable with those of the plagiogranite clasts from Corsewall Point. Again, the $^{87}Sr/^{86}Sr$ ratios have changed little since these samples formed, and are similar to the strontium isotope ratios of other plagiogranites found in ophiolitic complexes (Coleman and Peterman, 1975).

The initial $^{87}Sr/^{86}Sr$ ratios of the suites of granite clasts which define whole-rock isochrons can be used to compare clasts from different conglomerates, as granites of a similar age would be expected to have similar initial $^{87}Sr/^{86}Sr$ ratios if they were derived from related sources. The range in possible initial ratios in a suite of rocks is determined by the error on the isochron and is represented as a polygon on a plot of $^{87}Sr/^{86}Sr$ ratio against time (Sanz and Wasserburg, 1969). This is because lines within the error envelope about an isochron that have a higher gradient (and hence an older age) intercept the $^{87}Sr/^{86}Sr$ axis at lower values, and vice verca. If the error polygons from separate isochrons overlap, it is possible that the magmas represented by the two suites of rock had the same $^{87}Sr/^{86}Sr$ ratio at the time they formed.

The error polygons for the ages and initial $^{87}Sr/^{86}Sr$ ratios determinded from the whole-rock isochrons defined by granite clasts in the Corsewall Point and Glen Afton conglomerates are shown in Fig. 4.10. Although the errors on the initial $^{87}Sr/^{86}Sr$ ratios of the 1,265 Ma isochron for the Corsewall Point muscovite-biotite granites and the 1,231 Ma isochron for the Glen Afton biotite granodiorites cover a

similar range of values, the error polygons never overlap. This shows that the initial $^{87}Sr/^{86}Sr$ ratio of the Corsewall Point muscovite-biotite granites was higher than that of Glen Afton biotite granodiorites, and reflects the larger crustal component in the former group. However, the magma may also have contained a low-$^{87}Sr/^{86}Sr$ component in common with the Glen Afton suite. The Glen Afton muscovite-biotite granites yield an isochron with a slightly older age than the second group of Corsewall Point hornblende-biotite granites (Group A2b), so although the initial ratios of the two groups are indistinguishable, the error polygons do not overlap. The initial ratio of the Glen Afton muscovite-biotite granites may, however, have been increased as a result of the hydrothermal alteration of these clasts. The initial $^{87}Sr/^{86}Sr$ ratios of the 475 ± 20 Ma biotite granites from Corsewall Point and the 491 ± 14 Ma hornblende granites from Glen Afton cover separate ranges, which is consistent with the chemical evidence that the plutons which supplied these clasts were intruded in different settings, and hence, are unrelated (section 3.3.c).

Because the error polygons for the suites of clasts from the two conglomerates never overlap, separate plutons must have supplied the detritus to the Corsewall Point and Glen Afton conglomerates. Of the suites of clasts that do not define isochrons, there are no foliated granodiorites or foliated biotite granites in the Glen Afton conglomerate that are comparable with those that occur in the Corsewall Point conglomerate. The two trondhjemites from Glen Afton are more radiogenic than the single trondhjemite clast sampled from Corsewall Point in this study, and they do not plot on the mineral isochron obtained from a trondhjemite clast by Longman (1980). The plutons that supplied the trondhjemitic detritus to the two conglomerates also appear to have been different.

Further evidence for the separate sources of the detritus in the two conglomerates comes from the lack of petrographic similarity between the detritus of similar ages in the two deposits. The c. 1,200 Ma granites are represented by biotite granodiorites at Glen Afton and by muscovite-biotite granites at Corsewall Point. The muscovite-biotite granites from the Glen Afton conglomerate have an age of 661 ± 35 Ma which is within error of the age of the hornblende-biotite granites from Corsewall Point (600 ± 30 Ma and 603 ± 40 Ma). Although the 491 ± 14 Ma hornblende-biotite granites in the Glen Afton conglomerate have more in common petrographically with the 475 ± 20 Ma biotite granites at Corsewall Point, they have different geochemical characteristics.

The combination of the age, initial ratio and petrographic data shows that the granites which supplied detritus to the Corsewall Point and Glen Afton conglomerates were unrelated. However, the two source areas experienced igneous activity at similar times, and in both cases, the 1,200 Ma granites and the 600-700 Ma granites are derived from plutons intruded in continental settings. The main differences in the character of the source areas lie in the much greater abundance of granitic detritus characteristic of less mature arcs in the Glen Afton conglomerate, which includes the hornblende-biotite granites dated at 491 ± 14 Ma. In contrast, the 475 ± 20 Ma biotite granites from Corsewall Point have mature arc characteristics. Thus, the older crust in the two source areas contain different granites with some similar characteristics, but the younger granites are of contrasting types. Although the source areas of the two conglomerates may be based on similar crustal blocks, they must have been geographically distinct.

4.2.d Shinnel Formation.

No whole-rock isochrons were obtained from the granite clasts collected from the Shinnel Formation conglomerate. This is due mainly to the lithological diversity within the sample population, which is smaller than in other conglomerates. Consequently, there are only a few clasts in each group, and the groups do not have the same petrogenetic significance as at other localities (section 3.3.d). Some of the clasts show more intense alteration which is likely to have affected their composition, and may account for some rubidium depletion. However, they do not show the same strontium enrichment as the altered samples from Glen App, so the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios may not have been as severely affected by alteration processes.

Because of the alteration, the $^{87}Sr/^{86}Sr$ evolution curves for the two samples of deformed leucogranite (Group D1) are not projected back beyond the depositional age of the sediments (P. linearis zone, c. 442 Ma, McKerrow et al., 1985). Fig. 4.11 shows that both the clasts had the same Sr isotope composition at this time, which suggests that they may have been severly affected by alteration processes. The deformed leucogranites show close chemical affinities with the foliated biotite granites from Glen App (Group B4) and Fig. 4.11 shows that they have similar post-alteration $^{87}Rb/^{86}Sr$ ratios, given by the slopes of the Sr isotope evolution curves. However, the Sr in the Glen App clasts is less radiogenic, which may be related to the generally higher Sr concentrations that they show.

The muscovite-biotite granite clast from the Shinnel Formation conglomerate (Group D2 - sample SW 12) is chemically and petrographically identical to the muscovite-biotite granites from Corsewall Point (Group A1). Using the initial $^{87}Sr/^{86}Sr$ ratio of the whole-rock isochron defined by the Corsewall Point clasts (0.7046 ± 0.0020), SW 12 gives a model age of 1,121 ± 106 Ma, similar to the

whole-rock isochron age. SW 12 polts close to, but not on, the whole-rock isochron, and the differences between the Rb-Sr isotopic characteristics of this sample and the Corsewall Point muscovite-biotite granites can be accounted for by the greater degree of alteration suffered by this clast. However, the alteration is not intense enough to obscure the close relationship between the muscovite-biotite granites in each conglomerate, evident from the petrographic and geochemical characteristics, which imply that the clasts are derived from the same source.

The contrasting Rb-Sr isotope characteristics of the biotite-bearing granite clasts from the Shinnel Formation conglomerate (Group D3) reflect their petrographic diversity, but because they all show some sign of alteration, the isotopic data can only be used to compare them with granite clasts from other conglomerates in general terms. SW 16a is too heavily altered for any useful comparisons to be made, but SW 16b has a similar isotopic composition to the 491 ± 14 Ma Glen Afton hornblende-biotite granites (Group C3), with which it shows some petrographic and chemical affinity. It is likely therefore that it is derived from a similar source to the other clasts of this general type which occur in the Glen Afton and Corsewall Point conglomerates and are of Early Ordovician age.

ShW 10 has a similar chemistry and mineralogy to the two trondhjemite clasts from Glen Afton (Group C5 - section 3.3.d), and its whole-rock Rb-Sr isotope characteristics are also similar. All three clasts have low $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios and plot on a straight line on an isochron diagram, which yields an age of 438 Ma. This is not regarded as significant in absolute terms because of the small range in Rb/Sr ratios and the large uncertainties in the determination of the Rb/Sr ratios of low-Rb samples. Because the points are clustered, straight lines with a wide range of gradients fit these points, which

indicates that the samples had similar $^{87}Sr/^{86}Sr$ for a considerable period of time. Thus, the trondhjemites in the Glen Afton and Shinnel Formation conglomerates may have been derived from sources of a similar (?Ordovician) age, with similar initial ratios.

The clear petrographic differences between the granophyres from the Shinnel Formation (Group D4) and from Glen Afton (Group C4) are reflected by their different isotopic composition which shows that they were derived from unrelated sources. The $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios of the Shinnel Formation granophyres are higher than those of the Glen Afton clasts, but similar to those of the biotite bearing granite, SW 16b. Using the same initial $^{87}Sr/^{86}Sr$ ratio (0.7064), the Shinnel Formation granophyres give model ages in the range 460 to 505 Ma., similar to that of SW 16b, while the Glen Afton granophyres give ages in the range 635 to 860 Ma.

Although the alteration of the clasts in the Shinnel Formation conglomerates reduces the dependence that can be placed on the Rb-Sr isotope data, it serves to confirm and amplify the conclusions based on petrographic and geochemical criteria concerning the mixed sources of the clasts in this conglomerate, and their relationships with detritus in other deposits. Some clasts show affinities with the granitic detritus that occurs in the Corsewall Point and Glen App conglomerates, which because it is absent from the intervening Glen Afton conglomerate indicates reworking of these older deposits, rather than the continued erosion of the same source area (section 3.4). Some of the detritus is similar to that in the Glen Afton conglomerate, which may indicate that the same source area also supplied detritus to the Shinnel Formation conglomerate, but because a new, freshly eroded component is also present, which is petrographically and isotopically distinct, a new source area may be involved.

4.2.e Pinstane Hill.

The only Rb-Sr whole-rock isochron obtained from granite clasts in the Pinstane Hill conglomerate is defined by the four perthitic biotite granites belonging to Group E2. It yields an age of 458 ± 26 Ma, an initial $^{87}Sr/^{86}Sr$ ratio of 0.7068 ± 0.0005, and has an MSWD of 3.04 (Fig. 4.12). The MSWD may reflect some scatter of the data about the isochron resulting from alteration of these clasts, but it is not so large as to cast doubt on the validity of the isochron. The initial $^{87}Sr/^{86}Sr$ ratio of this suite of clasts is similar to that obtained from the 491 ± 14 Ma hornblende-biotite granites from Glen Afton (Group C3, Fig. 4.9). However, the age and initial ratio error polygons of the two isochrons do not overlap, but lie adjacent to one another (Fig. 4.13). The different petrographic features indicate that the two groups of clasts are derived from separate plutons, and although they have similar strontium isotopic characteristics, other evidence suggests that they are derived from unrelated sources (section 4.3.c).

The two different types of granophyric granite which comprise Group E3 have contrasting isotopic characteristics, which reflects their contrasting affinities with the different types of granophyric granites that occur in the other conglomerates. PS 44, like the chemically similar Shinnel Formation granophyric granites and porphyries, shows evidence of crystallization at low pressures (section 3.3.e) and has higher $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios. The Sr isotope evolution diagram (Fig. 4.14) shows the affinities of both groups of granophyric granite clasts with the low pressure perthitic biotite granites (Group E2). The line for PS 44 passes through the error polygon for the perthitic biotite granites, which shows that they had indistinguishable $^{87}Sr/^{86}Sr$ ratios at c. 458 Ma, and are probably derived from related magmas. The lines for the Shinnel Formation granophyres converge towards the polygon, but scatter about it, which reflects the more diverse nature of

this group, and their more distant relationship with the perthitic biotite granites (section 3.3.e). By contrast, PS 1, which crystallized at high pressures has a low $^{87}Sr/^{86}Sr$ ratio, within the range shown by the Glen Afton granophyric granites, which also formed at high pressures. The $^{87}Sr/^{86}Sr$ evolution line for this clast clips the edge of the error polygon for the perthitic biotite granites (Fig. 4.14), as do the lines for the Glen Afton granophyres. This indicates that the same source may have produced the low-Rb/Sr magmas intruded under high pressure conditions, and the high-Rb/Sr magmas intruded under conditions of low pressure. Because of the uncertainties of modelling the $^{87}Sr/^{86}Sr$ ratios of rocks with low Rb/Sr ratios, such an interpretation is regarded with caution, given the very different nature of the two types of granophyric granite, both petrographically and chemically.

Of the two foliated biotite granite clasts which comprise Group E1, one of them, PS 41, has a particularly high strontium concentration (Appendix 3), which indicates that some Sr has been introduced in calcite veins. Because of the effect of this on the $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios of the sample, modelling based on Rb-Sr isotopic composition is unreliable, and further consideration is precluded. PS 22 has an isotopic composition similar to the Glen App foliated biotite granites (Group B4), and in particular to AP 11 (Fig. 4.11). However, it is petrographically and chemically more simlilar to the deformed leucogranites in the Shinnel Formation conglomerate (Group D1), with which there may also be some isotopic affinity. It is possible that the deformed clasts in all three conglomerates are derived from a source of a similar age.

The two trondhjemitic clasts (Group E4) have the lowest $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios recorded in any of the granite clasts from this conglomerate, and differ slightly from those shown by the trondhjemites

in other conglomerates. However, with such low Rb/Sr ratios, it is difficult to demonstrate any affinity with other groups.

Although the granitic detritus in the Pinstane Hill conglomerate is petrographically distinct, it shows some chemical similarities to clasts from other conglomerates. This is confirmed by the strontium isotope data which show most clearly a relationship with the detritus in the Shinnel Formation conglomerate. Although the isotopic characteristics suggest that the plutons supplying the detritus are related, the greater petrographic variation amongst the clasts in the Pinstane Hill conglomerate suggests that this results from the continued erosion of the same source area, rather than the reworking of detritus from older conglomerates.

4.3 Sm-Nd Geochemistry.

The ^{147}Sm - ^{143}Nd decay scheme is not usually applicable to the determination of the age of granite intrusions because granites are enriched in light rare earth elements and consequently have low Sm/Nd ratios, which are usually rather uniform within a pluton. This results in a narrow range of $^{143}Nd/^{144}Nd$ values, insufficient in most cases to determine a whole-rock isochron. The usefulness of the Sm-Nd system lies in the similar geochemical behaviour of the two rare earth elements, which means that only igneous processes which involve the fractionation of rare earth elements are capable of altering Sm/Nd ratios, and the fact that Sm and Nd are much less mobile than Rb and Sr.

When using Sm-Nd isotopic data as a tool for determining the provenance of granite clasts, these characteristics have two consequences. Firstly, because the Sm/Nd ratio of a granite clast is much less likely to have been affected by post-crystallization processes

than the Rb/Sr ratio, its Nd isotope evolution can be predicted with much greater confidence than its Sr isotope evolution, and this allows more reliable comparisons to be made between individual clasts within a conglomerate, and between groups of clasts in different conglomerates. Secondly, because igneous processes within the crust fractionate rare earth elements to a lesser extent than the fractionation of crust from the mantle, the Sm-Nd isotopic composition of a granite clast can be used to determine model ages which may be characteristic of the crust from which the granite was derived.

The Nd isotopic composition of a sample at any particular time is expressed by an ε_{Nd} value which measures its $^{143}Nd/^{144}Nd$ isotopic ratio relative to the $^{143}Nd/^{144}Nd$ ratio of the bulk earth, given by the chondritic uniform reservoir (CHUR), at the same time (DePaolo and Wasserburg, 1976). The present day ε_{Nd} values $(\varepsilon_{Nd(0)})$ of granites are usually negative, which indicates that they contain Nd less radiogenic than the bulk earth, a result of long term Nd isotope evolution in crustal sources which have low Sm/Nd ratios.

By projecting the $^{143}Nd/^{144}Nd$ ratio of a sample back to the time at which it had the same $^{143}Nd/^{144}Nd$ ratio as some particular mantle source, a model age is obtained which expresses the average time at which the Sm and Nd of the different components of the granitic magma were extracted from that source. For instance, the time at which ε_{Nd} for a particular sample is equal to 0 is the time at which the $^{143}Nd/^{144}Nd$ ratio of that sample would have been the same as that of the undepleted mantle, or the chondritic uniform reservoir, and is referred to as T_{CHUR} (McCulloch and Wasserburg, 1978). Because of the differentiation of continental crust, the mantle has become depleted in light rare earth elements relative to CHUR, which means that it has a higher Sm/Nd ratio. Consequently, Nd in the depleted mantle source has evolved to more radiogenic compositions than the bulk earth, and ε_{Nd}

values have become more positive with time. A model for the Nd isotope evolution of the depleted mantle is given by:-

$$\varepsilon_{Nd(T)} = 0.25T^2 - 3T + 8.5 \quad \text{(DePaolo, 1981).}$$

The time at which the ε_{Nd} value of a sample would have been the same as that given by the depleted mantle model defined above is referred to as T_{DM} (DePaolo, 1981).

Because granitic magmas often contain an older reworked crustal component, their model ages are usually older than the age of intrusion and may therefore have little direct chronological significance. If a granite was formed purely by crustal anatexis, and the process involved little light rare earth element enrichment, it may yield model ages the same as that of the crust from which it is derived, but if the magma also contains a mantle-derived component, the model age is likely to have a value intermediate between the age of intrusion and the age of the crust. The actual value of the model age will depend upon the relative proportions of the two components, but provides an estimate of the minimum age of the crustal component of the magma. Granite clasts derived from different plutons may have similar model ages, and if the magmas contain a similar proportion of crustal material, this implies that the crustal component in each clast is likely to be of a similar age and have similar compositional characteristics.

If the age of an intrusion is known from other methods, its initial Nd isotope composition, $\varepsilon_{Nd(I)}$, can also be calculated from present day $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios. Clasts of the same age derived from magmas that contain similar proportions of mantle and crustal material of similar ages will have similar $\varepsilon_{Nd(I)}$ values. As the $^{147}Sm/^{144}Nd$ ratio of a sample is used to project its Nd isotopic composition back from its age of intrusion to the time at which it had mantle values, the model age that is obtained will depend upon the degree of light rare earth element enrichment associated with the formation of the magmas.

Thus, related magmas with similar initial Nd isotopic composition may yield different model ages. The degree of light rare earth element enrichment is expressed by the Sm/Nd ratio, and is a further important feature of the clasts that must be considered when interpreting their Sm-Nd isotopic data.

Sm and Nd were separated using a two column chromatographic procedure, and Nd isotope determinations were carried out using a fully automated VG Micromass 54-E mass spectrometer. Sm and Nd concentrations were determined by mass spectrometric isotope dilution analysis using a ^{149}Sm-^{150}Nd mixed spike and Sm/Nd ratios were converted to $^{147}Sm/^{144}Nd$ ratios by multiplication by a factor of 0.604491. Nd data were normalized to $^{146}Nd/^{144}Nd = 0.7219$ (O'Nions et al., 1977). The Sm and Nd isotope data are contained in Appendix 3. A decay constant for ^{147}Sm of $\lambda = 6.54 \times 10^{-12}$ years^{-1} and values of $^{147}Sm/^{144}Nd = 0.1966$ and $^{143}Nd/^{144}Nd = 0.512638$ for CHUR (Jacobsen and Wasserburg, 1980; Goldstein et al., 1984) were used in calculating ε_{Nd} values and T_{CHUR} model ages. DePaolo's (1981) depleted mantle model was used to calculated T_{DM} model ages. Full details of analytical techniques and statistical procedures are contained in Appendix 4. Fifteen clasts from four of the conglomerates were analysed; their ε_{Nd} values and model ages are shown in Table 4.2.

4.3.a Corsewall Point.

Eight samples from the four groups of granite clasts in the Corsewall Point conglomerate that yielded Rb-Sr whole-rock isochron ages were analysed for Sm and Nd isotopic composition. Fig. 4.15 shows that samples from the different groups have separate Nd isotope evolution curves, which provides further evidence that the petrographic division of the granite clasts outlined in Chapter 3 has genetic significance. As

a result, each group of clasts is characterized by different ε_{Nd} values and Sm-Nd model ages (see Table 4.2).

The initial ε_{Nd} values for the muscovite-biotite granites (Group A1) are negative (c.-8) and the ε_{Sr} values positive (c.+20 - ε_{Sr} values are calculated in the same way as ε_{Nd} values, and are a measure of the $^{87}Sr/^{86}Sr$ ratio of a sample at a particular time relative to that of the bulk earth. Present day bulk earth values for $^{87}Sr/^{86}Sr$ = 0.7047 and $^{87}Rb/^{86}Sr$ = 0.0847 (Hawkesworth and Norry, 1983) were used to calculate ε_{Sr}). The negative $\varepsilon_{Nd(I)}$ and positive $\varepsilon_{Sr(I)}$ values indicate some component of the magma was derived from an older crustal source with lower Sm/Nd ratios and higher Rb/Sr ratios than the mantle. The Sm-Nd T_{DM} model ages obtained from these clasts indicate that this component is at least 2,200 Ma old. However, the age and initial ratio error polygon of the Rb-Sr whole-rock isochron obtained from the muscovite-biotite granites (Fig. 4.5) shows that their original Sr isotope composition may not have been very much more radiogenic than the bulk earth (undepleted mantle), which implies that the Rb/Sr ratio of the crustal component was relatively low. For a $^{87}Sr/^{86}Sr$ ratio of 0.7046 (the initial $^{87}Sr/^{86}Sr$ ratio of the whole-rock isochron) to have evolved by 1,265 Ma in crust derived from the mantle at 2,200 Ma, a Rb/Sr ratio of c. 0.095 would be required. Rb/Sr ratios are typically less than c. 0.04 in granulite facies crust, and between c. 0.2 and 0.4 in amphibolite facies crust (Taylor et al., 1984). The crustal component in the muscovite-biotite granite clasts is represented by pelitic and quartzose xenoliths. The intermediate value estimated for the Rb/Sr ratio of the crustal component is consistent with the derivation of these xenoliths from a granulite facies or an upper amphibolite facies terrane.

The two groups of hornblende-biotite granite clasts (Groups A2a and A2b) both yield Rb-Sr whole-rock isochrons ages of about 600 Ma, and

TABLE 4.2 Sm-Nd model ages and ε_{Nd} values obtained from some granite clasts in the Southern Uplands conglomerates.

Sample	Petrographic Group	Rb-Sr Whole Rock Age	$\varepsilon_{Nd(0)}$	$\varepsilon_{Nd(I)}$	T_{CHUR}(Ga.)	T_{DM}(Ga.)
CoP 3	Group A1	1,265±130 Ma.	-22.4	-8.7	2.06	2.32
CoP 118	Group A1	1,265±130 Ma.	-21.1	-7.2	1.91	2.19
CoP 102	Group A2a	600±30 Ma.	-20.0	-13.6	1.84	2.13
CoP 105	Group A2a	?600 Ma.	-19.7	-13.4	1.86	2.16
CoP 106	Group A2a	600±30 Ma.	-19.7	-12.6	1.65	1.94
CoP 22	Group A2b	603±40 Ma.	-16.3	-11.5	2.01	2.35
CoP 104	Group A2b	603±40 Ma.	-17.5	-13.6	2.67	2.94
CoP 6	Group A4	475±20 Ma.	-6.8	-3.9	1.09	1.73
GA 39	Group C1	661±35 Ma.	-19.5	-12.7	1.87	2.17
GA 51	Group C3	491±14 Ma.	-6.2	-3.9	1.28	1.99
GA 172	Group C3	491±14 Ma.	-11.5	-8.7	1.97	2.42
GA 15	Group C4	?	-6.0	-	1.67	2.42
GA 24	Group C5	?	-2.5	-	0.95	2.14
SW 8	Group D4	?460 Ma.	-4.3	-0.5	0.52	1.15
PS 44	Group E3	?460 Ma.	-2.9	+2.2	0.26	0.81

they both had similar ε_{Nd} values at this time (Fig. 4.15; Table 4.2). This suggests that the magmas from which the granite plutons crystallized were derived from similar sources, but because they have different $\varepsilon_{Nd(0)}$ values, rare earth element fractionation must have taken place during magma genesis. The clasts which comprise Group A2a were derived from a more light rare earth element enriched pluton, with a lower Sm/Nd ratio, as a result of which they now contain Nd of a less radiogenic composition (Fig. 4.15). The less light rare earth element enriched samples, which comprise Group A2b, have higher Sm/Nd ratios and ε_{Nd} evolution curves with lower gradients (Fig. 4.15). Consequently, the Nd isotopic composition has to be projected further back to reach mantle values, and these clasts therefore yield older model ages. The Sm-Nd isotopic characteristics of the two groups of hornblende-biotite granite clasts supports earlier conclusions that they are derived from closely related, but distinct, plutons.

The hornblende-biotite granites yield similar model ages to the muscovite-biotite granite clasts and contained Nd that was of a slightly less radiogenic composition at 600 Ma (Fig. 4.15), which indicates that the two groups of clasts may contain crustal components with similar isotopic compositions. The hornblende-biotite granite clasts are derived from plutons that have mature arc characteristics (section 3.3.a), and intrusions from such a setting would be expected to contain a significant crustal component. However, consideration of the ε_{Sr} v. ε_{Nd} diagram at 600 Ma (Fig. 4.16) shows that the muscovite-biotite granites themselves are unlikely to represent the crustal component in the younger granites.

CoP 6, which belongs to the group of 475 ± 20 Ma biotite granite clasts (Group A4), has Sm-Nd isotopic characteristics that clearly distinguish it from the other groups of granite clasts in the Corsewall Point conglomerate (Fig. 4.15). It contains Nd of a more radiogenic

composition, and yields younger model ages (Table 4.2). CoP 6 also has a low $\varepsilon_{Sr(I)}$ value (+20, see Fig. 4.17), which may indicate that the biotite granites contain a smaller crustal component than the other groups of granite clasts. However, chemical evidence suggests that the biotite granites are derived from a mature arc (section 3.3.a), and CoP 6 itself contains petrographic evidence of a significant crustal component in the magma (section 3.2.a.iv). Alternatively, the biotite granites may contain a younger crustal component than other groups of clasts, which has not have evolved such unradiogenic Nd.

4.3.b Glen Afton.

Five clasts from Glen Afton conglomerate were analysed for Sm and Nd isotopic composition. The single clast from the 661 ± 35 Ma group of muscovite-biotite granites (GA 39 - from Group C1) that was analysed has very similar Nd isotopic characteristics to the first group of 600 Ma hornblende-biotite granites from Corsewall Point (Group A2a - see Fig. 4.18 and Table 4.2). The Nd isotope determination on this clast is less precise (Appendix 3), but provided that the two groups of c. 600 Ma clasts contain a similar proportion of crustallly-derived material, their similar Nd isotope characteristics may indicate that the crustal component in both groups is of a similar age. The ε_{Sr} value of GA 39 at 600 Ma is higher than most of the Corsewall Point clasts, but the same as CoP 105 (Fig. 4.16). However, the strontium isotopic composition of both clasts may have been altered by post-crystallization processes (sections 4.2.a and 4.2.c). The c. 600 Ma clasts from Glen Afton and Corsewall Point differ mineralogically and chemically and were derived from separate plutons, but the similar Nd isotope characteristics of the two groups of clasts indicates that they may be derived from more closely related sources than is otherwise apparent.

The two 491 Ma hornblende-biotite granite clasts (GA 51 and GA 172 - from Group C3) have slightly different Nd isotope characteristics (Fig. 4.18) which suggests some isotopic heterogeneity of the Nd isotope systematics in this group. GA 51 has an identical $\varepsilon_{Nd(I)}$ value to CoP 6, one of the 475 Ma biotite granite clasts from Corsewall Point (Group A4, see Table 4.2 and Fig. 4.18). It also yields similar model ages, which indicates that it may contain a similar crustal component to the Corsewall Point clasts. GA 172 has more negative ε_{Nd} values and yields older model ages, which may indicate that it contains a larger crustal component, or material derived from an older crustal source; it differs mineralogically from the other members of the group in lacking mafic minerals, and has a higher SiO_2 content. Although the Sm-Nd isotope data indicate that the granite clasts of Ordovician age in the Corsewall Point and Glen Afton conglomerates may be derived from plutons containing a similar crustal component, care should be taken as the two groups have different chemical characteristics and are mineralogically distinct. In addition, CoP 6 may not be typical of the Corsewall Point biotite granites, as it appears to contain a larger crustal component than the other clasts in its group.

Sm-Nd isotopic determinations were also carried out on two clasts that did not yield Rb-Sr whole-rock isochron ages, and whose affinities are uncertain. GA 15, one of the acicular hornblende granites (Group C4) has a distinct isotopic composition at 480 and 600 Ma (Figs. 4.16 and 4.17), which supports the petrographic and chemical evidence that this group of clasts represents a distinct component of the detritus and is not present in the other conglomerates. GA 24 is a trondhjemite (Group C5) which has immature arc characteristics. As would be expected for a clast derived from such a source, it has a slightly negative $\varepsilon_{Nd(I)}$ value, which is consistent with it containing only a small crustal component (Table 4.2).

4.3.c The Shinnel Formation and Pinstane Hill conglomerates.

Sm-Nd isotopic determinations were carried out on two petrographically similar, high-level granophyric granite clasts, one from the Shinnel Formation conglomerate (SW 8), and one from the Pinstane Hill conglomerate (PS 44). The perthitic biotite granites from Pinstane Hill (Group E1) are also derived from a high-level intrusion, and have similar chemical and Sr isotope characteristics to the granophyric granite clasts (sections 3.3.e and 4.2.e.). Consequently, the 458 ± 26 Ma Rb-Sr whole-rock isochron age obtained from the perthitic biotite granites is taken as the approximate age of intrusion of the plutons that supplied the granophyric granite clasts.

The two clasts contain Nd of a more radiogenic composition and yield lower model ages than any of the other clasts analysed for Sm and Nd (Table 4.2, Fig. 4.17), although they have similar Sr isotope characteristics to some of the other groups of granite clasts, particularly the Glen Afton hornblende-biotite granites (Group C4 - see section 4.2.e and Fig. 4.13). The positive ε_{Sr} values of the granophyric granites indicate that they are not derived directly from a mantle source. However, they are unlikely to contain a similar crustal component to that present in the granite clasts from other conglomerates, as such a component would have to contain Nd with an isotopic composition not greatly different from that of the mantle. Instead, these clasts may contain an older mantle-derived component which has fractionated to give higher Rb/Sr ratios, and would therefore contain Nd with typical mantle values, but Sr of a more radiogenic composition.

The Sm-Nd isotopic composition of the Shinnel Formation and Pinstane Hill conglomerate clasts is not identical, which reflects other differences between the granitic detritus in the two conglomerates, but both clasts are petrographically, as well as isotopically distinct from

the granite clasts that occur in the Corsewall Point, Glen App and Glen Afton conglomerates. It is likely therefore that the Shinnel Formation conglomerate of the Northern Belt, and the Pinstane Hill conglomerate of the Central Belt, were derived from similar source areas, distinct from those which supplied the older conglomerates.

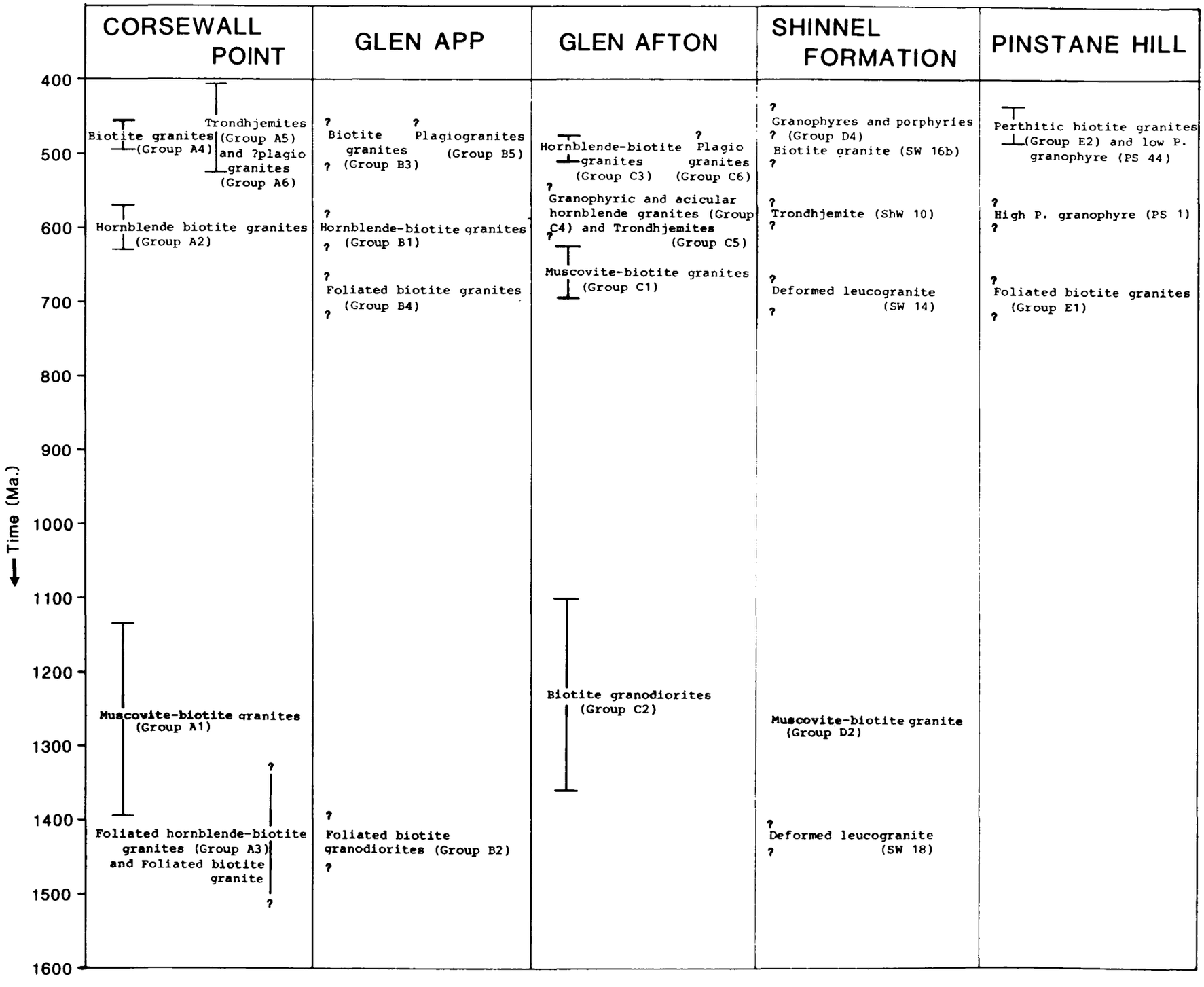
4.4 Conclusions.

Table 4.3 shows the age of the granitic detritus in each conglomerate, while Table 3.8 shows the petrographic and geochemical relationships between the different groups of granite clasts. This information can be combined with that obtained from the non-granitic clasts and the petrographic features of the associated greywackes (Chapter 2) to create a picture of the different source areas that supplied each conglomerate. Because all the conglomerates are derived from the north-west, the source areas must lie on the margin of Laurentia, and the characteristics of the different areas can be used to establish the relationships between them.

The oldest dated clasts in the Corsewall Point conglomerate are the 1,265 ± 130 Ma muscovite-biotite granites (Group A1). They exhibit a weak foliation which is more strongly developed in a few clasts. The foliated hornblende-biotite granodiorites (Group A3) are more strongly deformed, and yield similar or slightly older Rb-Sr model ages. This suggests that the muscovite-biotite granites were intruded into an already deformed terrane, and may explain the chemical characteristics which imply that the original pluton was intruded in a post-collisional setting. The deformed terrane also included quartzo-feldspathic gneisses which occur as rare clasts and which may be the source of quartzose xenoliths in the muscovite-biotite granites, garnet-sillimanite schists, which also form numerous xenoliths, and a foliated

TABLE 4.3 The age relationships between granite clasts in the Southern Uplands conglomerates.

The vertical scale represents the age of intrusion of the clasts, and the vertical bars represent the errors on ages determined from isochrons.



biotite granite, which occurs as a clast. The garnet-sillimanite schists would be more easily destroyed during transport, which explains their absence from the clast population of this conglomerate.

There is no evidence of any further igneous activity in the source area of the Corsewall Point conglomerate until the intrusion of hornblende-biotite granites (Groups A2a and A2b) at c. 600 Ma. They have chemical characteristics which indicate that they were derived from a mature volcanic arc, and ε_{Nd} and ε_{Sr} values which indicate that they contain a significant crustal component with isotopic characteristics similar to the crustal component in the muscovite-biotite granites. The source area therefore also contains a volcanic arc which formed during a period of subduction in the Late Precambrian.

Although the 475 ± 20 Ma biotite granites (Group A4) are more evolved than the hornblende-biotite granites and also show mature arc characteristics, they are probably derived from a separate arc as there are no clasts of intermediate age or composition, and they appear to contain a different crustal component. They form a group of clasts derived from one of a variety of granitic intrusions of Early to Middle Ordovician age, which includes the trondhjemite clast dated by Longman (1980) as 463 ± 62 Ma old. The Corsewall Point conglomerate was deposited towards the end of the Middle Ordovician (N. gracilis zone, c. 455 Ma, McKerrow et al., 1985), so the source area must have included a contemporary volcanic arc. The quartz-feldspar porphyries and acidic volcanic detritus are probably derived from higher levels of the same arc, but because the abundance of these components of the detritus declines up the sequence (section 2.2.c), it appears that the arc was being actively eroded.

The association of basic igneous detritus and chert suggests that the source area contained an ophiolitic component, which may also have been the source of the plagiogranite clast of oceanic affinity. The

increase in the abundance of gabbro towards the top of the conglomeratic unit indicates that active erosion was also exposing deeper levels of the ophiolite, and accounts for the north-westerly derived ferromagnesian-rich greywackes which dominate Tract 1.

The clast assemblage of the Corsewall Point and Glen App conglomerates is similar (section 2.2.c), but a detailed comparison of the granite clasts is made difficult by the effects of weathering which have altered both the chemistry and the isotopic composition of the Glen App clasts; correlation is largely dependent on petrographic characteristics. The Corsewall Point conglomerate contains petrographic equivalents of all the different types of granite clast that occur in the Glen App conglomerate, and in most cases the isotopic characteristics of the petrographically similar groups are consistent, if not the same. However, the foliated biotite granites in the Glen App conglomerate (Group B4) yield much younger Rb-Sr whole-rock model ages than the equivalent clast from Corsewall Point (CoP 25). This is due to differences in present day $^{87}Sr/^{86}Sr$ ratios, and cannot be explained entirely by differences in $^{87}Rb/^{86}Sr$ ratio (Fig. 4.5), which are more likely to affected by alteration processes. Consequently, the Glen App conglomerate may contain a younger deformed granite which is not present in the Corsewall Point conglomerate, or alternatively, given the petrographic and chemical similarities that exist between the two groups, one that has suffered isotopic disturbance more recently than the Corsewall Point clast. Some elements of the granitic detritus that occur in the Corsewall Point conglomerate, such as the muscovite-biotite granites and trondhjemites, are not present at Glen App, and those that the two conglomerates do have in common do not occur in the same proportions. Most notably, foliated biotite granites are more common in the Glen App conglomerate.

Because the two conglomerates contain granites which are probably of similar ages, and because they were deposited only 15 km. apart, it is likely that the two source areas were closely related and had similar characteristics. Both source areas contained a contemporary arc which supplied quartz-feldspar porphyries, and an ophiolitic component, the progressive erosion of which supplied basic igneous detritus and the few plagiogranite clasts that occur in both deposits. However, the older granites and deformed lithologies which are derived from older crust are not as common in the Glen App conglomerate, and basic detritus and quartz-feldspar porphyries are more abundant at some localities. This suggests that the ophiolitic component and the higher levels of the contemporary arc may have formed a more extensive part of the source area of the Glen App conglomerate, and the differences between the detritus in the two deposits suggests that their source areas were geographically distinct. Because the detritus from such closely related source areas remains distinct, it is likely that the conglomerates were deposited close to their respective sources.

The Glen Afton conglomerate was deposited three graptolite zones after the Corsewall Point and Glen App conglomerates, during the D. clingani zone. Because the D. clingani zone spans three North American graptolite zones and three Welsh trilobite and brachiopod stages, it is likely to be of longer duration than other graptolite zones. Consequently, the Glen Afton conglomerate is likely to be at least 5 Ma, or as much as 10 Ma, younger than the Corsewall Point and Glen App conglomerates. The Glen Afton conglomerate was derived from the north-west, and is associated with greywackes of the Blackcraig Formation. Like the greywackes associated with the Corsewall Point conglomerate, which are also derived from the north-west, they are rich in ferromagnesian minerals, in contrast to the quartz-rich greywackes of

the underlying Afton Formation, which were transported along the subduction trench from the north-east.

The granite clasts in the Glen Afton conglomerate yield similar radiometric ages to the clasts from Corsewall Point (Table 4.3), but there is little petrographic or chemical correspondence between the different groups of granite clasts of a similar age. The 1,231 ± 120 Ma clasts from Glen Afton are biotite granodioirites which show mature arc characteristics, while the 1,265 ± 130 Ma muscovite-biotite granite clasts from Corsewall Point have similar trace element characteristics, but a major element chemistry which indicates that they may be more properly classified as post-collisional. The 661 ± 34 Ma muscovite-biotite granites from Glen Afton have similar mature arc characteristics to the c. 600 Ma hornblende-biotite granites at Corsewall Point, but apart from clear mineralogical differences, the former show evidence of crystallization at low pressure, while the latter show evidence of crystallization at high pressure. Some of the Glen Afton muscovite-biotite granites are excluded from the isochron suite because they are foliated, but there are no deformed clasts amongst the Corsewall Point hornblende-biotite granites. The 491 ± 14 Ma hornblende-biotite granites from Glen Afton have a similar sodium-rich chemistry to the 475 ± 20 Ma biotite granites from Corsewall Point, but while the latter show mature arc characteristics, the former appear to be derived from an immature arc. The initial $^{87}Sr/^{86}Sr$ ratios of the suites of clasts from the two conglomerates are also distinct, which shows that separate plutons supplied detritus to the two conglomerates. The trondhjemite clasts in the Glen Afton conglomerate show immature arc characteristics, but the trondhjemite clast in the Corsewall Point conglomerate has continental affinities. The distinctive granophyric and acicular hornblende granite clasts in the Glen Afton conglomerate (Group C4) also have immature arc

characteristics and are not present in other deposits. All the arc-derived granite clasts in the Corsewall Point conglomerate appear to come from mature arc sources, and the presence of a less mature Ordovician arc in the source area of the Glen Afton conglomerate distinguishes it from the source area of the Corsewall Point conglomerate. The different nature of the arcs may also account for the differences in the the acidic volcanic detritus in the two conglomerates. The less mature arcs must have been accreted to the continental margin, and as this could not have occurred between the deposition of the Corsewall Point and Glen Afton conglomerates, the source areas of the two deposits must have been geographically distinct.

Both conglomerates contain plagiogranite clasts which are probably derived from an ophiolitic component present in both source areas. This component also supplied basic detritus to the two conglomerates and accounts for the similar ferromagnesian-rich petrography of the Corsewall Group and Blackcraig Formation greywackes. However, the differences in the petrography of the basalt clasts and the nature of the chert fragments (section 2.3.c) show that the ophiolite sources for the two conglomerates were not identical.

The various types of deformed granite clasts derived from the older crust in the source area of the Corsewall Point conglomerate were not found at Glen Afton. Both conglomerates contain clasts of quartzo-feldspathic gneiss, and hornblende schists also occur in the Glen Afton deposit. Nd isotopic data indicates that clasts derived from both source areas may contain crustal components of similar ages. As the two source areas also experienced periods of igneous activity at similar times, if not always of a similar nature, it is likely that the source areas belong to different parts of the same continental margin.

The Shinnel Formation conglomerate was deposited during the P. linearis zone, and is one graptolite zone, or about 3 Ma, younger than the Glen Afton conglomerate. Both conglomerates were derived from the north-west, and if the same source area continued to supply detritus to the Southern Uplands, the Glen Afton and Shinnel Formation conglomerates might be expected to contain a similar range of clasts, and the greywackes with which they are associated would be likely to have a similar petrography. However, the Shinnel Formation greywackes are very quartz-rich, and are almost completely devoid of ferromagnesian minerals (Floyd, 1982). The Shinnel Formation conglomerate contains very little basic detritus and a lower proportion of granite clasts than the Glen Afton conglomerate. The granite clasts are derived from a wide variety of sources and only two of them can be correlated with clasts in the Glen Afton conglomerate - a biotite granite (SW 16b) which is similar to the 491 ± 14 Ma hornblende-biotite granites, and a trondhjemite (ShW 10) which has similar characteristics to the Glen Afton trondhjemites. There are no clasts which correspond to either the 661 ± 35 Ma or the 1,231 ± 120 Ma mature arc granites, or any plagiogranite clasts, which, if they are derived from a similar source to the basic detritus, may indicate that the source area of the Shinnel Formation conglomerate lacks an ophiolitic component. The granophyric granites in the Shinnel Formation conglomerate are petrographically and isotopically distinct from those that occur in the Glen Afton conglomerate and represent a new component of the detritus.

Other clasts show some similarities with granite clasts that occur in the Corsewall Point and Glen App conglomerates. The muscovite-biotite granite clast (SW 12 - Group D2) is identical to the Corsewall Point muscovite-biotite granites (Group A1) and the two deformed leucogranite clasts show some affinities with the foliated biotite granites that occur both in the Corsewall Point and Glen App conglomerates. As such

clasts are absent from the intervening Glen Afton conglomerate, the most likely explanation for their presence in the Shinnel Formation conglomerate is that they have been reworked from already accreted and uplifted conglomerates of N. gracilis zone age.

The clast assemblage of the Shinnel Formation conglomerate is dominated by sedimentary detritus (including clasts of limestone and graptolitic shale) and quartzite clasts (Fig. 2.8); quartz-rich acid igneous clasts are also common, some of which are similar to the clasts that occur in the Glen Afton conglomerate. The upward increase in the abundance of sedimentary clasts in the Glen Afton conglomerate, which results in a transition to intraformational conglomerates at the top of the sequence, indicates that the supply of extrabasinal clasts from the continental margin was shut off during the D. clingani zone (Kelling and Holroyd, 1978). Input of clasts from this margin may not have been resumed until the granophyres and porphyries (Group D4) were supplied to the Shinnel Formation conglomerate in the P. linearis zone. However, these clasts have distinct Nd isotope characteristics which suggests that they are derived from a new source area, unrelated to that which supplied the Glen Afton conglomerate. Most of the other granite clasts are similar to varieties present in older conglomerates, and are therefore likely to have been derived by the reworking of older, uplifted sediment tracts. The uplift of older tracts may also be related to the supply of detritus from the continental margin being shut off during the D. clingani zone. If a significant proportion of the detritus in the Shinnel Formation is reworked, this may account for the quartz-rich nature of the clast assemblage and the associated greywackes.

The Pinstane Hill conglomerate is the only Silurian conglomerate in the Southern Uplands to contain an appreciable quantity of coarse granitic detritus. It is C. vesiculosus zone or younger in age, and is

aproximately 8 Ma younger than the Shinnel Formation conglomerate. It occurs in the Central Belt, which is separated from the Ordovician conglomerates of the Northern Belt by the Kingledores Fault. The granitic detritus in the Pinstane Hill conglomerate shows many similarities to that in the Shinnel Formation conglomerate, but is once again associated with ferromagnesian-rich greywackes. The perthitic biotite granites (Group E2) and one of the granophyric granites (PS 44) have similar geochemical and Rb-Sr and Sm-Nd isotopic characteristics to the Shinnel Formation granophyres, and although these clasts have different petrographic features, they all formed at low pressures and are probably of a similar age. The Pinstane Hill conglomerate also contains quartzites and foliated biotite granite clasts similar to those that occur in the Shinnel Formation conglomerate, a high pressure granophyric granite like those from Glen Afton, and trondhjemitic clasts of uncertain affinity. Clasts of chert and basic igneous detritus are also common.

The similarities between the detritus in the Shinnel Formation and Pinstane Hill conglomerates cannot be explained by simple sediment reworking of the Ordovician conglomerate as there are clear petrographic differences between the isotopically and geochemically similar clasts, and the associated greywackes are of strikingly different petrography. Granites derived from high-level plutons form the most prominent group of clasts in both the Pinstane Hill and Shinnel Formation conglomerates, and because they have such similar characteristics, it is likely that they are derived from closely related sources. However, the source area of the Pinstane Hill conglomerate also contains a basic component, which was not available during the deposition of the Shinnel Formation conglomerate. If the source areas of the two conglomerates were geographically related, it is likely that the basic component of the

detritus was added to the source area during the 8 Ma between the deposition of the Shinnel Formation and Pinstane Hill conglomerates.

Chapter 5

CHAPTER 5

THE PROVENANCE OF THE CONGLOMERATES.

5.1 Scotland and Ireland.

Because the detritus in the Southern Uplands conglomerates was derived from the north-west, the Scottish Highlands have traditionally been regarded as its source (Peach and Horne, 1899; Tyrrell and Begg, 1933; Walton, 1956; Holroyd, 1978). The various tectonic terranes that comprise the Scottish and Irish Caledonides did not have had their present distribution between the the Caradoc and the Wenlock, when the Southern Uplands accretionary complex formed, and therefore each area must be considered separately as a potential source. The distribution and age of the pre-Silurian granites that occur within each terrane are shown in Fig. 5.1, all reported Rb-Sr isochron ages being recalculated where necessary to accord with the decay constant for ^{87}Rb of $1.42 \times 10^{-11}\ y^{-1}$. The isotopic, petrographic and geochemical features of the granites that occur as clasts in the Southern Uplands conglomerates can be compared with these intrusions, and the geological history of each terrane can be compared with the geological histories of the conglomerate source areas summarized in the previous chapter. Thus it can be established whether or not any part of the British Caledonides supplied detritus to the Southern Uplands.

5.1.a Scotland north of the Highland Boundary Fault.

The north-west foreland, west of the Moine thrust, is excluded from these discussions as it consists mainly of 2,900 to 2,700 Ma old Lewisian granulite and amphibolite facies gneiss (Whitehouse, 1987) and 1,700 Ma granitic intrusions (Taylor *et al.*, 1984). Clasts as old as

the Lewisian do not occur in any of the conglomerates in the Southern Uplands.

In the northern Highlands, between the Moine thrust and the Great Glen fault, a long and complex history of deformation and igneous activity has affected the Moine metasediments. The Morar Division of the Moines was deposited unconformably on Lewisian basement, and probably in a separate basin to the Glenfinnan and Locheil Divisions, which have an uncertain relationship with the Lewisian (Fettes et al., 1986). Evidence that the earliest phase of deformation was of Grenvillian age comes from the Morar pelite, which yields a Rb-Sr whole-rock isochron age of 1,004 ± 96 Ma (Brook et al., 1977). The Ardgour granite, which intrudes the Glenfinnan and Locheil pelites (Barr et al., 1985), yields a similar Rb-Sr whole-rock isochron age of 1,027 ± 46 Ma (Brook et al., 1976). As the granite lacks a metamorphic aureole, contains the same deformational fabrics, and had the same initial $^{87}Sr/^{86}Sr$ ratio as the pelites (Brewer et al.; 1979, Barr et al., 1985), it probably formed by localized melting of Moine metasediments and was intruded during the peak of metamorphism at c. 1,000 Ma (Barr et al., 1985).

However, an eclogite from a Lewisian inlier within the the Moines yields Sm-Nd mineral isochron ages between 1,010 and 1,082 Ma (Sanders et al., 1984). If the mineral isochrons represent the age of the eclogite facies metamorphism in the basement, the deformation and metamorphism of the Moine schists, which only reached upper amphibolite facies conditions, but which rest unconformably on the Moines (Fettes et al., 1986), must be younger than 1000 Ma (Sanders et al., 1984). Whatever the precise age of the early deformation in the Moines, it must pre-date the 550 Ma Carn Chuinneag granite (Long and Lambert, 1963; Pidgeon and Johnstone, 1974), the 649 ± 30 Ma Strath Halladale migmatite complex (Brook, reported by Pankhurst, 1982) and a number of pegmatites with ages of about 750 Ma (van Breemen et al., 1978), which cut early

tectonic fabrics. The Argour granite developed a gneissic foliation during this deformational event, and so is unlikely to be related to the source of the mildly foliated 1,265 Ma muscovite-biotite granite clasts in the Corsewall Point conglomerate, or the unfoliated 1,230 Ma biotite granodiorite clasts in the Glen Afton conglomerate. Similar considerations preclude the Annagh gneiss of County Mayo, western Ireland, which is a syn-tectonic intrusion, and has a U-Pb zircon age of 1,070 ± 30 Ma, whilst a late tectonic granite from the same complex yields an age of 1,000 ± 30 Ma (van Breemen et al., 1978).

Caledonian reworking of the Moines post-dates the intrusion of the metamorphosed and deformed Glen Dessary syenite at 456 ± 5 Ma (van Breemen et al., 1979), but pre-dates the intrusion of pegmatites at 430 Ma (Fettes et al., 1986). This deformational event is also recorded by pelites which yield a Rb-Sr whole-rock age of 467 ± 20 Ma (Brewer et al., 1979). The Carn Chuinneag and Inchbae granites, which yield a Rb-Sr whole-rock isochron age of 548 ± 10 Ma (Long and Lambert, 1963) and a U-Pb zircon age of 560 ± 10 Ma (Pidgeon and Johnson, 1974), were extensively deformed at this time, and are therefore unlikely to be related to the source of the undeformed 600 Ma hornblende-biotite granites in the Corsewall Point conglomerate, or the 661 ± 35 Ma muscovite-biotite granites in the Glen Afton conglomerate. The Glen Dessary syenite is of a similar age to the unfoliated 458 to 490 Ma biotite granite clasts in the Southern Uplands, but in addition to being deformed, it also has a different composition. Deformational events in the northern Highlands at c. 1,000 Ma and c. 460 Ma make it an unlikely source of the granite clasts in the Southern Uplands.

The Grampian terrane, between the Great Glen and Highland Boundary faults, contains Dalradian metasediments which were deposited between the Late Precambrian and the Middle Cambrian on basement similar to that of the Moines of the northern Highlands (Powell and Phillips, 1985).

The main deformation and metamorphism in this area, the Grampian orogeny, was a Late Cambrain to Early Ordovician event. The early phases of deformation, D_1 and D_2, pre-date the 514 ± 7 Ma Ben Vurich granite (Pankhurst and Pidgeon,. 1976), which cuts such fabrics. However, the granite contains a D_3 fabric, which is probably contemporaneous with the peak of metamorphism and the intrusion of gabbros in north-east Scotland at 489 ± 17 Ma (Pankhurst, 1970). The oldest undeformed granite, the Strichen granite, which post-dates D_4, was intruded at 475 ± 5 Ma (Pidgeon and Aftalion, 1978).

If the basement to the Dalradian is similar to the Moines of north-west Scotland, it is also unlikely to be the source of the c. 1,200 Ma old granite clasts in the Southern Uplands. The Ben Vurich granite is not as old as the undeformed 600 to 660 Ma granite clasts in the Corsewall Point and Glen Afton conglomerates, and has been affected by a younger deformational event. Thus, it is improbable that this area contains the source of such clasts. Unfoliated Ordovician granites occur in north-east Scotland (Strichen, Kennethmont - 453 ± 4 Ma, Aberchirder - 444 ± 9 Ma, Longmanhill; Pankhurst, 1974), and in Ireland, the Ox Mountains contains the Sleive Gamph granodiorite (478 ± 12 Ma; Pankhurst et al., 1976), and South Connemara, the Oughterard granite (459 ± 7 Ma; Leake, 1978). Although granites of this age may be more extensive at depth in north-east Scotland (Pankhurst, 1974), their outcrop only occupies a small area at the present day, and is therefore likely to have been even less extensive in the past.

The 458 to 490 Ma granites clasts in the Southern Uplands conglomerates are biotite-bearing, like the intrusions of this age in north-east Scotland. However, the Scottish granites differ from the Southern Uplands clasts in containing more abundant alkali feldspar and occasional muscovite. Also, the initial $^{87}Sr/^{86}Sr$ ratios of the Scottish granites are usually higher than 0.710 (Pankhurst, 1979), but vary

between 0.705 to 0.707 in the Southern Uplands clasts. Pankhurst (1979) interprets the Scottish granites as post-tectonic crustal melts, in contrast to the Southern Uplands clasts, which have calc-alkali volcanic arc characteristics (Chapter 3). It is unlikely, therefore, that the Ordovician age clasts in the Southern Uplands were derived from this source. The Oughterard granite is more similar to the clasts of Ordovician age in its chemistry and petrography, but it also has a higher initial $^{87}Sr/^{86}Sr$ ratio (0.710; Leake, 1978). The Slieve Gamph granodiorite has an initial $^{87}Sr/^{86}Sr$ ratio similar to that of the Ordovician clasts (0.7056, Pankhurst et al., 1976) but contains a penetrative deformational fabric, which probably formed as a result of Llanvirn-Llandeilo sinistral shear (Hutton and Dewey, 1986), and is therefore unlikely to be a source of the undeformed biotite granites. The Grampian terrane only has an Ordovician phase of igneous activity in common with the source areas of the Southern Uplands conglomerates, but the granite plutons of this age are of a different character to the conglomerate clasts. It is therefore unlikely that the detritus in the Southern Uplands was derived from the Grampian Highlands.

5.1.b The Midland Valley.

Apart from the few outcrops of the Highlands Border Complex, the only rocks of pre-Silurian age presently exposed in the Midland Valley are the Lower Ordovician Ballantrae complex, and its Middle to Upper Ordovician cover of conglomerates and sandstones. The Ballantrae complex is ophiolitic, and was presumably obducted onto continental crust which lies beneath the Midland Valley. The nature of this crust has been deduced from geophysical surveying (Bamford, 1979) and from lower crustal xenoliths in Carboniferous volcanic vents (Upton et al., 1984).

The LISPB seismic profile shows mantle with a velocity of c. 8 kms^{-1}, lower crust with a velocity of c. 7 kms^{-1} and middle crust with a

velocity of > 6.4 kms^{-1} beneath Palaeozoic sediments in the Midland Valley (Bamford, 1979). Combining this information with the features of xenoliths that are likely to be representative of these different crustal levels, Upton et al. (1984) have produced a hypothetical section through the Midland Valley (Fig. 5.2). Ultramafic xenoliths from the mantle show evidence that it is in part metasomatized. The lower crust consists of anhydrous pyroxene granulites and meta-anorthosites, one granulite xenolith yielding a Sm-Nd whole-rock isochron age of 574 ± 137 Ma (Davies et al., 1984). This is younger than the ages obtained from mid crustal xenoliths, and implies that material has been magmatically emplaced at the base of the crust (Upton et al., 1984), possibly during a period of late Precambrian igneous activity.

The middle crust is represented by quartzo-feldspathic garnet-bearing granulites of sedimentary origin which yield a Rb-Sr whole-rock isochron age and two separate Sm-Nd model ages of about 1,100 Ma (van Breemen and Hawkesworth, 1980; Davies et al., 1984). While this may indicate that Grenvillian crust is present beneath the Midland Valley, U-Pb zircon ages from such xenoliths show that the quartzo-feldspathic granulites contain a crustal component at least 2,200 Ma old (Halliday et al., 1984). As the Sm-Nd model age represents the average age of all the components in the rock, the granulites must also contain a component younger than 1,100 Ma, the age of which would provide an upper limit for the time of metamorphism. However, the U-Pb geochemistry of the zircons is not inconsistent with Pb loss during a Grenville metamorphic event (Halliday et al., 1984).

Xenoliths of unfoliated granites are undated, but may be related to granite clasts that occur in Ordovician conglomerates south of Girvan (see below). If these granites intrude the granulite facies crust, they must be younger than the 1,100 Ma or younger metamorphic event, and are therefore unlikely to provide a source for the 1,200 Ma granite clasts

in the Southern Uplands. Although xenoliths of sillimanite bearing gneiss occur in the Midland Valley, they are also of granulite facies, and lack hydrous mineral phases such as biotite (Upton et al., 1984). Consequently, it is unlikely that the plutons which supplied the muscovite-biotite granite clasts to the Corsewall Point conglomerate were intruded into such crust, as the sillimanite-bearing pelitic xenoliths that they contain are biotite-rich and were probably derived from an amphibolite facies terrane (sections 3.2.a.i and 4.3.a). It is possible the muscovite-biotite granite clasts were derived from higher levels of a Grenvillian crustal block, but because there are no greenschist or amphibolite facies xenoliths in the Carboniferous volcanic vents, Upton et al. (1984) believe that the Lower Palaeozoic rocks directly overlie granulite facies basement (Fig. 5.2). In addition, if the c. 1,100 Ma Sm-Nd model ages are typical of Midland Valley crust, it is difficult to see how the magmas from which the 1,265 Ma and the 600 Ma granite clasts were derived could be generated in such a terrane, as they yield older Sm-Nd T_{CHUR} model ages, in the range 1,600 to 2,700 Ma, and therefore must contain a greater quantity of older crustal material than appears to be present in the Midland Valley.

Whatever the precise nature of the Midland Valley crust, and the contact of Lower Palaeozoic rocks with it, there appears to have been little basement exposed during the Ordovician. Middle and Upper Ordovician conglomerates resting unconformably on the of the Ballantrae complex consist mainly of clasts of various acidic and basic igneous rock types (Fig. 3 of Bluck, 1983). This clast assemblage is similar to that of the Southern Uplands conglomerates, which are also of a similar age. The Midland Valley conglomerates outcrop south of Girvan, at the southern edge of the Midland Valley block (Fig. 5.1), and as they contain large boulders derived from the north (Bluck, 1983), the

conglomerates accurately record the nature of sediment source areas in the Midland Valley that were being actively eroded at the time the Southern Uplands conglomerates were deposited. By comparing the clasts that occur in conglomerates in both areas, the contribution of detritus from the Midland Valley to the Southern Uplands can be assessed.

The stratigraphic and structural relationships between the Ordovician conglomerates in the Midland Valley were originally described by Williams (1962), and their relationships with the Ordovician conglomerates investigated in this study is illustrated in Fig. 5.3. The Kirkland conglomerate is probably of Upper Llanvirn age (Ingham, 1978) and is therefore older than any of the coarse clastic sediments in the Southern Uplands. Although it contains relatively little granitic detritus (Bluck, 1983), that which is present occurs as highly distinctive foliated alkali-rich granites. Twelve such clasts have yielded a Rb-Sr whole-rock isochron age of 648 ± 32 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7028 ± 0.0005 (MSWD = 10.4, Fig. 5.4; data from P.N. Taylor, personal communication, also reported by Ince, 1984). A mineral isochron from a similar clast yields an age of 486 ± 29 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7034 ± 0.0004 (MSWD = 0.83, Longman, 1980). Given their state of deformation, the whole-rock isochron is more likely than the mineral isochron to record the age of intrusion of these clasts, although the high MSWD of the whole-rock isochron may be the result of some open system behaviour during a deformational event. As undeformed clasts as old as 559 Ma occur elsewhere in the sequence (Longman, 1980), the mineral isochron may not represent the age of deformation either, unless the deformation was localized. Foliated clasts such as those that occur in the Kirkland conglomerate are not present in the Benan and Kilranny conglomerates, which indicates that during the Llandeilo and Caradoc, when the Southern Uplands conglomerates were deposited, this source of detritus was no longer

available. However, if the Kirkland conglomerate clasts are typical of the older deformed crust of the Midland Valley source areas, it is of a different age and character to the older deformed crust in the source area the Corsewall Point conglomerate, which contained foliated biotite granites and hornblende-biotite granodiorites that are probably older than 1,000 Ma (section 4.2.a).

The Benan conglomerate is the same age as the Corsewall Point and Glen App conglomerates (N. gracilis zone), but occurs on the opposite side of the Stinchar Fault (Fig. 5.3). If the original relationship between the conglomerates was the same as it is at present, similar source areas would have supplied all three conglomerates. Thus, a comparison of the granitic detritus in the Benan conglomerate (Longman, 1980) with that in the Corsewall Point conglomerate (this study) can be used to show whether or not the Southern Uplands and the Midland Valley were adjacent during the Llandeilo.

Longman (1980) analysed twenty-six clasts from the Benan conglomerate, and obtained mineral isochrons from nine of them. Only limited petrographic information was available for this study, but using chemical critera similar to those applied to the Southern Uplands clasts, the Benan conglomerate clasts can be divided into three groups (Table 5.1, Figs. 5.5 to 5.7). Four Rb-Sr mineral isochrons were obtained from the six clasts of alkali-rich perthitic and granophyric biotite granites, which yield ages between 466 and 471 Ma (Table 5.1). One clast also yielded a U-Pb zircon age of 475^{+17}_{-9} Ma (Longman, 1980). The initial $^{87}Sr/^{86}Sr$ ratios of the separate isochrons are highly variable (Table 5.1), but the Rb-Sr whole-rock analyses of five separate clasts yield an isochron with an age of 459 ± 10 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7086 ± 0.0015 (MSWD = 3.42, Longman, 1980). A second group of non-perthitic or granophyric biotite granites, which are

TABLE 5.1 The age and occurrence of different types of granite clast in the Ordovician and Silurian conglomerates of the Midland Valley, south of Girvan, using data from Longman (1980).

CONGLOMERATE	NO OF SAMPLES	TRONDHJEMITES	PERTHITIC AND GRANOPHYRIC BIOTITE GRANITES			BIOTITE GRANITES			GRANODIORITES AND TONALITES		
		Sample No	Sample No	Age	Initial ratio	Sample No	Age	Initial ratio	Sample No	Age	Initial ratio
BENAN	27	-	187	466±13Ma	0.700±0.008	198	544±48Ma	0.711±0.002	196	475±13Ma	0.7051±0.0002
			101	467±3Ma	0.7067±0.0005	188	545±11Ma	0.7126±0.0005	192	519±31Ma	0.7076±0.0003
			197	468±5Ma	0.7081±0.0007	176	559±20Ma	0.7095±0.0011	199		
			186	471±13Ma	0.701±0.008	190			195		
			194			181			193		
			177			185			191		
						183			184		
						181			180		
						178			179		
KILRANNY	8	299	284	470±6Ma	0.7069±0.0003	-			-		
		297	296								
		289	286								
		283	281								
TORMITCHELL	1	-	399	451±8Ma	0.7034±0.0004	-			-		
CRAIGSKELLY	7	591	579	458±4Ma	0.7102±0.0003	580	593±28Ma	0.7154±0.0007	-		
		583	462	462±8Ma	0.7105±0.0004						
			589								
			581								

less evolved (Fig. 5.6), contains three clasts that yielded Rb-Sr mineral isochrons with ages of about 550 Ma and initial $^{87}Sr/^{86}Sr$ ratios in the range 0.7095 ± 0.0011 to 0.7126 ± 0.0005 (see Table 5.1). Although the clasts are petrographically and chemically similar, they do not define a whole-rock isochron, and the mineral isochrons have high MSWD's (88, 8.25 and 3.4; data from Lomgman, 1980). This may indicate some isotopic disequilibrium within this group. The third group consists of hornblende- and biotite-bearing granodiorites and tonalites, two of which yielded Rb-Sr mineral isochrons with ages of 475 ± 13 Ma and 519 ± 31 Ma, and initial ratios of 0.7051 ± 0.0002 and 0.7072 ± 0.0003 (Table 5.1, data from Longman, 1980).

Like many of the granite clasts in the Corsewall Point conglomerate, the clasts in the Benan conglomerate show chemical characteristics which indicate that they were derived from mature volcanic arcs (Figs. 5.5 to 5.7). However, whilst the Corsewall Point clasts form a large number of unrelated groups, not all of mature arc origin, the clasts in the Benan conglomerate all belong to a similar chemical trend, best seen on the AFM diagram (Fig. 5.6). Because the variation in the age of the clasts does not correspond to their chemical evolution, it is unlikely that they are derived from a single volcanic arc. Instead it appears that the source area of the Benan conglomerate contained plutons that were intruded into volcanic arcs active at 470 Ma (perthitic biotite granites), c. 500 Ma (granodiorites and tonalites) and 550 Ma (biotite granites).

The Corsewall Point conglomerate contains biotite granites of the same age (475 ± 20 Ma) as the perthitic and granophyric biotite granite clasts form the Benan conglomerate. However, the textures diplayed by the Benan conglomerate clasts indicate that they are derived from a high level intrusion, whilst the Corsewall Point clasts are derived from a pluton intruded at greater depths (section 3.2.a.iv). The Benan

conglomerate clasts are also more alakli-rich (Fig. 5.5), and straddle the boundary between volcanic arc and within plate granites on the Rb v. Y+Nb diagram (Fig. 5.7), a characteristic of the granophyric and perthitic biotite granites that occur in the Shinnel Formation and Pinstane Hill conglomerates of Ashgill and Llandovery age.

The initial $^{87}Sr/^{86}Sr$ ratios of the mineral isochrons obtained from the Benan conglomerate clasts are not precisely determined because of the very high $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios of the separated feldspar fractions. Consequently, the age and initial ratio error polygon for the whole-rock isochron determined from these clasts is compared with the error polygons of the three isochrons obtained from Southern Uplands clasts of a similar age (Fig. 5.8). This shows that the Benan conglomerate clasts were derived from an isotopically distinct pluton which contained strontium of a more radiogenic composition than that which supplied the Southern Uplands clasts. The slope of the line joining the extreme points of an age and initial ratio error polygon represents the average $^{87}Rb/^{86}Sr$ ratio for the isochron suite, and Fig. 5.8 shows that the greatest difference between the isotopic characteristics of the Benan and Corsewall Point clasts is much higher $^{87}Rb/^{86}Sr$ ratios of the former group (7.0899 to 33.951, as compared to 0.6011 to 1.6289). As a result of this, the Benan conglomerate clasts have much higher whole-rock $^{87}Sr/^{86}Sr$ ratios at the present day (0.75569 to 0.92777, as compared to 0.70973 to 0.71664 for the Corsewall Point biotite granites).

Biotite granites derived from plutons intruded at greater depths have ages of c. 550 Ma in the Benan conglomerate, slightly younger than the 600 Ma hornblende-biotite granite clasts from the Corsewall Point conglomerate. Although the Corsewall Point clasts also show evidence of crystallization at high pressures, there is nothing to suggest that they are derived from related sources. Apart from the petrographic

differences between the two groups of clasts, they are also chemically distinct, and occupy different fields on the Na_2O-K_2O-CaO, AFM and Rb v. Y+Nb diagrams (Figs. 5.5 to 5.7). Whilst the Benan conglomerate clasts follow a trend parallel to that of mature arc volcanics on the AFM diagram (Fig. 5.6), the Corsewall Point clasts follow a trend at a high angle to this, parallel to the AF side of the diagram (section 3.3.a). The Benan conglomerate clasts do not define a whole-rock isochron, but their mineral isochrons have higher initial $^{87}Sr/^{86}Sr$ ratios than the Corsewall Point hornblende-biotite granites (0.7095 ± 0.0011 to 0.7126 ± 0.0005, as compared to 0.7059 ± 0.0003 and 0.7068 ± 0.0004 for the Corsewall Point clasts). Sr isotope evolution curves for the whole-rock analyses of the Benan conglomerate clasts do not intersect the error polygons for the the whole-rock isochrons obtained from the Corsewall Point clasts (Fig. 5.9), and, like the perthitic biotite granite clasts, they have higher $^{87}Rb/^{86}Sr$ and higher present day $^{87}Sr/^{86}Sr$ ratios. The Late Precambrian plutons that supplied granite clasts to the Benan and Corsewall Point conglomerates were isotopically distinct.

The two granodiorite clasts from the Benan conglomerate have Sr isotope characteristics that are comparable to those of clasts in the Corsewall Point conglomerate, but there are no granodiorites of a comparable age or any tonalites amongst the clasts collected at Corsewall Point. The only granodioritic clasts in the Corsewall Point conglomerate are foliated and yield model ages in excess of 1,000 Ma (section 4.2.a). Such old deformed clasts are lacking from the Benan conglomerate, as are equivalents of the 1,265 Ma muscovite-biotite granites. The Benan conglomerate also lacks trondhjemite and plagiogranite clasts, which suggests that the ophiolitic source available to the Corsewall Point conglomerate was not present in the source area of the Benan conglomerate. The more restricted range of detritus in the Benan conglomerate and the different age range,

petrographic, chemical and isotopic features of the granite clasts in the two conglomerates show that they must have been derived from distinctly different source areas during the N. gracilis zone.

Eight clasts were analysed by Longman (1980) from the Kilranny conglomerate, which occurs above the Benan conglomerate in the Ordovician succession at Girvan (Fig. 5.3). The sample includes four alkali-rich perthitic and granophyric biotite granites, with high $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios, similar to the Benan conglomerate clasts. One clast from this group yielded a mineral isochron with an identical age to the Benan conglomerate clasts (470 ± 6 Ma; Longman, 1980; Table 5.1), which indicates that the same source continued to supply detritus. However, the two other components of granitic detritus recognized in the Benan conglomerate are not present amongst the clasts collected from the Kilranny conglomerate, which instead contains a number of trondhjemitic clasts (Fig. 5.10). No mineral isochrons were obtained from the trondhjemites, but they have some similar chemical characteristics to the Byne Hill trondhjemites of the Ballantrae complex, dated at 483 ± 4 Ma (Bluck et al., 1980), and may be derived from a related source. The Byne Hill trondhjemite follows an immature arc trend on an AFM diagram (Bloxham, 1981), and plots in the field of oceanic plagiogranites and trondhjemites on an SiO_2 v K_2O plot (Fig. 5.11). This is in contrast to the mature arc characteristics of the trondhjemite clast from the Corsewall Point conglomerate (section 3.3.a), which plots in the field of continental trondhjemites on the SiO_2 - K_2O diagram (Fig. 5.11). A single whole-rock Sr isotope determination from one of the Kilranny conglomerate clasts yields a more radiogenic $^{87}Sr/^{86}Sr$ ratio than the Corsewall Point trondhjemite clast (0.70876 as compared to 0.70681). Consequently, the Corsewall Point trondhjemite is unlikely to be derived from Byne Hill, or from the realted source of the Kilranny conglomerate trondhjemite clasts.

A single perthitic biotite granite clast from the Tormitchell conglomerate (Fig. 5.3) yields a Rb-Sr mineral isochron age of 451 ± 8 Ma (Longman, 1980), slightly younger than the equivalent clasts in the Benan and Kilranny conglomerates (Table 5.1). On this basis, Bluck (1983) concluded that an active arc was being eroded in the Midland Valley. The Cascade conglomerate, which is of a similar age to the Glen Afton conglomerate (Fig. 5.3) does not contain any clasts large enough for geochemical analysis (Longman, 1980).

The Craigskelly conglomerate, which unconformably overlies the Ordovician succession south of Girvan, is of Lower Llandovery age (M. cyphus zone; Cocks and Toghill, 1973), and is slightly younger than the Pinstane Hill conglomerate in the Southern Uplands (M. acuminatus zone or C. vesiculosus zone). Despite being deposited 25 to 30 Ma after the Benan conglomerate (based on the time scale of McKerrow et al., 1985), the seven granite clasts analysed by Longman (1980) from the Craigskelly conglomerate are similar to those described above from the Ordovician succession (Fig. 5.10, Table 5.1). A single high pressure biotite granite clast has an identical composition to the c. 550 Ma biotite granites in the Benan conglomerate, and yields a slightly older Rb-Sr mineral isochron age of 593 ± 28 Ma. Although this is similar to the age of the hornblende-biotite granites in the Corsewall Point conglomerate, the Craigskelly conglomerate clast has a higher initial $^{87}Sr/^{86}Sr$ ratio (0.7154 ± 0.0007), and a Sr isotope evolution curve that does not intersect the age and initial ratio error polygon of the Corsewall Point hornblende-biotite granites (Fig. 5.9). It is therefore unlikely to be related to the source of the petrographically distinct Corsewall Point clasts. Of the four clasts of alkali-rich perthitic biotite granites from the Craigskelly conglomerate, two yield similar ages to the perthitic biotite granite clasts in the Ordovician conglomerates (458 ± 4 Ma and 462 ± 8 Ma; Longman, 1980). The chemical

characteristics of the two trondhjemite clasts in this sample have more in common with the Corsewall Point clasts (Fig. 5.11), but they are still isotopically distinct.

The similarity of the detritus in all the Midland Valley conglomerates shows that their source areas changed very little in the 25 to 30 Ma between the Llandeilo and Lower Llandovery. In contrast, there are marked changes in the sources of the Southern Uplands conglomerates during the same period. None of the granitic detritus in the Girvan succession corresponds to the clasts in the Corsewall Point conglomerate, which are more varied and were derived from a source area of a different character. The evidence from the deformed clasts in the Kirkland conglomerate and from the xenoliths in the Carboniferous volcanic vents suggests that the source areas of the Midland Valley and Corsewall Point conglomerates belonged to separate crustal blocks. Although the source area of the Glen Afton conglomerate was geographically distinct from that of the Corsewall Point conglomerate, it shared a similar igneous history (section 4.4). The granitic detritus in the Glen Afton conglomerate shows no greater similarity to that in the Girvan succession, and the source areas of the Southern Uplands conglomerates probably remained distinct from the Midland Valley throughout the Llandeilo and Caradoc.

The perthitic and granophyric biotite granites that occur in the Shinnel Formation and Pinstane Hill conglomerates are of a similar age (458 ± 26 Ma) and character to the 460 to 470 Ma perthitic biotite granites that occur in the Midland Valley conglomerates, but they have lower initial $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios (Fig. 5.8). The Sm-Nd model ages of these clasts (T_{DM}'s of 1150 and 810 Ma) are also more consistent with the limited Sm-Nd isotopic data available form the Midland Valley xenoliths. Trondhjemite clasts in both deposits have characteristics similar to those in the Girvan succession (Fig. 5.11). Although there

are no equivalents of the 550-600 Ma biotite granite clasts in the Shinnel Formation and Pinstane Hill conglomerates, it is possible that the source areas of the Southern Uplands and Midland Valley conglomerates had more in common during the Ashgill and Llandovery.

5.2 North America.

As it has been shown that the Southern Uplands conglomerates were not derived from the Scottish or Irish Caledonides, the detritus must have been deposited in a trench south-east of a source area elsewhere on the Laurentian margin. There is substantial evidence of large scale sinistral strike-slip displacements within the Caledonides (Dewey and Shakleton, 1984; Soper and Hutton, 1984; Hutton and Dewey, 1986) and evidence of sinistral transpression during the formation of the Southern Uplands accretionary complex (Stringer and Treagus, 1981; Anderson, 1987). Consequently, it is probable that the Southern Uplands was originally south-west of its present position, and alternative sources for the laterally derived sediments are likely to be found in this direction.

5.2.a Rockall.

On pre-drift reconstructions of the North Atlantic, the Rockall Plateau occurs to the west of Scotland (Fig. 5.12). The isotopic composition of Pb in the Tertiary Rockall granite, which occurs at the northern end of the Rockall Bank (Fig. 5.12), indicates that it contains a crustal component similar to that in the Skye granites, of probable Lewisian age (Moorbath and Welke, 1969). An acidic granulite from a drill site 70 km. south-west of the Rockall granite (locality A, Fig. 5.12) yields Laxfordian K-Ar whole-rock and mineral ages (1,670 ± 24 Ma and 1,566 ± 33 Ma respectively; Miller *et al.*, 1973), confirming the

continuation of Lewisian crust in this direction. However, an intermediate granulite from the southern end of the Rockall Bank (locality B, Fig. 5.12) yields an $^{40}Ar/^{39}Ar$ whole-rock age of 987 ± 5 Ma (Miller et al., 1973). Given the petrographic similarity of this sample to Lewisian lithologies (Roberts et al., 1973), the 987 ± 5 Ma age may record isotopic disturbance during a Grenvillian thermal event, rather than crustal reworking, or the addition of new Grenville age crust. Granulite clasts do not occur in the Southern Uplands conglomerates, and on the limited evidence available, there is no reason to suppose that there are any granitic intrusions in the Rockall Bank of suitable age that might have been sources for the Southern Uplands granite clasts.

5.2.b Newfoundland.

Further to the south-west, north-western Newfoundland was situated close to the margin of Lower Palaeozoic Laurentia (Fig. 5.12). The igneous history of this area is summarized in Table 5.2, and because of its similarity to the age of the granitic detritus in the Southern Uplands conglomerates, Newfoundland is a potential source of these clasts. The distribution of pre-Silurian granite intrusions in north-west Newfoundland is shown in Fig. 5.13.

The continental crust in this region forms part of the Grenville Province and is exposed in the Long Range Mountains of Newfoundland (Fig. 5.13) and in mainland Labrador and Quebec. It consists mainly of leucocratic quartzo-feldspathic gneisses of probable metasedimentary origin (Bostock et al., 1983), but differences between the Grenville terranes of Newfoundland and Labrador have led some authors to suggest that the Long Range may be allochthonous relative to the North American craton (Dewey et al., 1983; Erdmer, 1984). The metamorphism and deformation of the Labrador gneisses was probably associated with the intrusion of anorthosites and related plutons at about 1,400 Ma (by

TABLE 5.2 A summary of the igneous history of north-western Newfondland in comparison to the age of granite clasts that occur in Southern Uplands conglomerates.

NEWFOUNDLAND			CORSEWALL POINT	GLEN AFTON	PINSTAHE HILL
LLANVIRN TO LLANDEILO CALC-ALKALI GRANITES					
Dunamagon granite	460±12 Ma[1]	Hibbard (1983)	Biotite Granites (Group A4) 475 ± 20 Ma[2]	Hornblende-biotite granites (Group C3) 491± 14 Ma[2]	Perthitic biotite granites (Group E2) 458± 26 Ma[2]
Burlington granodiorite	461±15 Ma[1]	Hibbard (1983)			
Sunday Cove pluton	464±26 Ma[2]	Bostock et al. (1979)			
Hungry Mountain complex	467±8 Ma[1]	Whalen et al. (1987)			
LOWER ORDOVICIAN AND LATE PRECAMBRIAN TRONDHJEMITES AND PLAGIOGRANITES					
Bay of Island Plagiogranite	504±10 Ma[1]	Mattinson (1976)			
Coney Head complex	474±8 Ma[1]	Dunning (1987)			
Little Port complex	508±5 Ma[1]	Mattinson (1975)			
Twillingate granite	510±17 Ma[1]	Williams et al. (1976)			
Mansfield Cove complex	594±10 Ma[3]	Bostock et al. (1979)	Hornblende-biotite granites (Group A2) 600±30 Ma[2]	Muscovite-biotite granites (Group C1) 661±35 Ma[2]	
LATE PRECAMBRIAN ALKALI GRANITES					
Round Point granite	602±10 Ma[1]	Williams et al. (1985)			
GRENVILLIAN POST-METAMORPHIC GRANITES					
Portland Creek Pond pluton	1081±165 Ma	Pringle et al. (1971)	Muscovite-biotite granite (Group A1) 1,265±130 Ma[2]	Biotite granodiorite (Group C2) 1,231±120 Ma[2]	
Hawkes Bay pluton	1132±154 Ma	Pringle et al. (1971)			

[1] = U-Pb zircon age [2] = Rb-Sr whole-rock iscochron age [3] = $^{207}Pb/^{206}Pb$ zircon age

analogy with dated intrusions elsewhere), and reached granulite facies conditions (Bostock et al., 1983). Although the metamorphism and deformation of the gneisses in the Long Range may have taken place at the same time, anorthosites are rare in this terrane, which probably only reached the lowest grades of granulite facies metamorphism. Post-metamorphic granites are rare in Labrador, but are common in the Long Range (Fig. 5.13), where they may be associated with widespread retrogression to amphibolite facies conditions, and to greenschist facies in the eastern Long Range (Bostock et al., 1983). The Long Range can thus be distinguished from the rest of the Grenville Province in this part of North America.

The leucocratic gneisses of the Long Range consist of quartz, plagioclase and microcline, and some contain minor amounts of biotite. Due to the absence of mafic minerals, they lack a foliation, and have a granoblastic texture. Some particularly quartz-rich gneisses contain between 40% and 90% quartz. Mesocratic and melanocratic gneisses are also present and contain more biotite, less quartz, and in some instances, hornblende. Sillimanite-bearing pelitic schists occur in small quantities throughout the area (Bostock et al., 1983). The mineralogy and texture of the leucocratic gneisses is similar to the deformed quartzo-feldspathic clasts in the Corsewall Point and Glen Afton conglomerates. Clasts of mesocratic and melanocratic gneiss are less common, but hornblende schists are present in the Glen Afton conglomerate.

Because the granitic intrusions in the Long Range contain inclusions of leucocratic gneiss, and in some instances, pelitic schists, they clearly post-date the main metamorphism and deformation, although some contain a weak foliation and show evidence of strain. In the northern part of the Long Range, Bostock et al. (1983) distinguish between megacrystic granites which show signs of deformation, and

massive granites that are unfoliated. In the eastern and southern parts of the of the Long Range, Erdmer (1984) observed a variety of megacrystic granites, only some of which were foliated. Most show a cross-cutting relationship with the gneisses, but others are gradational with it. However, the megacrystic and massive granites follow similar chemical trends (Fig. 5.14, data from Bostock et al., 1983), which supports Erdmer's (1984) conclusion that the granites belong to a number of related but distinct suites, the intrusion of which occured during a period of deformation.

Two of the megacrystic granites, the Portland Creek Pond and Hawkes Bay plutons, have been dated by Rb-Sr whole rock isochron methods (Pringle et al., 1971), and yield ages of 1,081 ± 165 Ma and 1,132 ± 154 Ma (recalculated from the original data using the decay constant for ^{87}Rb of 1.42×10^{-11} y^{-1}), with initial $^{87}Sr/^{87}Sr$ ratios of 0.707 ± 0.005 and 0.706 ± 0.006, and MSWD's of 4.42 and 7.11 respectively. Sm-Nd analyses of four samples from the Portland Creek Pond pluton plot on a straight line (MSWD = 0.08) which yields an age of 1,073 ± 301 Ma. (Sm-Nd isotopic data for the Portland Creek Pond pluton and other Newfoundland granites sampled in this study are presented in Appendix 3.) The large error on the Sm-Nd isochron age is due to the narrow range of $^{147}Sm/^{144}Nd$ ratios in these samples, but because the result is consistent with the Rb-Sr isochron age it is likely that, despite their high MSWD's, the Rb-Sr isochrons represent the ages of intrusion of the Long Range plutons. The ages obtained by this method correspond to a period of deformation in the the Grenville Province (1,100 to 1,000 Ma; Bell, 1981) which accounts for the variably deformed state of the plutons.

The Long Range granites are of a similar age to the muscovite-biotite granites in the Corsewall Point conglomerate (Group A1; 1,265 ± 130 Ma) and the biotite granodiorite clasts in the Glen Afton

conglomerate (Group C2; 1,231 ± 120 Ma). Very large errors are associated with the initial $^{87}Sr/^{86}Sr$ ratios determined from the Long Range granites, but their age and initial ratio error polygons overlap with the error polygons obtained from the Southern Uplands clasts of similar age (Fig. 5.15). Thus, the Long Range plutons and the plutons that supplied the Southern Uplands clasts could have been derived from sources with similar Sr isotopic compositions at c. 1,200 Ma. The isochrons for the Corsewall Point clasts, the Glen Afton clasts and the Long Range granites all have high MSWD's, which indicates isotopic heterogeneity in the Newfoundland plutons and those that supplied the Southern Uplands clasts.

The Long Range plutons range in composition from granodiorite and quartz monzonite to granite sensu-stricto (Bostock et al., 1983). This variation encompasses the different petrographies of the clasts of comparable age that occur in the Corsewall Point and Glen Afton conglomerates. Chemical analyses are available for five plutons from the northern Long Range (Hooping Harbour, Lake Michel, Leg Pond, Cloud River and Fourché Harbour; Bostock et al., 1983), but not for the plutons from which isotopic data were obtained. Most of the intrusions are potassic (Fig. 5.14a) and range from being metaluminous to peraluminous ($\frac{Al_2O_3}{Na_2O+K_2O+CaO}$ from 0.9 to 1.2). These features are similar to those of the Corsewall Point muscovite-biotite granites, which also share some of the petrographic characteristics of the Long Range granites. Both the plutons and the clasts contain microcline, which shows perthitic textures, quartz that that shows some evidence of strain, and limited quartz-feldspar intergrowths. Like the Long Range plutons, some of the Corsewall Point clasts exhibit a weak foliation. The clasts may, therefore, have been derived from plutons that crystallized under similar conditions to the Long Range granites.

However, the Corsewall Point clasts lack alkali feldspar megacrysts which are characteristic of some of the Long Range granites, and contain muscovite, which is absent from the biotite granites of the Long Range. Amongst the accessory minerals, apatite and opaque minerals are more common in the Long Range granites, and zircon in the Corsewall Point clasts.

The mineralogical differences are reflected by chemical differences between the granite intrusions in the Long Range and the Corsewall Point muscovite-biotite granite clasts. The Long Range granites are richer in TiO_2 and P_2O_5, reflecting the different accessory mineral assemblages, but also follow separate trends to the Corsewall Point and Glen Afton clasts on the AFM diagram (Fig. 5.14b). The only exception to this is the Hooping Harbour pluton, which chemically bears the closest resemblance to the Corsewall Point clasts (Figs 5.14a & b).

The Sm-Nd isotope characteristics of the Corsewall Point clasts and the Long Range plutons are also different (Fig. 5.16). The Portland Creek Pond pluton contains Nd that is more radiogenic than that in the Corsewall Point clasts ($\varepsilon_{Nd(0)}$ values from -14.8 to -17.8 for the Portland Creek Pond pluton as compared to c. -22 for the Corsewall Point clasts) and yields younger model ages (Fig. 5.16). The $\varepsilon_{Nd(I)}$ values for the samples from the Portland Creek Pond pluton are c. -2, as compared to c. -8 for the Southern Uplands clasts, which indicates that the Long Range granites contain either a smaller or a younger crustal component. The T_{CHUR} model ages for the Portland Creek Pond pluton vary between 1,217 Ma and 1,280 Ma, which is similar to the age of intrusion of the pluton from which the Corsewall Point clasts were derived (Fig. 5.16). The Sr isotope composition of the Portland Creek Pond pluton would also have been close to bulk earth values at this time (Fig. 5.15). If both plutons were related to magmas derived from the bulk earth reservoir at c. 1,200 Ma, the differences in their Sm-Nd isotopic

characteristics may be related to the amount of older crustal material they contain.

Xenoliths are not reported form the Portland Creek Pond pluton, but quartzose and pelitic xenoliths are common in the Corsewall Point muscovite-biotite granites (section 3.2.a.i), which may, therefore, contain a larger crustal component. Both sets of xenoliths indicate that the pluton which supplied the Corsewall Point clasts was intruded into a terrane similar to the Long Range. The quartzose xenoliths could be the product of partial assimilation of quartz-rich gnesisses, which are a common component of the Long Range basement gneisses and also occur as clasts in the Corsewall Point conglomerate. The pelitic xenoliths contain primary sillimanite (section 3.2.a.i), and could be derived from the sillimanite-bearing pelitic schists that are also present in the Long Range. The massive Cloud River pluton contains such xenoliths (Bostock et al., 1983), but no isotopic data is available from this intrusion. However, zircons from Ordovician tonalites in the Coney Head Complex and the Hungry Mountain Complex, which occur east of the Long Range (Fig. 5.13), yield U-Pb upper intercept zircon ages of $1{,}640^{+300}_{-200}$ Ma (Dunning, 1987) and 2,090 ± 75 Ma (Whalen et al., 1987) respectively. Although the relationship between the crustal component in these magmas and the Grenvillian of the Long Range is unknown, the presence of continental crust in north-west Newfoundland as old as 2,000 Ma is consistent with the Sm-Nd model ages obtained from the Corsewall Point muscovite-biotite granite clasts (T_{CHUR} c. 2,000 Ma, T_{DM} c. 2,200 Ma).

Foliated biotite granite and hornblende-biotite granodiorite clasts the same age or slightly older than the muscovite-biotite granite clasts are also present in the Corsewall Point conglomerate. The Long Range contains some older foliated granodiorites, but these are usually

associated with anorthosites (Bostock et al., 1983), which do not occur as clasts in the Southern Uplands conglomerates. However, the relationship between the time of deformation and the age of intrusion of the granites in the Long Range means that foliated and unfoliated granites of a similar age could be derived from such a source.

Although it is not possible to find a precise match for any of the older clasts from the Corsewall Point conglomerate, its source area contained similar amphibolite facies basement lithologies and experienced deformation and a similar style of magmatism at the same time as the Long Range. Because of these similarities, the source area of the Corsewall Point conglomerate is likely to have been situated close to north-west Newfoundland.

There is no evidence of any further igneous activity in north-west Newfoundland until about 600 Ma (Table 5.2), which corresponds to the age of the hornblende-biotite granite clasts from the Corsewall Point conglomerate. Although the two Newfoundland granites of this age were intruded in separate tectonic settings, they both differ from the Corsewall Point clasts.

The Round Point granite yields a U-Pb zircon age of 602 ± 10 Ma (Williams et al., 1985), similar to the age of 615 ± 10 Ma obtained from a suite of basic dykes intruded into the Grenvillian gneisses of the Long Range (Stukas and Reynolds, 1974). The dykes acted as feeders for basalt flows which occur at the northern end of the Long Range and in Labrador and this igneous activity is related to a Late Precambrain phase of rifting event which established a passive continental margin in this region (Dewey et al., 1983). The Round Point granite occurs with mafic and silic volcanic rocks in an allochthonous thrust sheet emplaced above Ordovician platform carbonates, east of the Humber Arm (Fig. 5.13;

Williams et al., 1985). The granite and the volcanics were deformed by the Ordovician thrusting, and the granite varies from being massive to foliated, becoming schistose adjacent to the basal thrust. The Round Point granite shows features typical of rift-related granites - it is a high level intrusion, has a potassium-rich chemistry and plots in the within-plate granite field on the Rb v. Y+Nb diagram of Pearce et al. (1984). It is therefore unlikely to be the source of the 600 Ma hornblende-biotite granite clasts from the Corsewall Point conglomerate, which show calc-alkali, volcanic arc characteristics. However, it is interesting to note that the Round Point granite is a similar age to the 648 ± 32 Ma deformed alkali granite clasts reported by Ince (1984) from the Kirkland conglomerate of the Midland Valley of Scotland.

The Blue Ridge Mountains of Virginia also formed part of the Laurentian continental margin and contain a greater variety of granite intrusions related to the same Late Precambrian rifting event (Rankin, 1975). Although it is unlikely that the clasts in the Southern Uplands were derived from a source in such a remote part of the continental margin, this area provides an example of the types of pluton that might have developed elsewhere at this time. The Blue Ridge granites were intruded into Grenvillian gneisses between 706 ± 6 Ma and 570 ± 15 Ma (Table 5.3), and differ from the Round Point granite of Newfoundland by pre-dating basic igneous activity - metabasic dykes cut the granites and have a similar composition to basalts that occur unconformably above them (Odom and Fullager, 1984). In addition, the Blue Ridge granites are often unfoliated, although they have been subjected to low grade metamorphism during the Taconic orogeny.

The Blue Ridge granites are the same age as the Glen Afton muscovite-biotite granites (Group C1, 661 ± 35 Ma) and the Corsewall Point hornblende-biotite granites (Group A2, 600 ± 30 Ma). In general, the Blue Ridge granites show a greater degree of mineralogical

TABLE 5.3 A summary of Rb-Sr whole-rock isochron ages and initial $^{87}Sr/^{86}Sr$ ratios obtained from granite intrusions in the Blue Ridge Mountains of Virginia, and clasts of a similar age from the Southern Uplands.

Name of pluton	Rb-Sr whole-rock isochron age	Initial $^{87}Sr/^{86}Sr$ ratio	Source of data
Robertson River pluton	570 ± 15 Ma	0.7121 ± 0.0004	Mose and Nagal (1984)
Rockfish River pluton	646 ± 55 Ma	0.7172 ± 0.0035	Mose and Nagal (1984)
Crossnore granite	646 ± 9 Ma	0.7134 ± 0.0004	Odom and Fullagar (1984)
Mobley Mountain granite	652 ± 22 Ma	0.7045 ± 0.0005	Herz and Force (1984)
Striped Rock granite	681 ± 5 Ma	0.7081 ± 0.0009	Odom and Fullagar (1984)
Lansing granite	699 ± 5 Ma	0.7128 ± 0.0017	Odom and Fullagar (1984)
Beech granite	706 ± 6 Ma	0.7070 ± 0.0007	Odom and Fullagar (1984)
Corsewall Point hornblende-biotite granite	600 ± 30 Ma	0.7059 ± 0.0003	This study
	603 ± 40 Ma	0.7068 ± 0.0004	This study
Glen Afton muscovite-biotite granite	661 ± 35 Ma	0.7069 ± 0.0006	This study

similarity to the Southern Uplands clasts, although they usually have higher initial $^{87}Sr/^{86}Sr$ ratios (Table 5.3). A notable exception is the Mobley Mountain granite which has a similar age and a slightly lower initial $^{87}Sr/^{86}Sr$ ratio than the Glen Afton muscovite-biotite granites. Like the Glen Afton clasts, the Mobley Mountain granite is a biotite granite that also contains secondary muscovite and clinozoisite (Herz and Force, 1984).

Little chemical data is available from the Blue Ridge granites, but their mineralogy suggests that they may be less alkalic than the Round Point granite, and although some contain sodium-rich hornblendes, typical of alkaline granites (Bartholemew and Lewis, 1984), others have calc-alkaline affinities (J.D. Bell, personal communication). Some granites intruded into attenuated continental crust belong to calc-alakali suites, and contain calcic, rather than sodic amphiboles (Pearce et al., 1984), but it is difficult to reconcile the volcanic arc affinities of the Corsewall Point hornblende-biotite granite clasts with derivation from a rift-related setting. The Glen Afton muscovite-biotite granites have a more alkali-rich chemistry, but like the Corsewall Point clasts, trace element characteristics that show volcanic arc affinities (section 3.3.c).

Because late Precambrian rifting established a passive margin from the Grampian Highlands to the southern Appalachians, a source of 600 Ma subduction-related granite clasts is unlikely to be found within the Laurentian continent. However, a trondhjemite from the Mansfield Cove Complex of north-western Newfoundland yields a $^{207}Pb/^{206}Pb$ zircon age of 594 ± 10 Ma (Bostock et al., 1979). It is associated with the Lushs Bight island arc, part of a more extensive volcanic arc which formed above a south-easterly directed subduction zone within the Iapetus Ocean (McKerrow, 1987; see Fig. 5.17), and was accreted to Laurentia following collision with different parts of the continental margin at various

times during the Ordovician. Although the 600 Ma hornblende-biotite granite clasts in the Corsewall Point conglomerate are more likely to be derived from part of this arc, a suitable source does not occur in north-west Newfoundland. The Lushs Bight volcanic arc was entirely oceanic, and the granitic intrusions associated with it, such as the Mansfield Cove complex, are low-potassium trondhjemites, formed by the partial melting of basic igneous rocks (Malpas, 1979). The Corsewall Point hornblende-biotite granites have chemical and isotopic characteristics which indicate that they contain a considerable crustal component, and consequently, they must have been derived from an arc founded on continental crust.

Further west, a remnant of the volcanic arc is preserved in the Bronson Hill anticlinorium of New England. This part of the arc was built on continental crust (Robinson and Hall, 1980; Hall and Robinson, 1982), and although it was extensively deformed during the Devonian Acadian orogeny, granitic intrusions have been recognized in the gneissic basement which may have formed at 603 ± 78 Ma (Hills and Dasch, 1972). However, the Bronson Hill volcanic arc is also unlikely to be the source of the Southern Uplands clasts as it was not accreted to the Laurentian margin until the D. clingani zone (Fig. 5.17).

The palaeogeographic considerations outlined above also suggest that the 550 Ma biotite granite clasts from the Benan conglomerate in the Midland Valley were derived from an arc related to southerly directed subduction. As they have mature arc charctreistics the segment of the arc from which they were derived may also have been founded on continental crust. It has already been shown that the clasts in the Corsewall Point conglomerate were derived from a separate source area to those in the Benan conglomerate, but it is possible that the Corsewall Point clasts were derived from the westerly continuation of this arc. The source of the Glen Afton muscovite-biotite granite clasts remains

problematic, as there is no evidence of subduction as old as 660 Ma. As the error on this age determination overlaps with the error on the age of the Corsewall Point hornblende-biotite granites, it is possible that the clasts in the two conglomerates were derived from similar sources. Alternatively, the Glen Afton clasts may be derived from a source more similar to the Blue Ridge granites.

The Lushs Bight volcanic arc contains other trondhjemites younger than the Mansfield Cove complex (Fig. 5.13). The Twillingate granite yields a U-Pb zircon age of 510 ± 17 Ma (Williams et al., 1976), and the Little Port and Coney Head complexes, which form allochthonous fragments thrust onto the continental margin following the collision of the Lushs Bight volcanic arc (Williams, 1979), contain trondhjemites which yield U-Pb zircon ages of 508 ± 5 Ma (Mattinson, 1975) and 474 ± 2 Ma (Dunning, 1987) respectively. The trondhjemites are intruded into deformed amphoibolite facies metabasalts, and were probably generated by partial melting of amphibolites at the base of the volcanic arc (Malpas, 1979; Payne and Strong, 1979). A Sm-Nd T_{DM} model age of 561 ± 60 Ma (Fig. 5.16) obtained from a single sample of the Twillingate granite (Appendix 3) indicates that the magma was derived from a source with depleted mantle characteristics, which supports this hypothesis. More recently, Casey and Dewey (1984) have suggested that the Little Port complex formed by partial melting in an oceanic transform.

Other ophiolitic thrust sheets in western Newfoundland, also emplaced during the collision of the Lushes Bight volcanic arc, represent remnants of oceanic crust (Williams and Malpas, 1972). A plagiogranite in the Bay of Islands allochton has a similar U-Pb zircon age to the Little Port complex and the Twillingate granite (504 ± 10 Ma, Mattinson, 1976), but differs from them in that it is undeformed and is associated with gabbro rather than basalt. Because the gabbro yields Sm-Nd mineral isochrons with similar ages to the plagiogranite (508 ± 16

Ma and 501 ± 13 Ma; Jacobsen and Wasserberg, 1979), it is interpreted as the product of fractional crystallization of a basaltic magma within oceanic crust (Malpas, 1979).

The Newfoundland plagiogranites and trondhjemites have similar major element characteristics to the plagiogranite and trondhjemite clasts from the Southern Uplands (Figs. 5.18 to 5.20). They all follow a more K_2O-poor trend than that defined by the southwest Finland trondhjemites (Barker and Arth, 1976; Fig. 5.18a) and show evolved compositions on the AFM plot (Fig. 5.18b). In addition, the trondhjemite clasts from the Southern Uplands and the Twillingate and Little Port complex trondhjemites straddle the fields of oceanic and continental trondhjemites defined by Coleman and Peterman (1975) on a plot of K_2O v. SiO_2 (Fig. 5.19). The plagiogranite clasts, however, are generally more SiO_2-rich, and poorer in CaO than the Bay of Islands plagiogranite (Figs. 5.18a and 5.19). The Newfoundland plagiogranites are most easily distinguished from the trondhjemites by their higher concentrations of Ba, Zr and Y (Malpas, 1979). This forms the basis of the Rb v. Y+Nb tectonic discrimination diagram of Pearce et al. (1984), and results from the differing roles of fractional crystallization and partial melting in their petrogenesis (Malpas, 1979). This distinction also applies to the Southern Uplands clasts (Fig 5.20), which indicates that they may have been formed by similar processes.

The mineralogy of the Southern Uplands clasts and the Bay of Islands plagiogranite, the Little Port complex and the Twillingate granite are all typical of trondhjemitic rocks in general. They consist mainly of quartz and sodic plagioclase, with minor amounts of chloritized hornblende and biotite, and in the case of the Twillingate granite, some potassium feldspar. The Southern Uplands clasts differ in containing more abundant biotite and little hornblende, and although the Little Port complex and Twillingate trondhjemites are deformed, the

Southern Uplands clasts show no evidence of strain. In the case of the Corsewall Point clast, this may related to the depth of intrusion of the pluton from which the clast was derived - the Corsewall Point trondhjemite shows evidence of fractionation at low pressure (section 3.2.a.iv), whilst the deformation of the Twillingate granite is attributed to its intrusion at depth, at the base of a volcanic arc (Payne and Strong, 1979).

Although none of the Southern Uplands plagiogranites or trondhjemites yielded Rb-Sr whole-rock isochron ages, a single trondjemite clast from the Corsewall Point conglomerate yielded a Rb-Sr mineral isochron with an age of 463 ± 62 Ma (Longman, 1980). The large error associated with the isochron is a result of low Rb concentrations typical of trondhjemites, but the error overlaps with the range of ages shown by Newfoundland trondhjemites. Plagiogranites and trondhjemites with similar characteristics and of a similar age occur as intrusions in north-west Newfoundland and as clasts in the Southern Uplands conglomerates.

The timing of the collision of the Lushs Bight volcanic arc with the Laurentian continental margin can be deduced from the age of metamorphic soles developed during the obduction of ophiolites in western Newfoundland - 480 ± 5 Ma in the case of the Hare Bay allochthon (Dallmeyer, 1977) and 469 ± 5 Ma for the Bay of Islands allochthon (Dallmeyer and Williams, 1975). However, thrusting continued until the N. gracilis zone (Bird and Dewey, 1971; c. 455 Ma, McKerrow et al., 1985). The Burlington granodiorite and the Dunamagon granite (Fig. 5.13) were intruded at about 460 Ma (Dallmeyer and Hibbard, 1984), and as the Dunamagon granite straddles the boundary between the Lushs Bight terrane and the meta-sediments of the Mings Bight Group (Hibbard, 1982), it is likely that their intrusion post-dates the arc-continent collision. Thus, continental crust was available when the magmas were

generated, which accounts for the more potassium-rich nature of these granites, compared to the early Ordovician island arc trondhjemites. Other granites related to the collisional event are the Loon Pond and Sunday Cove plutons (Fig. 5.13) which are petrographically similar to the Burlington granodiorite. The Sunday Cove pluton yields a Rb-Sr whole-rock isochron age of 464 ± 26 Ma (Bostock et al., 1979).

The Burlington granodiorite shows a wider range of compositions than any of the groups of granite clasts from the Southern Uplands (Fig. 5.21). It consists of a number of separately intruded phases (Epstein, 1983) which range from quartz diorite and granodiorite to quartz monzonite and granite (Hibbard, 1983). Hornblende is the most common mafic mineral in the earlier, more basic phases, but later, quartz-rich phases are biotite-bearing and include garnet- and muscovite- bearing varieties (Epstein, 1983). Mafic inclusions are common throughout the pluton. Numerous attempts at dating the Burlington granodiorite have produced a variety of results, many of which are subject to large errors (see Hibbard, 1983, for a summary). More recently, a Rb-Sr whole-rock isochron age of 494 ± 34 Ma, a U-Pb zircon age of 461 ± 15 Ma and a $^{40}Ar/^{39}Ar$ hornblende age of 463 ± 5 Ma have been obtained (Hibbard, 1983). The argon age on hornblende is a cooling age, and its coincidence with the U-Pb zircon age led Dallmeyer and Hibbard (1984) to conclude that the pluton was intruded and rapidly cooled at about 460 Ma, an age which is within the error of that obtained from the Rb-Sr whole-rock isochron.

The Rb-Sr whole-rock isochron age of the Burlington granodiorite is similar to those obtained from the biotite granite clasts in the Corsewall Point conglomerate (Group A4, 475 ± 20 Ma) and the hornblende-biotite granite clasts in the Glen Afton conglomerate (Group C3, 491 ± 14 Ma). In addition, the Corsewall Point clasts are strikingly similar, both mineralogically and chemically, to the Burlington

granodioirite. Both have similar volcanic arc characteristics (Figs. 5.20 and 5.21) and contain mafic inclusions which suggest that they are derived from similar basic sources. The Corsewall Point clasts are biotite-bearing, like the more evolved phases of the Burlington granodiorite, with which they correspond chemically (Fig. 5.21). One of the clasts in the Corsewall Point isochron suite is a garnet- and muscovite-bearing variety (section 3.2.a.iv), similar to the garnet- and muscovite-bearing phase of the Burlington granodioirite. Four ananlyses of the garnet-muscovite granite from the Burlington granodiorite (Epstein, 1983) plot in or close to the field defined by the Corsewall Point biotite granites on the Na_2O-K_2O-CaO diagram (Fig. 5.21a) and at the end of the trend defined by these clasts on the AFM diagram (Fig. 5.21b). The garnet- and muscovite-bearing granite clast from Corsewall Point also lies at the end of this trend.

The initial $^{87}Sr/^{86}Sr$ ratio of Burlington granodiorite obtained from the Rb-Sr whole-rock isochron is lower than that of the Corsewall Point clasts (Fig. 5.15). As it is not clear from which phase of the Burlington granodioirite the samples that comprise the isochron suite were collected, it is possible that the differences may be due to comparing rocks of different composition. However, the initial $^{87}Sr/^{86}Sr$ ratio of the Sunday Cove pluton, which is of a similar age and composition, has a higher initial ratio than the Corsewall Point clasts (Fig. 5.15), which shows that magmas with a range of initial ratios similar to the Corsewall Point biotite granites were available in this area at c. 460 Ma. The Sm-Nd characteristics of a single sample of the hornblende-bearing phase of the Burlington granodiorite also differ from the garnet- and muscovite-bearing biotite granite clast from Corsewall Point (Fig. 5.16). The Burlington granodiorite sample has an $\varepsilon_{Nd(I)}$ value close to 0, whilst that of the Corsewall Point clast is -4. Because the Burlington granodiorite also has a lower initial $^{87}Sr/^{86}Sr$

ratio than the Corsewall Point biotite granites, the differences may indicate that the clasts, which correspond to the more evolved parts of the pluton, contain a larger crustal component. However, it is clear that the Corsewall Point biotite granites were derived from a source very similar to the Burlington granodiorite.

5.3 Palaeogeographic and tectonic considerations.

Granite intrusions of a similar age to the clasts that occur in the Corsewall Point conglomerate are present in north-west Newfoundalnd, but the detailed chemical and mineralogical characteristics of the clasts are not always consistent with derivation from this part of the Laurentian margin. The greatest discrepancy concerns the 600 Ma hornblende-biotite granite clasts which show mature volcanic arc affinities and have Sm-Nd characteristics which indicate that they were derived from a pluton intruded into older continental crust. The only subduction-related granites of this age presently exposed in Newfoundland form part of the Lushs Bight volcanic arc, which was built on oceanic crust. Consequently, it is not possible to identify the source area in the presently exposed landmass. Consideration of the distribution of 600 Ma subduction-related granites suggests that the Corsewall Point clasts were most likely to have been derived from a continuation of the arc terrane which supplied the Benan conglomerate, and hence that the source area was situated between Newfoundland and the Midland Valley. However, the Corsewall Point conglomerate also contains granitic detritus which has much more in common with Newfoundland than the source of the Benan conglomerate, and so it is probable that the source area was much closer to Newfoundland than the displaced Midland Valley during the *N. gracilis* zone.

The sedimentary history of north-western Newfoundland also indicates that the source area of the Corsewall Point conglomerate is unlikely to be found in the presently exposed part of the continental margin. Boulders derived from the Grenville terrane occur in the Early Cambrian conglomerates of the Irishtown Formation (James and Stevens, 1982), but the subsequent development of extensive shelf carbonates in north-west Newfoundland indicates that little terrigenous sediment was available during the Lower Ordovician. Emplacement of ophiolites during the Middle Ordovician involved the deposition of turbidites from the westerly advancing nappes, and although displacements continued into the N. gracilis zone, they mainly involved carbonate sediments, and are unlikely to have exposed Grenvillian basement. The Long Range mountains were emplaced above Cambrian and Ordovician carbonates by movements on the Long Range thrust, but this is most likely to be related to Acadian events (Dewey et al., 1983).

Conglomerates containing basic and acidic plutonic, volcanic and chert clasts, similar to the clast assemblages of the Southern Uplands conglomerates, occur throughout the Notre Dame Bay region of Newfoundland, immediately to the south of the Lushs Bight island arc terrane (Arnott et al., 1985). The conglomerates were deposited in a number of separate fault-bounded basins, and because deposition in each basin was dependent upon localized uplift associated with movements on boundary faults (Arnott, 1983), the conglomerates are of variable age. However, the N. gracilis zone, when is when the Corsewall Point conglomerate was deposited, was dominated by the deposition of organic-rich siltstones in the Notre Dame Bay region, and the oldest conglomerates are of D. clingani and P. linearis zone age (Arnott et al., 1985). Older conglomerates occur in the Dunnage mélange, which may range in age from Tremadoc to Llanvirn (Arnott et al., 1985). Horizons of polymict conglomerate within the mélange contain foliated and

unfoliated granite clasts (Kay, 1976), which indicates that a source similar to that which supplied the Corsewall Point clasts may have been present in north-west Newfoundland. The uplifted and dissected arc which supplied the Upper Caradoc and Ashgill age conglomerates lay to the north-east of Notre Dame Bay (Arnott et al., 1985). If uplift of a similar arc took place slightly earlier further to the east, the Corsewall Point conglomerate could have been derived from such an area.

Uplift of the volcanic arc is likely to be related to its collision with the continental margin. The coarse clastic sediments in the Southern Uplands were deposited in a subduction trench, but north-westerly directed subduction was not developed until after the collision of the volcanic arc. Thus, the timing of arc-continent collisions on the Laurentian margin provides a further important constraint on the location of the conglomerate source areas. The Southern Uplands are unlikely to be derived from anywhere further to the west of Newfoundland, as the Bronson Hill volcanic arc did not finally collide with New England until the D. clingani zone (McKerrow, 1983). Although the obduction of ophiolites in Newfoundland began in the Arenig (Dallmeyer, 1977), north-westerly directed thrusting continued until the N. gracilis zone (Bird and Dewey, 1971). Thus, it is unlikely that north-westerly directed subduction was established in Newfoundland by the time the Southern Uplands began to form. Collision of the volcanic arc probably took place earlier to the east, occurring during the Tremadoc in Scotland (McKerrow, 1987). Given a diachronous trend of arc-continent collisions from east to west, it is likely that the source of the Corsewall Point conglomerate lay to the east of Newfoundland.

The source area of the Glen Afton conglomerate has an igneous history similar to the source area of the Corsewall Point conglomerate, but petrographic and chemical differences between clasts of a similar age in the two deposits indicate that their source areas were distinct.

A similar range of granite types, including plagiogranites and trondhjemites, is present in both conglomerates, and, with the exception of late Precambrian subduction-related granites, is exposed in northwest Newfoundland. Clasts of quartz-rich gneiss in both conglomerates indicate that the two source areas contained similar crust, which might be related to the Long Range, but otherwise, the granite clasts in the Glen Afton conglomerate have fewer features in common with the granite intusions of Newfoundland. The precise source for the 661 ± 35 Ma muscovite-biotite granites is more difficult to determine, but because the errors on the age determination overlap with the errors on the age of the Corsewall Point hornblende-biotite granites, and because their Sm-Nd isotopic compositions indicate that they contain a similar crustal component, the Glen Afton clasts may be derived from a similar mature arc source to that which supplied the Corsewall Point conglomerate. The source area of the Glen Afton conglomerate was probably further from, rather than closer to, Newfoundland, but because the differences between the detritus in the Girvan and Corsewall Point conglomerates also apply the Glen Afton conglomerate, it is unlikely to have been as far east as the Midland Valley.

The Shinnel Formation conglomerate contains reworked granite clasts in addition to granophyric granites that do not occur in any of the older deposits. These clasts have similar major and trace element chemistries and similar Sm-Nd isotope characteristics to the 458 ± 26 Ma perthitic biotite granite clasts in the Pinstane Hill conglomerate. Consequently, it is likely that closely related sources supplied both conglomerates. These clasts are similar to the perthitic and granophyric granite clasts of a similar age that occur in the Girvan conglomerates, although they do not have such high Rb/Sr ratios. Also, plagiogranite clasts are absent from the Shinnel Formation and Pinsatne Hill conglomerates, a feature that distinguishes the Girvan

conglomerates from the Corsewall Point and Glen Afton conglomerates. Similar trondhjemite clasts occur in the Shinnel Formation, the Pinstane Hill and the Girvan conglomerates, but the Craigskelly conglomerate, which has a similar depositional age to the Pinstane Hill conglomerate, also contains 600 Ma mature volcanic arc clasts (Table 5.1) that are not present at Pinstane Hill. Thus, by the Ashgill and during the Llandovery, the Southern Uplands were being supplied by a source similar, but not identical, to that which existed in the Midland Valley, implying a further eastward shift in the location of the source area.

Chapter 6

CHAPTER 6

CONCLUSIONS

6.1 Introduction.

There are three assumptions on which this thesis is based:-

1) That groups of cogenetic granite clasts can be recognized and used to determine Rb-Sr whole-rock isochrons which record the ages of intrusion of the plutons from which the clasts were derived.
2) That the clasts in the Southern Uplands conglomerates were derived from source areas that lay immediately to the north-west, and that the age of the granite clasts can be used to locate these source areas.
3) That differences in the age and nature of the detritus between conglomerates result from changes in the location of the source areas that supplied the Southern Uplands. This imples that the site of deposition of the conglomerates also changed.

The samples which comprise each group of granite clasts generally show little petrographic or compositional variation, have distinct Sm-Nd isotopic characteristics and define Rb-Sr whole-rock isochrons which, in most cases, have low MSWD's. Thus, the assumption that the granite clasts in each group are cogenetic is likely to be valid. Where mineral isochrons are also available, they do not contradict the results obtained from whole-rock isochrons, which probably therefore record the age of intrusion of the plutons that supplied the clasts. The compositional variation shown by the groups of granite clasts is small in comparison to that shown by plutons from the Laurentian margin (compare Figs. 3.6 to 3.20 with Figs. 5.14 and 5.17 to 5.20). Although this may partly result from the method of classification used in this study, the different groups of granite clasts are unrelated, which

suggests that they were derived from small homogeneous parts of separate plutons.

The second and third assumptions are more difficult to verify, as they depend upon a knowledge of the drainage patterns at the Laurentian continental margin, which are not preserved. However, the conglomerates were deposited at an active continental margin, and by analogy with modern active margins, there was likely to have been significant relief. Small rivers with steep gradients and small drainage areas would therefore have been common, and such rivers could have transported clasts of the size seen in the Southern Uplands conglomerates. Larger rivers may have transported detritus over longer distances, but their loads would have consisted mainly of sand and silt grade material. The fact that the granite clasts can be divided into a relatively small number of groups with distinct characteristics also suggests that they were derived from a relatively small area, and that they have not been transported far.

Although the original drainage patterns are not preserved, the succession of conglomerates that occur in the Midland Valley, south of Girvan, contain detritus derived from a single source area that was being eroded at the same time as the Southern Uplands conglomerates were deposited. Although the Midland Valley conglomerates were deposited over a period of 25 to 30 Ma, from the Llandeilo to the Lower Llandovery, similar types of granite clasts occur throughout the succession (Table 5.1). The continued erosion of their source area, and any changes in drainage patterns that might have occurred during this period, appear to have had little effect on the detritus that was supplied. If similar erosional processes operated elsewhere on the Laurentian margin, the differences between the detritus in the Southern Uplands conglomerates are unlikely to result from the evolution of a

single source area. It is more probable that they reflect changes in the location of the source areas adjacent to the Southern Uplands.

6.2 The northern boundary of the Southern Uplands.

The Corsewall Point conglomerate, at the northern end of the Rhinns of Galloway, and the Benan conglomerates, at the southern margin of the Midland Valley, were both deposited during the N. gracilis zone, but contain distinct suites of granite clasts which indicates that they were supplied by separate source areas. There is some similarity between the age of the granite clasts in the Corsewall Point and Glen Afton conglomerates, and a clast identical to the Corsewall Point muscovite-biotite granites occurs in the Shinnel Formation conglomerate. Thus, the Corsewall Point conglomerate contains detritus that has more in common with that in the other Southern Uplands conglomerates than with the detritus derived from the Midland Valley. The Corsewall Point-Glen App tract therefore forms part of the Southern Uplands, and should be included in Tract 1, along with the rocks of a similar age in W. Nithsdale and at Noblehouse (Leggett et al., 1979).

Because the clasts in the Corsewall Point conglomerate were not derived from the Midland Valley, the Southern Uplands and the Midland Valley must have been separate during the Ordovician, and strike-slip displacements must have taken place on the Southern Upland Fault, which forms the boundary between the two terranes. In order that the Corsewall Point-Glen App tract be included in the Southern Uplands, the Southern Upland Fault must pass north of Corsewall Point, and it therefore follows the line of the Stinchar Fault in south-west Scotland, rather than the Glen App Fault and its continuation on the Rhinns of Galloway, which has traditionally been regarded as the continuation of

the Southern Upland Fault (Peach and Horne, 1899; Kelling, 1961; see Fig. 2.2).

6.3 The Southern Uplands as an accretionary complex.

The accretionary prism model for the origin of the Southern Uplands (McKerrow et al., 1977; Leggett et al., 1979) has recently been questioned, and a number of other models proposed which suggest that the Southern Uplands formed in a variety of different tectonic settings (Murphy and Hutton, 1986; Rock et al., 1986; Barnes et al., 1986; Stone et al., 1987; Morris, 1987). The debate is at present unresolved (Kemp et al., 1986; Leggett, 1987; Elders and Kemp, 1987), but centres around the significance of a source of basic igneous detritus that lay to the south of the Southern Uplands during the Ordovician. When considered in conjunction with the source of the north-westerly derived granite boulders, it is possible to show that the southerly source of the basic detritus is not inconsistent with the accretionary origin of the Southern Uplands, and such a model is presented below. There are two further aspects of the nature and provenance of the granite clasts which have a bearing on the origin of the Southern Uplands.

The tectonic setting in which the Southern Uplands formed can be deduced from the nature of the granite clasts that occur in the Southern Uplands conglomerates. The trondhjemite clasts have characteristics which suggests that they were derived from plutons associated with oceanic island arcs. As the clasts were derived from the north-west, the islands arcs must have been accreted to the continental margin prior to the depsoition of the Southern Uplands sediments. Likewise, the presence of plagiogranite clasts in the Corsewall Point, Glen App and Glen Afton conglomerates indicates that their source areas contained ophiolitic components that were obducted before the deposition of Tracts

1 and 2. The presence of both types of clast in the Southern Uplands conglomerates suggests that they were deposited oceanwards of the continental margin. Acidic volcanic detritus and Early to Middle Ordovician age granites (ages in the range 491 ± 14 Ma to 458 ± 26 Ma) with calc-alkali characteristics are present in the Corsewall Point, Glen Afton and Pinstane Hill conglomerates. This implies that a volcanic arc related to north-westerly directed subduction was established on the Laurentian margin, and as the Southern Uplands clasts were derived from the north-west, the sediments must have been deposited in a fore-arc setting, rather than the back arc setting suggested by some authors (Stone et al., 1987; Morris, 1987).

Within the Southern Uplands, the Shinnel Formation conglomerate (Tract 3d) contains a clast identical to the muscovite-biotite granite clasts in the the Corsewall Point conglomerate (Tract 1). The intervening Glen Afton conglomerate (Tract 2b) does not contain any such clasts, and was derived from a separate source area to that which supplied the Corsewall Point conglomerate. Consequently, the clast in the Shinnel Formation conglomerate is most likely to have been derived by the reworking of an older conglomerate. This in turn implies that the Corsewall Point conglomerate, or some related deposit, had been uplifted by the time the Shinnel Formation conglomerate was deposited. In accretionary complexes, underthrusting of newly accreted sediment packets causes the the uplift of previously accreted tracts during and prior to the deposition of younger sediments. The relief that results from the uplift of older tracts may cause ponding of sediments derived from the continental margin, and continued uplift may result in emergence of the trench-slope break. In the Southern Uplands, the upward decline in the abundance of extrabasinal clasts in the Glen Afton conglomerate (Fig. 2.7) indicates that the supply of sediment from the continental margin was cut off, which may be related to the uplift of

earlier accreted tracts during the D. clingani zone. The reworking of clasts in the Shinnel Formation conglomerate indicates that the trench-slope break was emergent by the P. linearis zone, and as the emergent trench-slope break may also have been a site of limestone deposition, it could be the source of the abundant limestone clasts in the Shinnel Foramtion conglomerate. The evidence of sediment reworking and of synchronous uplift and sedimentation during the formation of the Northern Belt is consistent with the operation of accretionary processes.

The main body of evidence in favour of an accretionary origin for the Southern Uplands is discussed elsewhere (Leggett et al., 1979; Kemp et al., 1986, Leggett, 1979). The evidence that arises from the provenance studies of north-westerly derived granite clasts is consistent with this model, and an accretionary origin for the Southern Uplands is assumed in the subsequent discussion.

6.4 The role of strike-slip displacements in the development of the Southern Uplands accretionary complex.

North-westerly directed subduction was established at the Laurentian continental margin during the Ordovician, following the collision of an island arc associated with southerly directed subduction (McKerrow, 1987). The oldest preserved sediments that were deposited in the subduction trench include the Corsewall Point and Glen App conglomerates which are of N. gracilis zone age. It has been shown that the source area for these conglomerates was probably located close to north-west Newfoundland (Fig. 6.1a), which implies that they were deposited south-east of this area and that the oldest tracts in the Southern Uplands were accreted to this part of the continental margin. On a pre-drift reconstruction of the North Atlantic, Corsewall Point

occurs about 1,500 km. to the east of this position (Fig. 5.12), and the Southern Uplands must have been affected by sinistral strike-slip displacements of this magnitude, relative to Laurentia, since the N. gracilis zone.

Where the strike-slip displacement of an accretionary complex is related to oblique subduction of the oceanic plate, lateral movements occur during the formation of the complex (Jarrard, 1986). In the Southern Uplands, differences in the detritus contained in conglomerates of different ages suggest that some lateral displacement took place at the same time as accretion, but not necessarily at a constant rate. The differences in the characteristics of the granite clasts in the Corsewall Point and Glen Afton conglomerates, and differences between the other components of the detritus they contain, indicate that the two conglomerates were supplied by separate source areas. However, the granite clasts are of a similar age in both deposits, and their source areas must have been sufficiently close to one another for them to have had similar igneous histories. The strike-slip displacements that occurred in the 5 to 10 Ma between the deposition of the Corsewall Point conglomerate (N. gracils zone) and Glen Afton conglomerate (D. clingani zone) are therefore likely to have been on a relatively small scale (Figs. 6.1a and 6.1b).

Most of the granite clasts in the Shinnel Formation conglomerate (P. linearis zone) are unlike any of the clasts that occur in the Corsewall Point, Glen App or Glen Afton conglomerates, but others are reworked from these older deposits. In addition, although the Shinnel Formation conglomerate was derived from the north-west, the greywackes associated with it are devoid of ferromagnesian minerals, a common component of laterally-derived greywackes associated with other conglomerates. The differences in both the nature of the granite clasts and the petrography of the greywackes indicates that a source area with

significantly different characteristics supplied detritus to the Shinnel Formation, and that significant strike-slip displacements took place following the deposition of the Glen Afton conglomerate. However, the presence of reworked detritus in the Shinnel Formation conglomerate shows that it was deposited in a trench adjacent to the older parts of the accretionary complex. As some of the detritus can be precisely matched with clasts that are present in the Corsewall Point conglomerate, major strike-slip displacements are unlikely to have taken place on the tract-bounding faults within the Northern Belt. Large scale strike-slip displacements must have affected the whole accretionary complex, transporting it as a "fore-arc sliver" (Jarrard, 1986) by movements on the Southern Upland fault.

Although there are much greater differences between the detritus in the Shinnel Formation and Glen Afton conglomerates than between the detritus in the Glen Afton and Corsewall Point conglomerates, they are separated by a much shorter period of time - just one graptolite zone, or about 3 Ma. Thus, the rate of strike-slip displacement was probably greater between the *D. clingani* and *P. linearis* zones than between the *N. gracilis* and *D. clingani* zones (Fig. 6.1c).

To the south-west, in the Rhinns of Galloway, sediments of a similar age and in a similar structural position to the Shinnel Formation - within Tract 3 and immediately to the north of the Orlock Bridge-Kingledores fault (Fig. 1.3) - contain basic detritus derived from a southerly source. This basic igneous source must have been situated on the Iapetus oceanic plate, and is therfore likely to have been a volcanic edifice, such as a seamount. Further south-west, in Ireland, similar detritus is present in older deposits, which implies that the source of basic igneous detritus migrated from this direction (Kelling *et al.*, 1987), possibly as a result of oblique subduction of the oceanic plate (Figs. 6.1a to 6.1c). The basic igneous source is no

longer preserved, but there is a gap of about 8 Ma, corresponding to most of the Ashgill and the earliest Llandovery, between the deposition of the youngest sediments in Tract 3, containin southerly derived basic detritus, and the oldest sediments in the Central Belt (Tract 4) which occur to the south of the Orlock Bridge-Kingledores fault and contain basic detritus derived from the north-west. Although tracts accreted during this period may have been removed by later strike-slip displacements, a hiatus in the accretion of sediment packets may have occurred at this time (Anderson and Oliver, 1986).

Tract 4 includes the Pinstane Hill conglomerate, which contains granite clasts very similar to the new component of the granitic detritus in the Shinnel Formation conglomerate (Tract 3). This suggests that closely related source areas supplied both conglomerates and that Tract 4 was accreted to the same part of the continental margin as Tract 3 (Fig. 6.1e). However, the greywackes associated with the Pinstane Hill conglomerate, and other north-westerly derived greywackes in Tract 4, are rich in basic igneous detritus, which is in marked contrast to the quartz-rich composition of the Shinnel Formation greywackes. In order to account for the addition of a basic igneous component to the source area that supplied the Shinnel Formation conglomerate, the volcanic edifice that lay to the south of the Southern Uplands during the P. linearis zone may have been accreted to the continental margin during the hiatus in sediment accretion in the later part of the Ashgill (Fig. 6.1d). However, there is no remnant of the volcanic edifice along the Orlock Bridge-Kingledores fault, and there is no deformation in the Northern Belt that might be related to the accretion of such a body during the Ashgill. It is therefore unlikely that the Northern Belt remained south-east of the source area of the Shinnel Formation conglomerate during the accretion of the volcanic edifice to the continental margin. The increased rate of strike-slip displacement

which affected the Northern Belt at the time of deposition of the Shinnel Formation conglomerate is likely to have continued during the Ashgill, and would have removed the Northern Belt from the area where the volcanic edifice was accreted (Fig. 6.1d). Sedimentation resumed in the subduction trench by the early Llandovery, south-east of the newly accreted volcanic edifice (Fig. 6.1e). The sediments which comprise the Central and Southern belts were accreted to this part of the continental margin, indepenently of the Northern Belt.

Subduction-accretion continued in the Southern Uplands until the late Wenlock (C. lundgreni zone), but there are no conglomerates younger than the Pinstane Hill conglomerate that contain granite clasts which can be used to illustrate the magnitude of post-Llandovery strike-slip displacements. However, the presence of transecting cleavage in the Central and Southern Belts provides evidence of continued sinistral transpression during the development of the rest of the accretionary complex (Anderson, 1987; Kemp, 1985, Stringer and Treagus, 1981). Thus, strike-slip displacements are likely to have continued and would have transported the Central and Southern Belts as a separate "fore-arc sliver" by movements on the Orlock Bridge-Kingledores fault. This is a major sinistral strike-slip fault and displacements on it eventually juxtaposed the Central and Northern belts (Anderson and Oliver, 1986).

Evidence from Silurian conglomerates in the south of the Midland Valley also shows that the Southern Uplands was not in its present position during the Wenlock. The Igneous and Quartzite conglomerates are of early and middle Wenlock age respectively, and both are derived from the south-east, the region now occupied by the Southern Uplands. As their names suggest, these conglomerates contain clasts that were not derived from an accretionary complex, which implies that a different terrane lay to the south-east (Bluck, 1983). The Greywacke conglomerate, which occurs higher in the same sequence, close to the

Silurian-Devonian boundary, contains clasts which may be derived from the Southern Uplands, but this is not proven (Bluck, 1983). Strike-slip displacemnts must have continued to affect the Southern Uplands after accretion had ceased in the late Wenlock.

The time at which the Southern Uplands finally docked with the Midland Valley is more difficult to determine. The oldest sediments that appear to straddle the Southern Upland fault are of Lower Carboniferous age, but they form only a small outcrop, south-east of New Cumnock (B.G.S. sheet 15, Scotland). Preliminary structural investigations indicate that displacements on the Southern Upland fault continued into the Early Devonian (Oliver, 1986). Sinistral movements on the Orlock Bridge-Kingledores fault pre-date the intrusion of igneous dykes towards the end of the Early Devonian, at c. 400 Ma (Anderson and Oliver, 1986), and Old Red Sandstone sediments, which may be of Lower Devonian age (Rock and Rundle, 1986), straddle the Orlock Bridge-Kingledores fault at its eastern end (Anderson and Oliver, 1986).

Thus it is likely that strike-slip displacements which began in the Caradoc continued to affect the Southern Uplands until the end of the Early Devonian, a period of about 63 Ma, using the time-scale of McKerrow et al. (1985), or 71 Ma, using the time-scale of Harland et al. (1982). This gives an average displacement rate of between 2.0 and 2.5 cm $year^{-1}$ for the 1,500 km displacement of the Southern Uplands relative to the Laurentian continent. This rate is comparable to that recorded by modern accretionary complexes (Jarrard, 1986), and because the displacements are in part synchronous with accretion, they are probably related to oblique subduction of the Iapetus oceanic plate.

Oblique closure of the Iapetus Ocean has also been invoked to explain large scale strike-slip displacements on other major faults in the British Caledonides (Dewey and Shakleton, 1984; Soper and Hutton, 1984). Bluck (1983, 1984) has demonstrated that the Midland Valley was

displaced along the Highland Boundary fault, and Hutton and Dewey (1986) have shown that Ordovician and late Silurian-early Devonian displacements affected Connemara and the South Mayo Trough. Thus, the British Caledonides consists of a number of terranes separated by a series of faults running sub-parallel to the Laurentian continental margin. As these faults all contain a component of sinistral strike-slip motion (Soper and Hutton, 1984), other Caledonian terranes have also been displaced form their original positions further west on the Laurentian margin. Consequently, the separation of the Midland Valley and the Southern Uplands was not necessarily as large as the total 1,500 km. of displacement that have affected the Southern Uplands, and some component of this displacement could have been taken up on the other tract-bounding faults in the British Caledonides.

Exotic terranes are defined as "fault bounded packages of rocks of regional extent characterized by a geological history that differs from that of neighbouring terranes" (Howell et al., 1985). This study has shown that the Southern Uplands was originally separate from the Midland Valley, and does not contain any detritus derived from the Scottish Highlands. Consequently, the Southern Uplands developed independently of other tectonic elements in the British Caledonides, and the strike-slip displacements which were an integral part of its formation are responsible for its present position in relation to other Caledonian terranes. Thus, the Southern Uplands provides an example of one of the many exotic terranes which comprise the Caledonian-Appalachian orogen.

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Appendices

APPENDIX 1.

ADDITIONAL PETROGRAPHIC INFORMATION FOR THE GRANITE CLASTS COLLECTED FROM THE CORSEWALL POINT AND GLEN AFTON CONGLOMERATES.

The textural features of each group of clasts are described in the main text (Chapter 3). The mineralogy of individual samples from the Corsewall Point and Glen Afton conglomerates, and any particular charactersistic they display, are listed in this Appendix.

A1.a Corsewall Point.

MUSCOVITE-BIOTITE GRANITES (GROUP A1).

CoP 3. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, opaque minerals, rare rutile. Some quartz overgrowths on plagioclase grains.

CoP 24. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Zircons are more abundant. Larger monazite crystals are present, contained in biotite grains.

CoP 27. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Some alteration of biotite to chlorite.

CoP 101. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, opaque minerals, apatite, rare rutile. Quartz is unstrained, layered pockets of biotite may represent the remnants of pelitic xenoliths.

CoP 117. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, opaque minerals, apatite. Alkali feldspar is less abundant, plagioclase crystals are less commonly euhedral.

CoP 118. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Quartz shows more extensive of strain, some biotite grains contain kinked twin planes. Garnet and sillimanite-bearing pelitic xenoliths are common.

CoP 119. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Some alteration of biotite to chlorite, and some replacement of plagioclase by sericite.

CoP 120. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Extensive recrystallization of quartz, biotite present as clusters of small grains, rather than as large independent crystals. Alkali feldspar is less abundant and plagioclase crystals are less commonly euhedral.

CoP 121. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Extensively alteration of alkali feldspar crystals, euhedral plagioclase unaffected.

CoP 122. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Some alteration of feldspars, but biotite is particularly fresh.

CoP 123. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Large muscovite crystals are more common. Some plagioclase crystals have deformed twin lamellae and some quartz is recrystallized.

CoP 124. Quartz, plagioclase, alkali feldspar, biotite, muscovite, zircon, monazite, apatite, opaque minerals. Zonation evident in large euhdral plagioclase crystals. Quartz shows evidence of strain, and biotite cleavage plains are deformed.

UNFOLIATED HORNBLENDE BIOTITE-GRANITES (GROUP A2a).

CoP 13. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite. Quartz shows undulatory extinction, hornblende of skeletal appearance.

CoP 102. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite. Hornblende of skeletal appearance. Hornblende more abundant in this clast.

CoP 105. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite, apatite. Hornblende is rare.

CoP 106. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite, apatite. Alkali feldspars show zonation. Hornblende of skeletal appearance.

CoP 110. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite. Biotite more common than hornblende, hornblende of skeletal appearance. Quartz show undulatroy extinction.

UNFOLIATED HORNBLENDE-BIOTITE GRANITES (GROUP A2b).

CoP 22. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite. Euhedral hornblende crystals, large alkali feldspar crystals, quartz grains have serrate margins.

CoP 104. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite. Biotite more abundant in this clast, quartz slightly less strained.

CoP 109. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite. Extensively deformed quartz, zoned feldspars.

FOLIATED HORNBLENDE-BIOTITE GRANODIORITES (GROUP A3).

CoP 2. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite, zircon, apatite. Extensively deformed.

CoP 23. Quartz, plagioclase feldspar, alkali feldspar, hornblende, biotite, zircon, apatite. Identical to CoP 2.

CoP 107. Quartz, plagioclase feldspar, alkali feldspar, biotite. Some biotite may replace primary hornblende. Biotite cleavages folded, alteration of biotite to chlorite.

BIOTITE GRANITES (GROUP A4).

CoP 6. Quartz, alkali feldspar, plagioclase, biotite, muscovite, garnet. Fractured garnet crystals associated with muscovite.

CoP 11. Quartz, alkali feldspar, plagioclase, biotite. Quartz shows evidence of strain, biotite is altered to chlorite, but is only present in minor amounts.

CoP 103. Quartz, alkali feldspar, plagioclae, biotite, minor hornblende. Quartz relatively unstrained, small mafic inclusions (hornblende + plagioclase) common.

CoP 108. Quartz, alkali feldspar, plagioclase feldspar, biotite. No hornblende in this sample, only small amounts of biotite. Limited intergrowths between quartz and feldspar. Quartz shows some evidence of strain.

CoP 25. Quartz, alkali feldspar, plagioclase, biotite. Extensive development of deformational fabrics, some alteration of biotite to chlorite. Microcline is common.

TRONDHJEMITE (GROUP A5).

CoP 28. Quartz, plagioclase feldspar, alkali feldspar, minor biotite. Zoned, perthitic alkali feldspar, subordinate to plagioclase.

PLAGIOGRANITE (GROUP A6).

CoP 29. Quartz, plagioclase, minor alakali feldspar, chlorite and epidote replacing ?hornblende. Dominated by large laths of plagioclase.

A.1.b GLEN AFTON.

MUSCOVITE-BIOTITE GRANITES (GROUP C1).

GA 1. Quartz, plagioclase, alkali feldspar, biotite, muscovite, clinozoisite. Muscovite occurs as platy crystals and in altered feldspars. Large alkali feldspar crystals enclose euhedral plagioclase crystals. Quartz shows shadowy extinction.

GA 21. Quartz, plagioclase, alkali feldspar, biotite, muscovite, clinozoisite. Biotite altered to chlorite, exsolution common in alkali feldspar crystals.

GA 39. Quartz, plagioclase, alkali feldspar, biotite, muscovite, clinozoisite. Zoned euhedral plagioclase feldspars are common, and muscovite is more abundant forming large platy crystals dispersed through out the rock.

GA 45. Quartz, plagioclase, alkali feldspar, biotite. Muscovite is rare in this sample which is more strongly deformed and has a more equigranular texture.

GA 170. Quartz, plagioclase, alkali feldspar, biotite, muscovite, clinozoisite. Identical textures to GA 1.

GA 173. Quartz, plagioclase, alkali feldspar, biotite. Muscovite is rare, similar deformational fabrics and more equigranular texture to GA 45.

GA 223. Quartz, plagioclase, alkali feldspar, biotite, muscovite, clinozoisite. Alkali feldspar slightly less abundant in this sample, and less commonly encloses euhedral plagioclase crystals.

GA 224. Quartz, plagioclase, alkali feldspar, biotite, clinozoisite. Muscovite is not common in this clast, alkali feldspar crystals are also less abundant, but have well developed perthitic textures. Zoning is evident in euhedral plagioclase crystals.

GA 226. Quartz, plagioclase, alkali feldspar, biotite, muscovite. Deformational fabrics are more strongly developed in this clast and include strained quartz and curved plagioclase twin lamellae. However, it differs from other deformed clasts by containing muscovite and large alkali feldspar crystals.

GA 231. Quartz, plagioclase, alkali feldspar, biotite, muscovite. Muscovite not as common in this clast which is cut by small epidote veinlets.

GA 232. Quartz, plagioclase, alkali feldspar, biotite, muscovite, clinozoisite. Large alkali feldspar crystals show well developed pokilitic textures.

BIOTITE GRANODIORTES (GROUP B2).

GA 2. Quartz, plagioclase, alkali feldspar, biotite, hornblende. hornblende is subordinate to biotite, biotite altered to chlorite, unstrained quartz.

GA 11. Quartz, plagioclase, alkali feldspar, biotite. Quartz show s some evidence of strain. biotite altered to chlorite.

GA 46. Quartz, plagioclase, alkali feldspar, biotite. Unstrained quartz, equigranular alkali and plagioclase feldspars.

GA 165. Quartz, plagioclase, alkali feldspar, biotite. Identical textures to GA 46.

GA 168. Quartz, plagioclase, alkali feldspar, biotite. Quartz shows evidence of strain, less equigranular texture.

GA 235. Quartz, plagioclase, alkali feldspar, biotite. Quartz show limited evidence of strain, anhedral alkali feldspars partially enclose euhedral plagioclase feldspar.

HORNBLENDE-BIOTITE GRANITES (GROUP C3).

GA 51. Quartz, plagioclase, alkali feldspar, biotite, hornblende. Quartz forms intergrowths with plagioclase and alkali feldspar, alkali feldspar shows well developed perthitic textures. Hornblende more abundant than biotite.

GA 171. Quartz, plagioclase, alkali feldspar, biotite, hornblende. Plagioclase contains perthitic overgrowths, quartz shows slightly more evidence of strain. Quartz-feldspar intergrowths less well developed.

GA 172. Quartz, plagioclase, alkali feldspar. Minor biotite, altered to chlorite, no hornblende. Small scale quartz-feldspsr intergrowths are common, alkali feldspar shows pethitic texture, some evidence of strain in quartz grains.

GA 221. Quartz, plagioclase, alkali feldspar, biotite, hornblende. Quartz-feldspar intergrowths absent from this sample, otherwise very similar top GA 171.

GRANOPHYRIC AND ACICULAR HORNBLENDE GRANITES (GROUP C4).

GA 15. Quartz, plagioclase feldspar, alkali feldspar, hornblende, apatite. Most the rock is of medium grain size and equigranular, but elongate needles of hornblende are imprinted on this texture. Apatite needles also present, and so feldspar crystal are elongate.

GA 25. Quartz, plagioclase feldspar, alkali feldspar, hornblende. Spectacular intergrowths of plagioclase and alkali feldspar with quartz, elongate hornblende needles overprint some intergrowths. Regularly crystalline areas separate intergrowths.

GA 27. Quartz, plagioclase, alkali feldspar, hornblende. Small radiating granophyric intergrowths. Elongate feldspar crystals, but equant hornblende.

GA 227. - as GA 25.

GA 229. - as GA 25

TRONDHJEMITES (GROUP C5).

GA 24. Quartz, plagioclase, alkali feldspar, minor biotite, altered to chlorite and epidote. A few large alkali feldspar crystals present which show perthitic textures, plagioclase is dominant.

GA 36. Quartz, plagioclase, alkali feldspar, biotite, zircon. Biotite altered to chlorite, both feldspars form limited intergrowths with quartz.

PLAGIOGRANITES (GROUP C6).

GA 169. Quartz and plagioclase feldspar, minor alkali feldspar which shows finely developed exsolution laminae. Radiating needles of epidote.

GA 228. Quartz, plagiocalse feldspar, minor alkali feldspar, radiating masses of epidote. Some intergrowths between quartz and feldspar, some evidence of strain shown by quartz and plagioclase.

APPENDIX 2.

CHEMICAL ANALYSES.

A.2.a CORSEWALL POINT.

MUSCOVITE-BIOTITE GRANITES (GROUP A1).

Sample No.	CoP 3	CoP 24	CoP 27	CoP 101	CoP 117	CoP 118	CoP 119
SiO_2	72.81	67.07	70.74	75.47	75.21	72.68	72.88
TiO_2	0.66	1.01	0.97	0.77	0.59	0.64	0.72
Al_2O_3	13.82	15.57	13.53	11,16	12.79	13.73	12.91
Fe_2O_3	4.04	6.77	5.92	4.54	3.80	4.36	4.62
MnO	0.06	0.11	0.08	0.06	0.08	0.07	0.07
MgO	1.57	2.45	2.69	1.74	1.19	1.43	1.68
CaO	0.91	1.27	0.70	0.97	1.19	1.52	1.33
Na_2O	1.94	1.97	2.14	1.81	1.89	2.19	1.94
K_2O	4.11	3.72	3.15	3.39	3.16	3.31	3.78
P_2O_5	0.07	0.07	0.08	0.08	0.10	0.06	0.06
TOTAL	99.99	100.01	100.00	99.99	100.00	99.99	99.99
Rb ppm	92.6	123.4	74.9	82.5	64.6	92.9	87.6
Sr	233.3	197.0	226.0	311.1	203.3	214.0	196.9
Y	24.9	19.6	15.3	14.0	29.3	19.7	15.5
Zr	188.1	279.8	233.0	199.1	240.7	163.2	218.0
Nb	9.6	13.8	12.3	10.5	9.7	10.5	9.1
Pb	22.9	18.0	17.0	17.9	21.8	17.1	17.9

Sample No.	CoP 120	CoP 121	CoP 122	CoP 123
SiO_2	71.04	73.62	72.44	72.39
TiO_2	0.89	0.44	0.72	0.75
Al_2O_3	13.68	14.11	13.83	13.52
Fe_2O_3	5.31	3.71	4.87	5.10
MnO	0.08	0.07	0.06	0.08
MgO	2.23	1.39	1.67	1.85
CaO	1.56	0.98	1.07	1.22
Na_2O	2.46	1.83	2.05	2.22
K_2O	2.64	3.74	3.17	2.79
P_2O_5	0.11	0.09	0.11	0.07
TOTAL	100.00	99.98	99.99	99.99
Rb ppm	55.2	76.4	88.5	68.6
Sr	224.9	189.5	188.4	211.1
Y	15.3	17.9	19.5	20.6
Zr	200.4	134.4	218.6	194.2
Nb	12.6	8.0	12.4	10.2
Pb	16.9	27.5	18.7	15.5

UNFOLIATED HORNBLENDE-BIOTITE GRANITES (GROUP A2a).

Sample No.	CoP 13	CoP 102	CoP 105	CoP 106	CoP 110
SiO_2	64.73	69.53	70.78	70.36	69.69
TiO_2	0.43	0.40	0.43	0.42	0.39
Al_2O_3	15.70	14.23	14.22	14.12	14.34
Fe_2O_3	5.85	4.37	4.33	4.67	4.53
MnO	0.11	0.10	0.09	0.10	0.09
MgO	2.85	2.18	2.22	2.34	2.62
CaO	3.43	3.15	2.34	2.43	2.38
Na_2O	2.98	2.81	2.78	2.86	3.21
K_2O	3.87	3.15	2.73	2.61	2.67
P_2O_5	0.07	0.07	0.07	0.07	0.06
TOTAL	100.01	100.00	100.00	99.98	99.98
Rb ppm	112.0	80.8	56.0	63.9	60.5
Sr	231.6	341.0	285.7	395.9	395.1
Y	15.7	13.6	24.4	14.2	11.9
Zr	110.7	112.1	125.4	126.3	103.9
Nb	6.9	6.7	9.0	8.0	7.1
Pb	10.0	11.6	15.5	12.4	11.6

UNFOLIATED HORNBLENDE-BIOTITE GRANITES (GROUP A2b).

Sample No.	CoP 22	CoP 104	CoP 109
SiO_2	68.06	68.05	68.40
TiO_2	0.38	0.47	0.44
Al_2O_3	14.84	14.88	14.82
Fe_2O_3	5.16	5.50	5.22
MnO	0.11	0.11	0.10
MgO	2.67	2.54	2.49
CaO	3.40	3.14	3.21
Na_2O	2.61	2.65	2.58
K_2O	2.70	2.60	2.68
P_2O_5	0.06	0.07	0.07
TOTAL	99.99	100.01	100.01
Rb ppm	70.6	60.7	58.9
Sr	215.2	377.2	300.6
Y	15.4	19.1	14.0
Zr	87.0	116.9	109.1
Nb	6.6	8.0	6.6
Pb	13.7	9.2	14.3

FOLIATED HORNBLENDE-BIOTITE GRANODIORITES (GROUP A3).

TRONDHJEMITES AND PLAGIOGRANITES (GROUPS A5 & 6).

Sample No.	CoP 2	CoP 23	CoP 107	CoP 28	CoP 29
SiO_2	66.62	67.00	69.40	75.67	77.94
TiO_2	0.58	0.54	0.53	0.23	0.11
Al_2O_3	14.98	15.44	14.75	12.39	12.33
Fe_2O_3	6.51	5.82	5.11	3.34	1.87
MnO	0.12	0.10	0.09	0.06	0.03
MgO	3.29	3.13	2.33	1.64	0.39
CaO	3.89	3.50	3.22	1.30	0.70
Na_2O	2.32	2.56	2.53	4.39	6.52
K_2O	1.60	1.82	1.95	0.93	0.09
P_2O_5	0.08	0.09	0.08	0.05	0.01
TOTAL	99.99	100.00	99.99	100.00	99.99
Rb ppm	41.4	47.2	43.7	16.8	2.7
Sr	267.8	332.8	281.4	226.2	61.3
Y	18.0	12.9	8.7	11.9	73.8
Zr	151.5	143.2	160.3	100.6	154.0
Nb	6.9	6.9	9.0	2.9	2.5
Pb	9.4	8.9	12.6	4.9	5.7

BIOTITE GRANITES (Group A4).

Sample No.	CoP 6	CoP 11	CoP 103	CoP 108	CoP 25
SiO_2	77.18	72.94	75.32	75.40	78.34
TiO_2	0.05	0.38	0.22	0.21	0.30
Al_2O_3	13.03	12.78	13.74	13.23	11.11
Fe_2O_3	1.30	3.83	3.12	2.51	2.79
MnO	0.04	0.08	0.07	0.05	0.05
MgO	0.34	2.44	1.18	0.79	0.86
CaO	0.76	1.51	1.67	1.58	1.68
Na_2O	4.44	3.13	3.56	3.40	2.41
K_2O	2.84	2.86	2.87	2.79	2.42
P_2O_5	0.02	0.06	0.05	0.04	0.05
TOTAL	100.00	100.01	100.00	100.00	100.01
Rb ppm	57.4	52.6	85.5	67.9	45.4
Sr	104.3	140.9	378.3	335.6	201.2
Y	37.8	14.8	16.2	21.9	19.1
Zr	64.8	113.5	87.9	108.8	235.0
Nb	5.7	8.2	3.9	6.9	12.1
Pb	17.0	8.9	10.7	7.4	12.8

A.2.b GLEN APP.

UNFOLIATED HOENBLENDE-BIOTITE GRANITES (GROUP B1).

Sample No.	AP 5	AP 6	AP 7	AP 10	AP 15
SiO_2	70.19	69.27	68.89	68.14	69.98
TiO_2	0.35	0.41	0.37	0.47	0.42
Al_2O_3	14.57	14.53	14.72	14.54	12.94
Fe_2O_3	4.56	4.85	4.59	5.26	4.52
MnO	0.09	0.10	0.10	0.09	0.08
MgO	2.14	2.62	2.53	2.37	2.51
CaO	2.89	2.56	3.20	3.54	4.24
Na_2O	3.81	3.33	3.52	3.25	3.77
K_2O	1.35	2.27	2.02	2.28	1.47
P_2O_5	0.06	0.06	0.06	0.07	0.07
TOTAL	100.01	100.00	100.00	100.01	100.00
Rb ppm	28.8	50.3	38.8	47.0	25.8
Sr	557.1	589.3	624.3	769.3	268.3
Y	11.7	13.7	15.0	17.8	16.7
Zr	92.8	99.9	88.2	106.8	113.0
Nb	6.4	6.8	6.4	6.8	7.6
Pb	25.0	13.9	15.7	14.3	11.6

FOLIATED GRANODIORITE (GROUP B2).

BIOTITE GRANITES (GROUP B3).

Sample No.	AP 13	AP 8	AP 17
SiO_2	70.47	73.70	73.88
TiO_2	0.46	0.21	0.20
Al_2O_3	14.44	13.66	13.29
Fe_2O_3	4.65	3.10	3.11
MnO	0.09	0.08	0.07
MgO	2.33	1.21	1.12
CaO	3.62	1.41	1.76
Na_2O	2.49	4.05	4.20
K_2O	1.37	2.53	2.32
P_2O_5	0.07	0.05	0.05
TOTAL	99.99	100.00	100.00
Rb ppm	29.5	73.9	62.6
Sr	455.6	757.6	808.4
Y	9.7	27.2	23.3
Zr	135.4	99.4	97.0
Nb	9.0	5.5	5.5
Pb	14.7	12.9	9.7

FOLIATED BIOTITE GRANITES (GROUP B4). PLAGIOGRANITE (GROUP B5).

Sample No.	AP 11	AP 14	AP 16	AP 2
SiO_2	76.29	71.30	75.48	76.33
TiO_2	0.10	0.28	0.21	0.19
Al_2O_3	12.33	14.77	12.26	12.07
Fe_2O_3	1.38	3.19	2.40	2.59
MnO	0.03	0.06	0.05	0.04
MgO	0.77	1.60	1.28	0.96
CaO	1.53	2.10	2.38	1.56
Na_2O	3.60	3.18	3.69	6.02
K_2O	3.96	3.43	2.21	0.23
P_2O_5	0.02	0.09	0.04	0.02
TOTAL	100.01	100.00	100.00	100.01
Rb ppm	64.0	88.0	45.4	1.2
Sr	218.7	699.3	500.9	88.0
Y	14.3	12.9	11.7	93.2
Zr	75.9	100.1	90.4	184.6
Nb	4.2	11.1	6.8	4.7
Pb	21.2	24.2	15.8	3.6

A.2.c GLEN AFTON.

MUSCOVITE-BIOTITE GRANITES (GROUP C1).

Sample No.	GA 1	GA 21	GA 39	GA 45	GA 170	GA 173	GA 223
SiO_2	73.66	74.44	71.68	73.11	74.72	73.29	74.35
TiO_2	0.25	0.26	0.28	0.32	0.23	0.29	0.24
Al_2O_3	14.25	13.90	15.25	13.79	13.77	13.69	13.88
Fe_2O_3	2.36	2.51	2.89	3.16	2.23	2.86	2.28
MnO	0.05	0.06	0.07	0.07	0.05	0.05	0.05
MgO	0.70	0.74	0.95	1.11	0.66	0.95	0.65
CaO	1.66	1.93	1.71	2.14	1.75	2.10	1.86
Na_2O	2.82	3.03	3.22	3.03	2.95	3.41	3.03
K_2O	4.19	3.08	3.87	3.19	3.60	3.31	3.60
P_2O_5	0.06	0.05	0.06	0.08	0.05	0.07	0.05
TOTAL	100.00	100.00	99.99	99.99	100.01	100.02	99.99
Rb ppm	96.0	77.6	103.5	68.0	85.9	66.1	80.3
Sr	187.0	197.8	226.2	253.3	200.9	250.7	207.2
Y	21.7	25.8	26.8	18.6	23.6	17.4	23.6
Zr	113.5	124.1	119.3	136.5	114.2	128.5	110.3
Nb	8.1	9.3	9.2	8.6	8.0	8.0	7.7
Pb	21.4	17.2	15.7	17.5	19.9	14.8	17.9

MUSCOVITE-BIOTITE GRANITES (GROUP C1) - cont.

Sample No.	GA 224	GA 226	GA 231	GA 232
SiO_2	74.46	74.10	74.09	74.19
TiO_2	0.27	0.22	0.26	0.20
Al_2O_3	13.89	14.09	13.19	14.18
Fe_2O_3	2.63	2.25	2.37	2.01
MnO	0.06	0.05	0.05	0.05
MgO	0.88	0.56	0.83	0.71
CaO	1.90	1.88	2.54	1.41
Na_2O	2.95	3.23	3.83	3.10
K_2O	2.92	3.59	2.76	4.12
P_2O_5	0.05	0.04	0.06	0.04
TOTAL	100.01	100.01	99.98	100.01
Rb ppm	72.6	65.8	58.8	97.3
Sr	275.6	209.8	207.1	231.8
Y	16.7	16.1	20.1	27.3
Zr	117.4	116.1	118.4	101.2
Nb	7.7	7.9	7.6	7.6
Pb	12.6	18.6	11.0	18.3

BIOTITE GRANODIORITES (Group C2).

Sample No.	GA 2	GA 11	GA 46	GA 165	GA 168	GA 225
SiO_2	69.01	70.85	70.67	73.32	75.18	69.25
TiO_2	0.36	0.48	0.37	0.38	0.28	0.60
Al_2O_3	14.95	15.29	14.26	14.05	13.79	14.93
Fe_2O_3	5.06	4.00	4.83	3.37	2.40	5.21
MnO	0.12	0.08	0.12	0.06	0.05	0.09
MgO	1.98	1.43	2.01	1.06	0.90	1.91
CaO	3.74	3.28	3.32	2.91	2.59	3.32
Na_2O	2.60	2.36	3.02	2.17	2.45	2.20
K_2O	2.11	2.14	1.32	2.62	2.29	2.36
P_2O_5	0.08	0.09	0.08	0.06	0.05	0.11
TOTAL	100.01	100.00	99.99	99.99	99.99	99.98
Rb ppm	51.9	57.7	40.9	64.4	55.3	59.3
Sr	253.4	180.6	247.3	218.6	200.1	188.4
Y	18.2	14.3	17.1	16.0	12.3	18.4
Zr	96.2	183.4	109.8	167.8	110.4	232.1
Nb	6.9	9.4	6.9	8.3	6.7	12.1
Pb	11.5	10.7	9.1	13.2	7.9	10.5

HORNBLENDE-BIOTITE GRANITES (GROUP C3)

Sample No.	GA 51	GA 171	GA 172	GA 221
SiO_2	74.95	76.66	77.62	76.71
TiO_2	0.25	0.21	0.05	0.15
Al_2O_3	12.99	12.39	12.77	12.52
Fe_2O_3	2.86	2.59	0.77	2.34
MnO	0.06	0.05	0.02	0.06
MgO	0.63	0.36	0.09	0.22
CaO	1.84	1.30	0.61	1.22
Na_2O	4.13	4.90	5.06	4.39
K_2O	2.22	1.51	2.99	2.37
P_2O_5	0.05	0.03	0.01	0.02
TOTAL	99.99	100.00	99.99	100.00
Rb ppm	64.3	48.4	72.7	50.4
Sr	253.0	126.5	73.8	89.5
Y	30.8	51.5	47.5	50.0
Zr	112.8	142.2	73.1	165.3
Nb	3.3	4.1	9.8	8.9
Pb	11.7	6.5	11.2	6.8

GRANOPHYRIC AND ACICULAR HORNBLENDE GRANITES (GROUP C4).

Sample No.	GA 15	GA 25	GA 27	GA 227	GA 229
SiO_2	67.13	76.82	70.81	76.54	74.67
TiO_2	0.71	0.23	0.39	0.24	0.31
Al_2O_3	14.82	11.80	13.64	11.97	11.81
Fe_2O_3	5.85	3.73	6.20	3.54	5.17
MnO	0.08	0.05	0.14	0.05	0.07
MgO	1.34	0.72	1.03	0.56	0.35
CaO	3.48	1.63	1.94	1.64	2.23
Na_2O	5.47	4.76	5.34	5.10	4.98
K_2O	0.87	0.24	0.42	0.34	0.37
P_2O_5	0.24	0.02	0.10	0.03	0.05
TOTAL	99.99	100.00	100.01	100.01	100.01
Rb ppm	20.1	4.1	7.3	6.3	6.9
Sr	132.4	108.7	114.4	116.3	122.0
Y	49.4	46.9	31.4	50.4	48.7
Zr	146.3	124.6	99.4	117.9	84.4
Nb	4.5	3.4	3.2	4.0	3.2
Pb	7.6	6.1	4.0	5.7	4.2

TRONDHJEMITES (GROUP C5)			PLAGIOGRANITES (GROUP C6)	
Sample No.	GA 24	GA 36	GA 169	GA 228
SiO_2	77.30	75.78	77.41	77.21
TiO_2	0.22	0.25	0.21	0.23
Al_2O_3	12.27	12.35	11.86	11.86
Fe_2O_3	2.60	2.76	3.29	3.20
MnO	0.04	0.04	0.05	0.05
MgO	0.47	0.58	0.34	0.22
CaO	1.49	2.64	0.58	0.58
Na_2O	5.14	5.22	6.19	6.57
K_2O	0.43	0.34	0.06	0.06
P_2O_5	0.04	0.05	0.02	0.02
TOTAL	100.00	100.02	100.01	100.00
Rb ppm	8.1	6.4	0.1	0.0
Sr	95.6	99.1	39.4	48.2
Y	42.0	44.9	100.6	102.8
Zr	103.7	141.4	286.4	292.7
Nb	3.2	4.1	4.7	5.3
Pb	6.6	5.7	3.7	2.8

A.2.d SHINNEL FORMATION CONGLOMERATE.

DEFORMED LEUCOGRANITE (GROUP D1).			BIOTITE-BEARING GRANITES (GROUP D3).		
Sample No.	SW 14	SW 18	SW 16a	SW 16b	ShW 10
SiO_2	77.10	76.55	68.49	75.79	77.06
TiO_2	0.16	0.19	0.43	0.12	0.23
Al_2O_3	12.84	12.92	15.32	12.25	11.96
Fe_2O_3	1.40	1.40	7.36	0.61	2.94
MnO	0.03	0.04	0.07	0.07	0.08
MgO	0.52	0.76	2.56	0.26	0.91
CaO	0.60	2.00	0.73	2.88	0.72
Na_2O	3.83	4.92	3.31	3.74	5.68
K_2O	3.47	1.16	1.69	4.26	0.38
P_2O_5	0.05	0.05	0.04	0.02	0.05
TOTAL	100.00	99.99	100.00	100.00	100.01
Rb ppm	69.6	28.3	45.2	114.1	4.8
Sr	163.4	231.5	191.6	195.4	96.9
Y	24.8	12.4	14.2	18.9	41.7
Zr	99.1	103.5	91.4	60.1	125.0
Nb	12.7	9.2	2.7	41.6	3.7
Pb	10.6	6.5	5.8	11.1	10.5

MUSCOVITE-BIOTITE GRANITE (GROUP D2).		GRANOPHYRES AND PORHHYRIES (GROUP D4).			
Sample No.	SW 12	SW 8	SW 17	ShW 5	ShW 8
SiO_2	69.41	76.42	76.96	78.23	76.20
TiO_2	1.08	0.21	0.28	0.19	0.22
Al_2O_3	13.56	12.13	11.82	11.45	12.60
Fe_2O_3	6.63	2.16	2.28	1.89	2.50
MnO	0.11	0.06	0.07	0.03	0.06
MgO	1.88	0.46	0.82	0.54	0.90
CaO	1.40	1.11	1.63	0.59	0.20
Na_2O	2.07	4.82	4.17	4.36	5.54
K_2O	3.63	2.63	1.92	2.70	1.77
P_2O_5	0.23	0.01	0.04	0.01	0.02
TOTAL	100.00	100.00	99.99	99.99	100.01
Rb ppm	103.2	43.7	41.3	36.9	25.4
Sr	219.6	109.8	135.5	74.5	60.8
Y	23.0	44.5	25.0	76.1	70.7
Zr	243.7	266.7	191.5	366.8	416.8
Nb	15.1	32.4	11.5	40.9	33.8
Pb	16.6	6.5	5.7	8.4	56.6

A.2.d PINSTANE HILL CONGLOMERATE.

FOLIATED BIOTITE GRANITES (GROUP E1).		PERTHITIC BIOTITE GRANITES (GROUP E2).			
Sample No.	PS 22	PS 41	PS 3	PS 13	PS 38	PS 43
SiO_2	76.92	75.27	78.31	77.62	76.19	77.23
TiO_2	0.20	0.29	0.14	0.14	0.27	0.11
Al_2O_3	12.45	13.95	12.02	12.17	13.07	12.02
Fe_2O_3	2.30	2.46	1.26	1.90	1.63	1.70
MnO	0.02	0.08	0.03	0.07	0.05	0.05
MgO	0.32	0.70	0.38	0.40	0.75	0.26
CaO	0.81	1.51	0.33	0.41	0.26	1.24
Na_2O	4.58	4.43	4.16	4.83	4.66	5.16
K_2O	2.38	1.24	3.35	2.45	3.07	2.22
P_2O_5	0.02	0.06	0.02	0.02	0.05	0.01
TOTAL	100.00	99.99	100.00	100.01	100.00	100.00
Rb ppm	38.3	26.4	58.6	45.4	41.2	36.7
Sr	127.6	619.1	69.7	78.5	164.6	102.5
Y	97.5	21.9	43.2	97.9	16.1	102.8
Zr	239.9	95.6	131.6	219.8	160.5	179.5
Nb	14.2	2.5	8.3	14.6	13.6	12.0
Pb	8.1	11.8	8.0	9.6	11.9	9.7

GRANOPHYRIC GRANITES (GROUP E3).			TRONDHJEMITES (GROUP E4).	
Sample No.	PS 1	PS 44	PS 2	PS 34
SiO_2	78.56	76.22	77.09	77.21
TiO_2	0.19	0.17	0.27	0.20
Al_2O_3	11.84	13.11	12.91	11.76
Fe_2O_3	1.80	1.24	1.33	2.63
MnO	0.08	0.02	0.01	0.06
MgO	0.59	0.25	0.46	0.53
CaO	0.54	0.62	1.58	1.64
Na_2O	6.14	4.70	5.83	5.69
K_2O	0.22	3.62	0.47	0.24
P_2O_5	0.03	0.03	0.04	0.03
TOTAL	99.99	99.98	99.99	99.99
Rb ppm	1.6	55.6	7.1	2.2
Sr	120.0	94.7	273.4	137.7
Y	39.3	38.5	50.8	41.5
Zr	127.8	202.7	153.8	131.5
Nb	4.3	42.0	7.8	3.9
Pb	15.0	25.8	4.8	5.6

APPENDIX 3

ISOTOPIC DATA

A.3.a Rb-Sr whole-rock data for granite clasts.

Sample no.	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Corsewall Point muscovite-biotite granites (Group A1)				
CoP 3	96.58	252.15	1.1469	0.72571
CoP 24	120.82	231.89	1.7722	0.73473
CoP 27	84.98	266.78	0.9491	0.72176
CoP 101	85.89	332.38	0.7699	0.71807
*CoP 117	68.73	224.54	0.9203	0.72596
CoP 118	96.67	236.77	1.2496	0.72703
CoP 119	90.35	201.25	1.3258	0.72884
*CoP 120	57.45	231.21	0.7202	0.72469
*CoP 121	77.02	193.34	1.1551	0.72939
CoP 122	90.55	193.76	1.3809	0.73072
CoP 123	71.37	215.86	0.9907	0.72298
CoP 124	36.03	131.10	0.9024	0.72129
Corsewall Point hornblende-biotite granites (Group A2a)				
CoP 13	114.97	259.69	1.3997	0.71790
CoP 102	85.25	368.13	0.6837	0.71162
*CoP 105	59.11	308.64	0.5622	0.71287
CoP 106	67.54	418.07	0.4708	0.71002
CoP 110	64.34	421.52	0.4439	0.70963
Corsewall Point hornblende-biotite granites (Group A2b)				
CoP 22	68.86	236.67	0.9334	0.71485
CoP 104	63.74	399.27	0.4651	0.71081
CoP 109	60.80	319.54	0.5580	0.71165
Corsewall Point foliated hornblende-biotite granodiorites (Group A3)				
CoP 2	46.11	295.36	0.4507	0.71297
CoP 23	51.04	371.93	0.3989	0.71166
CoP 107	46.63	302.30	0.4479	0.71364
Corsewall Point biotite granites (Group A4)				
CoP 6	74.80	140.98	1.6289	0.71664
CoP 11	55.40	178.75	1.0739	0.71291
CoP 103	90.72	405.31	0.6595	0.71001
CoP 108	74.17	362.87	0.6011	0.70973
*CoP 25	48.80	271.14	0.6567	0.71957
Corsewall Point trondhjemite (Group A5)				
CoP 28	19.84	270.50	0.2152	0.70681
Corsewall Point plagiogranite (Group A6)				
CoP 29	2.62	86.67	0.0289	0.70663

* = sample excluded from the isochron suite

Sample no.	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Glen App hornblende-biotite granites (Group B1)				
AP 5	31.38	585.07	0.1470	0.70702
AP 6	54.78	620.88	0.2511	0.70752
AP 7	41.85	648.65	0.1808	0.70679
AP 10	50.19	790.05	0.1785	0.70634
AP 15	28.53	288.04	0.2766	0.70685
Glen App foliated granodiorite (Group B2)				
AP 13	32.42	483.66	0.1855	0.70846
Glen App biotite granites (Group B3)				
AP 17	67.45	838.20	0.2294	0.70646
AP 18	71.37	211.24	1.0199	0.71620
Glen App foliated biotite granite (Group B4)				
AP 11	70.76	243.03	0.8712	0.71150
AP 14	91.28	728.25	0.3669	0.70852
AP 16	49.01	536.93	0.2595	0.70690
Glen App plagiogranite (Group B5)				
AP 2	4.78	97.08	0.0781	0.70556
Glen Afton muscovite-biotite granites (Group C1)				
GA 1	97.04	194.16	1.4479	0.72056
GA 21	83.92	215.23	1.1422	0.71784
GA 39	108.23	243.12	1.3145	0.71934
*GA 45	72.90	271.35	0.7750	0.71344
GA 170	91.39	224.68	1.2329	0.71841
*GA 173	71.26	274.75	0.7712	0.71290
GA 223	85.56	219.29	1.1300	0.71744
GA 224	76.71	285.94	0.7765	0.71437
*GA 226	69.37	219.97	0.9134	0.71737
GA 231	61.55	220.04	0.8098	0.71434
GA 232	99.00	240.77	1.1909	0.71797
Glen Afton biotite granodiorites (Group C2)				
*GA 2	56.15	266.32	0.5972	0.71347
GA 11	62.18	195.29	0.9195	0.72046
GA 46	45.37	262.88	0.4799	0.71244
GA 165	68.68	239.60	0.8582	0.71862
GA 168	59.04	221.37	0.7976	0.71764
GA 225	60.56	199.95	0.8774	0.71967
Glen Afton hornblende-biotite granites (Group C3)				
GA 51	68.06	283.76	0.7375	0.71160
GA 171	145.54	53.42	1.1265	0.71427
GA 172	91.67	80.01	2.8792	0.72668
GA 221	51.82	92.81	1.7511	0.71853
Glen Afton granophyric and acicular hornblende granites (Group C4)				
GA 15	20.45	141.83	0.4362	0.71112
GA 25	8.65	120.96	0.1250	0.70794
GA 27	8.11	124.88	0.2028	0.70826
GA 227	7.92	123.52	0.1855	0.70808
GA 229	7.58	125.60	0.1745	0.70800

Sample no.	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Glen Afton trondjemites (Group C5)				
GA 24	12.91	109.02	0.2639	0.70896
GA 36	8.49	108.52	0.2269	0.70886
Glen Afton plagiogranites (Group C6)				
GA 169	0.85	42.80	0.0576	0.70676
GA 228	1.15	51.84	0.0645	0.70686
Shinnel Formation deformed leucogranites (Group D1)				
SW 14	76.00	179.07	1.2417	0.71665
SW 18	32.34	266.74	0.3682	0.71139
Shinnel Formation muscovite-biotite granite (Group D2)				
SW 12	105.28	231.43	1.3432	0.72618
Shinnel Formation biotite-bearing granites (Group D3)				
SW 16a	48.68	203.65	0.6743	0.71036
SW 16b	119.42	208.58	1.6908	0.71784
ShW 10	7.92	113.91	0.1693	0.70839
Shinnel Formation granophyres and porphyries (Group D4)				
SW 8	50.54	123.89	1.1748	0.71411
SW 17	47.78	150.15	0.9064	0.71653
ShW 5	42.55	84.57	1.4580	0.71668
ShW 8	30.73	70.25	1.2358	0.71528
Pinstane Hill foliated biotite granites (Group E1)				
PS 1	30.34	649.96	0.1267	0.70768
PS 22	41.33	131.28	0.8944	0.71217
Pinstane Hill perthitic biotite granites (Group E2)				
PS 3	74.76	98.47	2.4067	0.72265
PS 13	51.12	94.12	1.7084	0.71781
PS 38	53.99	215.11	0.7433	0.71163
PS 43	39.09	139.81	1.0642	0.71397
Pinstane Hill granophyric granites (Group E3)				
PS 41	4.66	162.28	0.0770	0.70765
PS 44	62.59	106.18	1.7070	0.71796
Pinstane Hill trondhjemites (Group E4)				
PS 2	10.99	301.64	0.0894	0.70767
PS 34	5.61	157.93	0.0723	0.70724

A.3.b Sm-Nd whole-rock data for granite clasts.

Sample no.	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
Corsewall Point muscovite-biotite granites (Group A1)				
CoP 3	4.03	21.75	0.1119	0.511490±25
CoP 118	4.11	22.47	0.1107	0.511556±27
Corsewall Point hornblende-biotite granites (Group A2a)				
CoP 102	2.40	12.99	0.1117	0.511610±25
CoP 105	4.28	22.63	0.1142	0.511628±20
CoP 106	2.78	16.25	0.1032	0.511627±19
Corsewall Point hornblende-biotite granites (Group A2b)				
CoP 22	2.13	9.65	0.1332	0.511800±28
CoP 104	2.88	11.94	0.1456	0.511740±19
Corsewall Point biotite granite (Group A4)				
CoP 6	4.67	19.09	0.1477	0.512286±48
Glen Afton muscovite-biotite granite (Group C1)				
GA 39	5.33	27.94	0.1153	0.511637±58
Glen Afton hornblende-biotite granites (Group C3)				
GA 51	3.03	11.56	0.1586	0.512318±20
GA 172	5.63	22.56	0.1510	0.512046±20
Glen Afton acicular hornblende granites (Group C4)				
GA 15	5.42	19.43	0.1688	0.512331±19
Glen Afton trondhjemites (Group C5)				
GA 24	3.90	13.42	0.1759	0.512508±45
Shinnel Formation granophyric granite (Group D4)				
SW 8	6.89	31.75	0.1311	0.512416±18
Pinstane Hill granophyric granite (Group E3)				
PS 44	7.16	39.99	0.1082	0.512487±22

A3.c Sm-Nd whole-rock data for some Newfoundland granites.

Sample no.	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
Portland Creek Pond pluton				
PCP 4	7.65	50.13	0.0923	0.511803±18
PCP 5	17.46	99.43	0.1062	0.511876±13
PCP 6	11.20	79.24	0.0854	0.511724±15
PCP 7	4.71	28.52	0.0999	0.511841±20
Twillingate granite				
TW 1	2.40	8.85	0.1637	0.512868±20
Burlington granodiorite				
BG 2	5.48	27.34	0.1212	0.512414±19

APPENDIX 4.

ANALYTICAL TECHNIQUES AND STATISTICAL PROCEDURES.

A4.a Major element analyses.

Major element analyses were performed on a Phillips PW 1400 XRF spectrometer using fused glass beads. The beads were prepared from 1 gm. of rock powder (pre-ignited at 900°C for several hours to drive off any volatiles) and 5 gm. of dried Spectroflux 100 (Lithium tetraborate). The mixture was fused in a Pt/Au crucible at 1225°C for approximately 20 mins, with occasional swirling to ensure homogeneity of the mixture. The melt was poured into a Pt/Au mould and was rapidly cooled over a jet of compressed air.

Analyses performed on pre-ignited materials should generate totals of 100%, but errors associated with the bead making process produce deviations from this figure. Analyses totalling between 99 and 101% were regarded as acceptable, but it has been shown that by normalizing analyses to 100%, errors associated with bead making are reduced (Devey, 1986).

A4.b Trace element analyses.

The concentrations of six trace elements (Rb, Sr, Y, Nb, Zr and Pb) were also determined using a Phillips PW 1400 XRF spectrometer. The determinations were carried out using pressed pellets of crushed rock powder, prepared from 9 gm. of rock powder and 0.6 ml. of Moviol, an organic binding agent. Details of the standards used for calibration can be found in Devey (1986).

A4.c Rb-Sr isotope analysis.

Sr was separated from rock powders by dissolving 200 mg. of powder in a mixture of 5 ml. conc. HF and 1 ml. conc. HNO_3 which was subsequently evapourated. The samples were nitrated by the addition of 2 ml. of conc. HNO_3 and were converted to chloride by the addition 8 ml. of 6M HCl. The samples were then evaporated to incipient dryness before being equilibrated with 2.5M HCl. The solution was washed through a cation exchange column (using AG50-X12 200-400# resin) with 55 ml. of 2.5M HCl, and Sr was eluted with a further 16 ml. of 2.5M HCl.

Sr isotopic composition was determined using a VG Micromass 30 or a VG Isomass 54-E mass spectrometer by loading samples dissolved in water onto a single Ta fillament. To correct for mass fractionation, $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$. The Eimer and Amend Sr standard (accepted $^{87}Sr/^{86}Sr$ value = 0.70800) yieled an average result of 0.70778 on the Micromass 30 and 0.70801 on the Isomass 54-E. Analyses conducted on the Micromass 30 were therefore corrected by adding 0.00022 to the measured $^{87}Sr/^{86}Sr$ ratio.

Rb/Sr ratios were determined either by an XRF technique similar to that described by Pankhusrt and O'Nions (1973) using pressed powder pelts made in a similar way to that outlined above, or by mass spectrometric methods, using an ^{87}Rb-^{84}Sr mixed spike. Spike-sample equilibration was acheived during the initial dissolution of the sample in a mixture of concentrated HF and HNO_3. The solution was then treated in a similar manner to that described for Sr separations, but a fraction containing Rb was eluted separately. Rb concentrations were determined using a VG Micromass 30 mass spectrometer and samples were loaded onto Ta fillaments as chloroplatinates.

A.4.d Sm-Nd determinations.

Samples which were analysed for Sm and Nd isotopic composition were prepared by dissolution in a mixture of concentrated HF and HNO_3 to which a ^{149}Sm-^{150}Nd mixed spike had been added. The dissolution was performed in a sealed bomb held at 150°C for several hours. After evaporation the samples were converted to chloride by the addition of 6M HCl and were then equilibrated with 2 ml. of 3.0M HCl. The rare earth elements were separated from the samples by a cation exchange technique, using a AG50-X12 200-400 resin and the REE fraction was eluted using 3.0M HCl. After evaporation this fraction was equilibrated with 0.15M HCl and Sm and Nd were separated by a reversed phase chromatographic technique using Di-2-ethylhexylphosphoric acid on a PTFE bed. Sm and Nd were eluted as separate fractions using 0.3M HCl and were evaporated to dryness.

The separated Sm and Nd was loaded onto the Ta side filaments of a triple filament assembly using H_3PO_4 and 1M HNO_3. Re centre filaments were welded in place once the samples had been loaded. Samples were analysed using a VG Micromass 54-E mass spectrometer. Sm was run first to determine the Sm concentration and spike/sample ratio. Nd isotope ratios were corrected for mass fractionation using $^{146}Nd/^{144}Nd$ = 0.7219.

Fuller details of the procedures used for Sm and Nd isotopic determinations at Oxford are to be found in Whitehouse (1987).

A.4.e Statistical Proccedures.

Calculation of best fit lines and their associated errors for Sr isotopic data were carried out using the algorithms presented by York (1969) and were performed using programs adapted for the BBC microcomputer by M.J. Whitehouse. Decay constants of 1.42×10^{-11} y^{-1} and 6.54×10^{-12} y^{-1} for ^{87}Rb and ^{147}Sm respectively were used in calculating ages from isochrons and for model age determinations.

APPENDIX 5 - AN ALTERNATIVE CONCLUSION.

A MATTER OF ACCRETION.
(with apologies to J. Archer).

The large, shining muscovite-biotite granite clast hurtled across the fore-arc from the north-west and flung itself into the wide, welcoming arms of the subduction trench. Carried down the inner-trech wall by the gentle caress of a high density turbidity current, it finally came to rest in a submarine fan complex.

"Mmm", it thought to itself, as it settled comfortably into its associated basic-rich greywackes, "I must be south-east of the Long Range, and its only the N. gracilis zone!"

The 1,500 km journey that lay before this jewel of a clast would eventually juxtapose it with the rest of Scotland, but it wasn't going to be easy. No sooner had it become firmly fixed in place by diagenetic processes than a thrust rocketed through the sediment pile, and incorporated the unsuspecting tract into the accretionary complex. After that it was just a matter of rotation and uplift - graptolite zone after graptolite zone, the same old story, as more and more tracts were accreted to the base of the complex.

The monotonous routine was broken only by the emergence of the trench-slope break. The sediment pile poked its weary head above water, and the muscovite-biotite granite clast eagerly gulped its first gasps of fresh air for about seven million years. Looking about, it quickly realized that it was the P. linearis zone, and that meant only one thing - erosion and redeposition in the trench as part of the Shinnel Formation conglomerate!

The Northern Belt was now complete. Of course it had to move laterally prior to the accretion of a volcanic edifice during the Ashgill, but that just helped it on its way east. As the sun set on the Lower Devonian, the Southern Uplands wearily docked with the Midland Valley, and the muscovite-biotite granite clasts was finally at Corsewall Point, the end of an epic journey, which McKerrow (1985) reckoned had taken it 63 Ma. Harland (1982) thought it was more like 71 Ma, but what the heck, it still made a displacement rate of between two and two-and-a-half centimetres a year. Not a centimetre more, not a centimetre less, and not that bad, judging form the example set by modern accretionary complexes.

THE END.

Appendix 6 and 7

GEOLOGICAL JOURNAL, VOL. 22, 163–165 (1987)

Short Communications

Comment upon 'Late Caledonian dyke-swarms in Southern Scotland: new field, petrological and geochemical data for the Wigtown Peninsula, Galloway'

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The contribution by Barnes *et al.* provides a timely study of a group of minor intrusions in the Southern Uplands. We agree that they are an important part of the geology of the area, but we would contest the authors' assertion that their data requires a radical reinterpretation of existing regional models. They question an accretionary origin for the Southern Uplands on the following grounds: (1) That 'the intrusion of the oldest dykes and sedimentation of the youngest greywackes were penecontemporaneous'; (2) That dyke emplacement commenced during thrust (accretion) related deformation; and (3) That such dykes could only be emplaced 'several hundred kilometres behind the (subduction) trench'.

The validity of considering the 418 Ma age for the undeformed dykes as Late Wenlock is questionable. This is only the case if the time-scale of Ross *et al.* (1982) is used. This time-scale is based upon fission track dating and has large errors associated with individual calibration points. The time-scales of McKerrow *et al.* (1985) and Harland *et al.* (1982) are largely based upon more accurate Rb–Sr, U–Pb, Sm–Nd, ^{40}Ar-^{39}Ar and K–Ar age determinations. McKerrow *et al.* (1985) show that the errors associated with the calibration points used by Ross *et al.* (1982) overlap their own calibration but that when these data are considered in isolation, the effect is to produce younger estimates for the age of the Wenlock and Ludlow. Harland *et al.* (1982) give an age of 421 Ma for the base of the Ludlow, and McKerrow *et al.* (1985) an age of 420 ± 2 Ma. Thus, the 418 Ma age for the intrusion of the undeformed dykes appears more likely to be post-Wenlock, and hence post-dates sedimentation in the Southern Uplands.

From the information that is presented in this paper all that can be firmly deduced is that the 'D_2' event pre-dates the age of the oldest undeformed dyke 418 Ma. Clearly the deformed dykes must be older than this, but since

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only 'rare examples of sheared dykes are recognized' and 'all of the main magma types were available throughout this event', it would appear that 'D_2' took place early in the magmatic episode. Consequently, in the absence of any age data, the deformed dykes need not necessarily be much older than 418 Ma, and so it is likely that all the intrusions post-date the age of the youngest sediments in the Southern Uplands (*C. lundgreni* zone, *c.* 424 Ma. Harland *et al.* 1982).

The major pervasive deformation in the Southern Uplands ('D_1' of Barnes *et al.*) comprises southeast verging folds with associated cleavage. This deformational episode has been widely related to accretionary thrusting (Anderson and Cameron 1979; Stringer and Treagus 1981; Knipe and Needham 1986). All the intrusions described by Barnes *et al.* post-date 'D_1'. Subsequent folding in the Southern Uplands is relatively small-scale and highly localized. There is no consensus on the origins of post 'D_1' deformation and it has been variously described as being 'compatible with propagation late in the subduction process' (Cameron 1981) or 'late accretion or collisional deformation' (Knipe and Needham 1986).

Barnes *et al.* relate 'D_2' 'to the final assembly of the thrust pile' because the 'D_1' and 'D_2' folds are coaxial. The rotation to the present subvertical attitude of the southeastern (Upper Llandovery and Wenlock) part of the Southern Uplands cannot have evolved during thrusting and most probably relates to impingement of the Lake District arc terrain. Clearly, such rotations could produce folds with similar vergence, and coaxial to, 'D_1' folds and these would correspond to the 'D_2' of Barnes *et al.* There is no evidence to suggest that 'D_2' occurred during the addition of the youngest (Wenlock) thrust packets to the accretionary wedge.

Thompson *et al.* (1984) point out that 'ultrapotassic magmas from deep within the upper mantle' are characteristic of post-collisional settings in other orogenic belts as well as in the British Caledonides, and that their intrusion, which frequently overlaps the latest phases of folding, continues for several million years. This is consistent with the Late Silurian to Early Devonian age of the dyke swarm, and its temporal relationship to the impingement of the Lake District. Also, similar dykes occur throughout the British Caledonides (Rock 1986) which suggests that there is no spatial relationship to subduction. They may be more closely related to the sinistral strike-slip regime that affected the whole area at this time.

The geochronological and structural data presented by Barnes *et al.* contains no evidence of an overlap between intrusion of the dyke swarm and subduction–accretion. Instead the dykes are related to the tectonic regime associated with the final closure of Iapetus and are entirely consistent with existing plate tectonic models for the Lower Palaeozoic.

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The provenance of granite boulders in conglomerates of the Northern and Central Belts of the Southern Uplands of Scotland

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Abstract: Rb–Sr whole rock isochrons from several suites of granite boulders which occur in Ordovician and Silurian conglomerates in the Southern Uplands of Scotland yield ages of around 1200 Ma, 600 to 700 Ma and 470 to 490 Ma. The plutonic and tectonic history recorded by these clasts corresponds more closely with that of NW Newfoundland than with that of Scotland. The petrography of the clasts can also be matched with exposed granite plutons in Newfoundland. Since the conglomerates were derived from the NW it is concluded that the Southern Uplands lay to the SE of Newfoundland. A total of 1500 km strike-slip displacement occurred between the Caradoc and the Early Devonian, consistent with oblique subduction of the Iapetus Ocean below the North American continental margin.

The Southern Uplands of Scotland occupy an important position in the British Caledonides since they record evidence of the events associated with the closure of the Iapetus Ocean. The stratigraphy and structure have been interpreted as that of an accretionary prism (Leggett *et al.* 1979) which formed as a result of subduction of the Iapetus oceanic plate beneath Scotland. Although some new interpretations have been made (Murphy & Hutton, 1986; Stone *et al.* 1987) the accretionary prism model remains valid (Kemp *et al.* 1986). It is clear that strike-slip displacements have also played an important role in the final stages of closure of the Iapetus Ocean, affecting the Grampian Highlands, the Midland Valley (Bluck, 1983) and the Southern Uplands, as well as some of the 'suspect terranes' of the Appalachians (Keppie, 1985). The sense of these displacements may be deduced from structural studies, but it is more difficult to make estimates of the scale of movements. Sediment provenance studies can be used to provide direct evidence of the magnitude of strike-slip displacements.

Granite clasts occur in a number of Ordovician and Silurian mass flow deposits within the Southern Uplands. These clasts are particularly useful in the study of sediment provenance since they provide large, discrete samples which record petrological, geochemical and geochronological data from the source area. This information can be used to deduce the timing and nature of magmatism in areas originally adjacent to the Southern Uplands and to distinguish between source areas that may appear superficially similar. Thus it is possible to pinpoint precisely the source area of the sediments and to deduce the magnitude, sense and timing of the large-scale displacements which have affected the Southern Uplands during and since the Ordovician.

Ordovician conglomerates are present at Corsewall Point and Glen Afton and a Silurian conglomerate at Pinstane Hill (Fig. 1). All three conglomerate units are mass flow deposits and palaeocurrent data indicate that they were derived from the NW. They have been interpreted as parts of submarine fan complexes which form a lateral input into the subduction trench (Leggett, 1980). The large clast sizes (up to 1.5 m) suggest that the material has not been transported far; thus it is assumed that the source area lay close to the margin of the subduction trench. Elsewhere in the Southern Uplands many sand and silt grade turbidites show palaeocurrents from the NE which, together with Sm–Nd crustal residence ages, suggest that this finer grained material may have been derived from a more remote source than the mass flow conglomerates (Miller & O'Nions, 1984).

Sampling and dating techniques

In order to date the granite clasts from these conglomerates, the Rb–Sr whole-rock method was used. This requires that isotope ratios of different clasts be used on a single isochron plot. Clearly when dealing with the products of erosion, transport and deposition, there is no guarantee that the clasts were all originally from the same pluton, but careful use of petrological observations combined with geochemical data allows suites of boulders to be selected which can be reasonably considered as cogenetic. K_2O–CaO–Na_2O diagrams are used in this paper to illustrate the chemical differences between the different groups of boulders, although this distinction can also be made using other major elements and those trace elements analysed (Rb, Sr, Nb, Zr and Pb; unpublished data).

A further problem in dating sedimentary detritus is that the clasts have been subjected to a degree of weathering. These effects were minimized by removing the weathered skin of the boulders and removing any veins during sample preparation so that the crushed sample is fresh. Any large xenoliths were similarly removed.

Rb and Sr concentrations were determined using either an XRF method similar to that of Pankhurst & O'Nions (1973) or by mass spectrometric isotope dilution analysis using a Rb–Sr mixed spike. Rb and Sr were separated by cation exchange on the same columns and Rb was further purified by loading as a chloroplatinate following the method of Gale *et al.* (1975). For each method the accuracy of the Rb–Sr determination was ±1%. Sr isotope analyses were performed on a V.G. Micromass 30 mass spectrometer. $^{87}Sr/^{86}Sr$ ratios are corrected for mass fractionation by normalizing to an $^{88}Sr/^{86}Sr$ value of 8.37521, and are further standardized to a value for the Eimer and Amend standard of 0.70800. The accuracy of these determinations is ±0.01%. Fitting of isochrons followed the method of Williamson (1968). A decay constant for ^{87}Rb of $1.42 \times 10^{-11}\ a^{-1}$ was used to calculate ages from isochrons. For those isochrons with a MSWD greater than one the errors were expanded to reduce the MSWD to one. All ages and initial ratios in this paper are quoted with 2σ errors (95% confidence). The isotope data are presented in Table 1.

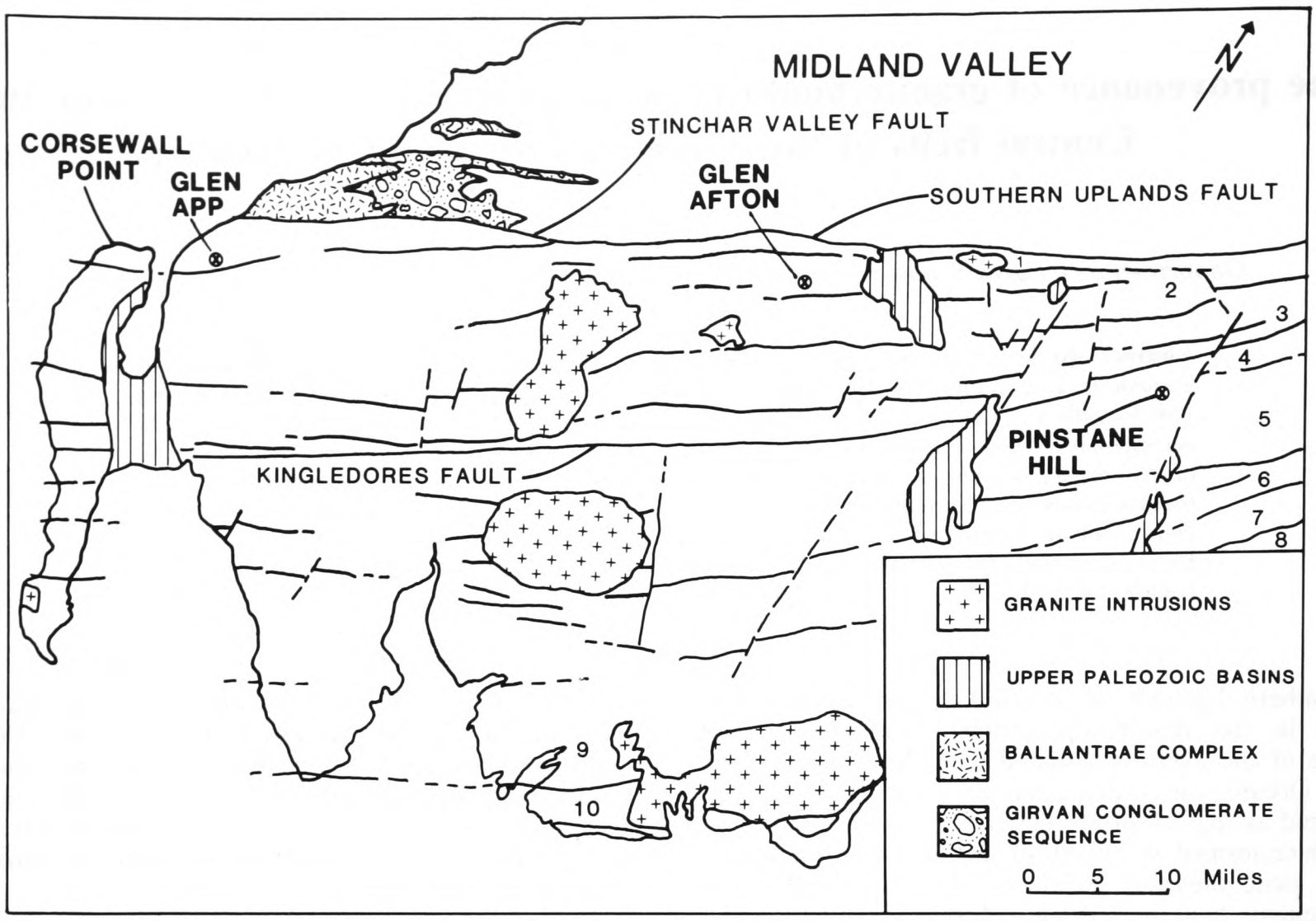


Fig. 1. A locality map (based on Leggett *et al.* 1982) of the western end of the Southern Uplands showing the position of the conglomerates investigated in this study, and the position of major faults. Numbers refer to the tracts of Leggett *et al.* (1982).

Petrological, geochemical and geochronological results

Corsewall Point

The granite clasts from Corsewall Point (grid ref. NX 982728), at the northern end of the Rhinns of Galloway, are from a thick sequence of conglomerates which also have equivalents along strike in Glen App. The deposit is of Late Llandeilo/Early Caradoc (probably *Nemagraptus gracilis* Zone) age (Kelling 1961; Floyd 1982; Leggett *et al.* 1979), and is part of the oldest sequence of sediments preserved in the Southern Uplands (Leggett *et al.* 1979), and hence probably the earliest to be incorporated into the accretionary prism. Leggett *et al.* (1979) considered that the northern boundary of the Southern Uplands follows the Stinchar Fault in this region, rather than the conventional line through Glen App which lies to the south.

The Corsewall Point conglomeratic sequence is at least 500 m thick and is largely made up of disorganized conglomerate bodies, some of which are channellized and erosive into earlier beds. They pass laterally into finer sandstones and silts. Others are of more considerable lateral extent, and beds are up to 4 m thick. Along with its lateral equivalents in the Rhinns of Galloway and Glen App, the Corsewall Point sequence has been interpreted by Holroyd (1978) as belonging to an inner fan facies association of a submarine fan. Palaeocurrent data (Holroyd 1978) indicate that sediment derivation was predominantly from the NW. The clast assemblage is dominated by granites, but acid volcanics, basalts and dolerites are also common. Chert fragments and gabbroic blocks are less common; intraformational clasts of greywacke and shale are also present.

From a sample of 30 granite clasts, five granite types have been recognized (Fig. 2). The most distinctive of these is a muscovite-bearing biotite granite which shows a weak foliation and contains abundant quartz xenoliths and more diffuse mafic xenoliths. Biotite is normally more abundant than muscovite, and plagioclase than alkali feldspar. There are limited quartz–feldspar intergrowths and the quartz shows strain extinction and sutured grain boundaries. Accessory minerals include apatite and zircon. The texture is hypidiomorphic granular. Nine clasts of this type define a Rb–Sr whole rock isochron which yields an age of 1265 ± 130 Ma, and an initial $^{87}Sr/^{86}Sr$ of 0.7046 ± 0.0020 (MSWD = 10.78). The high value for the MSWD reflects the scatter of points about the isochron. This is not thought to be a result of weathering, since there is little evidence of alteration of any of the mineral phases; nor is it likely to be a result of boulders coming from different plutons because of the remarkable uniformity of the petrography and chemistry of samples in this suite. It may reflect heterogeneity in the original magma, an interpretation that will be referred to later.

The most common granite clast type at Corsewall Point is an unfoliated hornblende–biotite granite. Two different varieties were distinguished on the basis of slight differences in chemistry and greater differences in petrography. The first group has a higher proportion of hornblende and small euhedral plagioclase crystals contained within large perthitic orthoclase and occasional microcline. The quartz grains show moderate effects of

Table 1. *Analytical results*

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Corsewall Point muscovite–biotite granites				
COP 101	85.89	332.38	0.7699	0.71807
COP 124	36.03	131.10	0.9024	0.72197
COP 27	84.98	266.78	0.9491	0.72176
COP 123	71.37	215.86	0.9907	0.72298
COP 3	96.58	252.15	1.1469	0.72571
COP 118	97.67	236.77	1.2496	0.72703
COP 119	90.35	201.25	1.3258	0.72884
COP 122	90.55	193.76	1.3809	0.73072
COP 24	120.82	231.89	1.7722	0.73473
Corsewall Point hornblende–biotite granites				
COP 110	64.34	421.52	0.4439	0.70963
COP 106	67.54	418.07	0.4708	0.71002
COP 102	85.25	368.13	0.6837	0.71162
COP 13	114.97	259.69	1.3997	0.71790
Corsewall Point hornblende–biotite granites				
COP 104	63.74	399.27	0.4651	0.71081
COP 109	60.80	319.54	0.5580	0.71165
COP 22	68.86	236.67	0.9334	0.71485
Corsewall Point biotite granites				
COP 108	74.17	362.87	0.6011	0.70973
COP 103	90.72	405.13	0.6595	0.71001
COP 11	55.40	178.75	1.0739	0.71291
COP 6	74.80	140.98	1.6289	0.71664
Glen Afton biotite granodiorites				
GA 46	45.37	265.77	0.4799	0.71244
GA 168	59.08	221.37	0.7976	0.71764
GA 165	68.81	239.55	0.8582	0.71862
GA 225	60.56	199.95	0.8774	0.71967
GA 11	62.18	195.29	0.9195	0.72046
Glen Afton muscovite granites				
GA 223	85.56	219.28	1.1300	0.71744
GA 232	99.00	240.78	1.1909	0.71797
GA 170	91.39	224.68	1.2329	0.71841
GA 39	108.23	243.12	1.3145	0.71934
GA 1	97.04	194.16	1.4479	0.72056
Glen Afton hornblende–biotite granites				
GA 51	68.08	283.76	0.7375	0.71160
GA 171	53.41	146.54	1.1265	0.71427
GA 221	51.82	92.81	1.7511	0.71853
GA 172	80.05	91.67	2.8792	0.72688
Pinstane Hill biotite granites				
PS 38	53.99	215.11	0.7433	0.71163
PS 43	39.11	139.81	1.0642	0.71397
PS 13	51.12	94.12	1.7084	0.71781
PS 3	74.76	98.47	2.4067	0.72265

strain. The second group has a more euhedral, equigranular texture, with zoned alkali feldspars present. The quartz shows no evidence of strain in this group. It is concluded that the two groups were derived from different plutons, and so were plotted on separate isochrons. The first group consists of three samples which yield a Rb–Sr isochron age of 603 ± 40 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7068 ± 0.0004 (MSWD = 0.12), while the second group of four samples yields a Rb–Sr isochron age of 600 ± 30 Ma, with an initial $^{87}Sr/^{86}Sr$ of 0.7059 ± 0.0003 (MSWD = 1.86).

A more sodium-rich set of granites is represented by a group consisting largely of quartz and feldspar, with biotite as the main mafic mineral, although small amounts of hornblende are present in one sample. The quartz is more highly strained than in the hornblende-bearing granites. One of the clasts in this group contains garnet and muscovite in addition, while other clasts contain small mafic xenoliths consisting largely of hornblende and plagioclase. The four clasts in this group yield a Rb–Sr isochron age of 475 ± 20 Ma, with an initial $^{87}Sr/^{86}Sr$ of 0.7056 ± 0.0002 (MSWD = 0.53).

Two other granite types are found at Corsewall Point. The plagiogranites consist mainly of large, subhedral plagioclase and quartz grains, with only minor amounts of perthitic alkali feldspar and biotite. The plagioclase is of albitic composition and shows no sign of strain, while the quartz grains are variably strained. They contain too little Rb for Rb–Sr dating, and plot in the 'ocean ridge granite' field of Pearce *et al.* (1984). Finally, three clasts of biotite–hornblende granodiorite were collected, which are strongly foliated and in thin section show recrystallization of quartz grains and kinking of biotite cleavage. These samples scatter on a Rb–Sr isochron plot, presumably as a result of open system behaviour resulting from deformational processes.

Glen Afton

The conglomerates at Glen Afton outcrop 6 miles south of New Cumnock, immediately to the north of the Afton reservoir dam (Grid ref. NS 628051). They are part of the Blackcraig Formation of Upper Caradoc age (*Dicranograptus clingani* Zone or younger; Floyd 1982). This is at least three graptolite zones younger than the Corsewall Point deposit, and occurs at the top of the sequence in tract 2 of Leggett *et al.* (1982). It is likely, therefore, that these sediments were deposited after the Corsewall Point sediments had been accreted.

The Glen Afton conglomerate unit is about 180 m thick and extends laterally for about 4 km, passing into thickly bedded greywackes of the Blackcraig Formation. Individual beds within the unit are up to 12 m thick, and generally show well-developed grading and erosive channellized bases (the mega-graded units of Kelling and Holroyd, 1978). A few clasts reach 1.5 m in diameter, although most are between 0.5 and 1 m. This represents a much smaller fan system than that at Corsewall Point, and it is interpreted by Holroyd (1978) as belonging to a mid-fan facies association.

Palaeocurrent data from within the conglomeratic unit and the surrounding greywackes show a predominant northwesterly derivation for the material (Holroyd 1978). The types of clasts show some differences from those at Corsewall Point. In addition to the granite clasts, granitic gneisses, felsic volcanics, acid porphyries, dolerites, basaltic material, some of which is heavily epidotized, some gabbro and a few clasts of quartzite are present. Intrabasinal material consists of chert, sandstone clasts and shale fragments, the latter two becoming increasingly important up the sequence. Thirty-two granite clasts were sampled at Glen Afton and a similar range of granite types was found here as at Corsewall Point, although there are some differences in chemistry, which are also reflected in petrography (Figs 2 and 3). The range in the age of the granite clasts is similar.

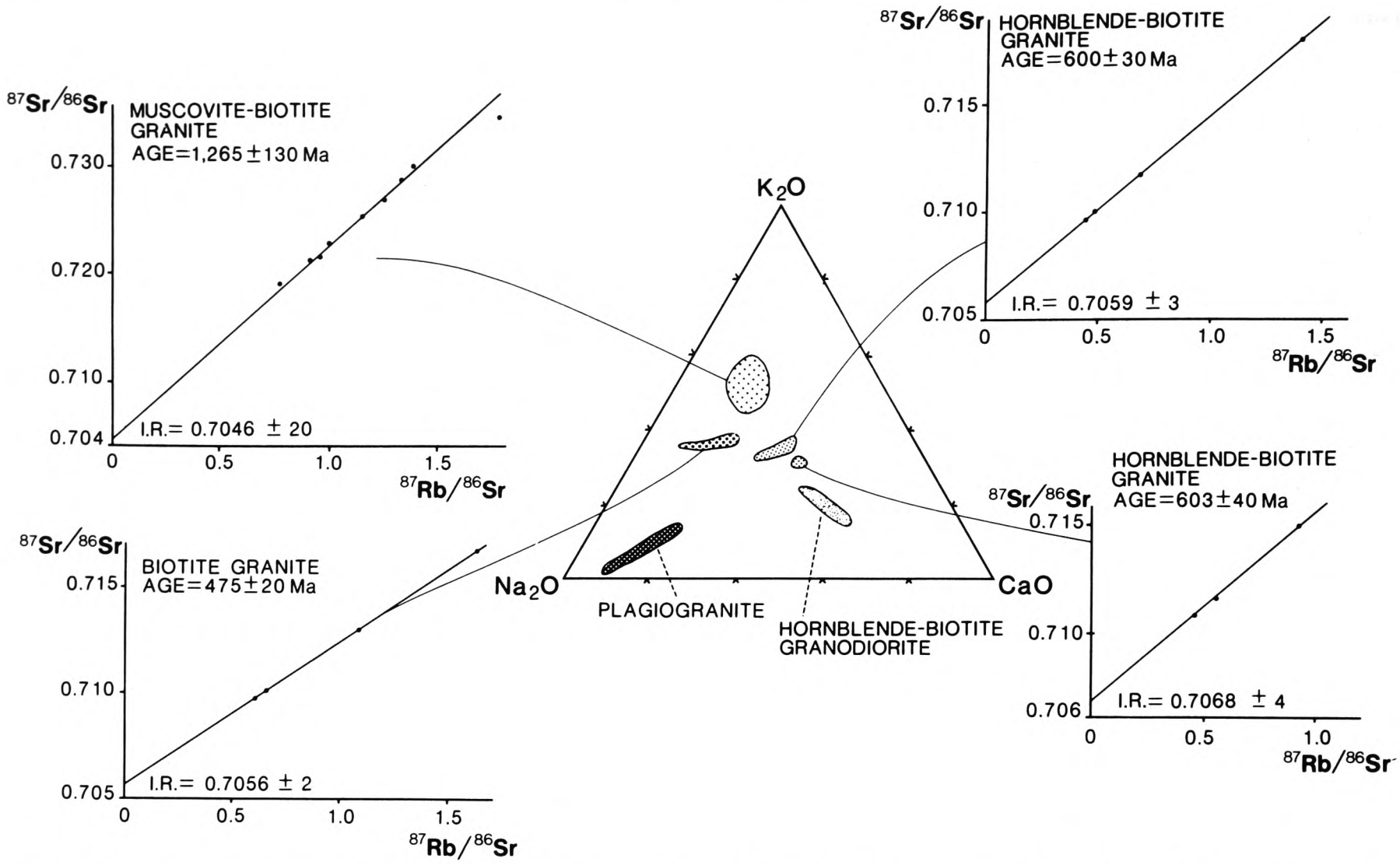


Fig. 2. Isochron diagrams for the different suites of granite clasts in the Corsewall Point conglomerate. The triangular diagram shows the differences in sodium, potassium and calcium contents of the petrographically distinct groups.

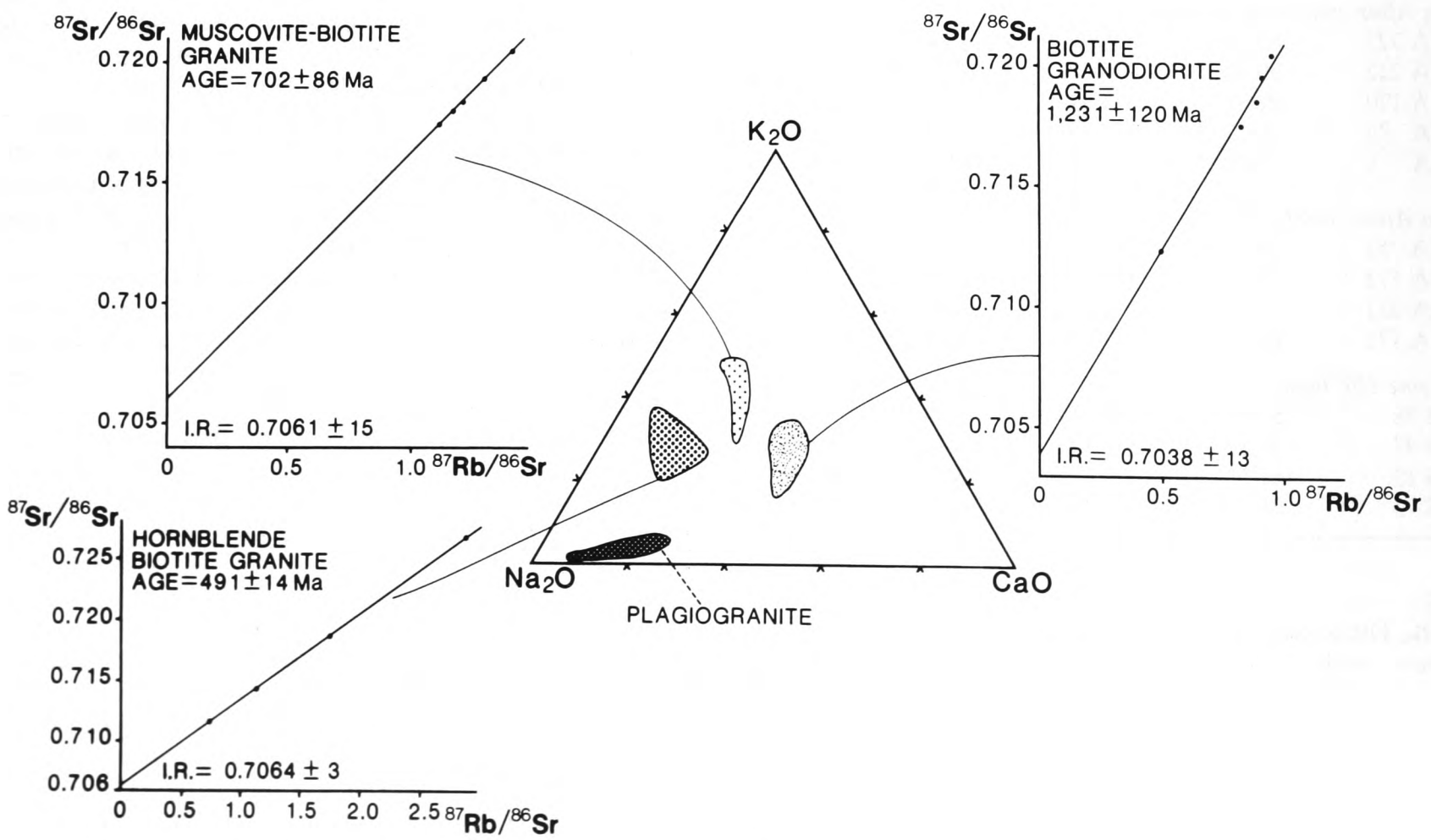


Fig. 3. Isochron diagrams and Na_2O–K_2O–CaO diagram for granite clasts from the Glen Afton conglomerate. Petrographic types shaded as in Fig. 2.

The oldest clasts are weakly foliated biotite-bearing granites which contain large, moderately strained, anhedral quartz crystals, a few large subhedral orthoclase grains and a large number of small plagioclase crystals, which occasionally have sanidine overgrowths, which are in turn intergrown with quartz. The biotite shows some alteration to chlorite. A five-point Rb–Sr whole rock isochron gives an age of 1231 ± 120 Ma with an initial $^{87}Sr/^{86}Sr$ of 0.7038 ± 0.0013 (MSWD = 5.89).

The muscovite-bearing granites are younger than their counterparts at Corsewall Point and petrographically quite distinct. The quartz is less strained and the biotite and plagioclase are undeformed. Large alkali feldspars enclose small euhedral plagioclase crystals and have limited intergrowths with quartz. Five samples from this group yield a Rb–Sr isochron with an age of 702 ± 86 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7061 ± 0.0015 (MSWD = 0.19).

The more sodic granites are represented by a group of hornblende–biotite granites. They are of granodioritic composition, with abundant sodium-rich plagioclase crystals and a few large perthitic alkali feldspars. There are limited quartz–feldspar intergrowths, the quartz being quite unstrained and forming large anhedral crystals. The biotite and hornblende form only a small proportion of the total mineralogy, and are present in varying relative proportions. Four clasts yield a Rb–Sr isochron with an age of 491 ± 14 Ma, with an initial $^{87}Sr/^{86}Sr$ of 0.7064 ± 0.0003 (MSWD = 0.67).

The remaining group of clasts are plagiogranites similar to those described from Corsewall Point, but with additional samples which show a spectacular development of granophyric textures in which quartz is intergrown with both alkali feldspar and plagioclase. In addition there are a small number of clasts with large acicular hornblende crystals which have grown across the main igneous fabric of the rock. This presumably reflects a thermal event not recorded by other clasts, but no samples suitable for dating could be collected.

The range of granite types present in the conglomerates at Corsewall Point and Glen Afton is similar, as is the range in age of the detritus. However, there is no direct correspondence between the age, chemistry and petrography of the two groups of clasts; this leads to the conclusion that the detritus was derived from a different area or a different level in a similar crustal block.

Pinstane Hill

The limited exposure of the conglomerate at Pinstane Hill means that the precise age of the deposit is unknown and that palaeocurrent data are scarce. Pinstane Hill is 8 miles NW of Moffat (Grid ref. NT 017168) and lies just south of the Kingledores Fault, a major sinistral strike-slip fault (Anderson & Oliver 1986), which separates Ordovician greywackes of the Northern Belt from Silurian greywackes of the Central Belt. The conglomerate occurs in tract 4 of Leggett *et al.* (1982), and by analogy with other outcrops along strike is probably of Lower Llandovery age, possibly in the *Cystograptus vesiculosus* or *Monograptus cyphus* Zones. Palaeocurrent indicators have not been observed in the field, but the conglomerate body has a lenticular shape, is interbedded with fine-grained sandstone, and passes laterally into granule grade conglomerates and coarse massive sandstones to the NE and SW. This pattern is compatible with the deposit being part of a channel, possibly in a fan complex, with sediment derivation from the NW.

Granite clasts form a smaller proportion of the coarse detritus in this deposit. Volcanic rocks, cherts and quartzite are the most common clast types, and basaltic clasts, vein quartz and schists, sandstone blocks and shale fragments are also present. The maximum clast size at Pinstane Hill is 30 cm. Ten granite clasts were sampled which show a more restricted range than is present at Corsewall Point or Glen Afton (Fig. 4). The plagiogranites are similar to those already described and again show some spectacular intergrowth patterns. The biotite granites are sodium-rich and contain some large euhedral grains of biotite which are partially altered to chlorite. Most of the biotite is interstitial to the dominant quartz and feldspar. Euhedral plagioclase crystals are overgrown by perthites which in turn are intergrown with quartz. A four-point Rb–Sr isochron for the biotite granites yields an age of 458 ± 26 Ma, with an initial $^{87}Sr/^{86}Sr$ of 0.7068 ± 0.0005 (MSWD = 3.04). Additionally, there are some deformed granites which show extensive recrystallization, but do not yield any geochronological information.

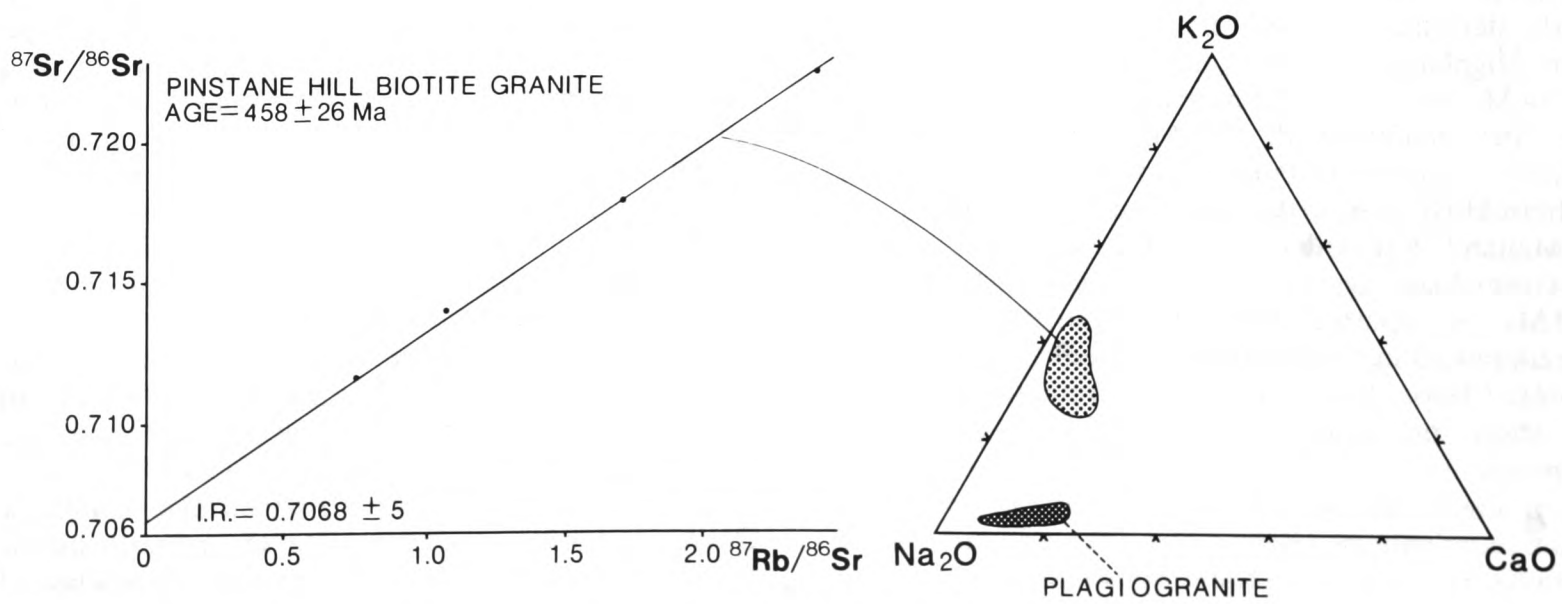


Fig. 4. Isochron diagram and Na_2O–K_2O–CaO diagram for granite clasts from the Pinstane Hill conglomerate. Petrographic types shaded as in Fig. 2.

The biotite granites are of a similar age and chemistry to the biotite granites at Corsewall Point and Glen Afton, although there are some petrographic differences. Consequently they may have a common source, but the absence of older granites in the detritus at Pinstane Hill, as well as the different petrography of some of the other clasts, suggests that by the Llandovery, the composition of the source supplying detritus to the northwesterly derived conglomerates in the Southern Uplands had changed again.

Possible sources for Southern Uplands granitic detritus

All three conglomerates included in this study contain clasts that have been derived from the NW. The large size of the clasts would suggest that they had originated not far from the continental margin, where they may have been rounded in a littoral environment. They were subsequently transported down the trench slope by mass flow processes into the deeper water facies of which they are now a part. The geochronological information obtained from the clasts provides criteria which may be used to identify suitable source areas. Such an area would contain foliated granites with an age of about 1200 Ma, undeformed granites with an age of 600 to 700 Ma and a variety of deformed and undeformed sodium-rich granites with ages between 470 and 490 Ma, and would lie close to the margin of Lower Palaeozoic Laurentia.

Scotland and Ireland

Traditionally, the Scottish Highlands have been regarded as the source of the coarse detritus in the Southern Uplands (Peach & Horne 1899, p. 210), since this area presently lies to the NW. However, granites as old as 1200 Ma are not known to occur anywhere in Scotland or Ireland. The Ardgour gneiss in Argyll has a Rb–Sr whole-rock age of 1020 ± 50 Ma (Brook *et al.* 1976) but none of the clasts sampled in the Southern Uplands have the gneissic foliation of this rock. Similar considerations preclude any of the other migmatite complexes in the NW Highlands, and the Annagh gneiss of County Mayo, which has an age of 1070 ± 20 Ma (Holland 1981, p. 12).

The Charn Chuinneag granite in Ross-shire has a Rb–Sr whole-rock age of 548 ± 10 Ma (Long & Lambert 1963) and is similarly deformed, as are the 'older granites' of the Grampian Highlands further south. These have ages of around 514 Ma and were deformed during the Grampian Orogeny; the undeformed, 600 Ma hornblende–biotite granite clasts at Corsewall Point could not have come from the Northern Highlands or the Grampian Highlands.

The Midland Valley basement may contain elements with a Grenvillian age. A Rb–Sr whole-rock age of 1101 ± 63 Ma is reported from garnet-bearing granulite xenoliths contained in Carboniferous volcanic vents (Davies *et al.* 1984). Clasts of comparable age from the Southern Uplands show no evidence of such high grades of metamorphism.

Much younger granite clasts are abundant in the Ordovician sediments of Girvan which are unconformable on the Ballantrae complex. These conglomerates outcrop immediately to the north of the Southern Uplands, and some were deposited at the same time as the Corsewall Point and Glen Afton conglomerates. Rb–Sr mineral ages from individual granite clasts which are largely undeformed yield ages which have an even spread from 451 to 559 Ma, with an additional single clast with an age of 593 ± 28 Ma (Longman 1980). Highly deformed alkali granite clasts in the Kirkland conglomerate, which is at the base of the sequence at Girvan, have a Rb–Sr whole-rock age of 648 ± 32 Ma (Ince 1984). No equivalent of this highly deformed material is seen in the boulders of the Southern Uplands, and apart from a similar age for some of the younger detritus in the Girvan conglomerates, there is little correlation between the age and petrography of the granite clasts found in the Midland Valley and in the Southern Uplands. The trondhjemites in the Ballantrae complex have a U–Pb zircon age of 483 ± 4 Ma (Bluck *et al.* 1980) and may be considered as a possible source for some of the younger sodium-rich granite clasts in the Southern Uplands.

However, it is clear that the Scottish Highlands, the Midland Valley and Ireland are unable to provide the range of granitic detritus found in the Southern Uplands and so it is necessary to look elsewhere along the margin of Laurentia. Since the Southern Uplands has been affected by an element of sinistral shear during its formation (Stringer & Treagus 1981; Anderson 1987) an alternative source area for the granite clasts must be sought further to the SW. The Rockall Bank has a basement of Lewisian gneiss, which has been affected by Grenville thermal events in the south (Miller *et al.* 1973), but can be considered as a continuation of the crust of NW Scotland (Moorbath & Welke 1968). It is unlikely to be a suitable source. Newfoundland provides the next sample of the Ordovician margin of Laurentia in this direction.

Newfoundland

Extensive outcrops of Grenville-age rocks are found in the Long Range of Newfoundland (Fig. 5). They consist of quartzo-feldspathic gneisses and some amphibolites which have been intruded by a considerable volume of post-metamorphic megacrystic and massive granites. Two of these plutons have been dated using Rb–Sr whole-rock isochrons. The Portland Creek Pond pluton gives an age of 1081 ± 165 Ma, with an initial $^{87}Sr/^{86}Sr$ of 0.7071 ± 0.0059 (MSWD = 4.42), and the Hawke Bay pluton gives an age of 1132 ± 154 Ma, with an initial $^{87}Sr/^{86}Sr$ of 0.7063 ± 0.0046 (MSWD = 7.12). (Data from Pringle *et al.* (1971) recalculated using ^{87}Rb $\lambda = 1.42 \times 10^{-11}\,a^{-1}$.) These granites and other plutons further to the north consist largely of quartz, plagioclase, microcline, orthoclase and biotite; distinctive petrographic features include deformed quartz grains, perthitic textures, myrmekitic intergrowths and apatite as a common accessory mineral (Pringle *et al.* 1971; Bostock *et al.* 1983).

A period of granite emplacement at about 600 Ma is seen in the Round Point Granite (Williams *et al.* 1985). It is a small, high-level intrusion with alkalic affinities, associated with a bimodal suite of volcanic rocks which occur in a thrust sheet structurally above the autochthonous sequence of Cambro-Ordovician carbonates of western Newfoundland. The granite has a U–Pb zircon age of 602 ± 10 Ma. Quartz and microcline dominate the mineral assemblage, and granophyric textures are common. Plagioclase, biotite and muscovite are also present. Deformation is variable and increases towards the thrust. The granite may be related to the rifting which affected this part of the continental margin

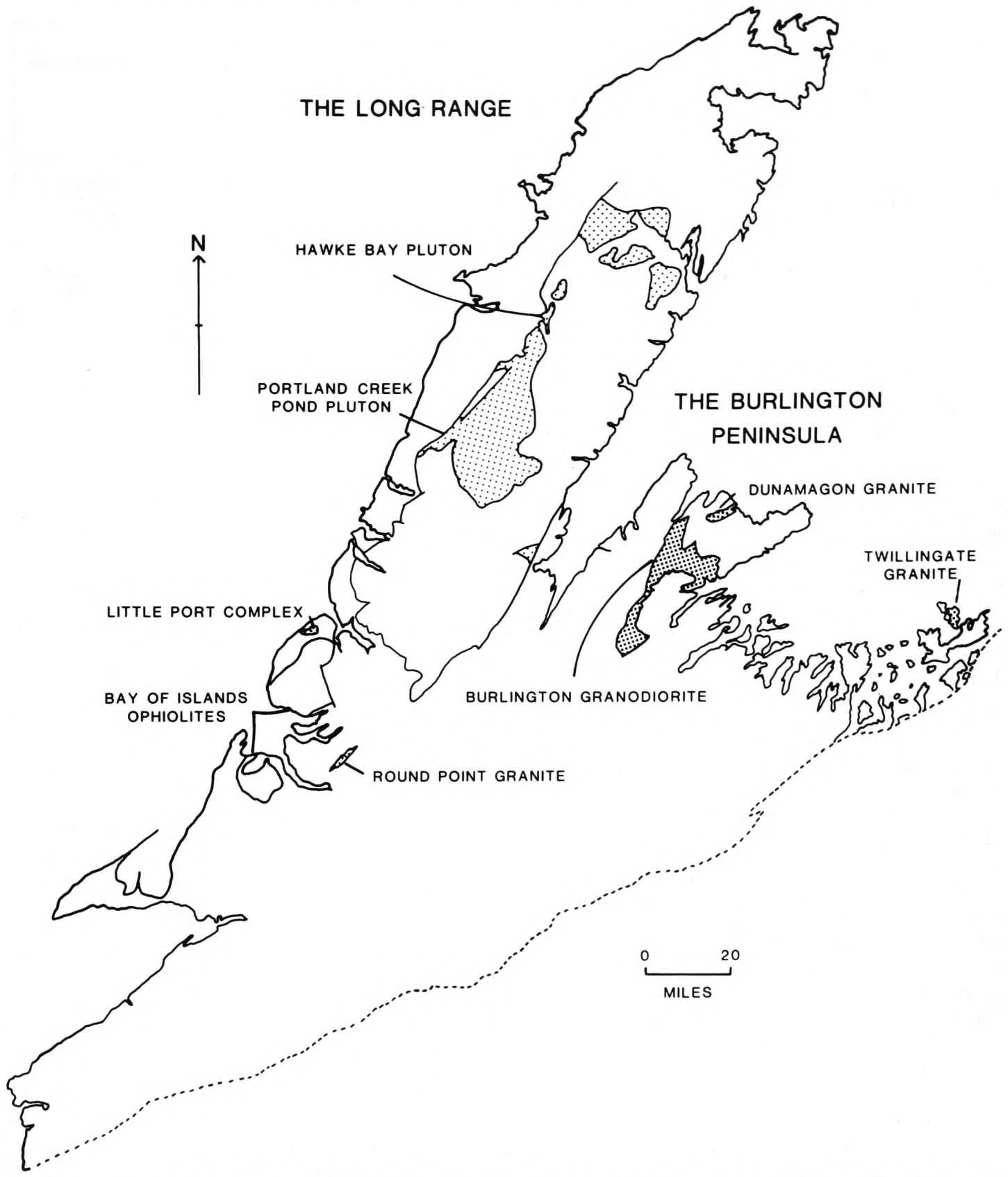


Fig. 5. Simplified geological map of NW Newfoundland showing the distribution of Ordovician and earlier granite plutons. Shading shows plutons with similar chemistry and petrography to the clast types identified in Figs 2, 3 & 4.

during the Late Precambrian (Williams *et al.* 1985), but there are no other granites of this age known from this region.

Ordovician granites in western Newfoundland are more numerous and variable in terms of chemistry and petrography. Lower Ordovician granites are associated with ophiolitic complexes—a typical oceanic plagiogranites occur within the Bay of Islands Complex and other trondhjemitic rocks occur in the Little Port Complex and on Twillingate Island. The latter two have been interpreted as island-arc granites (see Malpas 1979, for a summary), and have yielded U–Pb zircon ages of 508 ± 5 Ma for the Little Port complex (Mattinson 1975) and 510 ± 17 Ma for the Twillingate Granite (Williams *et al.* 1976). The plagiogranites of the Bay of Islands complex intrude gabbros and diorites and appear to form a differentiation series with them (Malpas 1979). They consist almost entirely of quartz and plagioclase of albitic composition and are chemically characterized by high Na_2O, very low CaO and K_2O, very low Rb and high Y (see Pearce *et al.* 1984). They are largely undeformed except where close to thrusts. These contrast with the Twillingate Granite and Little Port Complex trondhjemites which are highly deformed and show extensive cataclastic textures in thin section. Chemically they are richer in K_2O and Rb and poorer in Y and, petrographically, hornblende is present in addition to the quartz and sodic plagioclase.

Granites of Middle Ordovician age occur in the Burlington Peninsula—the Burlington Granodiorite—which

intrudes the Lower Ordovician Pacquet Harbour Group, has a Rb–Sr whole rock age of 494 ± 34 Ma and a $^{40}Ar/^{39}Ar$ hornblende cooling age of 464 ± 4 Ma (Hibbard 1984; Dallmeyer & Hibbard 1984). The Dunamagon Granite also intrudes this unit and yields U–Pb zircon ages of 460 ± 12 Ma (Hibbard 1984) and 435 ± 15 Ma (Mattinson 1977) which indicate a magmatic age of about 450 Ma. Other U–Pb, Rb–Sr, K–Ar and $^{40}Ar/^{39}Ar$ dates show considerable scatter which may indicate isotopic disturbance associated with deformation of this granite and later Acadian thermal events. The Burlington Granodiorite consists of a number of intrusive phases (Epstein 1983). Most typically it consists of euhedral quartz and perthitic alkali feldspar, with hornblende as the most common mafic mineral (Neale, cited by Hibbard 1984). The later phases are quartz-rich and contain biotite as the main mafic mineral, but with additional garnet and muscovite in some parts of the intrusion (Epstein 1983). The quartz commonly shows strain shadows and sutured boundaries. The Dunamagon Granite is a more alkali granite which contains abundant perthitic microcline and orthoclase, with biotite as the main mafic mineral. The quartz shows shadowy extinction patterns and deformation lamellae (Baird 1951).

A comparison of the Newfoundland granites and the Southern Uplands detritus

The preceding description of the pre-Silurian plutonic history of NW Newfoundland illustrates that granite intrusions of similar ages to the granite clasts of the Southern Uplands occur there (Fig. 6). A further comparison based on the petrography of the clasts and the intrusions of particular ages can be made. The greatest similarities to the granites of NW Newfoundland are seen in the granite boulders at Corsewall Point.

Considering first the *c.* 1200 Ma granites, the muscovite–biotite granites at Corsewall Point and the Long Range granites have a similar potassium-rich chemistry. Muscovite is more prominent in the clasts, while the Long Range granites are richer in microcline and apatite. Both show limited quartz–feldspar intergrowths, but this is more common in the Long Range granites. The Long Range granites are more strongly foliated in hand specimen, but in thin section both show comparable degrees of strain, with some recrystallization of quartz grains and folding of biotite and/or muscovite and plagioclase twin lamellae. The MSWD values of the isochrons from both the Corsewall Point muscovite granites and the Long Range intrusions are large, which suggests a scatter of points about the line for reasons other than analytical error. The exact values of MSWD are not directly comparable because of the considerably larger analytical error in the original data of Pringle *et al.* (1971) for the Long Range granites. It was suggested that the large MSWD of the isochron for the clasts was due to isotopic heterogeneity in the original magma. This might also be the case for the Long Range granites since the samples were all collected from a single pluton. Although this may reduce the significance of the result in terms of an absolute age determination, it shows that the isotopic characteristics of the intrusions and the clasts are similar.

The *c.* 600 Ma granites are not comparable. The granite of this age in Newfoundland is deformed and quite strongly alkalic. Microcline dominates the mineralogy, with muscovite also present. The clasts of this age from Corsewall Point

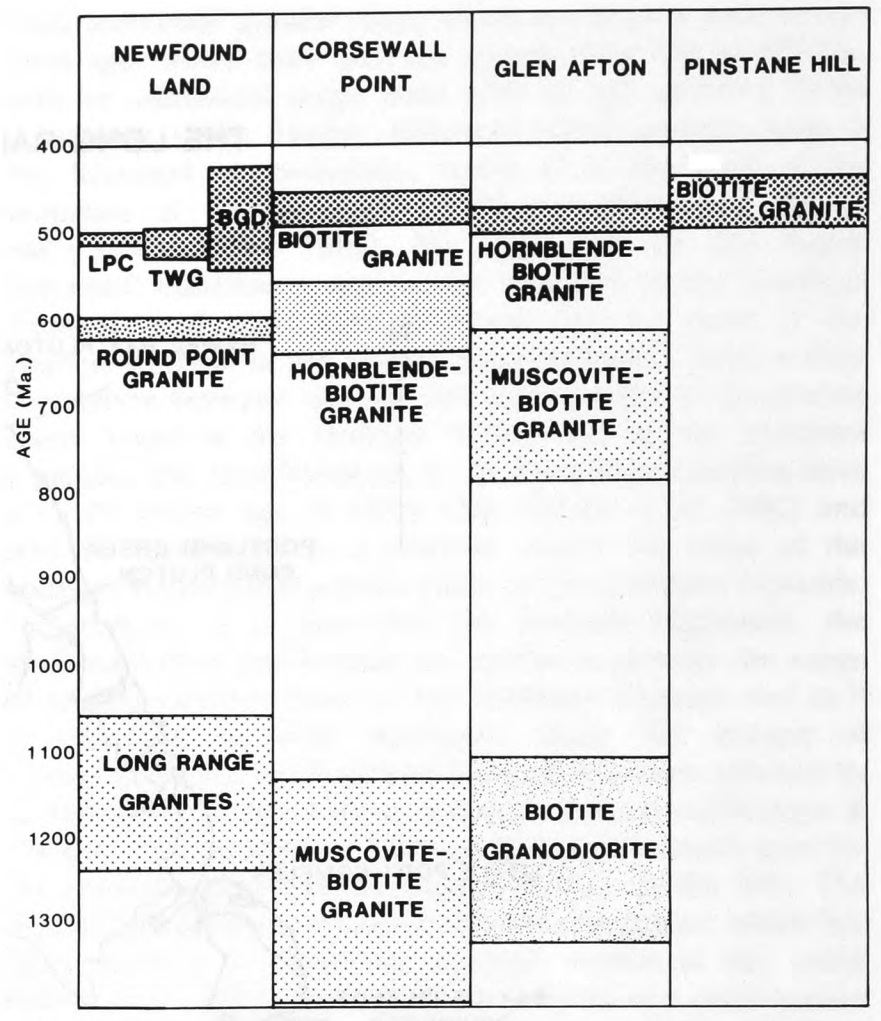


Fig. 6. A summary of the petrography and igneous history of the source areas of the Southern Uplands conglomerates and NW Newfoundland. The vertical scale represents age and the thickness of the bars shows errors in age determinations. Shading of the different petrographic types is the same as used in previous diagrams. LPC, Little Port Complex; TWG, Twillingate Granite; BGD, Burlington Granodiorite.

are unfoliated, rich in calcium, are hornblende-bearing and contain a much larger proportion of plagioclase. The Round Point Granite in Newfoundland is of very limited extent but hornblende granites of this age are characteristic of other parts of the Grenville province, particularly the Blue Ridge Mountains of western Virginia (Mose & Nagal 1984; Odom & Fullagar 1984).

Only one suite of clasts at Corsewall Point yielded an Ordovician age; these correspond very closely with the later stage biotite granites of the Burlington Granodiorite complex. One of the clasts in this suite contains large subhedral fractured garnets dispersed throughout the specimen, associated with small amounts of muscovite. The biotite-bearing late stages of the Burlington Granodiorite also have garnet- and muscovite-bearing phases, which show similar degrees of strain in thin section (Epstein 1983). The other clasts in this suite contain small mafic inclusions, also a characteristic of the Burlington Granodiorite. The major and trace element chemistry of this suite is very similar to that of the garnet-bearing phases of the Burlington Granodiorite.

Other sodium-rich clasts, although not dated, correspond to other Ordovician granites exposed in Newfoundland. Plagiogranites similar to those described from the Bay of Islands ophiolite form a small proportion of the clasts. Also, there are some highly deformed biotite-bearing clasts with a similar chemistry and petrography to the trondhjemites of the Little Port Complex and the Twillingate Granite.

Newfoundland is thus a suitable source for all the

granitic detritus found at Corsewall Point, with the exception of the 600 Ma granites. It is not so easy to make such direct comparisons with the detritus at Glen Afton. The *c*. 1200 Ma clasts have a more calcium-rich chemistry which is reflected by the large proportion of plagioclase present. Textures are less equigranular, and the presence of small euhedral plagioclase crystals enclosed in large anhedral quartz and alkali feldspar crystals contrasts with the interlocking anhedral textures of the Long Range and Corsewall Point granites of this age. However, this suite also shows a weak foliation in hand specimen and the quartz grains show evidence of considerable strain. The 702 ± 86 Ma muscovite-bearing granites are much more alkalic than the 600 Ma hornblende granites from Corsewall Point and resemble more closely the Round Point Granite from Newfoundland. However, these clasts are not as strongly potassic as the Round Point Granite, and have quite different trace element patterns. Granites of this age are known from elsewhere in the Grenville province (Odom & Fullagar 1984). The 491 Ma clasts are sodium-rich like their Newfoundland counterparts but contain hornblende in addition to biotite and are much less strained than the clasts at Corsewall Point. Although the Glen Afton clasts have a similar chemistry to the Ordovician trondhjemites of Newfoundland, it is not possible to make such detailed comparisons as it is for the clasts of a similar age at Corsewall Point. Plagiogranites are more abundant in Glen Afton and show a greater variety of textures, for instance the spectacular granophyric intergrowths, than those at Corsewall Point or in the Bay of Islands.

The material at Pinstane Hill forms a more limited basis for comparison. Both plagiogranites and biotite-bearing trondhjemitic rocks of Middle Ordovician age and having a sodium-rich chemistry are present, but they lack any distinctive petrographical features. As previously stated, these clasts could have had a similar source to the Ordovician clasts found at Corsewall Point and Glen Afton, but the absence of older material suggests that the source may be different. On the basis of the information currently available it is not possible to distinguish between a source similar to the Newfoundland granites of this age or one more similar to the Midland Valley where the Ballantrae complex contains trondhjemites with a similar Ordovician age and where there is no evidence for older granites.

Further comparisons can be made using initial strontium isotope ratios obtained from the suites of clasts, which should be similar to the initial ratios of granite plutons in the source areas. The initial ratios of the *c*. 1200 Ma clasts from Corsewall Point and Glen Afton overlap, within error, those obtained from the Long Range granites. This supports the view that the source areas for these two conglomerates were similar, and that a terrane such as the Long Range would be a suitable source. The Ordovician clasts show more scatter, and the initial ratio of the Corsewall Point biotite granite suite does not overlap with that of the Burlington Granodiorite; however, the Rb–Sr data were obtained from an earlier hornblende-bearing phase of the pluton, rather than the biotite–muscovite–garnet-bearing phase with which the comparison was being made.

Conclusions and implications

The study of granitic detritus in the Southern Uplands has shown that granite clasts with ages of 1200 Ma, 600–700 Ma and 470–490 Ma are present in the conglomerate bodies derived from the NW. Similar granites of these ages are not presently exposed in Scotland, but NW Newfoundland has a closely comparable plutonic history to that recorded by the conglomerate clasts. The deformation seen in the clasts is similar to that seen in granites of equivalent ages in NW Newfoundland, suggesting a similar tectonic history.

The closest comparison can be made between Newfoundland and the clasts in the earliest accreted sediments, at Corsewall Point. In the Early Caradoc the source area for the conglomerates was very similar to NW Newfoundland. It is unlikely that this area extended further to the east. Gravity and magnetic data (Haworth & Jacobi 1983) show that the easterly margin of the Grenville province lies close to the east coast of the Long Range peninsula and that it continues northwards, passing SE of Labrador. Seismic data (Keen *et al.* 1986) show that thinned Grenville crust extends no more than 70 km to the east of this line. Thus, the Southern Uplands must have been SE of Newfoundland at this time.

Three to four million years later, when the Glen Afton conglomerate was deposited, granite plutons of different petrography and with different deformational fabrics were shedding detritus into the subduction trench. The combination of age and initial isotope ratio information suggests that the source area was adjacent to that of the Corsewall Point conglomerate and had a broadly similar igneous history, differing only in the details of petrography and deformational history. The Lower Llandovery Pinstane Hill conglomerate was deposited approximately six million years later and it is possible that the source area had changed again by then.

Since the source areas of the conglomerates changed during the development of the Southern Uplands it is likely that strike slip movements began in the Caradoc. The Southern Uplands terrane must have been displaced approximately 1500 km from its original position SE of Newfoundland, relative to cratonic North America. This displacement took place during the formation of the accretionary complex, producing sinistral structures, and continued until the end of the Lower Devonian (McKerrow 1987), a period of 63 Ma (McKerrow *et al.* 1985) which gives an average displacement rate of about 2.5 cm a^{-1} for the Southern Uplands relative to cratonic North America. This would have resulted from the oblique subduction of the Iapetus oceanic plate.

Not all of this displacement needs to have occurred on the Southern Uplands Fault, which marks the northern boundary of the accretionary complex. Other faults in the British Caledonides have been affected by sinistral displacements (Bluck 1984; Dewey & Shackleton 1984; Hutton *et al.* 1985) which have also been interpreted as the result of oblique subduction (Soper & Hutton 1984). Thus it is likely that the major faults such as the Great Glen Fault, the Highland Boundary Fault and the Southern Uplands Fault, as well as numerous smaller faults within the Grampian Highlands and the Southern Uplands (and possibly unexposed faults in the Midland Valley) all absorbed some of the component of oblique subduction parallel to the continental margin. Such a complex pattern landward of an accretionary complex in a zone of oblique convergence occurs in New Zealand today (Walcott 1978), and is predicted by theoretical considerations (Dewey 1981). The displacements on the Southern Uplands Fault might be of the order of 300 km (McKerrow 1987). This could explain the juxtaposition of the Southern Uplands accretionary

complex and the proximal fore-arc basin of the Midland Valley (Bluck 1983).

The evidence presented here allows the sense and magnitude of the strike-slip displacements which have affected the Southern Uplands to be estimated. The scale of these movements shows that oblique subduction of the Iapetus oceanic plate was important during the formation of the Southern Uplands accretionary complex. This also affected other Caledonian terranes in the British Isles, each of which has a distinct tectonic history and boundaries marked by similar sinistral displacements. The Southern Uplands conforms to the criteria used to identify suspect or displaced terranes elsewhere (Keppie 1985), and so may be regarded as an example of one.

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APPENDIX 7.

Rb-Sr WHOLE-ROCK ISOCHRONS - ADDITIONAL CONSIDERATIONS.

A7.1 Corsewall Point muscovite-biotite granites - possible mixing effects.

Nine muscovite-biotite granite clasts from the Corsewall Point conglomerate (Group A1) were used to define a whole-rock isochron which yielded an age of 1,265 ± 130 Ma (Chapter 4.2.a.i). It was suggested that the high MSWD of this isochron (10.78) resulted from heterogeneities in the magma from which the granite crystallized, probably caused by the presence of incompletely digested pelitic xenoliths which are a common feature of this group of clasts. However, an alternative interpretation of these observations is that the isochron may represent a mixing line between igneous and pelitc end-members, in which case it would no longer necessarily follow that the clasts were derived from a pluton intruded at 1,265 ± 130 Ma.

The mixing hypothesis was assessed by considering a plot of present day Sr isotopic composition against the reciprocal of the Sr concentration in the samples used to construct the isochron (Fig. 4.2). A linear relationship between the data points on such a diagram would indicate that simple mixing between two isotopically distinct end-members could have taken place. A more complete plot of present day Sr isotopic composition against the reciprocal of Sr concentration in all the analysed granite clasts from the Corsewall Point conglomerate (Fig. A7.1) shows a tolerably good linear relationship between the c. 600 Ma hornblende-biotite granites (Groups A2a and A2b) and the

muscovite-biotite granites. This would suggest that if the isotopic variation in the muscovite-biotite granites is the result of mixing between two isotopically distinct end-members, the igneous end-member is most probably represented by the hornblende-biotite granites. Consistent results obtained from two Rb-Sr whole-rock isochrons, both with low MSWD's, and two independently determined Rb-Sr mineral isochrons (Longman, 1980) indicate that the hornblende-biotite granites crystallized at about 600 Ma (Chapter 4.2.a.i and 4.2.a.ii). It is therefore likely that any postulated mixing event must also have happened at about this time. The isotopic composition of the pelitic end-member is not known as the xenoliths are small and cannot easily be separated from the granite clasts.

It should be noted that the three samples of foliated hornblende-biotite granodiorite (Group A3) also plot on the trend defined by the unfoliated hornblende-biotite granites (Group A2) in Fig. A7.1. These clasts have Sr isotopic characteristics similar to those of the muscovite-biotite granites, but show no evidence of pelite contamination. Because they are strongly deformed it was assumed that they are much older than the 600 Ma hornblende-biotite granites, and a similar age to the muscovite-biotite granites (Chapter 4.2.a.i). However, if the relationships between the groups of granite clasts in Fig. A7.1 are taken as evidence of magma mixing at 600 Ma, then it might be expected that the Sr isotopic characteristics of the foliated hornblende-biotite granodiorites should also be consistent with such a process. The four clasts of biotite granite (Group A4) which yield a Rb-Sr whole-rock isochron age of 475 ± 25 Ma plot on a separate trend in Fig. A7.1, and have distinct Sm-Nd isotopic characteristics (Chapter 4.3.a). Consequently, it is likely that the biotite granite clasts were derived from an unrelated pluton, and they are not considered further in this discussion.

The feasibility of the mixing hypothesis can be assessed by considering the Sr and Nd isotopic characteristics of the different groups of granite clasts at 600 Ma, when mixing is assumed to have occurred. It can be seen from Fig. A7.2 that at this time the muscovite-biotite granites contained Nd of a similar or slightly less radiogenic composition than the hornblende-biotite granites and granodiorites, and Sr of a considerably more radiogenic composition. Additional Sm-Nd isotopic determinations have been carried out on clasts from the Corsewall Point conglomerate and the results are presented in Table A7.1.

In order to illustrate the effects of pelite contamination on the isotopic composition of the hornblende-biotite granite magma, the field defined by the isotopic composition at 600 Ma of samples from the Moine schist is also shown. Rb-Sr whole-rock isochrons defined by suites of samples from different units in the Moine schist indicate that they have suffered Rb and Sr isotopic re-equilibration subsequent to 600 Ma, but the "domain average" Rb and Sr isotopic composition of each suite has evolved from a common source at about 1,000 Ma (Brewer et al., 1979). These values have been used to estimate the Sr isotopic composition of the Moine schists at 600 Ma and have been combined with independently determined Sm-Nd analyses of different samples of pelite from the Morar division of the Moines (van Breemen and Hawkesworth, 1980).

The domain average composition of the Knoydart pelitic gneiss (the only unit of the Moines for which both Rb-Sr and Sm-Nd isotopic data is available) was used to generate the mixing curve illustrated in Fig. A7.2. The curve shows the combined effect on Nd and Sr isotopic composition of adding pelitic material to the magma from which the Group A2a hornblende-biotite granites crystallized, and it is clear from this diagram that the range in Sr isotopic composition shown by the different samples of muscovite-biotite granite could be reproduced by melts

TABLE A7.1 Aditional Sm-Nd whole-rock data for granite clasts from the Corsewall point conglomerate.

Sample no.	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
Corsewall Point muscovite-biotite granites (Group A1)				
CoP 3	4.13	22.31	0.1120	0.511527±19
CoP 118	4.18	22.81	0.1107	0.511536±27
CoP 119	4.45	24.00	0.1122	0.511569±23
CoP 123	5.02	27.30	0.1111	0.511608±19
Corsewall Point foliated hornblende-biotite granodiorites (Group A3)				
CoP 2	2.71	9.97	0.1640	0.511843±27
CoP 107	2.51	17.36	0.0873	0.511529±18

TABLE A7.2 Isotopic composition at 600 Ma of melts generated by mixing hornblende-biotite granite and Knoydart pelitic gneiss.

	Igneous end member	50% pelite	60% pelite	70% pelite
Rb ppm	80	107	113	119
Sr ppm	390	305	288	271
$^{87}Sr/^{86}Sr$	0.7059	0.7111	0.7124	0.7140
Sm ppm	3.15	6.52	7.19	7.87
Nd ppm	17.29	35.67	39.35	43.02
$^{143}Nd/^{144}Nd$	0.511191	0.511355	0.511358	0.511386

	80% pelite	90% pelite	Pelitic end member
Rb ppm	124	129	135
Sr ppm	254	237	220
$^{87}Sr/^{86}Sr$	0.7157	0.7178	0.7197
Sm ppm	8.54	9.22	9.89
Nd ppm	46.69	50.37	54.05
$^{143}Nd/^{144}Nd$	0.511391	0.511400	0.511400

containing between 70% and 90% pelite. The Rb and Sr concentrations in the theoretical mixtures (Table A7.2) are also comparable with those in the muscovite-biotite granites themselves (Appendix 3). This shows that it is possible to generate the observed Sr isotopic characteristics of the muscovite-biotite granites by the contamination of a granitic magma similar in composition to the hornblende-biotite granites, but the marked differences between the Nd isotopic composition of the theoretical mixtures and the actual samples show that the Moine pelite itself could not have been the contaminant. To explain the observed relationship between the Nd isotopic composition of the different groups of granite clasts it would be necessary to invoke a crustal contaminant containing Nd of a much less radiogenic composition than that in the Moine pelite, which in turn implies that the contaminant would also have had a much older crustal residence age. Because of the similar crustal residence ages of the Lewisian gneiss, the Moine schists and the Dalradian metapelites (Miller and O'Nions, 1984), it is unlikely that a suitable contaminant could be found in Scottish continental crust.

Further evidence of the extent to which the isotopic variation shown by the muscovite-biotite granites can be attributed to the contamination of a magma by pelitic xenoliths comes from a consideration of the relationship between the isotopic composition of the clasts at 600 Ma (the time at which mixing is assumed to have taken place) and various chemical parameters that independently measure the contamination of a magma by a pelite. If contamination was the main control on isotopic variation in this group of clasts, the samples containing the most radiogenic Sr and the least radiogenic Nd at 600 Ma should also be those that show the greatest evidence of pelite contamination. It would also be expected that any correlation between isotopic composition and indicies of contamination within the muscovite-biotite granites

should project back to the composition of the hornblende-biotite granites - the presumed uncontaminated end-member.

The pelitic xenoliths contain abundant biotite, sillimanite and muscovite, which indicates that they are highly aluminous. The Al_2O_3 content of the granites is therefore likely to reflect the amount of pelitic material they contain. In Figs. A7.3a and A7.3b there is limited evidence of a relationship between Al_2O_3 content and isotopic composition within the muscovite-biotite granites, but most of the data is scattered and the correlation is not as strong as might be expected in mixtures containing the range of pelite concentrations required to generate the observed Sr isotopic variation. More significantly, however, the trends shown by the muscovite-biotite granites are unrelated to any trends within the hornblende-biotite granites and granodiroites, and in addition, the muscovite-biotite granites are generally less aluminous than the clasts belonging to other groups. It is therefore unlikely that the hornblende-biotite granites represent a parent magma that was contaminated by the pelite xenoliths in the muscovite-biotite granite clasts.

The muscovite-biotite granites are distinguished from the hornblende-biotite granites by the presence of muscovite and the absence of hornblende; petrographic features that are reflected by the generally more potassic nature of the muscovite-biotite granites. If this relationship between the two groups of clasts is also attributed to the assimilation of pelitic xenoliths, K_2O content may also be used as a measure of contamination. Although there is some evidence of a correlation between K_2O content and $\varepsilon_{Nd(600)}$ in the muscovite-biotite granites (Fig. A7.3d), the relationship between K_2O and $(^{87}Sr/^{86}Sr)_{600}$ is random, and is unrelated to the behaviour of K_2O in the other groups of clasts (Fig. A7.3c).

The good correlation of both TiO_2 and Zr with isotopic composition in the hornbelnde-biotite granites and granodiorites (Figs. A7.3e to g) may be taken as evidence of crustal contamination within these groups. However, these trends are not apparent in the muscovite-biotite granites, where the data is scattered, further suggesting that contamination in the two groups is unrelated.

Finally, although only limited data is available, there is no evidence within the muscovite-biotite granites of a positive correlation between the two isotopic parameters of crustal contamination (Fig. A7.3h). The negative correlation observed provides further evidence that the presence of pelitic xenoliths was not the most important factor in determining the isotopic composition of the muscovite-biotite granite clasts.

Although it has been shown that it is possible to generate the observed Sr isotopic characteristics of the muscovite-biotite granites by contaminating a hornblende-biotite granite magma with a pelite, there is little chemical evidence to suggest that such a mechanism has operated in this case. Undoubtedly, the uneven distribution of pelitic xenoliths has had some effect on the isotopic composition of the muscovite-biotite granite clasts, and this is reflected by the scatter of data points about the best fit straight line on the isochron diagram (Fig. 4.1). Most of the variation in isotopic composition is therefore attributed to Sr isotope evolution in samples with different Rb/Sr ratios, subsequent to the crystallization of the granite. The period of time that has elapsed since crystallization can therefore be estimated by the use of an isochron diagram, and some of the uncertainty in the age determination caused by the presence of xenoliths is accommodated by expanding the errors on individual analyses to reduce the MSWD of the best-fit straight line to one. Further evidence that the result obtained from this isochron represents a period of igneous activity in

the source area of some of the Southern Uplands conglomerates comes from the presence in the Glen Afton conglomerate of petrographically distinct clasts which show no clear evidence of crustal contamination, but which yield a similar Rb-Sr whole-rock isochron age (1,231 ± 120 Ma; Chapter 4.2.c).

A7.2 Exclusion of selected data points from isochron suites.

The original field relationships between granite clasts in a conglomerate cannot be directly observed and particular care is required in order to ensure that cogenetic suites of samples are used to construct Rb-Sr whole-rock isochrons. If samples of mixed origin are combined on a single isochron, there is a danger that a spurious result may be produced. In this study, the selection of samples for isochron suites was based on groups of clasts with broadly similar chemical and petrographic characteristics, but where there was variation within a group it was necessary to exclude certain samples in order to reduce the risk of including clasts of mixed origin. Clasts that showed the effects of significant alteration or deformation were also excluded as the Rb and Sr they contain may have been remobilized subsequent to crystallization.

The MSWD of an isochron measures the scatter of data points about the best fit straight line, and can be used to test the validity of the assumption that the samples used to construct it are cogenetic. However, in instances were some samples belonging to a petrographically defined group of clasts were excluded from an isochron suite, there is a danger that the estimate of the MSWD, and hence the degree of uncertainty associated with the age determined, may be artificially low. If the isotopic homogeneity of a group of clasts is to be accurately

assessed, it is necessary to show that the excluded clasts could not be genetically related to the other members of the group, or that they contain Rb and Sr that has been remobilized, as a result of either weathering or deformation.

An estimate of the extent to which the composition of a particular clast has been affected by alteration processes comes from a consideration of their K/Rb and Zr/Nb ratios. None of these elements are incompatible in granites, and both ratios may therefore reflect fractionation, as well as contamination. Consequently, in some instances it may be expected that a correlation would exist between these two ratios in unaltered groups of clasts. However, K and Rb are much more mobile than Zr and Nb, so clasts that have been significantly altered are likely to show much greater variation in K/Rb ratios, and are likely to plot away from any trends present in the unaltered clasts belonging to the same group. Clasts in which trace elements have been remobilized can therefore be identified, and excluded from isochron suites.

A7.2.i. Corsewall Point muscovite-biotite granites (Group A1).

Three samples (CoP 117, CoP 120 and CoP 121) were excluded from the calculation of the 1,265 ± 130 Ma isochron yielded by the remaining clasts in this group. A plot of K/Rb v. Zr/Nb (Fig A7.4) for all the samples of muscovite-biotite granite shows no clear relationship between these parameters. However, the excluded clasts all have higher K/Rb ratios than the clasts belonging to the isochron suite, which indicates that remobilization may have resulted in a loss of Rb relative to K. A loss of Rb is also consistent with the observation that these clasts have lower $^{87}Rb/^{86}Sr$ ratios than other clasts containing comparable amounts of radiogenic strontium, and explains why they plot to the left of the 1,265 ± 130 Ma isochron (Fig. 4.1). Element mobility may be

attributed to alteration in CoP 121, and to biotite recrystallization associated with deformation in CoP 120 (Chapter 4.2.a.i, page 109). However, there is no clear evidence of the cause of the high K/Rb ratio in CoP 117.

A7.2.ii Corsewall Point hornblende-biotite granites (Group A2a).

CoP 105 was excluded from the suite of four samples used to define a 600 ± 30 Ma isochron because of petrographic evidence of considerable alteration (Chapter 4.2.a.i, page 110). Fig A7.5a shows that there is a good correlation between K/Rb and Zr/Nb in this group of clasts, and consequently it is not immediately obvious that the higher K/Rb ratio of CoP 105 is due solely to alteration. To assess the effects of fractionation, K/Rb ratio is also plotted against SiO_2 (Fig. A7.5b), and in this diagram CoP 105 plots above the trend defined by the four unaltered samples. It should also be noted that CoP 105 and CoP 106 have almost identical major element chemistries (see Appendix 2), and consequently it might be expected that if the K/Rb ratio was entirely fractionation-dependent, it should have a similar value in the two clasts. It is likely therefore that the higher K/Rb ratio of CoP 105 can be attributed at least in part to alteration, which justifies the exclusion of this clast from the isochron suite.

A7.2.iii Corsewall Point biotite granites (Group A4).

CoP 25 was excluded from the determination of the 475 ±20 Ma isochron obtained from the remaining four clasts in this group because of petrographic and geochemical evidence which suggests that it was derived from an unrelated source. CoP 25 is strongly foliated, while the other clasts in this group show only limited evidence of strain (Chapter 3.3.b), and on all plots of chemical data, CoP 25 falls outside the field defined by the other clasts in this group (Figs. 3.6 to 3.9).

It was therefore concluded that this clast should properly have been assigned to a separate group (Table 3.8).

A7.2.iv Glen Afton muscovite-biotite granites (Group C1).

The chemical coherence of the eleven clasts of muscovite-biotite granite from the Glen Afton conglomerate is illustrated by the good correlation displayed between CaO and K_2O in Fig A7.6a. This suggests that all the clasts are derived from a related source, but three of the samples are foliated and scatter about the 661 ± 35 Ma isochron defined by the eight remaining clasts. The foliated clasts generally have higher K/Rb ratios than the unfoliated samples, but because there is a good correlation between K/Rb and Zr/Nb (Fig. A7.6b), this is not obviously a result of remobilization during deformation. A good correlation also exists between K/Rb and SiO_2 (Fig. A7.6c) which suggests that fractionation may have had a considerable effect on the range of K/Rb ratios shown by these clasts. However, GA 226 clearly deviates from the trends defined by the other clasts which suggests that its trace element content may have been more severely affected by deformation processes. If this is the only sample excluded from the isochron calculation, the remaining clasts yield an isochron with an age of 747 ± 91 Ma, an initial $^{87}Rb/^{86}Sr$ ratio of 0.7054 ± 0.0013 and an MSWD of 12.9. This agrees within error with the result obtained from the eight point isochron, and provides a further indication that the foliated and unfoliated clasts are derived from related sources. However, the increased scatter of the points about the ten point isochron may be taken as evidence that the foliated clasts have suffered variable degrees of trace element remobilization during deformation.

The five most potassic clasts in this group (Fig A7.6a) are also the most petrographically similar. They show the clearest evidence in thin section of hydrothermal alteration, but still define an isochron

with an MSWD of 0.19 which yields an age of 702 ± 86 Ma (see Elders, 1987, contained in Appendix 6), a result that is in agreement with the age obtained from the eight point isochron. This is taken as evidence that hydrothermal alteration processes have not had an undue effect on the Rb and Sr isotopic characteristics of these clasts, but the 661 ± 35 Ma isochron defined by all the unfoliated members of this group is regarded as the best estimate of the age of intrusion of these clasts.

A7.2.v Glen Afton biotite granodiorites (Group C2).

GA 2 was excluded from the 1,231 ± 120 Ma isochron (MSWD = 5.89) yielded by this group of clasts. However, it has similar chemical characteristics to the other members of the group, as illustrated by the plot of CaO v. SiO_2 (Fig. A7.7), and a K/Rb ratio that is within the range of values shown by the other clasts. Consequently, there are no chemical grounds on which to exclude GA 2, and if it is included in the isochron suite, a similar, but less accurate isochron which yields an age of 1,289 ± 184 Ma (MSWD = 14.21) is obtained. However, GA 2 is distinguished petrographically from the other clasts as it is the only sample to contain hornblende in addition to biotite. Because this raises the possibility that GA 2 may not have been derived from an identical source, the 1,231 ± 120 Ma is regarded as the better estimate of the age of intrusion of this group of clasts.

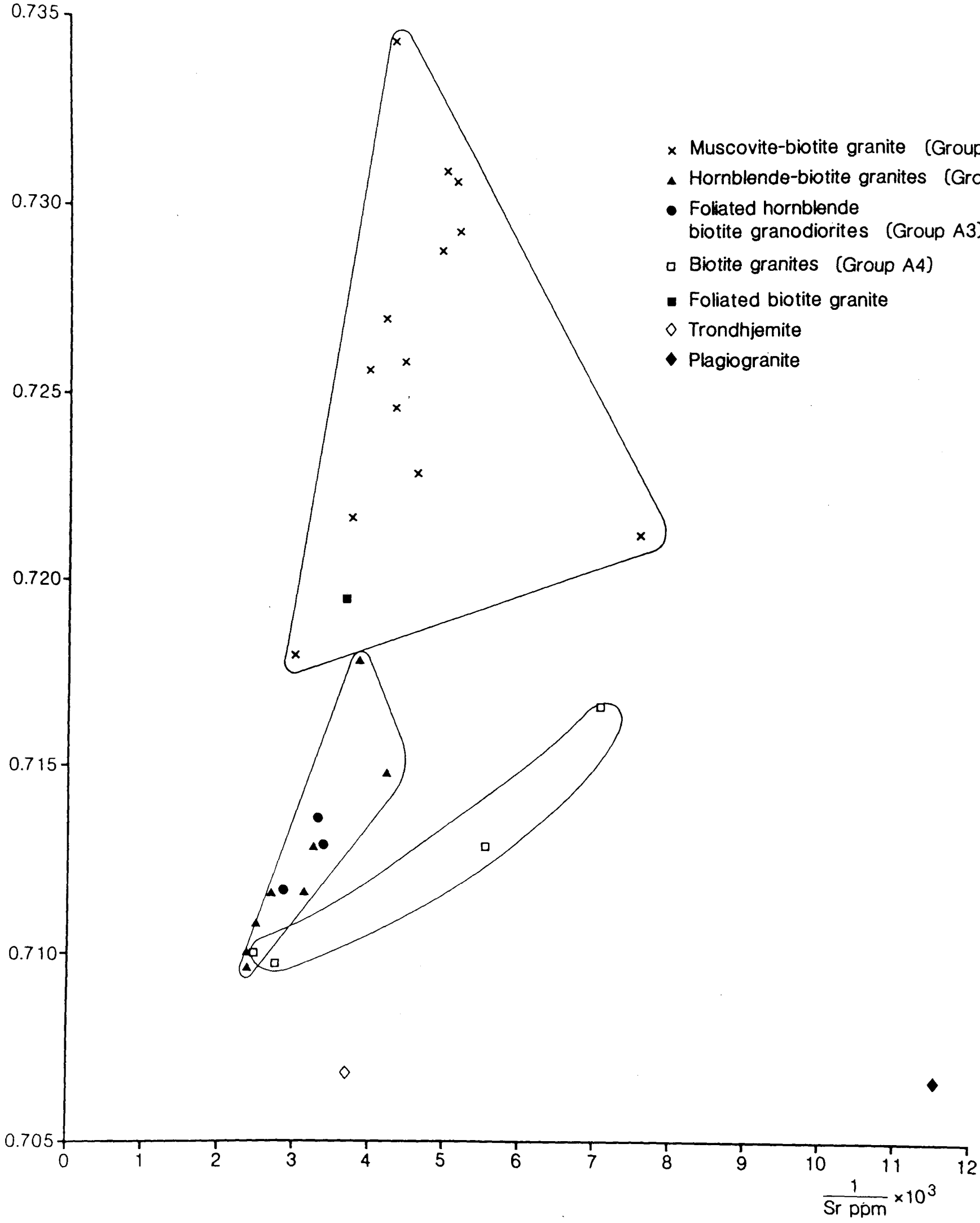


Fig. A7.1. A plot of present day $^{87}Sr/^{86}Sr$ against 1/Sr ppm x 10^3 for all the analysed granite clasts from the Corsewall Point conglomerate. The different petrographically defined groups of clasts are distinguished by the symbols illustrated in the key.

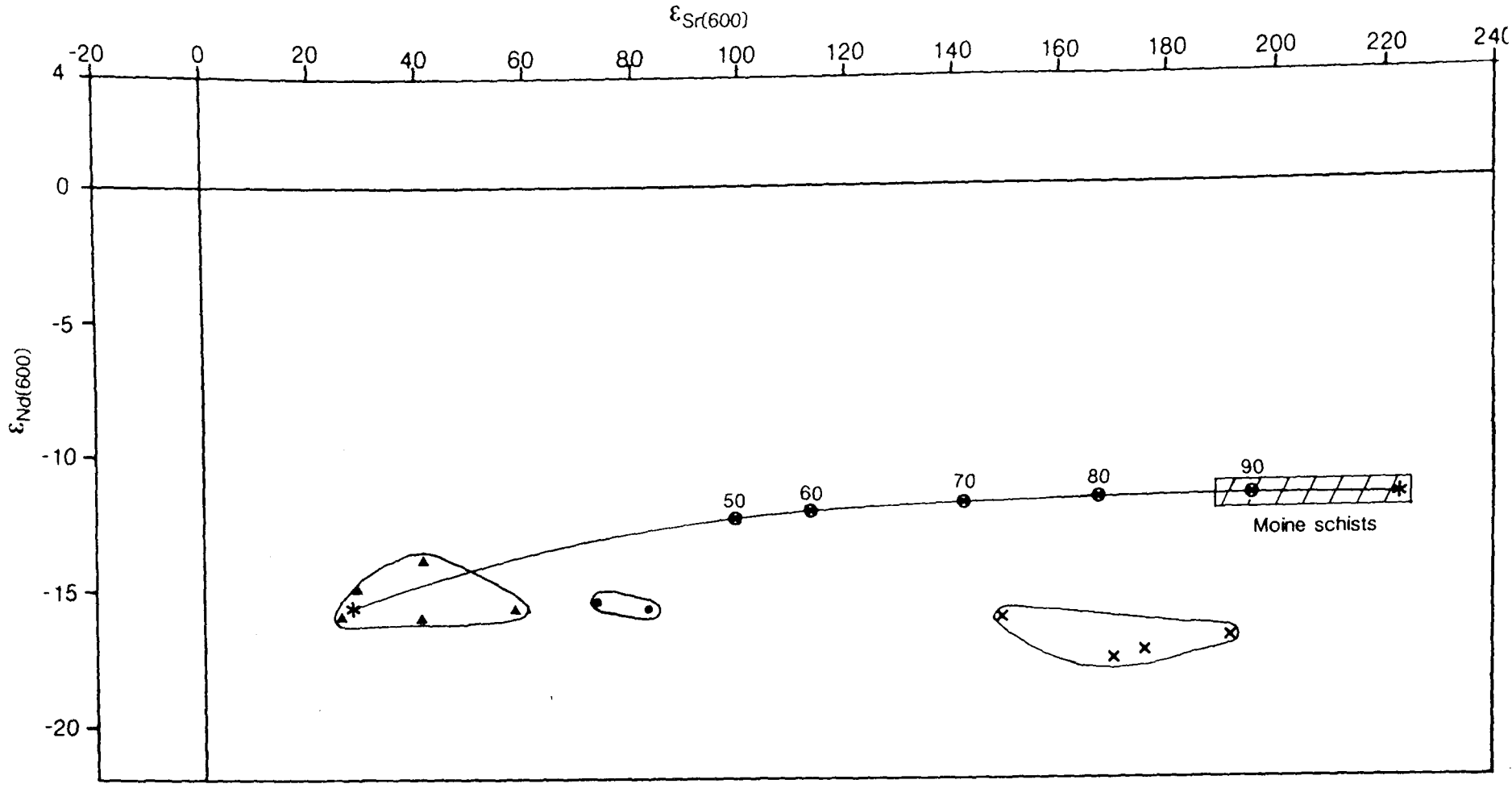


Fig. A7.2. A plot of ε_{Sr} v. ε_{Nd} at 600 Ma for unfoliated hornblende-biotite granites (triangles), foliated hornblende-biotite granodiorites (dots) and muscovite-biotite granites (crosses) from the Corsewall Point conglomerate. Also illustrated is the field defined by samples from the Moine schist, and a mixing curve illustrating the isotopic composition of melts containing varying proportions of hornblende-biotite granite magma and Knoydart pelitc gneiss. The composition of each end-members is denoted by an asterisk, and the percentage of pelite in the different mixtures is shown by the number adjacent to the data points on the mixing curve. Isotopic data for the Moine schist from Brewer et al., (1979) and van Breemen and Hawkesworth (1980).

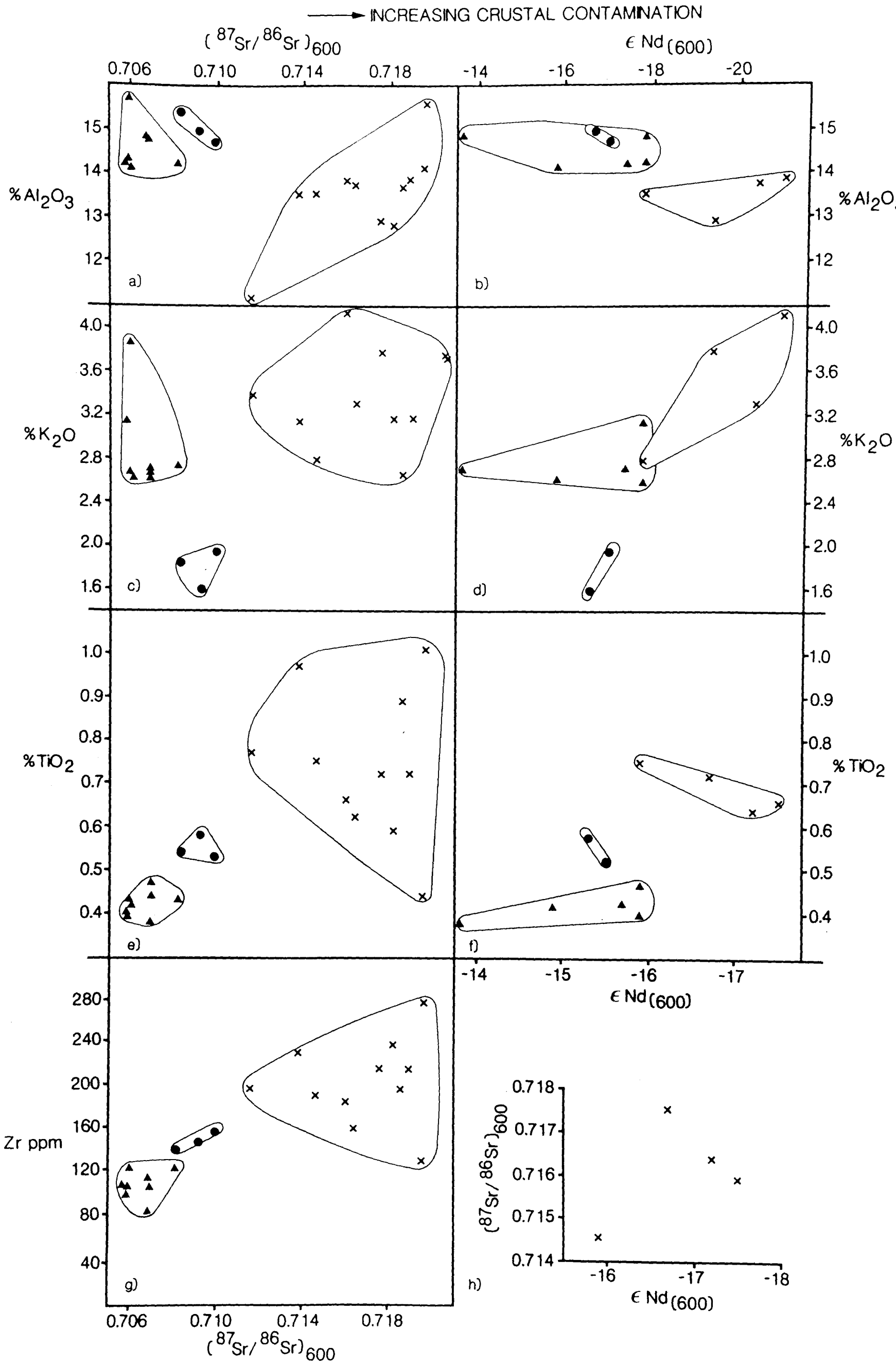


Fig. A7.3. Graphs showing the relationship between isotopic composition at 600 Ma and chemical composition in groups of granite clasts from the Corsewall Point conglomerate. Symbols as in Fig. A7.1.

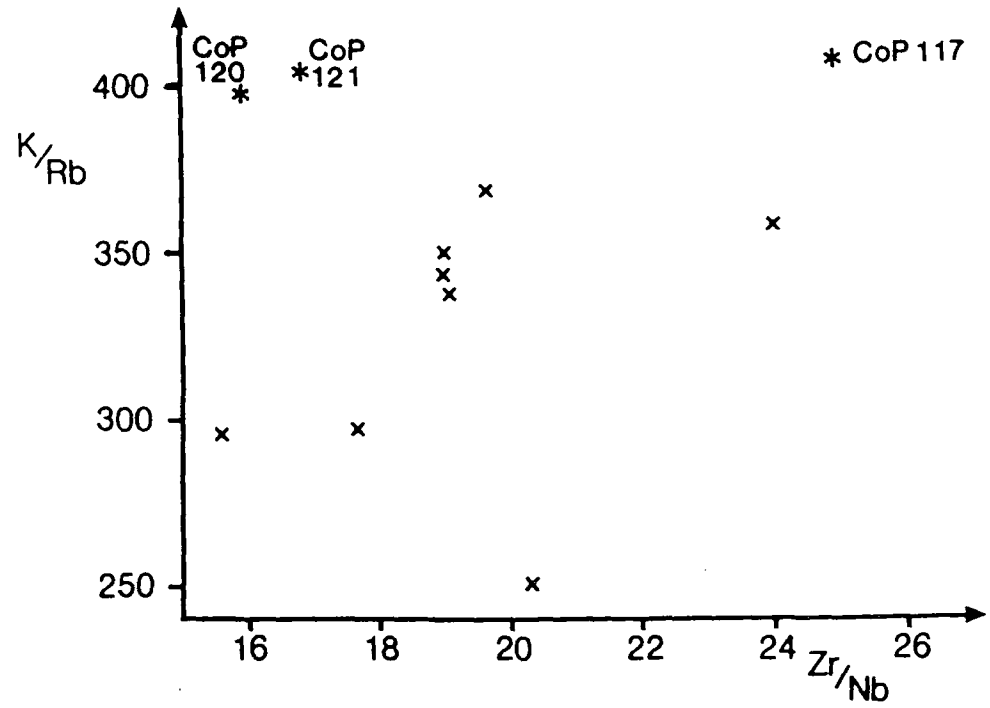


Fig. A7.4. A plot of K/Rb v. Zr/Nb for the muscovite-biotite granite clasts from the Corsewall Point conglomerate (Group A1). Clasts excluded from the isochron suite are marked by asterisks and are identified by sample numbers.

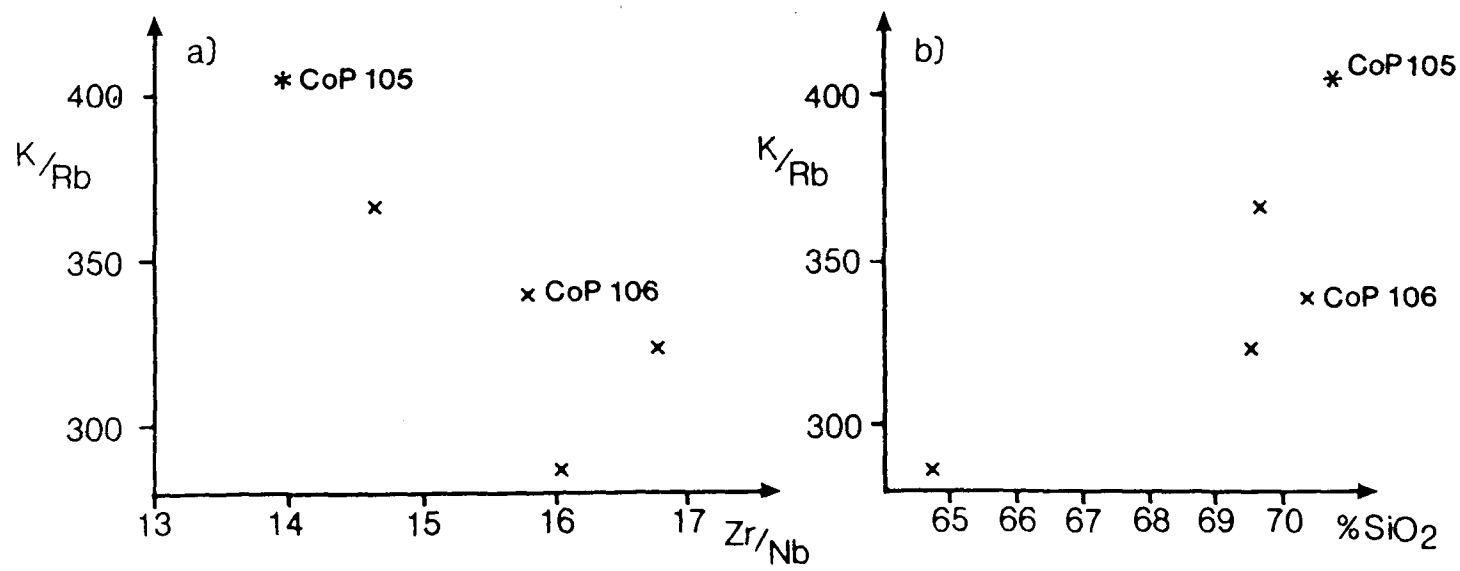


Fig. A7.5. A plot of K/Rb v. Zr/Nb (Fig. A7.5a) and SiO_2 (Fig. A7.5b) for samples belonging to the Group A2a hornblende-biotite granites from the Corsewall Point conglomerate. CoP 105 and CoP 106, which have very similar major element chemistries, are identified by sample numbers; CoP 105, which was excluded from the isochron suite, is also identified by an asterisk.

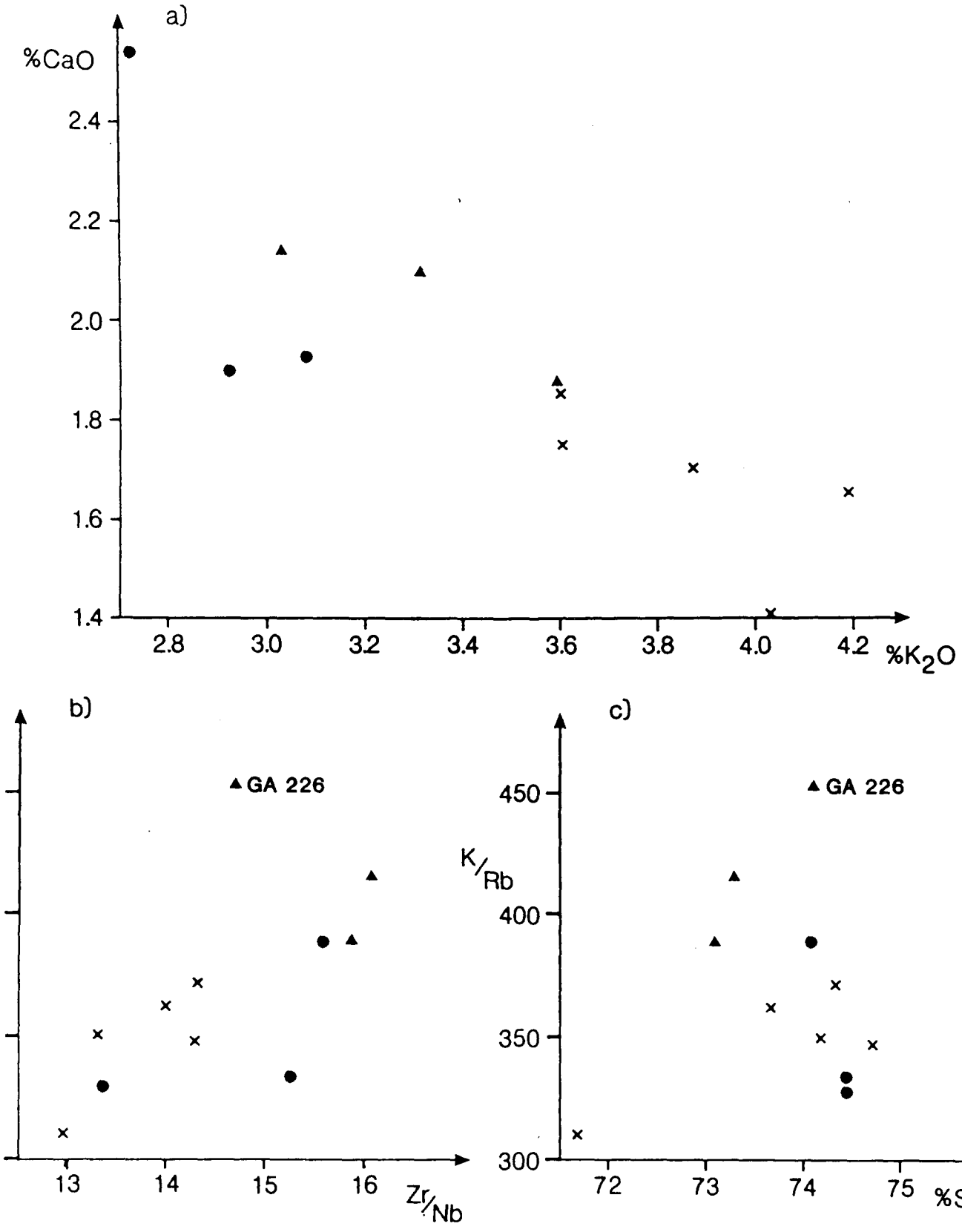


Fig. A7.6. Plots of CaO v. K_2O (Fig. A7.6a) and of K/Rb v. Zr/Nb (Fig. A7.6b) and SiO_2 (Fig. A7.6c) for the muscovite-biotite granite clasts from the Glen Afton conglomerate (Group C1). The triangles represent foliated clasts that were excluded from the isochron suite; all the remaining samples were used to define a 661 ± 35 Ma isochron. The five most potassic samples, represented by crosses, define an isochron with an age of 702 ± 86 Ma (see Fig. 4.7).

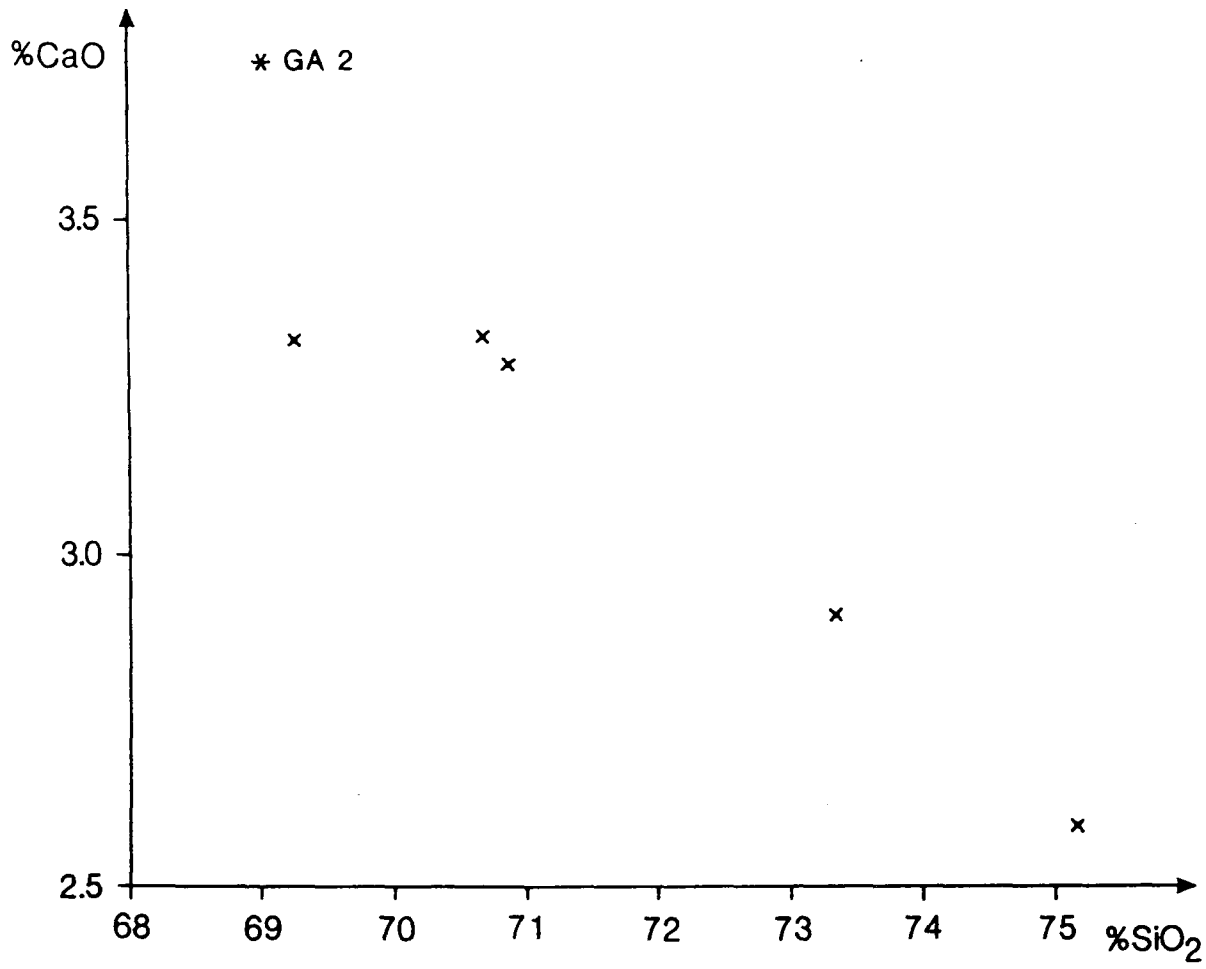


Fig. A7.7. A plot of CaO v. SiO_2 for the biotite granodiorite clasts from the Glen Afton conglomerate (Group C2). GA 2, which was excluded from the isochron suite, is identified by an asterisk.