THE ANATOMY OF MESOZOIC CARBONATE PLATFORM-MARGINS, SOUTHERN APENNINES, ITALY

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Short Abstract

The stratigraphy and sedimentology of Mesozoic carbonate platform-margins cropping out in southern Italy are investigated. New stratigraphic data are presented from northern and eastern slopes of the Apennine carbonate platform, based on locally-correlated field sections. Thin-section petrography is used to demonstrate the spatial and temporal distribution of derived lithoclasts. Results indicate that southern Apennine platforms underwent repeated erosion during Cretaceous time and possible reasons for this are discussed. Petrographic studies also provided outline sediment parageneses for slopes and platforms, with special reference to the detailed geochemistry of secondary dolomite formation on the eastern margin of the Apulian platform, whose growth is indicated by proton microprobe microanalysis to have been influenced by redox changes.

The sedimentary facies and sediment geometries of Upper Cretaceous to Lower Tertiary slope sediments mapped in the Frosolone area are discussed in a case-study. Cross-sections showing geometries of key beds are presented, and depositional controls are discussed. Outcrop data suggest an Early to Middle Jurassic age of basin formation of this sector of the Lagonegro-Molise basin. A further case study from the Mesozoic slope in the Gran Sasso shows sediment geometries at reflection seismic scale, and relates them to possible depositional control by relative sea-level fluctuations.

Finally, data from southern Apennine platforms and basins are combined in a tentative sequence stratigraphic framework for the Middle Cretaceous. The results of one-dimensional subsidence modelling are presented in order to separate and describe the signals of local tectonics and relative sea-level fluctuations affecting the southern passive-margin of Mesozoic Tethys.

Long Abstract

The stratigraphy and sedimentology of Mesozoic carbonate platform-margins cropping out in southern Italy has been investigated by means of field mapping at 1:10,000 scale, measured stratigraphic sections and photointerpretation, aided by stratigraphic correlation of field data. Two main platform entities, the Apennine and Apulian platforms respectively, were seperated in Mesozoic time by the Lagonegro-Molise basin (Mostardini and Merlini, 1986).

Measured stratigraphic sections from the northern slope of the Apennine platform (Gran Sasso) record deposition in a slope/basin environment during the Cretaceous, to Early Tertiary, as do sections from the eastern slope of the Apennine platform (Matese mountains). Outline sediment parageneses from these localities indicate a normal pattern of steady burial with the precipitation of dull/bright cathodoluminescent calcite cement, interrupted in the platform facies of the Matese by late stage dissolution and precipition of non-luminescent calcite spar, possibly related to unconformity development. The paragenetic history of the eastern slope of the Apulian platform (Gargano Peninsula), however, indicates pervasive late-diagenetic alteration, including extensive dissolution and precipitation of non-luminescent calcite spar and zoned secondary dolomite. The detailed trace-element geochemistry of secondary dolomites of the Gargano is investigated by proton microprobe microanalysis (Fraser *et al.*, 1989) and decoupled elemental behaviour, allied to the shape of Zn elemental peaks and homogeneous Sr distribution within crystals suggests that crystal-growth was redox-controlled and occurred by input of discrete batches of pore-fluids.

Micropalaeontological data from foraminifera, algae and nannoflora in thin section have allowed the identification of important geological events which occurred on the northern and eastern slopes of the Apennine platform. Carbonate turbidites can be regarded as a two-component system as a simplest approximation, being composed of newly-produced sediment and lithoclasts (Eberli, in press). Dating of the biodetrital component in the Gran Sasso produced agreement between the ages of planktonic and benthonic foraminifera within the limits of stratigraphic resolution, suggesting contemporaneous redeposition at this locality. Export of shallow-water carbonate sediment into the slope environment was most pronounced during the Early Aptian, Latest Aptian to Early Albian, Late Albian, Early Middle Cenomanian and Late Maastrichtian. Dating of the lithoclastic component in the southern Apennines by means of microfauna preserved in derived lithoclasts, reworked into slope facies shows that repeated platform erosion took place during the ?Early Hauterivian, Early Aptian, Late Albian, Middle Cenomanian, ?Early Campanian and Maastrichtian stages of the Cretaceous. The derived lithoclasts in slope facies of the Matese mountains area were studied in particular detail, and Hauterivian to Aptian slope sediments contained derived lithoclasts of both Upper Jurassic and Lower Cretaceous platform and slope/basin facies, whilst Campanian to Maastrichtian slope sediments contained derived clasts of Upper Jurassic, Lower Cretaceous and Upper Cretaceous platform and slope facies. By consideration of derived clasts in association with sediment geometries in Campanian-Maastrichtian to Lower Tertiary sediments (see below), erosion of the platform is tentatively attributed to lowering of eustatic sea level. However, stratigraphic data from the Matese area imply that differential subsidence

took place during the Cretaceous, possibly related to renewed regional crustal extension (see below), therefore providing uplift which can explain the present-day outcrop pattern in the Matese mountains, which requires up to 1000 m erosion during the Cretaceous to account for the sediments missing below the Campanian-Lower Tertiary slope facies.

Field mapping of Upper Cretaceous to Lower Tertiary slope sediments in the Frosolone area of Molise at 1:10,000 scale demonstrates the presence of a NNE-facing palaeoslope since Early to Middle Jurassic times, a result which suggests the origin of this part at least of the Lagonegro-Molise basin during the regional phase of crustal extension in the Liassic (Bernoulli and Jenkyns, 1974). Campanian to Maastrichtian slope sediments of the Frosolone and adjacent Matese mountains are arranged into three depositional sequences (*sensu* Mitchum, 1977) with a total thickness of approximately 150 m, characterised by unconformable contact with ?Upper Triassic to Lower Cretaceous platform facies, which can be traced basinward into correlative conformities in the Frosolone area. The base of each of the upper two sequences is marked by a distinctive lithoclastic calcirudite key bed. These beds are lenticular parallel to the strike of the palaeoslope on a scale of 5-7 km. Inspection of cross-sections and local map data (f.161 Carta Geologica d'Italia) lead to the interpretation of the Campanian-Lower Eocene slope facies of the Frosolone and Matese areas as a first-order turbidite complex (*sensu* Mutti and Normark, 1987). Three such complexes (with a width of 10-15 km and an active life-span of 20-30 my) can be distinguished as local depocentres in a broader slope apron in the Matese area, being of Cenomanian-Santonian, Campanian-Early Eocene and Late Eocene to Early Miocene age respectively. The large age-range of derived clasts and distinctive sedimentary features (large-scale cross-stratification in a slope environment) displayed by the calcirudite key beds points to the likelihood of their origin by erosion during lowstands of relative sea-level.

Mapping at 1:10,000 scale in the Gran Sasso d'Italia, coupled with interpretation of cliff-sections tied to measured stratigraphic sections for time-control, has enabled the recognition of lithofacies, including calcareous turbidites, locally confined in gulleys on the slope, slump and "creep" facies, comparable to those of a modern "accretionary" carbonate slope (Harwood and Towers, 1988). These facies can be divided into three major lithofacies associations, each characterised by a distinctive depositional geometry. These were: (1) downlapping turbidites with subordinate interbedded wackestones and lime mudstones, organised in *downlapping* depositional packages (DLP); (2) predominantly fine-grained calcareous turbidites, wackestones and lime mudstones, reworked into mounded facies (approximately 400 x 400 x 10 m) displaying low-angle foreset geometries indicating contour-parallel flow, and having *bidirectional downlapping* geometries (BDD) and; (3) thinly-bedded dominantly fine-grained wackestone and lime mudstone facies organised into *onlapping* depositional packages (ONL). DLP groups of beds locally display coarsening and thickening upwards, with concomitant increase in the proportion of newly-produced sediment in the form of reworked benthonic foraminifera, features which are consistent with the hypothesis of carbonate platform-margin progradation and increased sediment production rates during highstands of relative sea-level (Droxler and Schlager, 1985; Eberli and Ginsburg, 1987, 1989). The slope sediments of the Gran Sasso have been divided into cycles of BDD-DLP-ONL geometries which could have been produced by cyclic fluctuations of relative sea-level. In particular, three well-developed cycles of Late Campanian to Maastrichtian age are exposed on Mt. Corvo. Within these cycles, vertical and laterally-offset stacking of amalgamated calcareous turbidites are observed. Amalgamated turbidites are deposited in relative topographic lows on the slope created by the relief of mounded (BDD) facies. In cases where laterally offset stacking occurs, turbidite packages belong to seperate BDD—DLP-ONL cycles. Further depositional cycles are exposed on Pizzo Intermesoli, and suggest similar sediment depositional patterns for the Aptian to Cenomanian.

The evidence for fluctuations of relative sea-level in the southern Apennine region is reviewed, suggesting the importance of such fluctuations during the Middle Cenomanian and Late Maastrichtian. Published stratigraphic data **from** the southern Italian region are used in conjunction with field data to produce an outline sequence stratigraphy for the Middle Cretaceous of the southern Apennines. Four major depositional sequences are recognised, the first lasted from the Earliest Aptian to the ?early Late Aptian, the second from the ?early Late Aptian to the early Late Albian, followed by a third from the Late Albian until the early Middle Cenomanian and a fourth from the early Middle Cenomanian until the ?Late Turonian.

Stratigraphic data from the region are used to produce a database for subsidence modelling of the southern Apennines. Modelling studies, by means of decompaction, backstripping and curve-fitting against model cooling curves indicate that the first-order subsidence history of the platforms is comparable to that predicted by rifting and thermal contration on a passive margin, in this case rifting commenced in the Early Jurassic (Bernoulli and Jenkyns, 1974; Winterer and Bosellini, 1981). In all cases, however, subsidence of Apennine platforms overtakes subsidence predicted by the cooling-plate model during the Late Cretaceous, with an average time of cross-over in the Cenomanian to Turonian stages. The possible reasons for this deviation are discussed in the context of the regional tectonic environment. The subsidence data are compatible with the concept of renewed regional crustal extension during the Late Cretaceous, an event which can explain many of the deeply-eroded unconformities of this age in Italy and Yugoslavia (see above).

" Before the mountains were born
or you brought forth the earth
and the world,
from everlasting to everlasting
you are God.
You turn men back to dust,
saying, "Return to dust, O sons
of men."
For a thousand years in your sight
are like a day that has just gone
by,
or like a watch in the night. "

Psalm 90: v.2-4 (NIV)

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Mark I. Whiteman,

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Table A2 Crustal parameters used for the calculation of footwall uplift (after Jackson *et al.*, 1988).

CHAPTER 1: INTRODUCTION

1.1 Rationale

Recent work on carbonate platforms worldwide has changed emphasis from a descriptive and qualitative approach towards a more analytical, mechanistic approach (Humphrey and Quinn, 1989; Eberli and Ginsburg, 1989), by which rates and magnitudes of processes are incorporated into models as an additional check on their likely validity. The increasing volume of data available on ancient carbonates has assisted this approach, thereby enabling a fuller quantitative understanding of the processes by which former platforms grew, developed and were destroyed through time (Bond *et al.*, 1989). Quantitative data is provided wherever possible during this thesis, although it is firmly rooted in field observations.

Anatomy is defined in the Concise Oxford Dictionary as "*the study of a body to ascertain its component parts, their structures, relationships and functions*". Field observations and the quantitative data derived from them have been used to construct dynamic models to account for the behaviour of carbonate platforms in the southern Apennines, Italy, which incorporate variables such as changes in anatomy with time and cyclic oscillations in relative sea level. Furthermore, numerical data obtained from the southern Italian region has been used as the basis for one-dimensional geophysical subsidence modelling, in order to understand the response of the "working parts" of a carbonate platform to the overall mechanism(s) responsible for its growth and development. This type of study has proved successful in the analysis of several other carbonate platforms of presumed passive-margin type*, but has not previously been attempted for the platforms of the Apennines. Since the databases and analytical methods available to geologists are continually improving, every attempt has been made in this thesis to provide as clearly as possible the basic field data.

* for example, Bond *et al.*, (1988)

Tabulations of inputs into numerical models are also given, in the hope that future workers will be able to use them to check their conclusions or for inclusion into a larger geological database.

It should be made clear from the outset that this thesis does not attempt to provide an exhaustive geological summary of findings on every aspect of one particular platform-margin, but rather to use two selected case-studies, combined with data (both field and published) from other margins in the southern Apennine region, with the goal of providing a unifying framework for their Mesozoic growth and development based on identifiable driving mechanisms. It is hoped that the work presented will stimulate further research and discussion, possibly leading towards a more *inductive* method of analysis in the region (see Matthews and Frolich, 1987, for an example). The data from this thesis should contribute towards some of the goals of the Global Sedimentary Geology Program (GSGP) (Ginsburg *et al.*, 1986) Cretaceous Resources, Events and Rhythms Project (CRER), Working Group 4 "Cretaceous Carbonate Platforms". Specifically, the Working Group aimed to:

(1) "determine rates of sediment production, rates of aggradation and large-scale facies patterns of Cretaceous platforms and evaluate the differences between platforms of the Cretaceous greenhouse Earth and those of the present-day icehouse Earth";

(2) "construct at least parts of a sea-level curve solely from the record of carbonate platforms to avoid the problems of sequence boundaries caused by the change-over from siliciclastics to carbonates and *vice versa*" and;

(3) "examine the repeated global crises of platforms in the Cretaceous, in particular the puzzling coincidence of world-wide drowning and oceanic anoxia" (Schlager and Philip, 1989).

It was envisaged that the first goal could be accomplished by the documentation of case-studies of carbonate platform facies from around the world, which could subsequently be compared and abstracted, and including data on rates of vertical upbuilding and sediment accumulation. The case-studies of chapters 4 and 5 provide such data for the southern Italian region. The second goal was to be tackled by the compilation of the history of growth and exposure of platforms from different areas of the world, which would be used to construct relative sea-level curves to be stacked and compared to to other measures of sea level movement, namely the curve of coastal onlap derived from seismic profiles (Haq *et al.*, 1987) and the record of cratonic flooding (for example Hancock and Kauffmann, 1979). Data from the southern Apennines will be used in an attempt to isolate the record of relative sea-level fluctuations in the region in chapter 6. The possible causes of platform drowning during the Cretaceous will be addressed by synthesising field and published data from the southern Apennines and reviewing this in the light of models developed during the thesis and other worldwide examples. Events singled out for especial study by CRER Working Group 4 which will be discussed during this study are those of the Aptian, Late Albian and Cenomanian/Turonian.

1.2 Carbonate platform-margin models

Cretaceous carbonate platform facies have been shown crudely to match the standard facies belts of Wilson, (1975; Masse and Philip, 1981). Models for platform-margins have been proposed by Read (1985) which adequately describe the transitions between margins with differing slope profile (figure 1), although the importance of lateral as well as vertical growth of carbonate platforms has only recently become established (Bosellini, 1984; Eberli and Ginsberg, 1987, 1989). Indeed, Eberli and Ginsburg (1989) estimated that the Cenozoic progradation of the Straits of Florida was as much as 25 km, suggesting that lateral growth may outpace vertical growth by a ratio of up to 80:1.

Few attempts have been made to incorporate dynamic factors such as the changes in platform anatomy with time known to have occurred in some ancient carbonate platform margins (Read, 1985; Bosellini, 1984) into models for Apennine platform-margins. The effects of other dynamic factors such as possible cyclic variations in relative sea level upon Apennine platform anatomy both in the short- and long-term have previously received scant attention (but see Colacicchi, 1987). A more serious problem for the application of standard facies models to describing Apennine platforms at particular times (as opposed to explaining changes with time) is the derivation of the most complete classifications largely from studies made in the 1970's and early 1980's on modern carbonate platforms in the Bahamas (for example Read, 1982, 1985). These models account for the growth and development of accretionary carbonate margins quite successfully, but do not readily explain either (1) the thick accumulations of derived calcirudites and breccias on Tethyan palaeoslopes, particularly during the Liassic (for example Castellarin *et al.*, 1978); or (2) locally high proportions of derived lithoclasts of widely differing ages eroded from southern Apennine platforms and redeposited on the slopes, particularly during the Late Cretaceous (chapters 3, 4). Clearly, the processes which acted upon the Apennine platforms were in some cases different from those which drive sediment production and redeposition in the present-day Bahamas. Ancient carbonate slope deposits have been interpreted as constituting both submarine fans (Cook and Egbert, 1981; Ruiz-Ortiz, 1983; Wright and Wilson, 1984; Watts, 1988) and aprons of sediment (Mullins and Cook, 1986).

The type of exposures available in the Apennine thrust belt (figure 3) commonly contain only limited outcrop evidence for upper slope deposits, making positive distinction between fans and aprons very difficult due to the lack of evidence for possible feeder channel systems to fan lobes. Another weakness to the facies model approach to slope sediment organisation lies in the hydrodynamic differences between siliciclastic and carbonate gravity-flow sediments (mentioned by Colacicchi and Baldanza, 1986). Submarine fan models derived from siliciclastic sediments may be innappropriate to the study of carbonate slope deposits, due to the close proximity of depositional and erosional features, indicating a locally very irregular flow regime (Colacicchi and Baldanza, 1986; section 5.7). This basic difference is reported by Colacicchi and Baldanza, (1986) to be due to the comparatively low mud concentration in carbonate turbidites, which therefore have a higher internal friction than their siliciclastic counterparts, and lose kinetic energy more rapidly. Apart from papers by Castellarin *et al.*, (1978), Cantelli *et al.*, (1978), Colacicchi and Baldanza, (1986), and a brief description by Vecsei and Eberli (1989) there are no other known reports of detailed slope sediment geometries from the southern Apennines. It is therefore the aim of this thesis to carefully document outcrop studies of sediment geometries in order to improve understanding of the Mesozoic palaeoslopes in the region, rather than to attempt to force the outcrop data to fit pre-existing facies models on uniformitarian grounds. Nevertheless, some discussion is given concerning possible similarities of the ancient slope deposits of the Apennines with other published examples.

1.3 Cyclicity in calcareous turbidite systems

One of the areas in which recent research has increased our understanding of carbonate systems, and also raised considerable debate, is the question of depositional controls. Both tectonic activity and sea-level fluctuations can produce cyclicity in the stacking patterns within calcareous turbidite systems (Eberli, in press). Time may also be an important factor in governing which of these effects is most pronounced in an individual turbidite system. Mutti and Normark (1987) (primarily from study of siliciclastic systems) state that the largest submarine fan complexes form over tens of millions of years, and require a relatively stable basin and a long-term supply of sediment. It is in these long-lived systems that the effects of global sea-level changes are most pronounced (figure 111). By contrast, turbidite basins formed in active tectonic settings tend to be short-lived, and local tectonic control greatly influences the development of the turbidite deposit. Eberli (in press) elaborated on the specific controls on carbonate turbidite deposition. For a prograding platform-margin, the progradational stacking pattern is controlled by sea-level fluctuations (figure 2). In extensional basins, tectonics appears to be the controlling factor during the initial stages of rifting. Steep fault scarps are extremely unstable and tend to release large mass-flows. As the relief becomes buried, slope instability decreases, turbidite volume and frequency decrease, and an overall thinning- and fining-upward sequence is deposited (Evans and Kendall, 1977; Price 1977; Eberli 1987).

The exact nature of sea-level control on carbonate turbidite deposition remains an area of debate (Thiede, 1981; Shanmugan and Moiola, 1982, 1984; Mullins, 1983a; Boardman and Neumann, 1984; Droxler and Schlager, 1985; Sarg, 1988; Haak and Schlager, 1989). The fact that carbonate turbidites are in the simplest case a two-component system (lithoclasts and biodetritus) must be taken into account when evaluating the relationship between turbidite frequency and sea-level fluctuations (Eberli, in press). Droxler and Schlager (1985) demonstrated that newly-produced sediment is exported into deep-water areas mainly during sea-level highstands when production on the platform is high. Harris (1988) proposed that marginal erosion during lowstands of sea level increases the rate of talus deposition, although the frequency of basinal calcareous turbidites decreases. The system becomes further complicated when the carbonate and siliciclastic environment interfinger (Dolan, 1989). A sea-level/frequency plot of turbidites from a carbonate platform with a siliciclastic hinterland probably may give a mixed signal with one peak at highstands, when carbonate sediment is produced on the rim, and another peak at lowstands, when sand bypasses and erodes the carbonate shelf. It can be concluded from the available published data that analysis of the component assemblage is necessary in order to evaluate the relationship of turbidite frequency to sea level. Two other important factors are the depositional setting (for example isolated platform or ramp) and the slope profile of the system.

1.4 Temporal change in platform anatomy

One of the most remarkable aspects of the carbonate platforms in the southern Apennines is their puzzling behaviour during the Middle to Late Cretaceous. At a time when carbonate platforms the world over were drowning, the platforms in the Apennines underwent brief (?repeated) emersion episodes and local backstepping but remained the persistent locus of shallow-water sedimentation until the Early Tertiary (locally until the Miocene). Examples of drowned Cretaceous platforms abound (Schlager, 1989) and include the mid-Cretaceous platforms of the Gulf of Mexico, (Buffler *et al.*, 1980, 1984; Addy and Buffler, 1984; Corso, 1988; Schlager *et al.*, 1984; Winker and Buffler, 1988) and many Pacific seamounts (Schlager, 1981).

1.5 Western Mediterranean

The Western Mediterranean region (figure 3) comprises a series of small interconnected seas underlain by basins that have experienced Cenozoic extension and deposition. The basins developed on either stretched continental crust (e.g. Balearic basin) or, in part, Cenozoic oceanic crust (e.g. Tyrrhenian basin; figure 3). Mountain belts of the Alpine system almost entirely surround these basins. The mountain belts (e.g. the Apennine mountain belt) are generally the result of convergence between the African and European plates and intervening blocks or microplates, and gravity spreading of overthickened crust. This study will be concerned with rocks from the southern Apennine mountain belt, in particular the Abruzzo and Molise districts (figure 4).

1.6 Problems outstanding

The southern Apennines is a region where some fundamental geological questions still need to be answered. No general consenus has yet been reached on the first order palaeogeography during Jurassic time (section 2.2), and the ages of some major palaeogeographic/structural elements are poorly known. Furthermore, the first-order subsidence history of the region is poorly understood, in particular the Upper Cretaceous strata display frequent examples of deeply eroded unconformities which imply major uplift and erosion not usually associated with an extensional tectonic regime.

Although numerous stratigraphic studies have been undertaken in the southern Apennines, many of these are concerned with the stratigraphy of platforms or basins, whilst few give details of the intervening slope areas. An important part of this thesis, then, has been to establish the detailed stratigraphy of the slope environment in order to facilitate correlation and sedimentological analysis.

No modern sedimentological analysis has been published of the slope sediments of the eastern or northern margins of the Apennine platform (figure 5). The bulk of this thesis will therefore be taken up by the presentation of such an analysis, concentrating firstly on depositional systems and their geometries, and secondly on controls on deposition within the carbonate slope environment. These data will then be assimilated into a tentatative sequence stratigraphic framework (*sensu* Mitchum, 1977) for the region within the framework of the published geology of the western

Mesozoic Tethys Ocean.

1.7 Thesis Structure and Aims

The initial aim of this thesis was to study the sedimentary and structural history of some Cretaceous carbonate platform-margins. This was a complex problem, for two reasons. Firstly, the complicated and poorly understood present-day structure of the southern Apennines, brought about during Apennine thrusting, strike-slip and extensional faulting, which had in most cases completely dissected the Mesozoic platform- to-basin transition. Secondly, the remote nature of the Gran Sasso d'Italia, an area almost completely without surface water during the summer months, and which contains inaccessible outcrops of steep limestone cliffs up to 1000 m high. The initial aim has been addressed along with other lines of research which opened up during the course of this study. The main problems addressed are:

(1) to place time constraint on the major stratigraphic and sedimentological events on southern Apennine platform-margins.

(2) to study the sedimentology of Cretaceous to Early Tertiary carbonate slope depositional systems.

(3) to determine the relationship of Mesozoic tectonic activity to the development of southern Apennine carbonate platform-margins.

(4) to model the Mesozoic subsidence history of the southern Apennines in the framework of the Tethys Ocean.

(5) to synthesise this data into a Cretaceous sequence stratigraphic scheme for southern Italy.

(6) to initiate a study of the geochemistry of late-stage zoned dolomites from the Apulian platform—margin.

Following this introductory chapter, a stratigraphic framework for the area will be outlined in the second chapter. The stratigraphic framework is modified from earlier work and is expanded predominantly using data from field studies of the northern and eastern margins of the Apennine platform and the eastern margin of the Apulian platform. The third chapter will deal with particular petrographic themes which arose during the study, particularly the timing and nature of erosion of the lithoclastic component of Apennine slope deposits, and the major post-burial diagenetic events which modified the platform and slope sediments, addressing the question of the growth of secondary dolomites in terms of changes in redox potential. The fourth chapter will deal with the sedimentology of Cretaceous slope deposits from the eastern margin of the Apennine platform, emphasising the sediment geometries of redeposited carbonates and the controls of local tectonics and relative sea-level change on sedimentation. The fifth chapter will continue the themes of the fourth, but at a larger scale, concentrating on the geometries of whole stratigraphic units form the northern slope of the Apennine platform. The sixth chapter will collate the stratigraphic and sedimentological data into the history of the region within a sequence stratigraphic framework and uses field and published data to model the subsidence of the region in order to explain the Mesozoic development of southern Apennine carbonate platforms observed in the field. The final chapter will present the main conclusions of the thesis.

Chapter 2:
Stratigraphic Framework of Southern Apennine Carbonate Platform- Margins.

2.1 Introduction

The purpose of this chapter is firstly to present an up-to-date, coherent stratigraphic framework for the southern Apennines as a whole, based on recent outcrop, borehole and seismic data. During this presentation, areas in which the existing stratigraphic scheme is weak will be pointed out, to lead the way to more detailed discussion in subsequent chapters. Secondly, measured field stratigraphic sections will be summarised briefly, along with the main results from micropalaeontological analyses carried out in thin section in conjunction with Dr. M.D. Simmons, Dr. A.A.H. Wonders and J. Pearce at the Stratigraphy Branch of British Petroleum Research International Limited., Sunbury-on-Thames. These micropalaeontological analyses are presented in full in appendix 3. Thin sections were analysed for planktonic and benthonic foraminifera, and in some cases for nannoflora and algae. Discussion of the sedimentological significance of the stratigraphic sections is postponed until the relevant chapters (4 and 5) where it is treated in the light of field mapping and outcrop data. Finally, stratigraphic data from field sections measured in this study partially forms the basis for detailed subsidence analysis presented in chapter 6.

2.2.1 Outline of southern Apennine stratigraphy

The Mesozoic and Tertiary platform and basinal carbonates of the southern Apennines represent rocks which were originally deposited on the African (Adria) margin of Neotethys (Panoramide Complex of Ogniben, 1969). The "African margin" prior to the early Miocene emplacement of the Liguride Complex was divided into a series of platforms and basins with different configurations in the southern Apennines and

Sicily. The southern part of the Adriatic block comprised an internal Apennine platform with the Liguride basin to the west and the Lagonegro-Molise basin and Apulian platform to the east. Evidence for an intermediate platform to the east of the Apennine platform, bounded to the west by the Lagonegro basin and to the east by the Molise basin has been put forward by D'Argenio *et al.*, (1975b) and Scandone *et al.*, (1974), but is inconclusive. The clear continuity of the Lagonegro and Molise basins (Mostardini and Merlini, 1986) suggests that the tectonic windows of the supposed intermediate platform at Campagna and Monte Alpi (figure 5), may be either upthrown blocks of the Apulian platform (Dewey *et al.*, 1989) or klippen of the Apennine platform on Lagonegro-Molise basin sediments (Ogniben, 1985; Mostardini and Merlini, 1986). The Lagonegro-Molise basin was probably continuous with the Imerese basin of Sicily. The connection between the Apennine platform and the Panormide platform in Sicily is unclear, as Mesozoic platform carbonates of the African margin do not crop out in southern Calabria.

East of the Lagonegro-Molise basin was the Apulian platform which extended northwards to the northern Apennines, interrupted by the Apulian basin (Mostardini and Merlini, 1986) and the Gargano basin (Martinis and Pavan, 1967). The area of study for this thesis is in the southern Apennines, therefore a brief description will be given in the following sections of the stratigraphy of the main platforms and basins in the area, the majority of which now form E-verging thrust sheets.

2.2.2 Apennine platform

This platform comprised the Triassic to Lower Miocene platform carbonates and flysch which now crop out in the Apennine mountain chain. Exceptions are the platform carbonates of the Campania and Mt. Alpi tectonic windows (section 2.2.1) and of the Maiella mountains (figure 5), which probably belong to the Apulian platform. The

Apennine platform sequence (figure 6; after Knott, 1988) comprises Triassic pelites at its base, overlain by calcareous-dolomitic platform facies of Late Triassic to Eocene age, themselves unconformably overlain by Early Miocene platform limestones (D'Argenio *et al.*, 1975b). Outcrops of transitional facies have been recognised along the eastern side of the platform, facing the Lagonegro-Molise basin (D'Argenio *et al.*, 1975b). In the southern Apennines, slope facies are less well known, but have been described from a number of localities (figure 5; section 2.4).

Miocene turbidites onlap the platform facies unconformably and diachronously. The transgressive turbidites are of early Miocene age near the internal margin of the Apennine platform and of mid-Miocene age (Langhian) near the external margin (Ogniben, 1985). The general absence of Palaeogene deposits on the central part of the Apennine platform suggests large-scale emergence before Aquitanian time. The erosion or non-deposition can be explained by uplift due to the formation of a peripheral bulge ahead of the advancing thrust sheets and the associated foredeep. The gradual onlap of the transgressive flysch onto the carbonate platform (Selli, 1962; Pescatore, 1978) would reflect the foreland migration of the peripheral bulge.

The original width of the Apennine platform prior to thrusting is estimated, from restored sections interpreted from reflection seismic profiles, to have been between 150 and 200 km (Mostardini and Merlini, 1986). The deformation of the platform is generally considered to have been initiated in Early Miocene time when the platform overthrust the Lagonegro-Molise basin.

2.2.3 Lagonegro-Molise basin

Eastwards of the Apennine platform were the Mesozoic to Cenozoic basinal sediments from the the Lagonegro and Molise areas including varicoloured clay (Silicide Complex) and an overlying Miocene wildflysch succession. The Lagonegro-Molise basin comprised a lower succession (Triassic to early-Middle Cretaceous) and an upper succession (Late Cretaceous to Early Miocene). The lower succession (figure 7) comprises the "calcareous- siliceous-marly" series (*calcari con selce, scisti silicei* and *galestri* black shale and marl) which outcrops extensively in the Lagonegro area, near Tricarico in the south and around Benevento in the north (figure 5). Exposure is reduced further to the north, but the succession has been recognised from the Frosolone 2 well (Pieri, 1966; Mostardini and Merlini, 1986), and in limited outcrop at Pesche, near Isernia (section 4.3). The upper succession (figure 7) comprises the Flysch Rosso, Cretaceous to Oligocene varicoloured clay and Miocene flysch of the Irpinian basin (Pescatore, 1978), the latter including the Numidian quartzarenitic flysch derived from the African craton (Ogniben, 1969).

The original width of the Lagonegro-Molise basin, based on reconstructed cross-sections, is considered to have been of the order of 200 km (Mostardini and Merlini, 1986). The entire sequence is duplicated in two thrust slices in the Lagonegro area (Scandone, 1972). Deformation of the Lagonegro-Molise basin is considered to have been initiated in Langhian time (Mostardini and Merlini, 1986). The width of the basin was reduced by emplacement of the Apennine platform over the internal margin, and the resulting deeper, narrower basin was infilled with terrigenous sediments (Irpinian basin, Pescatore, 1978). The external margin of the Lagonegro-Molise basin extensively overthrusts the Apulian platform. The origin and early history of part of the Lagonegro-Molise basin will be discussed in section 4.3.

2.2.4 Apulian platform

An internal and external Apulian platform have been recognised on seismic sections (Mostardini and Merlini, 1986). The internal Apulian platform (figure 8) constitutes various thrust sheets situated topographically higher than the regional elevation of the external Apulian platform which lies to the east and is characterised by normal faulting. The external and internal Apulian platforms may have been separated by the Apulian basin (Mostardini and Merlini, 1986) which extended for 100 km to the north of Monte Vulture (figure 5). Slope and transitional facies have been recognised in various wells (Mostardini and Merlini, 1986). The Apulian basin was, however, not recognised by Cello *et al.*, (1989) in a recent study of the frontal zones of the Apennines in the Molise district. The internal Apulian platform comprises a sequence of Cretaceous carbonate rocks that may be overlain by a thin succession of Palaeogene and Miocene deposits, or directly by Early Pliocene deposits, or tectonically by thrust sheets of the Lagonegro-Molise basin (figure 5). The overthrust western margin of the internal Apulian platform, recognised on seismic sections (Mostardini and Merlini, 1986), lies parallel to, and roughly 30 km inboard from, the Tyrrhenian coast (figure 5). The width of the internal Apulian platform is estimated to have varied from between 60 and 130 km (Mostardini and Merlini, 1986). The deformation of the internal Apulian platform commenced towards the end of Early Pliocene time, forming east-verging thrust sheets emplaced onto the Apulian basin.

The Apulian basin (Mostardini and Merlini, 1986; figure 5) situated between the internal and external Apulian platforms, comprised a Jurassic to Miocene sequence, the base of which has not yet been reached in wells (figure 8). The upper part of the sequence comprises varicoloured clay overlain by mid-Miocene calcareous flysch (Faeto flysch). Deformation of the Apulian basin started after Early Pliocene time, and thrust sheets of the basin lie upon early Pliocene deposits (Mostardini and Merlini, 1986).

The external Apulian platform forms the present foreland to the Apennine mountain chain and comprises Mesozoic carbonate and thin Cenozoic deposits. The platform deepened rapidly towards the west and its internal margin is marked by Mesozoic slope and transitional facies in the subsurface. Overthusting of the internal Apulian platform over the external Apulian platform was initiated along this zone of weakness between platform and basin (Mostardini and Merlini, 1986). In places thrust sheets of Lagonegro-Molise basin deposits lie directly upon the external Apulian Platform (Pescatore and Tramutoli, 1980). As mentioned above, Late Cenozoic normal faults dominate the external Apulian platform, but possible late contractional structures have been recognised from seismic sections in the Potenza-Sant'Arcangelo area (Mostardini and Merlini, 1986).

2.2.5 Outstanding stratigraphic problems

One of the major problems is the age of the northern part of the Lagonegro-Molise basin, a problem made worse by the lack of outcrop of the Lower Series of the basin (as defined in section 2.2.3). This problem will be addressed in chapter 4, on the basis of field studies carried out in the Matese mountains area (see figure 5).

2.3 Carbonate-platform stratigraphy

Cretaceous carbonate-platform outcrops have been studied in the Maiella mountains, Matese mountains, and Mt. Sirente. Stratigraphic studies proved difficult in these sediments due to sparse and/or long-ranging microfauna, but are reported briefly here in order to provide a comparison with contemporaneous slope facies and to facilitate further discussion in the wider context of peri-Adriatic Middle Cretaceous carbonate-platform stratigraphy.

A measured section at La Gallinola (Matese mountains; figure 32; section reproduced in enclosure 1) consisted of approximately 136 m of rudistid-bearing wackstones, floatstones, bafflestones and framestones, with intercalations of micrite and rare peloidal grainstones. Worthy of note in this section are common, very thin (<10 cm) finely laminated micrite beds, and also occasional intraformational conglomerates, containing micrite clasts (<30 cm) and subordinate rudistid limestone clasts.

The age of the section was interpreted to be Cenomanian on the basis of specimens of *Lithocodium* algae (Cenomanian or older) coupled with the presence of bauxite and emersion features (karstic weathering, ?emersion breccias), most likely of Late Albian age, a few metres below the base of the section.

A second section in the Matese mountains, at S. Polo Matese (enclosure 1) comprised rudistid-bearing floatstones and bivalve-bearing wackestones and packstones with frequent very thin (<5 cm) intercalations of finely-laminated micrites. These lithologies directly superposed a 34 m thick polygenic mud-supported breccia, itself overlying a bauxite horizon. Specimens of *Cuneolina laurentii/C. camposaurii*, *Nummoloculina* sp. and *Orbitolina conica* suggest a likely Late Albian to Early Cenomanian age for this section, implying that the bauxite outcrop is of Late Albian age (see section 6.5). Comparison with the sedimentation history of the section at La Gallinola suggests that the breccia horizon may have formed during the early stages of a major relative sea-level rise following the relative sea-level fall which facilitated bauxite formation (see sections 6.5 and 6.6 for discussion of sea-level changes affecting platforms in the region). Both of the sections examined in the Matese mountains have the characteristics of an open-shelf environment with moderate to high wave-energy, in agreement with numerous other studies of such platform facies in the region (for example Carbone and Sirna, 1981).

A reconnaisance section from the West Wall of the Maiella massif revealed micrites and peloidal packstones and wackestones overlain abruptly by bauxite and karst breccias, capped by a palaeosol horizon. Specimens from lithologies above the palaeosol contained *Salpingoporella dinarica*, suggesting an age of Late Aptian or older for this emersion episode (see section 6.5). Overlying lithologies* comprised bored ?hardground horizons, overlain by burrowed micrites and capped by thinly-laminated (of algal origin?) micrites intercalated with thicker (<1 m) carbonate beds displaying cavernous porosity. These successive lithologies are arranged in 4-6 m units, interpreted as shoaling-upwards cycles. The possible significance of this section will be discussed in section 6.5.

2.4 Stratigraphy of platform-to-basin transitions

Carbonate platform-to-basin transitions have been recognised and studied in a number of localities in the southern Apennines (table 1 and references therein: figure 5), including the Lagonegro area (Norian and younger transitional facies), Matese mountains (this study, chapter 4), Marsica, the Meta mountains, Maiella mountains, Gargano Peninsula, Mt. Bulgheria (this study, section 2.4.1), the Gran Sasso d'Italia (this study, chapter 5), Vallo di Diano, Mt. Sirente and the Lepini mountains (figure 5). In the following sections, stratigraphic data obtained from some of these margins during this study will be presented. Full stratigraphic details of measured field sections are reproduced in appendix 2, and a full listing of biostratigraphic data from measured sections is given in appendix 3.

2.4.1 Western Apennine (Lucania-Campania) platform-margin

Data from Scandone *et al.*, (1963), and Robson (pers. comm., 1989) suggest the presence of a platform-margin in the Mt. Bulgheria area (figure 5) during much of the Mesozoic. This margin could correspond to the western edge of the former Apennine platform (section 2.2.2). During the Late Cretaceous, marginal facies consisted of very similar rudistid-bearing calcirudites and calcarenites, interbedded with micrites and radiolarian micrites, to those encountered on the eastern margin of the former platform at Frosolone, Matese mountains, Pietraraoia, and elsewhere (figure 32). It therefore seems

* Lithologies overlying the bauxites have been dated as Cenomanian in age (Bernoulli, pers. comm., 1990). If the identification of *Salpingoporella dinarica* is correct, this might indicate an extended range into the Cenomanian.

Margin.	Locality.	Reference
? Western margin, Apennine platform.	Mt. Bulgheria Capri	Scandone et al., 1963: J. Robson, pers. comm., 1988; this study, section 2.4.1. Barratolo and Pugliese, 1987.
Eastern margin, Apennine platform.	Lagonegro Matese Meta Vallo di Diano Mt. Sirente Lepini Marsica.	Scandone, 1967, 1972; Wood, 1981. Pescatore, 1963, 1964, 1969; Ietto, 1963, 1969; Manfredini, 1964; Clermonte, 1977, 1982; Clermonte and Pironon, 1979; Pironon, 1980; this study, chapter 4. Pescatore, 1965; Clermonte, 1977; Clermonte and Pironon, 1979; Clermonte, 1982; D'Andrea and Urgera, 1986. Marsella and Pappone, 1986. Praturlon and Sirna, 1976. Alberti, 1954; Negretti, 1957; Colacicchi, 1966; Praturlon and Sirna, 1976. Colacicchi and Praturlon, 1965a, b; Praturlon, 1968; Colacicchi et al., 1978, 1985; Colacicchi, 1987.
Northern margin, Apennine platform.	Gran Sasso d'Italia.	Scarsella, 1953, 1954, 1955a, b, 1957; Calembert et al., 1972a, b; Adamoli et al., 1978, 1982a–c; Zamparelli, 1964, 1966; Bernoulli, 1967; Chiocchini and Mancinelli, 1978; Chiocchini et al., 1982; Crescenti 1969a–b; Crescenti et al., 1969; this study, chapter 5.
? Western margin, Apulian platform.	Maiella.	Praturlon and Sirna, 1976; Crescenti et al., 1969; Accarie and Beaudoin, 1988.
Eastern margin, Apulian platform.	Gargano.	Pavan and Pirini, 1966; Masse and Borgomano, 1987; this study, section 6.2.1.

likely that the western margin could have been influenced by similar geological events to the eastern margin at this time.

2.4.2 Western Apennine (Latium-Abruzzo) platform-margin (Umbrian basin)

Stratigraphic sections were measured at Mt. Terminilletto (not presented) and Mt. Valloni (Rieti mountains). The stratigraphy of the Jurassic section at Mt. Terminilletto has previously been described by Cantelli *et al.*, (1978). The section consists of micrites and cherty micrites with interbedded redeposited calcarenites and calcirudites containing various proportions of sponge spicules, echinoderm platelets, algae, peloids, intraclasts and ooids. The stratigraphic distribution of ooid-rich redeposited beds (dispersed throughout the Dogger sediments) suggests that some repeated process was responsible for their formation, rather than a single "oolite-shedding" event. Indeed, the ooid-forming process must have been occurring at other times during the Mesozoic, since ooid- rich beds have been observed intercalated with Cenomanian rudistid-bearing lithologies at La Gallinola in the Matese mountains (section 2.3; figure 32). ~~The possible controls on formation of ooid-rich redeposited beds are discussed in section 6.3.2.~~ The main reason for the prevelance of oolitic facies in the Tethyan realm during the Dogger (Bosellini, 1989) may well be the lack of framebuilding organisms in the outer shelf environment following the major Liassic phase of partial platform destruction (see for example Bernoulli and Jenkyns, 1974). During the Malm, redeposited beds rich in skeletal detritus are again common, suggesting that the shelf-edge had again been fully colonised.

2.4.3 Northern Apennine (Latium-Abruzzo) platform-margin (Umbria-Marche basin)

Detailed stratigraphic sections from the Gran Sasso are summarised in figure 9. Full sections are reproduced in enclosure 1. The purpose of this section is to provide a brief description of each section and the most important microfauna contained therein, to facilitate discussion in chapter 5.

The measured section at Pizzo Cefalone (previously studied by Bernoulli, 1967; figure 9) consists of some 750 m of Jurassic sediments, capped by nannofossil-bearing limestones of the Maiolica Formation (Bernoulli, 1967). Directly overlying the Maiolica formation are 55-60 m of redeposited calcirudites, and calcarenites containing reworked specimens of *Palorbitolina lenticularis* and *Pseudocyclammina vasconica* and *Palaeodictyconus* sp. (figure 10) within the basal redeposited bed, these species forming a common association in Lower Aptian sediments of the Tethyan realm. Subsequent beds contain specimens of *Hedbergella* sp., *Lithocodium aggregatum* (figure 11), and *Palaeodycticonus* sp., suggesting an ?Early Aptian age. Some 17 m of thinly-bedded Upper Aptian to Lower Albian calcirudites, calcarenites and micrites follow, distinguished from the underlying beds by the presence of *Hedbergella trochoidea* and *Ticinella bejaouensis*. The final 35 m of the section are composed of more thickly bedded Upper Albian coarse skeletal grainstones and calcirudites containing transitional forms between advanced *Ticinella* sp. and primitive *Rotalipora* sp.. A further 20 m of sediment (not sampled), reported to be of Late Albian to Early Cenomanian age (Bernoulli, 1967) remain before the summit of Pizzo Cefalone.

The section measured on Pizzo Intermesoli (figure 9) was commenced some 45 m above the top of the Maiolica Formation (for technical reasons) in sediment composed of 33-40 metres of thickly-bedded rudstones, grainstones and packstones, some beds containing boulder-sized clasts. Planktonic microfossils examined in thin section from this part of the section included *Rotalipora ticinensis* to *R. subticinensis* transitional forms, *Biticinella breggiensis*, *Planomalina buxtofi*, *Hedbergella planispira*, *Rotalipora ticinensis*, and reworked specimens of the benthonic species *Miliola nezzazata*, *Orbitolina subconcava* and *Orbitolina cuvillieri* (figure 12). This fossil assemblage suggests an age for the sediment within the upper part of the Upper Albian *Rotalipora ticinensis* zone (within the lower *Planomalina buxtofi* zone of Wonders, 1978). The following 9-16 m of sediment are thought to represent the Lower Cenomanian, although no microfauna of this age were positively identified. Planktonic microfossils in the overlying 16 m of clast-supported to matrix-supported rudstones and bioclastic grainstones, interspersed with thinly-bedded micrites, however, yielded a Lower Middle Cenomanian age. These microfossils include *Hedbergella simplex, Rotalipora appenninica, Rotalipora cushmani* (figure 13a-b), *Ticinella subticinensis, Favusella* sp. (figure 13c), and reworked benthonic *Orbitolina* sp., (figure 13) the latter two indicating an age of Middle Cenomanian or older. Above the previous beds are approximately 95 m of predominantly micrites and fine wackestones, assigned a Late Cenomanian to Turonian age on the basis of specimens of *R. cushmani* in the first 50 m, and *Globotruncana linneiana* sp. in overlying beds (predominantly micrites, not discussed in detail here). The final 50 m of sediment below the summit (again predominantly micrites and marls with minor bioclastic grainstone and wackstone intercalations) of Pizzo Intermesoli yielded specimens of *Marginotruncana* sp. and *Globotruncana elevata*, implying a Santonian to Campanian age. Sedimentological implications of this section are discussed in chapters 5 and 6.

A stratigraphic section ranging from Cenomanian to Eocene in age was measured on Monte Corvo (section Mt. Corvo I, figure 9). The basal 11.5 m of the section consist of thinly-bedded micrites with interspersed fine packstones and wackestones of probable Early to Middle Cenomanian age, based on the identification of *Rotalipora* sp. and *Preglobotruncana* sp. in thin section. Immediately overlying these beds are 38 m of similar lithology of Early Middle to Middle Cenomanian age, the lowest of these beds containing *Rotalipora cushmani, R. appenninica* and *Orbitolina conica,* confirming an Early Middle Cenomanian age. Subsequent beds, with more frequent rudstone intercalations, contain *R. cushmani*, and *Preglobotruncana gibba* (figure 14) suggesting a Middle to Late Cenomanian age. After a gap of 45 m, 13 to 24 m of cherty micrites with rare intercalated rudstones crop out, bearing *Marginotruncana coronata* and *Globotruncana linneiana* sp. (figure 15), the former suggesting a Santonian to Coniacian age. The remainder of the sequence consists of partially recrystallised radiolarian-bearing micrites, grainstones and rudstones, sometimes slumped (see chapter 5 for sedimentological details). Microfossils identified from the first 12 m include *Globotruncana linneiana* sp., *Globotruncanita* sp., *Pseudotextularia* sp. and *Orbitoides media*, (accompanied by a Coniacian to Maastrichtian nannofossil assemblage-see appendix 3) implying a Campanian age. The succeeding 96 m were dated as Maastrichtian by identification of *Contusatruncana contusa* (*Rosita contusa*), *Globotruncana bulloides*, *Siderolites calcitropoides*, and *Orbitoides apiculata* (figure 16). These beds are overlain by a very thin Palaeocene section (approximately 8 m) of thinly bedded pink and green micrites and marls, Cretaceous-Tertiary boundary beds containing *Discocyclina* sp., passing upwards into assemblages including *Morozovella angulata* and *Planorolites* sp., associated with an ?Eocene nannofloral assemblage (see appendix 3). The sedimentology of the south face of Mt. Corvo adjacent to the section is discussed in chapter 5. In order to overcome the problems of recrystallisation encountered in the previously described section, a further section was measured on Mt. Corvo (Mt. Corvo II). This section comprised 96 m of micrites, wackestones, packstones and rudstones, with intercalated slumps, bearing *Heterohelix* sp., *Globotruncanita* sp., *Siderolites calcitropoides*, *Planoglobulina* sp., *Contusatruncana contusa*, *Orbitoides apiculata*, *Sigalia* sp. and reworked *Omphalocyclus macroporus* of Maastrichtian age (figure 17). The terminal 24 m consisted of three 8 m thick amalgamated calcirudite beds, containing possible specimens of *Discocyclina* sp., and may reach into the Lower Tertiary. The sediment body geometries and sedimentology of these redeposited beds are discussed in sections 5.6 and 5.7. In common with the previous section, the Palaeocene is reduced to a very thin (5-6 m) section of thinly-bedded micrites, wackestones and packstones immediately overlain by 38 m of micrites, packstones and rudstones initial beds containing the algae *Distichoplax biserialis* and *Lithothamnium* sp., in association with foraminifera including *Rotalia* sp., *Morozovella* sp. (primitive forms), *Planorolites chapmanii* sp., *Bacillogypsinoides* sp.,*Subbotinia* sp., and *Globorotalia pusilla* sp., indicating an Early Eocene age. Subsequent beds contain reworked Eocene benthonic foraminifera including *Nummulites* sp., *Alveolina* sp. and *Orbitolites* sp.. The final 14 m of the section are composed predominantly of slumped marls, micrites, packstones and large lithoclasts (figure 9; enclosure 1), bearing reworked *Turborotalia cerroazulensis*, *Nummulites* sp., *Assilina* sp., and *Discocyclina* sp., indicating a latest Middle Eocene to earliest Late Eocene age (P13-P14) (figure 18).

Several other stratigraphic sections were studied in less detail during the course of mapping, including Pizzo Camarda, Valle dell'Rio Arno, and Acquare della Formica (see appendix 3). Eocene nannofloral assemblages were identified at Pizzo Camarda, in similar pink micrites with interbedded fine packstones and wackestones to those found on Mt. Corvo I. At Acquare della Formica, the entire Jurassic and Lower Cretaceous section above dolomitised platform limestones of probable Hettangian age (Adamoli *et al.*, 1982c) is reduced to less than 170 m, since above this level micritic sediment containing *Orbitolina* sp. and *Palaeodictyconus balkanensis* (Upper Barremian) were sampled. Sediment sampled 70 m above the platform dolomites contained *Cayeuxia* sp. and the nannofossil *Watznaueria barnesae*, impling a Late Jurassic to Early

Cretaceous age. The lithology of this sediment (nannofossil-bearing chalky pelagic limestones) strongly suggests that it is the lateral equivalent of the Maiolica Formation (Tithonian to Barremian) outcropping throughout the region. In fact, Adamoli *et al.*, (1982c) have suggested that the Maiolica Formation directly overlies Hettangian platform dolomite at Aquare della Formica, and this may be correct, although a thin (<70 m) Jurassic pelagic carbonate section could be present between the two. The approximately 220 m of Aptian to Lower Eocene carbonates which overlie the Maiolica Formation have not been studied in detail, but there seems to be no obvious reason to conclude that the lower, rudistid-bearing redeposited beds in this part of the section are not Aptian to Albian in age, in common with similar sediments sampled in other sections (for example Pizzo Cefalone). This is contrary to the interpretation of Adamoli *et al.*, (1982c) that Aptian to Albian sediment is absent at this locality. The implications of the stratigraphic section are discussed in section 5.7.

2.4.4 Eastern Apennine (Latium-Abruzzo-Campania) platform-margin

Stratigraphic sections were measured in the Matese mountains (figure 5) in order to understand in detail the timing and mode of partial destruction of the carbonate platform in the area during the Late Cretaceous. Some sections were also measured to provide stratigraphic control whilst mapping the sediment-body geometries of slope sediments in the Frosolone area (see chapter 4). Sedimentological discussion of these sections is presented in chapter 4, whilst full stratigraphic sections are provided in enclosure 1. A summary of selected stratigraphic sections is given in figure 19.

Sections measured on Mt. Croce (figures 32, 71) comprised between 47 m (Mt. Croce II) and 98 m (Mt. Croce I) of lithoclastic rudstones, grainstones and micrites bearing *Globotruncana linneiana* sp., *Discorbia* sp. and *Orbitoides* sp., suggesting a Campanian to Maastrichtian age. In common with other localities in the Matese mountains, reworking of earlier Cretaceous and Jurassic sediment in derived lithoclasts was an important feature of this section (see section 3.2). Palaeocene sediments have not been positively identified in thin section studies, but, in common with many other localities in the region, appear to comprise only 20 m or less of thinly-bedded micrites, fine grainstones and packstones, immediately overlain by fine to medium-grained packstones and wackestones from which have been identified the alga *Distichoplax biserialis*, and *Discocyclina* sp., *Assilina* sp., *Alveolina* sp. and *Morozovella angulata* sp., a Late Palaeocene to Early Eocene assemblage. The marked local thickness variations and sedimentology of the redeposited sediments cropping out on Mt. Croce are discussed in section 4.10.

The measured section at Macchiagodena (figure 19c) yielded only rare specimens of *Orbitoides* sp. of probable Maastrichtian age, in common with those sediments studied at S. Angelo in Griotte (figure 19a). Sediments of identical lithofacies sampled near Pietraoia (figure 32) were confirmed to be also of Late Cretaceous age by the identification of Late Cretaceous *Globotruncana* sp., indicating that the redeposition of sediment was a common feature in wide areas bordering the eastern edge of the former Apennine platform at this time.

Microfossils identified at Frosolone during mapping included *Alveolina schwagerii*, *Nummulites* sp., *Morozovella* sp., *Siderolites calcitropoides*, *Lithothamnium* sp., *Rotalia* sp., *Chapmanina* sp., *Globigerina* sp. and *Globerinopsis* sp., confirming the Maastrichtian to Eocene age of the outcrops. The identifications made are similar to those reported by Pironon (1980) for the same area, and have been used to produce the stratigraphic key on the map of redeposited sediments in the Frosolone mountains (figure 34). The subject of reworked lithoclasts with widely differing ages, a very common phenomenon at Frosolone, is discussed in section 2 .3.

The exposures in the limestone quarry at Frosolone display typical stratigraphic details from the area (figure 20). Here, two 20 m thick calcirudite beds of probable Maastrichtian age (by lateral tracing of beds during mapping), bearing rudistid and other shallow-water-derived skeletal material, are overlain by approximately 20 m of thinly-bedded red and green micrites and marls containing *Morozovella* sp. (Middle to late Palaeocene) themselves containing a further intercalated calcirudite bed after 3 m. On the contact between the micrites and the underlying Maastrichtian calcirudites was observed an olistolith (100x30 m; figure 46f-g) of bedded redeposited rudist-bearing grainstone. Minor synsedimentary faults in the calcirudites are sealed in the overlying thinly-bedded Middle/Upper Palaeocene micrites (figure 20c-d). The implications of these stratigraphic relationships for the behaviour of the platform-margin as a whole are discussed in chapter 4.

2.4.5 Eastern Apulian platform-margin

The sedimentology of the Cretaceous slope sediments on the Gargano peninsula was studied briefly to provide a comparison with the behaviour of the eastern margin of the Apennine platform. A detailed measured road section between Manfredonia and Monte San Angelo (enclosure 1) comprised 45 m of calcirudites, graded calcarenites, micrites and chalks, dated as Upper Albian on the basis of specimens of *Rotalipora appenninica* and *R. ticinensis/R. subticinensis*. The presence of reworked planktonic species was cited by D'Argenio *et al.*, (1975a) as evidence that individual grains were resedimented on this margin prior to cementation (see section 3.4). Sediment immediately overlying this (of similar lithology for 23 m) contained *Rotalipora reicheli* and *R. appenninica*, suggesting an Early Middle Cenomanian age. The last 2.5 m of this part of the section consists of pelagic chalk, implying temporary cessation of redeposition on the slope (?during part of the Early Turonian). Specimens of

Marginotruncana ?pseudolinneiana and *Marginotruncana ?marianosi* were identified in a redeposited bed immediately above, suggesting a Latest Middle to Early Late Turonian age. The subsequent 18 m of the section are dominated by chalk, presumed to be of Middle to Late Turonian age, in agreement with Masse and Borgomano (1987), who assert the lack of redeposition on the slope during the Middle and Late Turonian. This interpretation is strengthened by the identification of *Marginotruncana pseudolinneianna* sp. and *Marginotruncana sigali* in the first redeposited bed overlying the chalk (implying a Late Turonian to Early Coniacian age). There follow 27 m of section chiefly composed of chalk with planktonic foraminifera, and 72 m or more of calcirudites, graded calcarenites and thin chalk intercalations of probable Late Cretaceous age. The section has been used during subsidence modelling as a comparison with sediments of Middle Cretaceous age from the eastern margin of the Apennine platform (section 6.7).

Chapter 3:
Petrographic Studies of Southern Apennine Platform-margins: Implications for Models of Platform Anatomy.

3.1 Intodaction

This chapter will provide evidence for large-scale processes which controlled changes in platform-margin anatomy during the Mesozoic by means of thin-section petrography (polarised light and cathodoluminescence) and geochemical analysis (proton microprobe microanalysis).

The growth response of carbonate-platform systems changes with time, depending on a number of variables (sections 1.1, 6.3). One result of this is a temporal change in Tethyan microfacies, which has been noted by a number of authors. One example is the marked export of oolitic sands into basins in the Middle Jurassic, from the Atlantic (Nova Scotia, Portugal), through the Mediterranean (Morocco, southern Spain, Balearic islands, Alps, Apennines, Jugoslavia, Greece), Oman and Somalia (Bosellini *et al.*, 1981a, b; Ruiz-Ortiz, 1983; Searle *et al.*, 1983; Barnolas-Cortinas, 1984; Wright and Wilson, 1984; Watts and Garrison, 1986; Bernoulli and Weissert, 1987). Oolitic facies are generally much less common at other times in the Tethyan region. Another example of seemingly time-specific biofacies is the occurrence of ribbon radiolarites, particularly common during the Oxfordian stage of the Jurassic (Jenkyns and Winterer, 1982).

D'Argenio *et al.* (1975a) documented the common latest Jurassic-earliest Cretaceous association of broken and regenerated radial-fibrous ooids and nodular thalli of *Cyanophyta* in Italian and Yugoslav platforms, and noted the close similarity of these with sediments of the same age from offshore Gentry Bank in the Bahamas. This again strongly suggests the occurrence of certain platform microfacies on a wide regional scale at particular times.

Other examples of extensive temporally-restricted microfacies include the rudistid-bearing facies of the Middle and Upper Cretaceous (Wilson, 1975). Many such biofacies are clearly the product of faunal evolution and climatic change (Carannante and Simone, 1986). Despite this, the reasons for some of the temporal changes, such as "oolite shedding" are less obvious, and the available evidence derived from field data in the present study was discussed in section 2.4.2.

A second striking petrographic feature of the southern Apennine sediments sampled was the observation that, at certain times, erosion of lithified material rather than accretion of newly-formed carbonate sediment was predominant in some study areas. The temporal distribution of such erosional facies and their possible implications for the factors controlling platform anatomy will be discussed in section 3.2. In conjunction with examining field specimens, recent additions to the regional literature were used to provide as complete a pattern of regional carbonate-platform responses as possible.

The third petrographic aspect to be dealt with in this chapter is that of the diagenetic changes undergone by platform and basin carbonates in the southern Apennines. Studies by Meyers (1974, 1978), Meyers *et al.* (1988) and Grover and Read (1985), amongst others, have suggested that cathodoluminescent petrography and geochemical data may yield valuable information concerning the large-scale movements of pore-waters through the transitional platform-to-basin environment. Such movements should be a response to major hydrological events which occurred in the margins subsequent to deposition. With this rationale in mind, generalised sediment parageneses for selected areas will be outlined in section 3.3.1, with the intention that this will stimulate further studies to try and link burial histories with specific major events affecting the platform-margins. It is hoped that, as more data becomes available, an inductive, computer-modelling approach to predicting platform-to-basin stratigraphy and diagenetic histories may become possible in this region, as outlined by Matthews and Frolich (1987) (see also Humphrey and Quinn, 1989).

Since conventional microanalytical techniques, such as electron-microprobe microanalysis have been found to provide insufficient resolution of trace element concentrations (specifically, Mn, Fe, Zn and Cu), recourse was made to a novel microanalytical technique, the high-resolution scanning proton microprobe (SPM), which has recently become available for geological studies. Studies by SPM microanalysis (section 3.3.2) have enabled further, geochemical, constraints to be placed on the pore-water evolution of platform-margin dolomites from the Gargano Peninsula (eastern margin of the former Apulian platform), and a tentative attempt is made to relate these geochemical results to petrographic data from the same platform-margin.

3.2. Age-ranges of derived clasts

3.2.1 Derived clasts in the southern Apennines

Samples collected during fieldwork were routinely thin-sectioned and petrographically analysed to ascertain their microfacies and micropalaeontological content (section 2.2). It became apparent at an early stage in this analysis that sediment redeposited on the palaeoslopes during the Mesozoic was not uniformly contemporaneous in origin. In particular, derived clasts from the Frosolone area (Matese mountains) were shown to be of a variety of ages by micropalaeontological analysis. In order to determine whether or not this characteristic was present regionally, sediments from the Gran Sasso d'Italia were investigated in a similar way (see below). To provide a more complete regional picture, data from recent publications pertaining to the age-ranges of derived clasts was collected and tabulated (figure 21). These data provide a complex picture which will be discussed in the following paragraphs.

Derived lithoclasts were observed in both Lower Cretaceous and Campanian to Maastrichtian sediments in the Matese mountains area. Upper Berriasian to Lower Hauterivian siliceous packstones and lithoclastic rudstones at Pesche (figure 25; section 2.2) contained specimens of *Trocholina umbo* (Kimmeridgian to Tithonian), *Cayeuxia moldavici* (Kimmeridgian to Tithonian), *Lithocodium* sp. and *Calpionella* sp. (Tithonian to Valanginian) within lithoclasts (figure 22). Campanian to Maastrichtian lithobioclastic rudstones at Frosolone (Morgue Quadra) (figure 25; section 2.2) contained specimens of *Cayeuxia* sp. (Kimmeridgian to Tithonian) and *Trocholina conica* (Upper Jurassic) within lithoclasts (figure 23a-b). *Cayeuxia* and *Lithocodium* were also observed in Upper Jurassic platform carbonates from Campitello Matese (figure 32) and Mt. Camposauro (see also D'Argenio *et al.*, 1975a; figure 32), confirming the likely local platform origin of lithoclasts containing these algae (figure 23c-e). At Carpinone, (figure 25) Campanian to Maastrichtian lithobioclastic rudstones contained *Lithocodium* sp. (Latest Jurassic to Early Cretaceous age), whilst in similar sediments at S. Angelo in Griotte (figure 25) specimens of *Triploporella* sp.,*Cuneolina* sp., *Lithocodium* sp., *Cayeuxia* sp., and *Trocholina* sp. were encountered (figure 24a-f). On Mt. Croce, (figure 25) Campanian to Maastrichtian lithoclastic rudstones unconformably overlying Upper Triassic dolomites were found to contain reworked *Haplophragmoides* sp. (Upper Jurassic to Lower Cretaceous; figure 24g). Interestingly, Upper Cretaceous redeposited lithoclastic rudstones sampled 3 km northeast of Pietraroia (figure 25), also situated on a part of the inferred palaeoslope between the former Matese platform and the Molise-Sannio basin (section 4.3) contained specimens of *Trocholina elongata, Trocholina gigantea* and *Trocholina alpina*, of Late Jurassic age (figure 24h) confirming that these sediments were also derived by erosion of Jurassic platform sediments (probably those of the Matese mountains).

Redeposited sediments from the inferred palaeoslope in the Gran Sasso (chapter 5) presented a very different picture. Figure 21 indicates that reworking was contemporaneous (within the limits of micropalaeontological dating by planktonic foraminifera in thin section) during the Albian and Maastrichtian stages of the Cretaceous. These stages are indicated to afford a comparison with other margins, and are used since sediments of these ages are amongst the most closely dated in the Gran Sasso. However, contemporaneous reworking is indicated by sediments of other stages sampled in the Gran Sasso, and lithoclasts much older than the parent sediment are absent. For example, sediment of Middle Cenomanian age on Mt. Corvo contained *Rotalipora monsalvensis, Rotalipora cushmani* (figure 13a-b), *R. appenninica* and *Orbitolina conica*, all of Early to Middle Cenomanian age, whilst sediments from Pizzo Intermesoli, dated as Upper Albian by means of planktonic foraminifera contained reworked specimens of the benthonic species *Orbitolina subconcava* and *Orbitolina cuvillieri* (figure 12) both of Late Albian age, in good agreement with the planktonic foraminiferal stratigraphic ages. Reworked specimens of the benthonic foraminifera *Siderolites calcitrapoides* and *Omphalocyclus macroporous* (figure 17c-d) were discovered in Maastrichtian bioclastic calcarenites and calcirudites on Mt. Corvo, both species being of Maastrichtian age themselves, again indicating penecontemporaneous reworking.

The difference between the age-ranges of derived clasts in the Matese mountains and the Gran Sasso is thought to be a real one, since extensive sampling of measured sections was undertaken in both areas, reducing the likelihood of locally biased sample populations. Figure 25 shows the widespread distribution of localities in the Matese Mountains where long-ranging populations of clasts were encountered, and also those localities where contemporaneous reworking was observed in the Gran Sasso.

Several other platform-margins were investigated by reviewing recent literature in order to detect any regional pattern of reworking, if present (figure 21). On the Marsica margin (figure 5), Colacicchi *et al.* (1978) reported predominantly bioclastic redeposited sediments (calcirudites and calcarenites) of Barremian to Albian age, with reworked *Orbitolina* sp., suggesting a contemporaneous origin. Maastrichtian "megabreccias" from Marsica, however, are reported to contain a range of clasts from Liassic (*Palaeodasycladus* limestone) to Upper Cretaceous. Masse and Borgomano (1987) reported Berriasian lithoclasts within sediments of Upper Albian age on the eastern palaeoslope of the Apulian platform (Gargano peninsula; figure 5), whereas during the Berriasian to Barremian redeposited sediments at this locality consisted of wackestones to packstones with reworked Trocholinids, Orbitolinids, Miliolids, Dasyclads and *Lithocodium/Bacinella*- bearing bioaggregates (Luperto Sinni and Masse, 1987) of contemporaneous bioclastic type. The contemporaneity of the reworking is clear, as is also the case in the Gran Sasso, since redeposited sediments are interbedded with pelagic sediments containing Radiolaria, and Calpionellids. Some small lithoclasts are reported, but are not apparently long-ranging. Reworking of older material (Cenomanian platform and slope-derived clasts) resumed during the Coniacian to Early Campanian stages, although Maastrichtian redeposited calcirudites and calcarenites are composed of contemporaneous Rudist debris from the adjacent platform.

The Maiella mountains of Abruzzo have recently been studied by Accarie (1987) and Accarie and Beaudoin (1988) who discovered the presence of thick lenticular calcirudites of Middle and Upper Cenomanian age on the inferred palaeoslope in the area, composed of clasts of lithified Lower Cretaceous platform limestones. This formation passes laterally into fine-grained pelagic carbonates towards the inferred site of the former basin. The overlying Turonian to Lower Campanian formations consist of micrites rich in *Globotruncana*, with interbedded calcirudites and calcarenites containing skeletal clasts of Cenomanian or younger age, and also beige to grey Lower Cretaceous limestones rich in benthonic foraminifera and dasycladacean algae. The Upper Cretaceous (Campanian pp. to Maastrichtian) redeposited sediments are reported to be lenticular to continuous calcirudites composed of contemporaneous rudist debris and benthonic foraminifera (especially *Orbitoides* sp.)

Finally, from the Mt. Maddalena, Marsella and Pappone (1987) reported Jurassic to Cretaceous lithoclastic and bioclastic calcirudites and calcarenites directly overlying Upper Triassic to Lower Jurassic dolomite. These redeposited sediments contained *Salpingoporella* sp., *Clypeina jurassica* FAVRE, *Bacinella irregolaris* RADOICIC, *Protopeneroplis striata* WEYNSCHENK and *Labyrintina mirabilis* WEYNSCHENK. This assemblage suggests a range of clast ages from Bajocian/Bathonian to Lower Aptian, although the lower part of the formation is reported to contain *Cayeuxia* sp. and dasycladacean algal fragments, some of which may be of Triassic age. A very long age-range of clasts (from Upper Triassic to Upper Cretaceous) is apparently present within Campanian to Maastrichtian lithoclastic calcirudites and calcarenites ("calcari cristallini") with specimens of *Thaumatoporella* sp. (Upper Triassic or younger) and *Clypeina jurassica* (Upper Kimmeridgian to Portlandian) having been recognised within lithoclasts.

The presence of derived clasts with a large age range is not confined to the southern Apennines, similar occurrences having been documented from the Upper Cretaceous to Eocene *Scaglia* formation throughout Sicily by Gullo and Vitale (1987). For instance,

* the terms "clasts with wide age ranges" and "long-ranging clasts" are used in this thesis to mean that *derived lithoclasts from many different older formations were found in sediment with a younger dated age.* The lithoclasts themselves may be precisely dated and the term does not imply that the sediment in which they are redeposited has an ambiguous or poorly-constrained age.

in the Giuliana area (Mt. Genuardo Unit) of the Saccenese domain, a 100 m thick calcirudite "megabreccia" overlies an Upper Triassic to Lower Cretaceous basinal succession, and is in turn overlain by 25 m of Maastrichtian pink pelagic marl containing rolled blocks, and another level of breccia comprised of Upper Triassic to Jurassic shallow-water carbonate clasts. The "megabreccias" are commonly associated with erosional surfaces cutting Triassic to Jurassic platform sequences.

3.2.2 Implications of derived clasts for platform anatomy

Clearly, the presence of derived clasts with wide age ranges* in redeposited sediments implies some form of erosion of the carbonate platforms. This erosion could be accomplished by (i) current action denuding a steep platform-to-basin escarpment, (ii) by the incision of submarine canyons, or alternatively (iii) subaerial erosion by means of karst weathering processes could supply detritus to be remobilised by currents. Any or all of these processes could be made more effective by heightened tectonic activity (such as earthquakes and fault movements) or fluctuations of relative sea-level. The fact that long-ranging clast assemblages are reported from many different stratigraphic stages implies a process which operated effectively many times during the Mesozoic. Erosion of lithoclasts in the Cretaceous (see section 3.2.1) occurred in the ?Early Hauterivian, Early Aptian, Late Albian, Middle Cenomanian, Early Campanian and Maastrichtian stages or substages at minimum (figure 21), and other occurrences may very likely have escaped detection due to lack of biostratigraphic resolution.

Given the above well-established times of platform erosion, are there any possible common processes which could be responsible for all such events? One possible model could be that marked erosion episodes occurred during major lowering events of relative sea-level (Harris, 1988). Such an origin for calcirudites has been proposed by

Yose and Heller (1989) from studies of Pennsylvanian carbonates in California. According to these authors, sea-level lowstands (corresponding to the maximum rate of sea-level fall) may result in wave base impingement and large-scale collapse of the outer-ramp-slope system (figure 26). Such a process could conceivably result in an assemblage of derived clasts with a variety of ages, although it is difficult to imagine a collapse so large that it could yield clasts ranging in age from Late Triassic to Late Cretaceous. It is important to note that collapse need not occur in an allocyclic system, driven by sea level cyclicity, so that the sedimentary response would be expected to vary from margin to margin. Even though more examples of Cretaceous sections are needed from the southern Apennines, it is apparent from figure 21 that the response of different margins to any common underlying driving mechanism for erosion was different. For instance, whilst erosion of Berriasian lithoclasts was occurring on the Gargano Peninsula during the Late Albian, redeposited sediments from the Gran Sasso and Marsica were predominantly contemporaneous in origin (albeit with intercalated calcirudites in the Gran Sasso; section 5.6). Similarly, although erosion of Upper Jurassic and Lower Cretaceous lithoclasts took place in the Matese, during the Maastrichtian, and erosion of Upper Triassic to Liassic clasts in the Mt. Maddalena and Marsica, penecontemporaneous erosion occurred in the Gran Sasso, Gargano and Maiella mountains.

Circumstantial evidence for the role of relative sea-level changes in mediating platform erosion during the Cretaceous comes from the stratigraphic distribution of emersion features on the carbonate platforms. Evidence for such features will be discussed in section 6.6, but, briefly, emersion features are known from the Lower Aptian (Gargano; Masse and Borgomano, 1987), Upper Albian (Maiella; Accarie, 1987; Yugoslavia; Radoicic, 1987; Abruzzo; Bardossy *et al.*, 1977), Early to Middle Cenomanian (Abruzzo;

Bardossy *et al.*, 1977; D'Argenio *et al.*, 1987; Yugoslavia; Radoicic, 1987) and Maastrichtian (Abruzzo; Carbone, 1984, Sicily; Gullo and Vitale, 1987). In view of the apparent time-coincidence between so many clast-erosion events and platform emersion features, it will be an important theme in chapters 4, 5 and 6 to assess other field and published evidence for the link between the sedimentological behaviour of the southern Apennine platform margins and possible fluctuations of relative sea-level.

The problem of the extremely wide age-ranges of clasts on some margins is one that remains. It is thought that some tectonic activity during the Cretaceous (renewed crustal extension?) must be implicated to explain the exposure of rocks ranging from Late Triassic to Late Cretaceous in age during a single erosion episode. In order to test this hypothesis, field studies presented in section 4.9 will be used in section 6.7 to provide a possible explanation for the erosion of such large thicknesses of sediment.

3.3 Diagenetic pathways

3.3.1 Regional sediment parageneses

Thin section petrography was used as a tool to look for clues to the behaviour of the southern Apennine platform-margins through time, with particular reference to the passage of fluids through the sediment during burial. Major geological events undergone by the platforms, such as unconformity formation and/or subaerial exposure of the platforms, or the passage of late hydrothermal fluids through the rock might be expected to influence the burial diagenesis of sediments, both on the platform and palaeoslope. Generalised sediment paragenetic sequences for the Matese area (platform and slope), and Gargano (slope) are shown in figure 27. These sequences will be discussed in turn in the following paragraphs.

Cretaceous sediments from the palaeoslopes in the Matese and Gran Sasso areas (figure 27a) underwent extensive early micritisation of grains, accompanied by dissolution, presumably of unstable or metastable mineralogies such as aragonite. Early-formed, isopachous, (?marine) cements are poorly developed, perhaps due to rapid closing of pore-systems to the surface by rapid lithification of the micrite matrix between grains. Dissolution is thought to have been followed by pervasive early burial calcite cementation, filling most remaining pore-space, since little early compaction of grains is visible. Late diagenetic changes included neomorphism of early calcite cement to form coarse megaspar, calcite vein formation and fracture filling, and in some cases late dolomitisation and ferroan calcite veining. Some or all of these late diagenetic events were probably deformation-related, at least in part, and may be attributed to Apenninic thrust tectonics.

On the carbonate platform in the Matese mountains area (figure 27b), similar early micritisation of grains and lithification of the micrite matrix of the sediment took place. In some localities on the outer shelf (for example S. Polo Matese), this was accompanied by very early dissolution of some unstable mineralogies to form mouldic pores in skeletal grains (especially Rudist tests). These pores, probably formed in a shallow (?mixed meteoric/marine) environment, were partially infilled by internal sediment in the form of geopetal infillings (figure 28a). Locally well-developed isopachous (probably marine) calcite cement coated some grains. Further dissolution of metastable mineralogies was accompanied by precipitation of dull to dull/bright cathodoluminescent calcite spar (figure 28c-d) (a typical burial spar progression often interpreted as resulting from increasingly reducing conditions during burial, for example Meyers, 1974, 1978; Grover and Read, 1983; section 3.3.2). Early stages of this spar include syntaxial overgrowths, especially on crinoid grains. In some localities (for instance Campitello Matese), partial dolomitisation may have taken place at this stage. Burial spar precipitation in Barremian to Aptian carbonates (Lower Cretaceous) on the Matese platform at Mt. Camposauro and Campitello Matese was interrupted by a further phase of dissolution to form large vuggy pores, in which precipition of non-luminescent clear calcite megaspar occurred (figure 29). This cement may be interpreted as being related to the formation of the bauxitiferous unconformity during the Late Albian and/or Middle Cenomanian (see also section 3.3.3). Late diagenetic alteration of platform carbonates included calcite neomorphism to megaspar and in some localities calcite veining and late dolomitisation, some of these late changes again possibly being due to regional deformation.

The Cretaceous sediments of the eastern margin of the Apulian platform, from the site of the former palaeoslope on the Gargano Peninsula, underwent a somewhat different burial history (figure 27c). Early synsedimentary micritisation of grains and lithification of the micrite matrix between grains was accompanied by extensive early dissolution and precipitation of early pore-lining calcite spar cement in a meteoric/ phreatic environment (Bernoulli, 1972;* figure 28b). Visual estimates suggest that in many parts of the sequence, the proportion of skeletal components, composed of unstable/metastable mineralogies, to carbonate mud ("periplatform ooze") in redeposited carbonates was much greater on this margin than on the Matese or Gran Sasso margins (see section 3.3.3). This initial compositional difference may account for the more effective development of isopachous calcite cements in the Gargano sediments. Marine cementation was followed by extensive dissolution of grains composed of unstable mineralogies, accompanied by rather limited precipitation of dull to dull/bright luminescent calcite burial spar (figure 30a-b). Precipitation of this spar in pore spaces may have been inhibited by the loss of pore connectivity associated with the pervasive isopachous calcite cements, preventing passage of

* plates XII-XIV

sufficient volumes of fluid through individual pores to allow complete occlusion. Locally, a further ?late phase of dissolution has been identified from the Gargano sediments, particularly those of the Lower Cretaceous Mattinata limestones (figure 30c-d). This late dissolution event was accompanied by the precipitation of non-luminescent equant- to mega-spar cement in some pore spaces (figure 30e-f). Despite the multiple phases of dissolution and precipitation of burial cement which have affected these rocks, preserved mouldic and interparticular secondary porosity reaches values of around 30-35% locally.

3.3.2 Proton microprobe microanalysis

In an effort to characterise the geochemical conditions under which burial cements were precipitated in the Cretaceous palaeoslope environment, use was made of a recently developed microanalytical technique, Particle- (or proton-) Induced X-ray Emission, or PIXE, using the Oxford Scanning Proton Microprobe (SPM). Studies by Fraser *et al.* (1984) had suggested that chemical elemental analysis at concentrations of between 1 and 20 ppm (depending on the element and the matrix) at a spatial resolution of 1 µm were routinely obtainable for trace elements in mineralogical samples using this technique.

The SPM is a microbeam instrument like an electron microprobe, but uses a highly focussed beam of protons instead of an electron beam to generate X-rays. Because of the much larger mass of protons as compared with electrons, a high energy proton beam is scattered much less by a given sample than a comparable beam of electrons. This gives the proton microprobe two major advantages when compared with the electron microprobe: (i) higher spatial resolution because the beam is scattered less and (ii) a lower X-ray background (Bremsstrahlung) caused by deceleration of the incident beam. Instrumentation and operation of the Oxford SPM are discussed fully by Watt and Grime (1987), whilst the many important problems associated with relatively "thick" geological specimen targets and analytical calibration are being studied by Feltham (pers. comm., Oxford, 1989). In the context of the present study, the superior spatial resolution and lower elemental detection limits as compared with more conventional instruments were necessary in order to apply the SPM to the chemical analysis of cements in redeposited carbonates.

Zoned secondary dolomites from the Upper Berriasian to Valanginian "limestones and dolomites of Mt. Iacotenente" were chosen for analysis by SPM since they contained well-developed, concentrically-zoned rhombs of approximately 150 μm diameter. These rocks are thought to originate from a position on the Cretaceous palaeoslope (Masse and Borgomano, 1987 showed these limestones and dolomites to be the lateral equivalent of the lower part of the Lower Cretaceous Mattinata limestones; figure 100). The individual dolomite crystals were found to display cathodoluminescent zonations on a scale which was suitable for the spatial resolution of the SPM (figure 31b-c). The analytical methods used and interpretation of these zonations as mapped by PIXE are reported fully by Fraser *et al.* (1989). Selected one-dimensional line-scans from the study are reproduced in figure 31a; notable features of these traverses are (1) the decoupled behaviour of the various elements, Mn and Fe displaying sharp, independent concentration peaks, whereas Sr shows no discernable zonation, and (2) the shape of Zn elemental concentration peaks, which have a steep internal (nearest the crystal core) boundary, representing a rapid rise in concentration, and a more gently inclined external side, corresponding to a more gradual decline in Zn concentration.

These data led to the interpretation that crystal growth (probably replacing a precursor micritic sediment) was largely controlled by fluctuations in redox potential within the pore-fluid, since redox-sensitive elements (Mn and Fe) show strong local zonation, whereas elements with a single oxidation state (Sr) display no measurable zonations. Furthermore, the shape of the Zn elemental peaks suggests that crystal growth could have been effected by at least two discrete influxes of pore-waters through the rock. The most likely source of Zn in a carbonate platform-to-basin transitional environment is probably the reduction of Fe and Mn oxide-hydroxides, in basinal mudstones, liberating Zn into solution. The solubility of Zn in solution is also controlled by the effects of Eh-pH on sulphide-sulphate equilibria. No such redox controls operate to change the equilibrium concentration of Sr in solution. Fraser *et al.*, (1989) state that the separation of these elements into two groups according to the influence of redox effects on their equilibrium solubilities, is strong evidence for the importance of redox changes in controlling zoning in the Gargano dolomites.

3.3.3 Implications of diagenesis for Cretaceous platform-margin behaviour

Preservation of primary porosity on the Gargano (Apulia) platform margin may have been assisted by its probable leeward palaeogeographic position during the Mesozoic. Analogous windward and leeward differences are known from the modern Bahamian platforms (Cook *et al.*, 1983) and have been inferred from other ancient platforms (Abott, 1988). Early dissolution in meteoric/phreatic conditions apparently took place on the platform, with accompanying calcite cement precipitation binding grains together. Subsequently, lithoclasts, bound by such early calcite cements, and with a high primary porosity, were redeposited on the slope in mass-flow deposits (Bernoulli, 1972). The lack of tectonic overburden or flysch deposition on the Gargano Peninsula led to a lesser degree of pressure-solution and a greater retention of primary porosity here than elsewhere in the southern Apennines. The porosity preserved at the present day may also have been enhanced by late-stage dissolution (section 3.3.1; figure 30c-f) in the sediments. A likely reason for this diagenetic history is the subaerial exposure of the Apulian platform during part of the Cenomanian, in common with the known timing of emersion and bauxite formation on the Apennine platform. Shallower burial mimimised

* Lithoclasts containing vadose cements have also been reported form the Upper Albian of the Gargano (Masse and Borgomano, 1987).

the late diagenetic effects noted in section 3.2.2.

The comparatively low proportion of early porosity occupied by early burial calcite spar cements on the Gargano palaeoslope may have assisted the passage of subsequent burial fluids through the rocks. In section 3.3.2 it was noted that calcite cements formed during multiple (two or more) phases of dissolution and precipitation, on the basis of thin-section and cathodoluminescent petrography. These distinct phases of cementation require large fluxes of fluids to have passed through the sediments during their burial (between 10,000 and 50,000 pore volumes are required to completely fill a pore with cement; Bathurst, 1975). Furthermore, it was concluded from section 3.3.2, and following Fraser *et al.* (1989) that the formation of the replacive dolomites of the Gargano was most likely achieved by two or more discrete influxes of pore-water into the sediment. Recent field observations (Davey, pers. comm., 1989) indicate that replacive dolomites occur in Lower Cretaceous sediments throughout the Gargano peninsula, suggesting that the pore-water movements which created such alterations affected at least a 30-40 km length of the former eastern Apulian platform-margin. Preliminary observations suggest that cathodoluminescent characteristics of the dolomites are similar throughout the area.

One possible model to reconcile these observations is a steady burial of the slope sediments during the Cretaceous and Early Tertiary, during which time the precipitation of dull/bright cathodoluminescent calcite spar took place, followed by a late-stage dissolution event, possibly caused by fluctuating potentials driving batches of pore-water through the margin.* These fluids, carrying trace-elements such as Zn and Cu (and also Sr) may have caused dissolution and creation of secondary porosity as they passed through the rocks of the platform-margin and, locally, both ?calcite and dolomite formation. Trace element distributions within secondary dolomites (see above) suggest

* Fraser *et al.*, (1989).

that at least two discrete phases of fluid were introduced into the rocks. The textural relationship between secondary dolomites and associated calcites suggests that the latter may have been produced after dolomite formation had occurred.

The passage of late-stage, fluids through the platform-margin helps to explain the petrographic, sedimentological and geochemical evidence from the Gargano margin. The redeposited sediments of the Gargano have yielded diagenetic information which may provide clues to major events affecting the eastern Apulian platform-margin as a whole during the Cretaceous and Tertiary.

Chapter 4:
Sedimentology and Mesozoic platform-margin anatomy of the Matese Mountains.

4.1 Introduction

The Matese region (figure 32) provides potential for understanding and interpreting Mesozoic carbonate platform-margins in the southern Apennines for three main reasons.

Firstly, the type-exposures of the Molise-Sannio series (D'Argenio *et al.*, 1975b) adjoin outcrops of platform carbonates in the Matese Mountains, and to the north in the Frosolone mountains. This series of basinal deposits has been described as being Upper Cretaceous to Tertiary in age (Pescatore, 1965) although deep well data from Frosolone suggest the existence of much older Jurassic or Triassic basinal rocks (Martinis and Pieri, 1964) in the area. The question of the age of the Molise basin is an important palaeogeographic problem, and will be addressed in section 4.6, using new stratigraphic data.

Secondly, the Molise-Sannio series rocks in the Frosolone area afford good exposure of redeposited carbonates with distinctive sediment-body geometries. In other regions, such as the Gulf of Mexico, similar deposits have provided major hydrocarbon reservoirs (Enos, 1974, 1977, 1985). Despite this important exploration potential, very little is known about the geometries of the sediment bodies or the sedimentology of the flows which formed them. This problem has been tackled by detailed 1:10,000 field mapping, and intensive sedimentological studies, which form the backbone of this chapter.

The third reason for the importance of the Matese region in southern Apennine geology is the presence of an Upper Cretaceous unconformity between the platform facies and Molise-Sannio basinal facies. The apparent uplift associated with this unconformity raises questions about the regional tectonic setting during the Cretaceous. In particular, if renewed crustal extension had occurred, this could provide opportunity for hydrocarbon entrapment by forming structural traps. The regional implications of the Upper Cretaceous unconformity will be discussed in chapter 6, but this chapter will develop a model to account for the Mesozoic development of the platform-margin in the area, based on detailed field observations.

4.2 Stratigraphy

4.2.1 Early studies

Early studies on the Matese were performed by Tenore, (1872), Salmoiraghi, (1881), Cassetti, (1893, 1894, 1895, 1898), Fittipaldi, (1900), Sacco, (1910, 1912, 1935), Grzybowski, (1921), Cacciamali, (1924), Cortese, (1926), Rovereto, (1927), Behrmann, (1936, 1958), De Lorenzo, (1937), Beneo, (1949), Lazzari, (1950), Scarsella and Manfredini, (1955), Zaccara and Maino, (1957, 1958). The first edition of the Geological Map of Italy, published in 1934, was accompanied by a general paper on the Matese (Ufficio Geologico, 1934).

4.2.2 Molise-Sannio series

Studies for the second edition of the geological map in Italy (Servizio Geologico d'Italia, 1971) initiated modern studies on the area with works by stratigraphic schemes for the Molise-Sannio series being published by Selli, (1957), Signorini, (1962), Signorini and Devoto, (1962), Pescatore, (1965), Cocco, (1971), and Pironon, (1980), (figure 33). Other papers on the relationship between the Matese platform facies and the basinal rocks of the Molise-Sannio series were published by Selli, (1962), Zanfra, (1963), Manfredini, (1963), Devoto, (1963), Pescatore, (1963, 1964), D'Argenio, (1963b)

Catenacci *et al.*, (1963), Vallario, (1964), and Sgrosso and Torre, (1968).

4.2.3 Matese-Monte Maggiore series

Stratigraphic schemes for the Matese platform facies were published by Crescenti and Sartoni, (1963), and Scarsella and Manfredini, (1955). Other works on the platform in the area were carried out by Sgrosso, (1963, 1964), Ietto, (1964), Pieri, (1966), Crescenti and Vighi, (1970), De Rosa, (1976), Barratolo, (1980), and Accordi *et al.*, (1982). The stratigraphic scheme for the Molise-Sannio series and the Matese-Monte Maggiore platform series followed in this thesis are given in figure 34 and appendix 1 respectively. Stratigraphic data obtained during this study are presented more fully in chapter 2.

4.3 Local geology

This area formed part of the eastern margin of the Apennine platform during the Mesozoic (see section 2.4.4). The carbonate platform in the Matese was a site of shallow-water carbonate sedimentation from the Late Triassic until the Late Cretaceous (Maastrichtian), and also during the Eocene to Miocene. A regionally important emersion horizon is recorded in the Lower Cenomanian by the presence of karst bauxites, and although other emersion periods are almost certainly present, they are not palaeontologically resolvable. A second important unconformity in the Matese is expressed by the overstepping of Campanian to Maastrichtian redeposited, gravity-flow derived and pelagic limestones onto Lower Cretaceous, Jurassic and Triassic platform facies (Ietto, 1969). The apparent uplift and erosion required to generate this unconformity (up to 1000 metres) gave rise to speculations of renewed regional crustal extension, and this hypothesis will be tested in chapter 6.

The date of origin of the Molise basin is still under debate (D'Argenio *et al.*, 1975b, 1980, 1986; Channell *et al.*, 1979; Mostardini and Merlini, 1986; but see section 4.6). However, the northward extension of the Late Triassic (Norian) Lagonegro basin (Scandone 1967; 1972) into the Molise basin is suggested by the basinal sediments known in the Molise subsurface (Frosolone 2 well; Martinis and Pieri, 1964), with cherty limestones, marls and intercalations of volcaniclastics and resedimented carbonates of Triassic to Jurassic age. It is thought that these sediments could be equivalent to the "calcareous-siliceous-marly" series (calcari con selce, scisti silicei and galestri black shale and marl) of Triassic to Early-Middle Cretaceous age which outcrops extensively in the Lagonegro area, near Tricarico to the south and around Benevento in the north.

Studies of the platform-margin in the Matese were carried out by Ietto (1964, 1969), who distinguished the basic elements of the platform, transitional and basinal facies, and this was further highlighted by the publication of the two geological sheets, Foglio 161 and 162, Isernia and Campobasso (Servizio Geologico d'Italia, 1971). Accordi *et al.*, (1982) provided further details of the various facies and of the relationship of benthonic communities to the differing substrates across the zone. Facies persistence is noted until the Cenomanian, from which time skeletal shelf-edge sedimentation gave rise to large thicknesses of bioclastic sediments, forming sedimentary wedges between the platform and basin. These authors also note the rapid progradation of the marginal facies toward the basin, and inward, over shelf lagoon facies. Such changes, beginning in the Aptian-Albian, are related by Accordi *et al.*, (1982) to a tectonic phase which apparently affected all the shallow-water platforms of Central Italy (Crescenti, 1969a; Crescenti *et al.*, 1969; Carbone, 1984). Progressive drowning of sections of the former platform are referred to, although the mechanism by which this was achieved is unclear.

The present study is based on detailed 1:10,000 scale mapping of the type facies of the Molise-Sannio Series (D'Argenio *et al.*, 1975b), and on sedimentary logging of transitional sediments at several localities on the inferred palaeoslope in conjunction with logging of contemporaneous platform sequences where preserved. Sedimentary logs are reproduced in full in enclosure 1.

These field data, coupled with biostratigraphic and petrographic studies, have enabled constuction of sedimentological models of the former Lagonegro-Molise basin margin.

4.4 Palaeogeography

The Matese area, trending broadly east-west, represents an embayment in the eastern margin of the north-south trending former Apennine platform (figure 32). This geometry is supported by palaeoslope and palaeocurrent data (section 4.10), which indicate a northerly to north-easterly directed palaeoslope during the Mesozoic. The embayment geometry is thought to reflect the initial geometry produced during Rhaetian to Liassic rifting on the southern passive margin of the Tethys ocean, in which east-west lateral structures offset the platform margin. On the regional geological maps, several such lateral offsets are visible, characterised by continuity of platform-to-basin transition facies.

4.5 Structural geology

Clermonté (1977, 1982), Parotto (1980), Mostardini and Merlini (1986) and Cello *et al.* (1989) all interpreted the Matese Mountains and Frosolone area as a single major thrust sheet, with only minor internal shortening (figures 35, 36). Bedding data from Frosolone (figure 37b) suggest the presence of a gently-folded culmination above a major thrust. This is a structural style also suggested by Hill and Hayward, (1988), from regional map interpretation, and Mostardini and Merlini, (1986), based on seismic and borehole data. Thrusting commenced in the Langhian (Ietto, 1969, Clermonté, 1977), with a NNE-directed transport direction (figure 38), deduced from lineations, fold vergence directions and regional structural data (see above). Calcite-filled dilational fissures associated with thrusting have an E-W to NW-SE extension direction (figure 38). The commencement of thrusting was followed by a phase of sinistral strike-slip motion along ENE-trending faults, accompanied by normal faulting with an N-S to NE-SW extension direction, (figure 38; figure 37a), probably beginning in the Tortonian and continuing until the Pliocene. Nannofossil data (given in full in appendix 3) suggest an age of NN11 (Early to Middle Serravallian) or younger for a strike-slip fault near Gallo (figure 39). The high angle between the fault and locally-formed extensional fissures could indicate that the fault formed under conditions of strong negative dilatation within the thrust sheet whilst thrusting continued (Ramsey and Huber, 1983; figure 38).

Sediment-filled extensional fissures (figure 40) have also been dated and the earliest ones include fossil assemblages of Middle Miocene age. The normal faults are probably related to the opening of the Tyrrhenian sea.

The timing of events given above allows for less than three million years between the onset of thrust compression in the Langhian and the commencement of strike-slip and extension (if the Serravallian age is accepted).

The basic structural continuity of the Matese mountains, with their Mesozoic platform carbonates, and the Frosolone area of slope-to-basin Mesozoic carbonates, is an important prerequisite for studying the area as an example of a Mesozoic carbonate platform-to-basin transition.

4.6 Molise basin

4.6.1 Mesozoic history.

The Mesozoic history of this platform-margin (summarised in figure 43) has been reconstructed from outcrops at Pesche, Carpinone and Gallo Matese (figure

32). During the Triassic to Early Liassic, the area was covered by a broad, shallow-water carbonate platform (figure 43a; for palaeontological details, see Carannante *et al.*, 1978). Part of the platform was drowned during the regional Rhaetian-Liassic extensional tectonic phase (evidence for this phase is to be found in Bernoulli and Jenkyns, 1974) to form the Molise basin (figure 43b). From the Early Liassic until the ?Bajocian, no sediment was preserved in the area of the palaeoslope. As section 4.7 suggests, however, sedimentation of this age took place elsewhere in the region. This could suggest either local absence of carbonate production, or bypassing of sediment further into the basin. Nannofossil evidence suggests that a ribbon radiolarite formation (figure 41) which unconformably overlies ?Upper Triassic to Lower Liassic platform carbonates at Pesche could be of Bajocian or younger age. Such radiolarites are commonest in the Oxfordian stage of the Jurassic* in the Tethyan region (Jenkyns and Winterer, 1982). The presence of this formation suggests a Liassic age for the origin of the Molise basin. A ribbon radiolarite formation overlying a carbonate platform sequence has previously been described by Price (1977) from Othris, Greece, and is thought to indicate at least local shutdown of carbonate production and redeposition, although not necessarily deep water. In this case the effect must have been local since platform facies of Jurassic age are found in the eastern Matese. At several localities, including Pesche, Carpinone, ~~and Gallo~~, reworked cherty clasts have been discovered in Upper Cretaceous redeposited limestones, suggesting that an area of several square kilometres was covered in the ribbon radiolarite formation. The fate of redeposited sediment of Jurassic age is a matter of speculation. A possible interpretation is outlined in cartoon form in figure 43c. It seems likely that sediment bypassed large areas of the platform-to-basin transition here, in common with many other areas of the

* Tethyan radiolarites are frequently Middle Callovian to Kimmeridgian in age, but may be as old as Upper Triassic (Baumgartner, 1987).

southern Apennines during the Jurassic (Marsella and Pappone, 1987; Adamoli *et al.*, 1982c; J. Robson, pers. comm., 1989).

At Pesche, the chert is overlain by pelagic and redeposited carbonates which contain an Early Cretaceous (?Late Berriasian to Early Hauterivian) nannofloral assemblage, (see appendix 3) suggesting that pelagic sedimentation occurred here in the Early Cretaceous, in common with other areas in the southern Apennines. In turn, these nannofossil limestones are overlain by Hauterivian or younger redeposited carbonates of probable mass-flow origin (figure 42), containing reworked Calpionellid limestone clasts, typically of Late Jurassic age (Tithonian to Kimmeridgian), which is further evidence for pelagic deposition on the site of the former Triassic platform prior to the Late Cretaceous. The calpionellid-bearing limestones are probably the lateral time-equivalent facies of the calpionellid limestones (Late Jurassic to Early Cretaceous age) documented from other areas in the Apennines. The data of Cocco (1971) imply continuous deposition from Albian to Senonian time, and redeposition was marked during the Campanian to Paleocene interval (figure 43g).

4.6.2 Summary of Mesozoic history

(1) Late Triassic to Early Liassic (figure 43a).

The region was covered by a broad, shallow-water carbonate platform.

(2) Middle Liassic? (figure 43b).

Crustal extension took place, with the generation of tilt-block geometries. The axis of the basin was probably oriented north-south, with major block-bounding faults trending roughly east-west in the Matese, due to the situation on a presumed embayment in the original platform margin. The strongest subsidence in the basin occurred to the east of the Matese area, following the axis of the Molise basin. This would give the platform margin in the area a strong component of subsidence towards the east; thus figure 43b is drawn showing an hypothesised east-north-east dip direction for the Matese block. It is envisaged that non-deposition or erosion must have taken place over much or all of the surface of the block during the Liassic, most probably being concentrated along the direction of true dip.

(3) Bajocian to Tithonian (figure 43c).

Part of the platform had stopped producing carbonate and was draped by a ribbon radiolarite, whilst shallow-water carbonate production continued in the eastern Matese. Redeposited material could have been transported in an easterly direction towards the main depocentre of the basin down the dip slope of the block. From the Kimmeridgian onwards, part of the "drowned" portion of platform was covered by pelagic calpionellid- bearing limestones, similar to the coeval "Maiolica" facies of Latium-Abruzzo of the same age.

(4) Berriasian to ?Early Hauterivian (figure 43d).

Bioclastic redeposited sediments were transported from the site of carbonate production on the platform into the Molise basin. These sediments are intercalated with pelagic limestones.

(5) Hauterivian to ?Aptian-Albian (figure 43e).

Areas of formerly pelagic deposition became the site of lithoclastic redeposited facies development, sediments of Hauterivian or younger age bearing clasts of Upper Jurassic (Kimmeridgian to Tithonian) age. This suggests some platform erosion* (see section 3.2). During this time-period, rudist bivalves became a major sediment producer on the platform, causing rapid growth of skeletal buildups at the platform edge.

* The ?Callovian-Neocomian interval has a maximum thickness of 300 m in the northeastern Matese (Cestari *et al.*, 1975).

(6) ?Aptian-Albian to Early Campanian (figure 43f).

Local differential subsidence took place (data of Cocco, 1971), which could be related to a phase of renewed crustal extension (see below; sections 4.10, 6.7.6, appendix 2).

(6) Campanian to Eocene (figure 43g).

During this interval, a large area of the former platform became covered by redeposited bioclastic limestones, overstepping Triassic, Jurassic and Lower Cretaceous platform facies (Whiteman, 1988). Continued erosion of the platform* and ?fault rejuvenation is suggested by the presence of derived lithoclasts of Late Jurassic to Late Cretaceous age found in calciclastic sediments throughout the Matese area.

The model outlined above for the Matese is consistent with the regional geological history of partial platform drowning during the Rhaetian-Liassic extensional tectonic phase, followed by differential subsidence of tilt-blocks until at least end-Jurassic times, at which stage previous topography appears to have been largely reduced in the basins by the Maiolica formation (Koopman, 1983).

4.7 Comparison with Meta mountains

A comparison is made in figure 44 between the basinal stratigraphy of the Matese Mountains and that of the nearby Meta Mountains (40km to the west of the Matese; figure 5). Data for the Meta are taken from a recent paper by D'Andrea and Urgera (1986). It is clear that both areas display a stratigraphic gap (i) between Lower Liassic platform limestones and overlying redeposited or cherty sediments and (ii) between the Upper Jurassic pelagic sediments and Hauterivian (or younger) redeposited carbonates (especially in the Meta Mountains).

Despite the basic stratigraphic similarity of the two areas (figure 44), the

* The Callovian-Maastrichtian interval has a thickness between 520 and 1300 m (Cestari *et al.*, 1975). The total amount of Cretaceous erosion must lie between these two values (see appendix 2).

details are very different:

1. In the Meta, the "calcari oolitici inferiori" (Late Liassic to Early Dogger, D'Andrea and Urgera, 1986) redeposited unit formed at a time when a stratigraphic gap (or ribbon radiolarite)* was forming in the Matese. The "calcari oolitici inferiori" unit may be at least partially the time equivalent of the Vajont formation of the southern Alps (Bosellini *et al.*, 1981a-b). Such local ribbon radiolarite formation suggests that sea-floor topography must have controlled depositional patterns at least during part of the Jurassic.

2. Upper Jurassic nannofossil-bearing limestones were deposited regionally (by inference from redeposited clasts in the Matese) from the Malm until at least the Hauterivian, although only Oxfordian to Kimmeridgian sediment is recorded in the Meta Mountains. This suggests that again the stratigraphic gap was produced by local variations in palaeoslope, rather than total non-deposition. The Lower Cretaceous gap may not be present in the Matese, continuous deposition being consistent with other areas in the southern Apennines.

From the ?Hauterivian onwards in the Cretaceous, episodic redeposition took place in both the Meta and Matese, with apparently no major stratigraphic gaps. Since the two localities were less than 40km apart on the eastern margin of the former Apennine platform (figure 5), it is suggested that the palaeoceanography of the two areas would not have been dissimilar during the Jurassic. Also, carbonate production is assumed to have occurred at a similar rate along the whole of the shelf-edge in the region, in the absence of any persistent or regional emersion horizons on the platform. Thus it is suggested that local differences in submarine slope-angle could have been responsible for the differing sediment-fill and stratigraphic gaps in this case. Tectonic activity and

* This possibility is unlikely since most Tethyan ribbon radiolarites are Callovian to Kimmeridgian in age (Baumgartner, 1987).

relative sea-level fluctuations are thought to be other factors influencing redeposition on carbonate platform-margins. The response to the known major extensional tectonic phase in the Lower Liassic (partial platform drowning) (Crescenti, 1969a-b; Crescenti *et al.*, 1969; Bernoulli, 1972; Bernoulli and Jenkyns, 1974; Bosellini and Winterer, 1975; Colacicchi *et al.*, 1978; Bernoulli *et al.*, 1979; Winterer and Bosellini, 1981) is the same in the Matese and Meta, as elsewhere in the Apennines. Thus, major tectonic events might be expected to influence both these localities, so the observed stratigraphic differences seem inexplicable in this way. Eustatic influence may have contributed to submarine erosion, but cannot explain the change from chert to carbonate sedimentation from one area to another.

In summary, the submarine slope-angles produced during Liassic tectonics are thought to have been an important influence on carbonate redeposition, especially during the Liassic. During the Cretaceous, however, reduced subsidence rates (section 6.7) may have made sedimentation more sensitive to fluctuations of relative sea-level.

4.8 Matese: Lithofacies

4.8.1 Lithoclastic calcirudites

Lithoclastic calcirudites occur in both lenticular and laterally continuous beds. Lenticular beds typically pinch out within two to five-hundred metres (figure 45). The beds are composed of poorly-sorted clasts of pelagic micrite or wackestone and lithified clasts of skeletal rudistid limestones and oolitic or peloidal grainstones (figure 46d-e). The matrix typically comprises lime mudstone or wackestone with rudist, red algae and echinoderm fragments.

Thick (up to thirty metres) calcirudite beds commonly have channellised bases, although locally thay have flat, unscoured bases (figure 46a-c). Those beds with channellised bases sometimes incise into underlying sheetlike deposits (figure 45). Two calcirudite beds observed at Frosolone (Morgia Quadra; MT 1 and MT 2-see below) have cobble- to boulder- sized clast-supported bases which suggest a debris flow transport mechanism (figure 46b).

In transverse section, the uppermost locally lenticular calcirudite bed of the Maastrichtian (MT 2) locally displays trough-shaped cross-stratification on the scale of several metres to tens of metres width (figure 47), whilst longitudinally prograding foresets up to two metres in height are sometimes visible (figure 48). These foresets are thought to represent the same dune-type bedform as the large scale cross-stratification, but cut parallel to the direction of flow, rather than perpendicular (see discussion below). This is confirmed by soft-sediment traction overfolds with eastward vergence (section 4.8.5) in the outcrop with foreset development.

Sediment-geometries of calcirudite beds exposed at Frosolone are presented in map form in figure 49, and by means of restored cross-sections through the mapped area in figure 50. Restored cross-sections have been produced by removing the affects of compression (gentle folding and minor reverse faults) and Late Miocene to Pliocene normal faulting (section 4.5) and assuming the Cretaceous-Tertiary boundary as a horizontal datum level. This level was chosen because it is clearly recognisable in the field in the Frosolone area as the contact between the major Maastrichtian redeposited bed MT 2 and thinly-bedded pink to white pelagic lime-mudstones of Paleocene age, or foraminiferal calcarenites and lime mudstones of Early Eocene age.

It is apparent from these cross-sections that bed MT 2 (the uppermost Maastrichtian bed) is lense-shaped in transverse section (perpendicular to the mean NE palaeoflow direction; section 4.10) on the scale of 7 km from NW to SE (see sections D and B; figure 50). Locally, both MT 1 and MT 2 can be traced laterally into two or more discrete calcirudite beds, suggesting that they may not represent a single flow "event" but rather repeated influxes of sediment with a significant time duration. This is important in the context of possible flow-triggering mechanisms (see section 4.9). Inspection of sections C and D (figure 50) suggests that the Maastrichtian calcirudites may be truncated in a toplap relationship to the overlying Tertiary slope sediments. If this is correct, then the Cretaceous-Tertiary boundary represents an important contact between two sediment packages with distinct internal geometries. The geometries in restored cross-sections are consistent with evidence from the Carta Geologica d'Italia f.161 (Isernia) and may provide information about slope sediment organisation on a larger scale (see section 4.9).

Calcirudites are interpreted to be calciturbidites and debris flows. These beds contain a range of lithoclasts from a variety of different formations, ranging from Late Jurassic to Late Cretaceous in age (see section 3.2). These are mixed with clasts derived from the surrounding sediments. Where lenticular beds occur, this suggests that the latter were derived at least in part by erosion of the surrounding sediments. Clasts may also have been derived from mass-movements further up slope, such as slumps and debris flows. Slumps were commonly observed in the Matese region (see section 4.10). The skeletal grain matrix and skeletal lithoclasts mixed with pelagic clasts suggests that debris flows or mixed debris flow and turbidites moving downslope from coeval rudist buildups may have been major agents of erosion of intraformational clasts. The high proportion of large clasts derived from shallow marine settings suggests that the area may have been on a leeward margin (cf. Mullins and Neumann, 1979).

Four calcirudite beds which are at least half an order of magnitude greater in thickness than the beds in the surrounding sequences have been identified. Two of these distinctive beds, referred to here as MT 1 and MT 2 respectively, occurring in the Maastrichtian to Palaeocene stages, have been tentatively correlated by their lithological characteristics and stratigraphic position across the study area over a region of 150km^2, from Frosolone to Gallo (see figure 51). MT 1 has been calculated as having a minimum volume of 1.8km^3, whilst MT 2 reached 1.4km^3. Both these volumes exceed the threshold of Mutti *et al.*, (1984) for so-called megaturbidites. It must be stressed that the volume estimates expressed here are minimum estimates, since the deposits cannot be traced northwards into the former Molise basin due to the present-day flysch outcrop pattern. At Frosolone, where the two beds disappear beneath the flysch, MT 1 has a thickness of 25 metres, and MT 2 some 22 metres. It is possible that ponding of the flows was occurring in this area, especially in view of the palaeocurrent data of Pirinon (1980), which indicate southerly directed palaeoflow to the north of the Frosolone mountains. Although direct palaeontological correlation of MT 1 and MT 2 is not possible, their recurrence in all measured sections, coupled with their sedimentological characteristics (see above) is suggestive of collapse of a large area of the outer-shelf-slope system (see section 4.9).

At Frosolone, MT 2 contains blocks of lithified rudistid skeletal calcarenite up to 100x20 metres in size, corresponding to the D1 level (poorly-sorted megabreccia) of Mutti *et al.*, (1984) overlain by carbonate megabreccia with clasts of lime mudstone (D2 level). Conventionally, a seismic trigger has been ascribed to such beds (Seguret *et al.*, 1984), although other mechanisms may be equally likely, as discussed in section 4.9.

The local presence of large-scale dune-type bedforms (see above) in the topmost redeposited bed of the Maastrichtian (MT 2) at Frosolone is puzzling in a supposedly deep-water slope environment. Such large bedforms have not previously been reported from turbidite sediments and are more characteristic of a shallow-marine or fan-delta environment. Swinchatt (1967) described large-scale cross-stratification from a shallow-marine carbonate unit, however. Swinchatt (1967) reported experimental evidence from Jopling (1965) which suggested that an angular contact between toesets and the basin floor (see figure 48) is most likely where a small depth ratio exists (i.e. the basin is deep relative to the current). The formation of foresets was attributed by Swinchatt (1967) to flow separation over a channel-floor discontinuity.

4.8.2 Skeletal calcarenite

Skeletal calcarenite is a major lithofacies which comprises much of the calciclastic sequences. This lithofacies is dominated by rudist bivalves (typically Radiolitids), but also found are echinoderms, bryozoans, gastropods, red algae and benthonic foraminifera. Calcarenite beds are laterally continuous and generally thinner-bedded than calcirudite beds. Graded bedding, planar-lamination, cross-lamination (figure 52) ripples and fine lamination (i.e. parts of the Bouma sequence) are common, indicating deposition by turbidity currents. Graded Ta and Ta-b (top-cut-out) and Tc-e and Td-e (base-cut-out) calciturbidites are most common, but classic Ta-e calciturbidites also occur. Erosional bases are infrequent, and flutes and sole-markings are extremely rare, due to the lack of lithological contrast necessary for differential weathering.

Sorting is often poor and interstitial lime mud is present in variable amounts, indicating rapid deposition and lack of winnowing. Rudist fragments and intraclasts were locally imbricated, in response to currents.

Skeletal calcarenites are interpreted as calciturbidites derived from coeval rudistid buildups. A high degree of reworking of rudist debris is indicated by the reduction of shell material to fine size fractions.

4.8.3 Seismite

This lithofacies was encountered at Gallo, and consists of pelagic micrites and planar bedded fine calcarenite, chaotically mixed with calcirudite (figure 53). The micrite and fine calcarenite forms "rafts" of plastically deformed layered sediment up to a metre or more in length, and sometimes forming measurable slump overfolds. The lithofacies forms packages of up to six metres in thickness, bound above and below by planar bedded fine calcarenites and micrites. The packages are laterally continuous for at least one kilometre. Small scale synsedimentary faults are often found in association with this facies (figure 54).

Seismite facies are interpreted as being the product of *in situ* autoclastic brecciation and mixing with an incoming debris flow. The seismite deposits consist of up to seventy percent of large, plastically-deformed blocks of micrites and fine calcarenites, identical to those of the surrounding formation. The degree to which these blocks have retained their bedded identity suggests that they were remobilised whilst semi-lithified. Partial reworking of these blocks rather than in-situ breccia formation is implied by the presence of the calcirudite matrix, partly of platform origin, and also by the local occurrence of erosional basal contacts with underlying lithologies. It is suggested that these deposits bear a striking resemblance to the "seismite" deposits (*sensu stricto*) of Spalletta and Vai (1984). These authors explain the formation of the features observed as the result of a first seismic autoclastic brecciation, due to shallow-seated earthquakes, of a thin pelagic mud layer lithified at the sediment-water interface. Brecciation was followed by disruption, small-scale transport and embedding of the clasts in a gravity-driven turbidity flow from the shallow-water platform, triggered by the same seismic event.

Although the explanation given by Spalletta and Vai (1984) may be plausible in this case, there are some differences in the characteristics of the rocks they describe and those of the deposits at Gallo. The clasts of these authors range up to thirty centimetres, whilst blocks at Gallo are up to one metre in length. This is interpreted as implying much more limited transport of the remobilised pelagic material. Also, the blocks at Gallo are at times clearly deformed by slump overfolds (figures 55, 56; see section 4.10 on palaeoslopes), which are interpreted as being caused by slumping of the whole seismite package down the local palaeoslope, possibly as the result of a further earthquake shock. Limited palaeocurrent and map evidence suggests emplacement of calcirudite material from the south (the site of the former platform), whilst the data from the slump folds themselves would imply movement downslope towards the south (i.e. towards the platform). This corresponds well to the type of setting envisaged by Spalletta and Vai (1984) for seismites and is in agreement with the overall geological model proposed for the Matese during the Late Cretaceous (figure 43f-g).

4.8.4 Lime mudstones and wackestones

These beds usually range from 1 to 10 centimetres in thickness (figure 58), and are locally separated by marly partings. The beds are fossil-poor, rarely containing *Globigerina*-type planktonic foraminifera and radiolarians. Bioturbation is very common (figure 59). With Paleocene to Lower Eocene strata, this lithofacies has a distinctive pink colouration.

This lithofacies is interpreted as the equivalent of modern periplatform ooze. The fine-grained limestones were deposited in deep waters during the Early Tertiary, at least in the northern part of the area, where radiolarians are present in some beds. These fossils are found in association with simple globular planktonic foraminifera, possibly indicating water-depths of between 200 and 1000 m or more. Abundant bioturbation indicates a low-energy environment with slow to moderate sedimentation rates.

4.8.5 Folded micrites and wackestones

Lime mudstones and wackestones locally show small-scale intrastratal deformation (typically <60cm amplitude, <1metre wavelength), interpreted as slump folds (figure 60). Some of this soft-sediment deformation locally occurs beneath thick beds of calcirudite and appears to be due to traction folding beneath these mass-flows (figure 61). Large-scale slump folds were not recognised in the Matese mountains (but see section 5.5.3).

The small-scale intrastratal deformations observed may have been associated with the mass-movements which triggered calciturbidites on the upper slopes. Some of the slumps occurred further downslope, and may have played a part in the reworking of lime mudstones of slope origin, incorporated frequently into mass-flow deposits. The lack of large-scale soft-sediment deformation may suggest that rocks representing the upper slope are not exposed in this area.

4.9 Facies associations-calciclastic successions

In localities where a complete Late Cretaceous to Early Tertiary stratigraphic succession is developed (Mt. Croce at Gallo) the lower part of the sequence is dominated by lime mudstones with intercalated thinly-bedded graded calcarenites and lithoclastic conglomerates. The upper part of the Campanian to Maastrichtian section is dominated by thick calcirudite beds. In other localities, the sections are calcirudite-dominated, and this is thought to be due to poor exposure of the underlying lime mudstone-dominated part of the succession. There is good lateral continuity of beds on a scale of one to two kilometres or more where mapped at Frosolone (see enclosure 1), which suggests the presence of a carbonate slope-apron, continuously developed along the lower to mid-slope adjacent to the carbonate platform. This is clearly seen in figure 63, looking down the inferred palaeoslope, in which sheetlike and lenticular redeposited sediments persistently recur over a distance of more than ten kilometres along the strike of the palaeoslope. The development of lime mudstone-dominated followed by calcirudite-dominated successions could suggest the progradation of inner apron facies basinwards (northwards) over facies of the outer apron (*sensu* Mullins and Cook, 1986) through time. An alternative explanation might be that the calcirudite-dominated part of the section is the product of a relatively short-lived "event", such as collapse of the shelf-edge-slope system. When bed-thickness and grain-size trends were plotted, (figure 62), no long-term coarsening trend was observed, as would be expected in a prograding slope-apron (for example, Yose and Heller, 1989). A collapse of the shelf-edge is thought therefore to be a likely possibility. The reasons for collapse of a carbonate slope system could be due to either (i) tectonic or (ii) eustatic control, or both. In the first case, seismic shock or fault movement could trigger shelf-edge collapse (as proposed by Cook *et al.*, 1972). Such activity could produce the type of mixed lithoclastic and bioclastic flow with boulder-size clasts seen in the Matese area, but such activity would be expected to be random in time and spatially restricted.

In the Matese area, two distinctive, thick beds were deposited during the Maastrichtian but these are not in the part of the section associated with "seismite" facies (section 4.8.3).

In the case of a eustatic control on deposition, both high-stands and lowstands of relative sea-level must be considered as potential initiators of collapse. During a sea-level high-stand, increased sediment-gravity flow frequency might be expected, given the rimmed-shelf setting with rudist buildups at the shelf-edge (Boardman *et al.*, 1986, Droxler and Schlager, 1985), and this could result in oversteepening and collapse of the shelf-edge-slope system. This mechanism would again be expected to leave a record of progradation (coarsening- and thickening-upwards) which is not observed in this area (but see the discussion in chapter 5). Alternatively, collapse may be induced during a sea-level lowstand by several mechanisms, including (i) storm-wave-base impingement on the outer shelf, (ii) increased bioerosion of the outer-shelf, (iii) chemical dissolution induced by fresh-water seepage and (iv) undercutting via acidic dissolution caused by the oxidation of sulphides carried in brines that seep from the base of the slope-escarpment (Paull and Neumann, 1987). The lowstand collapse of the platform margins in the Matese area is thought to be a likely mechanism because of the distinctive composition of the beds MT 1 and MT 2, predominantly rudist debris and platform-derived lithoclastic material with a wide range of ages, in contrast to the more peloidal and lime-mud rich surrounding turbidite sediments. In addition to erosion of the platform, olistoliths, composed of bedded, redeposited, rudist-rich calcarenites, indicate erosion of the upper slope (figure 46f-g).

Haak and Schlager (1989) have recently demonstrated that the relative abundance of skeletal components in calcareous turbidites is greatest during glacial periods (i.e. times of relative sea-level lowstand) by examination of Quaternary core material from the Tongue of the Ocean, Bahamas. This is because nonskeletal sediment is produced in the interior of the platform, therefore its growth and subsequent export to the surrounding flanks are at a maximum when the banks are flooded.

If the assertion is correct that the beds MT 1 and MT 2 were deposited during lowstands of sea-level, then they could be chosen as possible depositional sequence boundaries, in

* This pattern of depositional sequences is also seen in the Maiella mountains of Abruzzo (Bernoulli, pers. comm., 1990).

the sense of Vail *et al.*, (1977). In addition to two such boundaries, at the base of MT 1 and MT 2 respectively, another boundary can be observed where the Campanian-Maastrichtian slope facies lie onlap Late Triassic to Lower Cretaceous platform facies (for instance at Gallo; figure 71). At Gallo (figure 71), the complete Campanian to Maastrichtian section displays an onlap relationship to the older platform facies. The unconformities between the sequences at Gallo can be correlated with their corresponding conformities in the basin in the Frosolone area. The Campanian to Maastrichtian lies conformably on earlier Cretaceous basinal facies, and beds MT 1 and MT 2 pass "conformably" both stratigraphically upwards and downwards into thinly-bedded calciturbidites and micrites. The identification of three possible Late Campanian to Maastrichtian depositional sequences* in the Matese area is consistent with observations made on the depositional geometries in the Gran Sasso (chapter 5), and is also in agreement with the predicted pattern of eustatic sequences proposed by Haq *et al.*, (1987).

If the assertion that MT 1 and MT 2 were deposited during lowstands of sea-level is correct, then the observation of dune-scale bedforms locally in MT 2 could be explained by the impingement of storm wave-base on the area of the slope at Frosolone. The pattern of onlap of Maastrichtian slope facies onto the site of the former platform in the Matese mountains suggests that the slope sediment was being produced in sufficient quantities to infill most of the eroded relief of the platform. It is likely that as the slope sediments prograded northwards (during rise in sea level; section 6.2.4) they also aggraded to keep pace with sea-level rise. During a subsequent major third-order sea-level fall (such as the one postulated by Haq *et al.*, 1987 in the latest Maastrichtian) this could leave the slope apron at exceptionally shallow depths and allow the possibility of large-scale bedform development in lowstand deposits such as MT 2.

Grain-size and bed-thickness plots for Mt. Croce and Colle la Torre (figure 62) show further cycles of sedimentation within the Early Tertiary. In particular, three fining-upward, thinning-upward cycles are recognised in Eocene sediments. During the Tertiary, there is strong evidence for the presence of distally-steepened ramps in the southern Apennines (Accordi *et al.*, 1982; Carbone, 1984; Accarie, 1987). According to Yose and Heller (1989), during rapid sea-level highstands, the outer ramp is drowned due to rapid sea-level rise and/or expansion of the oxygen mimimum zone onto the shelf during transgressions (Boardman and Malinky, 1985; Schlager, 1981). Rhythmically bedded lime mudstones are deposited in the outer ramp, and lime mudstones are deposited along the basin margin due to low depositional energies and low productivity in the outer ramp. As sea-level falls, shoaling in the outer ramp results in increased storm influence, and a lowering of the normal wave-base in the outer ramp results in a gradual increase in the frequency and volume of turbidites and slope- and shelf-edge-derived debris flows. When the rate of sea-level fall is at a maximum (lowstand), major collapses of the outer ramp/upper slope are triggered by the impingement of storm wave-base. Subsequent gradual sea-level rise would cause gradual waning of the frequency and volume of turbidites. The thick bed at the Upper Middle Eocene to Late Eocene boundary (Colle la Torre section enclosure 1) is also a boundary between two distinctive lithofacies, the first characterised by abundant *Alveolina* sp., and the second by *Gypsina* sp. (Pironon, 1980). The transition between the two different benthonic communities seems likely to have been brought about by some environmental change, such as a change in water depths, which made conditions stressful to the former group. Following this change, the ecological niche occupied by *Alveolina* could be taken over by

Gypsina.

Further evidence in support of a sea-level control of sedimentation at the top of the Middle Eocene is found in the occurrence of a thick (slump sheet?) ~~bed~~ bed of this age in the Gran Sasso (see section 2.4.3). The latter bed can be traced laterally into what is interpreted as basin-floor fan facies which overlie older, onlapping beds, and therefore lies at a boundary between two packages of sediment with distinct depositional geometries. Within the stratigraphic resolution obtainable, these two beds are of the same age, suggesting important events controlling depositional patterns were occurring on a regional scale, (between the two areas 150 km apart).

Finally, the question of the large-scale organisation of the carbonate slope in the Matese area must be addressed. Evidence presented in section 4.8.1 demonstrated the lenticular geometry of major Maastrichtian calcirudite beds in transverse section on a scale of 7 km. Mapping showed that thick Late Eocene to Oligocene calcirudites also outcrop in the Frosolone area, passing laterally into thinly-bedded calcarenites and lime mudstones from west to east (see Frosolone map, enclosure 2). The thickest development of Late Eocene calcirudite beds lies to the WNW of the thickest development of Maastrichtian calcirudites, which are overlain predominantly by thinly-bedded facies. Inspection of Carta Geologica d'Italia f.161 (Isernia) confirms this pattern of outcrop and also shows the Campanian—Maastrichtian section thinning westwards (figure 36, section 1) where underlying ?Cenomanian to Santonian-Campanian slope sediments develop their greatest stratigraphic thickness. A possible explanation for this is shown in figure 57, in which the main depositional depocentre of a mappable formation develops in the topographic low created by the topography of the previous mappable formation. The Cretaceous to Early Tertiary architecture of the slope facies in the Matese can therefore be demonstrated on a scale of 20-25 km, and this architecture is likely to be repeated along the length of the carbonate slope, as suggested by the geometries visible in figure 63. Given the general continuity of Campanian-Maastrichtian slope facies (albeit with thickness variations; figure 36, section 1) the system is not envisaged as a fan system in the siliciclastic sense. Sediment was most probably produced along the whole length of the carbonate shelf-edge, but the thickest depocentres on the slope occurred in local (10 km width) topographic lows caused by the distribution of earlier slope sediments, and perhaps ultimately by syn-extensional submarine topography.

What then is the dominant control which causes abandonment of a particular depocentre and the development of a new one? The arguments presented above suggest that major relative sea-level fluctuations may have been the primary control over the development of Maastrichtian slope sequences in the Matese area. This is a problem which will be addressed by examination of field data from the Gran Sasso d'Italia (chapter 5).

The margin appears to have exhibited a "scalloped" morphology, suggestive of erosion/collapse events (see Mullins and Hine, 1989), visible for the Paleocene to Eocene in the present-day outcrop pattern. This pattern may also have been present during the Late Cretaceous, judging by the palaeoslope and palaeocurrent data for the area (figure 66; section 4.10) and the distribution of calciclastic facies (see enclosure 2).

In summary, field data suggest the presence of a partially tectonically controlled, partially sea-level controlled carbonate slope-apron during the Late Cretaceous and Early Tertiary in the Matese mountains, with abundant reworking both of shelf-derived bioclasts and lithoclasts and slope-derived lithoclasts and semi-consolidated to lithified lime mudstones.

4.10 Matese mountains-palaeoslopes

4.10.1 Introduction

An attempt was made to define the orientation of the palaeoslope which connected the Matese carbonate platform (to the south) with the Molise Basin (to the north) following Liassic drowning of part of the regional carbonate platform (see section 4.6). In this study, use was made of cross-stratification (where present) in redeposited beds, sole marks on the base of carbonate turbidites (very rare), traction overfolds in micrites beneath carbonate debris-flow beds, imbricate pebbles located at the base of redeposited beds, and soft-sediment overfolds within slump-packages in redeposited sequences.

4.10.2 Data analysis

4.10.2.1 Soft-sediment overfolds

Both fold axial-plane and hinge-lineations of overfolds in soft-sediment slide-sheets were recorded, along with the sense of overfolding, where possible. Data from each separate locality were plotted on equal-area stereonets and the down-slope direction estimated by the mean axis method of Jones (1940) and the separation arc method of Hansen (1965). Prior to calculating the downslope direction, data were corrected for tectonic tilt by rotating measurements about the spherical mean bedding orientation for the locality. Palaeoslope solutions obtained by both methods, along with mean resultant length $\bar{R}$ (a measure of dispersion) are tabulated in table 2. In cases where the mean axis lay within the separation arc, the former value was used as a palaeoslope estimate, following the recomendation of Woodcock (1979). Palaeoslope solutions are shown on a regional map in figure 64. Slump data for individual localities

Locality	Data type	$\bar{\theta}^{o}$	R	$\bar{R}$	n	Bedding dip/ azimuth
Indiripete	imbricate clasts	268 (088)	17.31	0.48	36	14/096
Indiripete	cross-stratification	072	–	–	1	14/096
Colle la Torre	imbricate clasts	183 (003)	8.25	0.49	14	19/224
Capriati (Mt. S Crocella)	imbricate clasts	104 (283)	3.96	0.99	4	10/276
Pesche	bedding	–	10.61	0.97	11	17/287 (spherical
Pesche	imbricate clasts	289	21.58	0.86	25	" / " mean)
Mt. Patalecchia	slump overfolds (mean axis)	112 (012)	8.27	0.92	9	12/245
" "	(separation arc)	096 (006)	–	–	9	12/245
Miranda	slump overfolds	268 (358)	–	–	25	25/116
"	(separation arc)					
"	(mean axis)	273 (003)	24.23	0.97	25	25/116
Longano	slump overfolds (mean axis)	263 (353)	2.97	0.99	3	16/174
"	(separation arc)	261 (351)	–	–	3	16/174
Rave la Noce (Jurassic)	slump overfolds (separation arc)	299	–	–	6	20/284
" " "	(mean axis)	031 (301)	3.22	0.54	6	20/284
Gallo	slump overfolds (separation arc)	188	–	–	34	various
"	(mean axis)	100 (190)	16.63	0.49	34	various
Gallo	cross-stratification	046	–	–	1	9/308
"	cross-stratification	020	–	–	1	21/102
Monteroduni	cross-stratification	261	–	–	1	18/183
Frosolone	cross-stratification	075	19.28	0.69	28	not applicable
Frosolone	sole marks	073	3.83	0.96	4	not applicable
Frosolone	traction overfolds	067	5.34	0.67	8	not applicable

are shown plotted on equal-area stereonets in figure 65.

4.10.2.2 Cross-stratification

Data were collected by measuring orientations of the slip-faces of dune-size cross-sets, found in some redeposited beds on the palaeoslope, interpreted as turbidites (see section 4.8.2). The measurements for each locality were plotted on stereonets to obtain the orientation of palaeoflow, which was corrected for tectonic tilt by untilting about the local bedding orientation. It should be noted that this operation is thought to have little effect on the end-orientations obtained since (i) tectonic tilt was always $<20^{\circ}$ (see Collinson and Thompson, p.188), and (ii) limestone weathering prevented accurate determination of dune slip-face orientations to better than $\pm$ 10°. The vector mean palaeocurrent azimuth direction was computed for each locality, along with dispersion $\bar{R}$ (figure 66; individual palaeocurrent rose diagrams are shown in figure 67).

4.10.2.3 Imbricate clasts

In localities where no cross-stratification was observed, measurements of imbricate clasts (figure 68) at the base of redeposited beds (interpreted as turbidites) were made. Poles to clasts were plotted on stereonets and corrected for tectonic tilt by rotation around the spherical mean bedding orientation for each locality. Clast data were averaged to find their vector mean and dispersion. It was assumed that up-current dip of clasts was typical, thus the calculated palaeoflow azimuth was given by the vector mean clast dip-azimuth minus 180°. The value $\bar{R}$ was also calculated as a measure of dispersion (table 2; individual stereonets for separate localities are shown in figure 69).

4.10.2.4 Sole marks and traction overfolds

These (rarely observed) features were recorded on rose-diagrams (figure 70).

The vector mean azimuth and dispersion R were measured (see table 2). An example of a traction overfold beneath a five-metre thick debris-flow/turbidite from the Frosolone area is shown in figure 61.

4.10.3 Palaeoslope interpretation

Data collected for the Lower Cenomanian to Maastrichtian-Paleocene (Upper Cretaceous) strata provide a complex picture (figures 64, 66). Palaeoflow on the slope north of the eastern Matese platform was toward the north-north-east to east--north-east. Slump data from Mt. Patalecchia suggest that the down-slope direction was towards the north to north-north-east. The mean palaeoflow data from the Frosolone area from cross-stratification, traction overfolds and sole marks all agree within 12°. This north-easterly palaeoslope is in good agreement with the platform-to-basin facies transitions observed in the area and visible on Carta Geologica d'Italia foglio 161 (Isernia).

The palaeocurrent and palaeoslope data from the western Matese are more difficult to interpret. Current azimuths at Capriati and Monteroduni suggest westerly palaeoflow, whilst those at Gallo imply north to north-easterly flow. Slump data from Longano (to the north of Gallo) also gives a northerly palaeoslope solution. Whilst none of these localities has a satisfactory number of data points, the north-west to westerly deflection of palaeocurrents at the western limit of the area is in accordance with azimuths displayed in map form (but not tabulated) by Pironon (1980) for the Palaeogene immediately overlying the Upper Cretaceous palaeosurface (unit 1+2 {iii} on enclosure 2). The most intriguing data, however, are those slump overfold data from Gallo, which yield a southerly-directed palaeoslope solution, despite palaeocurrent data implying northerly palaeoflow. These observations make sense when the regional map and stratigraphic data are considered. During the Late Cretaceous, a part of the Matese platform drowned and erosion occurred down to the level of the Triassic in the Gallo area.

Evidence for the erosion is seen in the form of broad north-east trending erosional canyons, filled by onlapping Campanian to Maastrichtian redeposited carbonates (section 4.9). The canyon at Gallo (figure 71) has a half-width of at least one kilometre, and a depth of at least ninety metres, estimated from the thickness variations in the Upper Cretaceous redeposited sediments. Erosion must have taken place prior to the Campanian to Maastrichtian, whilst sediments of the latter age would have been funnelled from their source (the shelf-edge) through the laterally-confined canyon towards the base-of-slope apron further north. As the canyon filled during the Maastrichtian, later calcirudite beds came into direct erosional contact with the surrounding Triassic dolomite surface (figure 71; section 4.9).

The linear west-north-west to east-south-east map-trend and distribution of the present-day outcrop in the Matese, along with the palaeocurrent data, and other stratigraphic and structural considerations (see sections 6.7.6; appendix 2) are consistent with the hypothesis of rotation and erosion of a large (approximately 30 km square) extensional tilt-block crest during the Late Cretaceous. The northerly palaeoflow at Gallo is the result of redeposition of derived carbonates from the persistent platform some 10-15 km further to the south-south-west onto the drowned, eroded marginal block.

Further evidence for the regional extent of the northerly palaeoslope to the north of the Matese is provided by slump data at Miranda (figure 65b). It is suggested that slopes at this locality were very gentle since a high proportion of overfolds appear to verge against the inferred downslope direction (i.e. towards the south).

This phenomenon has also been observed in the Lower Cretaceous of the Gargano, where slump-folds in Maiolica formation nannofossil limestones (interpreted as being deposited in a very gently-sloping basinal environment) locally verge against the inferred regional palaeoslope.

Localities at Pesche (?Valanginian to Coniacian) and Indiripete (figures 66, 69a-b) both yielded puzzling palaeocurrent azimuths indicating easterly to east-south-easterly palaeoflow, which would be parallel to the strike of the inferred palaeoslope. This could be interpreted to indicate the presence of contour-parallel transport of material (see also section 5.5.4). Such flow is also anticipated by the degree of dispersion in palaeocurrent azimuths at Frosolone, which form a weakly bimodal distribution. Traction overfolds show a NW-SE trend at Frosolone (figure 70), suggesting that they may have been formed by lateral spreading of a NE-advancing mass-flow (palaeocurrents indicate predominantly northerly to easterly flow; figure 66).

A final palaeoslope observation is provided by the prescence of slump overfolds at Rave La Noce, in Jurassic platform interior facies. These give a local west-north-westerly palaeoslope orientation, which is difficult to interpret, but confirms the presence of local relief on the platform during the Jurassic.

Taken as a whole, the various palaeoslope data provide valuable insights into the Late Cretaceous development of the platform-margin in the Matese mountains area. Although data are not easily obtained in this type of carbonate environment, if a range of different indicators are employed and interpreted in the light of other sedimentological and structural data, a plausible regional picture can be constructed. It is urged that this type of approach be applied in other "difficult" carbonate platform-to-basin transition areas. The present study has focussed on the Late Cretaceous to Early Eocene palaeoslope; Pironon (1980) should be consulted for data on the Late Eocene to Miocene palaeoslope and palaeocurrents in the Matese area. The general picture painted by Pironon (1980) is that of continued erosion of the margin of the carbonate platform, and redistribution of sediment into the Molise basin by northerly-flowing palaeocurrents, prior to the onset of thrusting in the Late Langhian. Interestingly, Pironon shows some southerly-directed palaeocurrent azimuths (his figures 91 to 95) to the north of the Frosolone area, implying a structural high (another tilt-block crest?) within the presumed area of the Molise Basin, locally sourcing redeposited sediments.

Chapter 5:
The Gran Sasso d'Italia: Carbonate slope sediment-body geometries and depositional systems.

5.1 Introduction

The Gran Sasso d'Italia (henceforth referred to as the Gran Sasso) records an important part of the anatomy of the carbonate platform-margin, namely the middle to lower parts of the palaeoslope. Situated 100 km east-north-east of Rome (figure 5) and rising to 2912 m altitude, the highest point in the Apennines, the Gran Sasso was singled out for especial study for three main reasons.

Firstly, the relief in the area (approximately 1500 m) offers excellent large-scale exposures of Mesozoic and Lower Tertiary carbonate slope sediments over a horizontal scale of up to ten kilometres. At the altitudes encountered in the Gran Sasso (predominantly above 2000 m) this has enabled detailed observations of sediment-body geometries to be made. Such observations are of potential value in petroleum reservoir studies since, (i) in some regions, redeposited carbonates already form substantial reservoirs (Cook *et al.*, 1972; Enos, 1974, 1977, 1985, 1988; Viniegra, 1981; Cook *et al.*, 1983; Cook and Mullins, 1983; Aguayo *et al.*, 1985; Hobson *et al.*, 1985), (ii) more deep-water carbonate reservoirs are likely to be discovered in the future as exploration and research continues into this domain (Cook and Enos, 1977; Scholle, 1977; Flores, 1978; Mullins *et al.*, 1978; Cook, 1979; Mullins and Neumann, 1979; Santiago, 1980; Cook and Egbert, 1981; Enos and Moore, 1983) and (iii) difficulties in imaging potential petroleum target carbonate sand-bodies in the subsurface by seismic reflection, due to insufficient acoustic impedence contrast between carbonate sands and lime mudstones, makes outcrop studies of such rocks essential to constucting useful carbonate petroleum reservoir models.

The second reason for detailed study of the Gran Sasso is again based on the large-scale continuity of slope facies, which allows models for carbonate slope development (see chapter 1) to be tested and refined. In the past, models have been proposed which were not well founded in outcrop studies, or were based on presumed analogies with siliciclastic environments. This chapter will describe the character of a Mesozoic carbonate slope based on field outcrop patterns to help redress this lack of balance.

Thirdly, the continuous stratigraphic record of sedimentation from Liassic until Miocene times provides superior biostratigraphic control for events in the platform-to-basin transition to that on the adjacent platform, (where stratigraphic gaps and lack of time-significant fauna hamper such studies).

This chapter attempts to put a time-scale on the processes of pelagic sedimentation and resedimentation, enabling distinction of possible controls on sedimentation by tying in local and regional geological observations of known age to stratigraphically dated events in the Gran Sasso, a theme which will be continued in chapter 6.

5.2 Stratigraphy

5.2.1 Intoduction

This section will review work on the area by previous authors, and summarise the stratigraphic findings of this study. Measured stratigraphic sections are given in full in enclosure 1, and are summarised in figure 9. Further details regarding the stratigraphic work carried out in the area have already been given in chapter 2.

5.2.2 Early Studies

The earliest studies performed in the area were those of Baldacci and Canavari, (1884), Canavari (1881, 1885), Sacco (1907), Cacciamali (1924) and Catalisano (1938). Work for the Teramo (Foglio 140) sheet of the Carta Geologica d'Italia, published in 1965, was carried out by Moretti (1951), Renz (1951), Alberti (1953, 1954), Scarsella, (1953, 1954, 1955a, 1955b, 1957, 1958, 1959) and Manfredini (1958). These authors were able to distinguish "facies abruzzese di scogliera" (neritic carbonate platform facies of the Latium-Abruzzo platform) from "facies di transizione" (redeposited carbonates and lime mudstones belonging to a palaeoslope) and "facies umbro-marchigiana" (basinal facies of the Umbria-Marche pelagic basin).

5.2.3 Gran Sasso

Stratigraphic schemes for the Gran Sasso were proposed by Zamparelli (1964, 1966), Crescenti (1969a, 1969b) and Adamoli *et al.*, (1982a, 1982b). Other papers were produced by Bernoulli, (1967), Crescenti *et al.*, (1969), Barbera, (1967), Alessandri *et al.*, (1968), De Nocera (1973). Chiocchini and Mancinelli (1978) produced a biostratigraphic correlation scheme between Triassic to Lower Cretaceous successions of the Latium-Abruzzo carbonate platform, transitional sediments of the Gran Sasso, and basinal sediments of the Umbria-Marche basin. Papers concerning the Gran Sasso in a wider regional context were written by Demangeot (1952, 1965), Manfredini, (1963, 1975a-b), (including a synthesis of central Apennine geology and a tentative palaeogeographic reconstruction for the Gran Sasso) Parotto and Praturlon (1975), and Passeri (1977). Adamoli *et al.*, (1978) provided a set of palaeogeographic reconstructions for the area from the Triassic until the Early Cretaceous, but failed to substantiate these with any detailed field data. Castellarin *et al.*, (1978) analysed the evolution of the Abruzzo and Umbria-

Marche basins in relation to the proposed kinematics of the so-called "Anzio-Ancona line", although the exact function of this lineament through Mesozoic and Tertiary time is still a matter of discussion (see section 5.4). The stratigraphic scheme for the Gran Sasso followed in this thesis is given in figure 72.

5.2.4 Latium-Abruzzo carbonate platform

Studies on the carbonate platform facies adjacent to the Gran Sasso were carried out by Praturlon (1964, 1966a, 1966b), Colaccichi, (1966), ~~Colaccichi and Pialli, (1967),~~ Devoto (1964), Bosi and Bertini (1970), Centamore *et al.*, (1971), Chiocchini (1977), Chiocchini and Mancinelli, (1977), Carbone (1984) and Accordi *et al.*, 1987. Bosi and Bertini (1970) traced neritic outer-shelf facies laterally from Ovindoli-Secinano-Navelli-Calascio-Monticchio to Sella di Corno, and noted the transition from bioclastic and oolitic limestones (Upper Dogger to Lower Malm) to skeletal *Ellipsactinia*-bearing limestones ("calcari organogeni ad Ellipsactinie"; Upper Malm to Neocomian). These are succeeded in turn by skeletal rudistid and orbitolinid-bearing limestones. Colacicchi and Praturlon, (1975) also attempted to delimit the approximate position of the Mesozoic shelf-edge in the region (figure 76). The stratigraphic scheme for the Latium- Abruzzo carbonate platform followed in this thesis is given in appendix 1.

5.2.5 Umbria-Marche Basin

Lotti (1926) distinguished the "umbro-marchigiana facies" (basinal facies) from the "facies abruzzese" (platform facies). This facies contrast was also emphasised by Scarsella (1951). Stratigraphic schemes for the Umbria-Marche Basin were published by Centamore *et al.*, (1971), Chiocchini *et al.*, (1976) and Micarelli *et al.*, (1977). These works are reviewed in Chiocchini and Manchinelli's (1978) correlation between the Umbria-Marche basin and the Latium-Abruzzo platform. Other important stratigraphic works on the basin include Arthur and Fischer (1977), Alvarez *et al.*, (1977), Bortolotti *et al.*, (1970), Luterbacher and Premoli Silva (1964), Premoli Silva and Paggi, (1977), Renz (1936), Wonders (1977, 1978). The stratigraphic scheme used in this thesis for the Umbria-Marche basin is given in figure 73.

5.3 Local Geology

5.3.1 Mesozoic platform-margin development

The Gran Sasso formed a zone of transition during the Mesozoic between the Latium-Abruzzo carbonate platform (to the south) and the Umbria-Marche pelagic basin to the north (figure 74). During the Late Triassic, the area was the site of a broad, epicontinental shallow-water carbonate platform (see for example Carbone, 1984). This platform persisted until Early Sinemurian times (Early to Middle Liassic) (Chiocchini and Mancinelli, 1978), when the well-documented regional Liassic extensional tectonic phase (Crescenti, 1969a-b; Bernoulli, 1972; Bernoulli and Jenkyns, 1974; Bosellini and Winterer, 1975; Colacicchi *et al.*, 1978; Bernoulli *et al.*, 1979; Winterer and Bosellini, 1981) resulted in partial platform drowning and the formation of the Umbria-Marche basin. In the Gran Sasso, radiolarian-bearing lime mudstones of the Corniola formation overlie the Calcare Massicio platform facies. Continued faulting during the Liassic is supposed by Castellarin *et al.*, (1978, 1982) to have been responsible for the intercalation of megabreccias of shallow-water-derived material in the Corniola. From the Liassic onwards, Carbone (1984) recognised several different types of depositional environment in the central Apennines:

(i) Persistent platform areas, in which, in addition to keeping pace with tectonic subsidence, the accumulation rate counterbalanced relative changes in sea-level, causing cycles from shallow-subtidal to supratidal facies. The evolutionary trend was apparently towards an increase in open platform facies during the Late

Cretaceous, when skeletal buildup facies (Caprinid-coral rudstones, Hippuritid banks, Orbitoid shoals) prograded into inner platform areas. During falls in relative sea-level, sedimentation ceased, and subaerial erosion and diagenetic processes took place. Carbone attributed to such events the Cenomanian bauxites, microkarstic surfaces at the Cretaceous-Tertiary boundary (Microcodium levels), tropical flora in Late Triassic and Liassic platform sequences, and the extensive secondary dolomitisation of the platforms. Persistent platform sequences generally ceased at the end of the Cretaceous and were covered by Middle Miocene open-shelf carbonate facies ("Calcari a Briozoi e Litotamni"). The sedimentary hiatus decreases from the inner shelf to the platform-margin.

(ii) Drowned platform "steps" were developed by downfaulting of parts of the Triassic platform (see above) during the Middle Liassic, and also apparently during the Dogger to Early Cretaceous, when some former platform areas were covered by skeletal grainstones and rudstones of the Terratta formation (Tithonian). Carbone (1984) envisaged a third phase of platform destruction occurring from the Cenomanian onwards, characterised by retreating platform-margins and the contemporaneous growth of prolific rudist skeletal buildups. Redeposited skeletal grainstones ("calcari saccaroidi" or "calcari cristallini") occur on the drowned "steps" of this age. The contact between the "calcari cristallini" and underlying platform limestones is apparently time-transgressive across the margins of the Latium-Abruzzo carbonate platform. Recently, Accordi *et al.*, (1987) have noted the presence of derived skeletal material of Late Cretaceous age (up to Maastrichtian) at Valle d'Anzano in the Gran Sasso, suggesting the persistence of some skeletal buildups in the area until the end of the Cretaceous, at a time when the "calcari cristallini" reached its maximum extent.

(iii) Basins, which were discussed above.

(iv) Seamounts, which are interpreted by Carbone (1984) as portions of platform isolated during the Liassic tectonic phase, and subsequently forming bathymetric highs in the Umbria-Marche basin, capped by reduced or condensed pelagic and hemipelagic series. Stratigraphic gaps in these sequences in the central Apennines and western Greece are thought (Bernoulli, 1967) to be due to non-deposition and/or penecontemporaneous erosion in fully pelagic conditions rather than to continued Jurassic tectonic movements. This interpretation is in contrast to that of Chiocchini *et al.*, (1982) who attribute erosion of the seamounts during the Dogger to renewed fault movements. These latter authors also attribute erosion and local emergence of the platform between the Early and Middle Cretaceous to an "intense tectonic phase". The problem of controls on sedimentation will be further addressed in section 5.8, whilst discussion of the subsidence history of the area is postponed until Chapter 6.

5.3.2 Mesozoic History: Summary.

(i) Late Triassic to Early Sinemurian.

During this period, the region was a site of neritic carbonate sedimentation. The Calcare Massiccio of the central Apennines is the southerly time-equivalent of the Dolomia Principale of the Southern Alps.

(ii) Late Sinemurian to Late Dogger

The Middle Liassic tectonic phase led to deep-water sedimentation (Corniola Formation; Late Sinemurian to Middle Liassic) on the site of part of the former platform, with intercalations of megabreccias and turbidites amongst pelagic mudstones. The new site of the shelf-edge in the Gran Sasso is thought to have been from S. Stefano di Sessanio to Castel del Monte (Chiocchini *et al.*, 1982). Locally, the Corniola Fm. is overlain by thin developments of "verde ammonitico" (Late Liassic to Aalenian), the time-equivalent of the "ammonitico rosso" facies of the Southern Alps.* At the same time on the shelf-edge, skeletal facies became subordinate to oolitic sediments.

This facies is in turn overlain by the "pelagische kalke" (Dogger) of Bernoulli (1967).

(iii) Malm

During the Malm, skeletal buildups developed once more on the shelf-edge, and the Terratta Formation reflects the redeposition of this material as mass-flows into the basin, with locally variable thicknesses (see section 5.7). During the Middle Tithonian, the Terratta Formation was overlain by the "Scisti ad Aptici", crinoidal calcarenites (Bernoulli, 1967), which pass upwards into nannofossil-bearing chalky limestones (Maiolica formation) by the Late Tithonian. Differential thicknesses of Jurassic sediment in the Gran Sasso are clearly demonstrated by Chiocchini and Mancinelli (1978) and Adamoli *et al.*, (1982c). At Acquare della Formica (figure 9) and Grotta dell'Arco, the Calcare Massiccio is reported by Adamoli *et al.*, (1982c) to be overlain by a very thin sequence of nodular limestones (approx. 3 m), covered in turn by the Early Cretaceous Maiolica formation, whilst at Pizzo Cefalone (1.3 km to the NW) it is overlain by a Jurassic series between 380 m (Crescenti, 1969) and 480 m in thickness (Bernoulli, 1967). It is therefore likely that a Jurassic fault structure existed between these two localities. The variations are also expressed as differences in sediment-body geometry (figure 95, section 5.7).

(iv) Early Cretaceous

During this period, the shelf-edge was colonised by *Lithocodium* and *Bacinella* which formed a low-relief algal-ridge (Chiocchini and Mancinelli, 1977). This was gradually covered by shelf-lagoon deposits during the Early Cretaceous, as

* and Umbrian Apennines

* in the basin

subsidence rates decelerated, and fault-scarp relief was partially smoothed* by the Maiolica formation (see Koopman, 1983). This effect reduced the extent of the high-energy zone at the shelf-edge, reducing skeletal productivity, and resulting in only occasional turbidite deposits intercalated in the Maiolica.

(v) Aptian to Albian

An abrupt facies change occurred in the basin in the latest Barremian to Earliest Aptian (Chiocchini and Mancinelli, 1978, section 2.4.3), where the Maiolica formation is overlain by skeletal redeposited carbonates of the Mt. Acquaviva formation, whilst rudist buildups became dominant at the shelf-edge. The basinal deposits of this age are discussed in sections 5.5 to 5.7.

(vi) Cenomanian to Early Eocene

During the Early Cenomanian, the platform was emergent, and bauxite deposits developed. Rudist buildups continued to dominate the shelf-edge, whilst redeposited limestones (containing shelf- and slope-derived components) were intercalated with lime mudstones in the Scaglia formation. Periods of erosion of the shelf-edge clearly took place (see section 5.6), particularly pronounced at the end of the Cretaceous, by which time some parts of the platform were again emergent. During the Early Tertiary the morphology of the platform-margin became gradually established as that of a carbonate ramp (Carbone 1984), with very low sedimentation rates characterising basinal areas during the Paleocene, increasing again during the Eocene (section 5.5.5).

(vii) Late Eocene to Middle Miocene

Sedimentation continued in a ramp-type environment, with benthonic communities dominated by larger foraminifera. Middle Miocene skeletal limestones (containing bryozoans and *Lithothamnium* algae) disconformably overlie older Tertiary platform sediments and, in places, Upper Cretaceous sediments. During the Middle Miocene, a gradual transition to mixed siliciclastic-carbonate flysch deposition coincided with the final destruction of the platform during Apenninic thrusting (section 5.4).

5.4 Apenninic compressional tectonics

5.4.1 Previous studies

The main structural elements of the Gran Sasso, namely the large recumbent fold forming the northern part of the chain, were recognised as important features by Sacco (1907), Cacciamali (1924) and Catalisano (1938), although subsequent work on the area merely formed a small part of more regional studies (Behrman, 1936, Bally, 1954, Demangeot, 1965). These studies suggested a strong horizontal component of compression in the region. Scarsella (1953, 1954, 1957) made an important contribution with the publication of the sheets 139 (L'Aquila) and 140 (Teramo) of the Carta Geologica d'Italia in 1955 and 1963 respectively, which clearly show a major overthrust extending from the region of Cittaducale to the front of the Sibillini Mountains (figure 75), although papers produced during mapping did not emphasise the importance of horizontal compressive forces (Alberti, 1953, 1954, 1956, 1957, Manfredini, 1958, 1975a, and those of Calembert *et al.*, 1972a, 1972b, Cogefar, 1979). Demangeot (1965), Parotto and Praturlon (1975), and Parotto (1980) interpreted the Gran Sasso as being partially overthrust northwards over the Laga Flysch by reverse faults, whilst the latter two papers suggest that the major displacement occurred at depth below the Laga Flysch. Adamoli *et al.*, (1982a, 1982b, 1982c) and Ghisetti and Vezzani (1983) divided the Gran Sasso range into structural units, separated by low-angle thrust planes, themselves thrust over the Laga Flysch as a single unit. The nature of the displacement in the Gran Sasso will be discussed further in section 5.4.5.

The current model for the Gran Sasso, proposed by Ghisetti and Vezzani (1983, 1986a, 1988a) presents a picture of an arcuate thrust belt along which the Latium-Abruzzo carbonate platform overrides the Marche foreland fold and thrust belt. From east to west the Gran Sasso-Morrone thrust system displays variable styles of deformation. In the eastern part, the major structures are systems of north-verging imbricate thrust-faults, bounding different thrust sheets deformed internally by overturned folds (Ghisetti and Vezzani 1986a-b). To the west of Mt. Corno Grande, the imbricate system of thrust faults is substituted by two thrust planes, which are substituted progressively along strike by a large overturned fold system. This overturned fold led some authors (Manfredini, 1958, 1975a) to speculate about the autochthony of the Latium-Abruzzo carbonate platform. It will be argued below from field evidence and regional geological studies (section 5.4.4) that the overturned fold is displaced along a system of thrust faults propagating northwards at depth below the Laga Flysch.

5.4.2 Transcurrent lineaments

The term "Anzio-Ancona" line was introduced by Migliorini (1950) to describe the major structure separating the northern and southern Apennines. Scarsella (1951) emphasised the facies contrast across the structure between the deep-water Umbria-Marche sequence and the neritic Latium-Abruzzo sequence. This contrast was used by Castellarin *et al.*, (1978) to postulate a Jurassic extensional fault system. Tortonian extension was followed by dextral strike-slip faulting during the Messinian, with displacements of the order of 15 to 50 km, and finally compressional overthrusting during the Early to Middle Pliocene. According to Castellarin *et al.*, (1978, 1982) the structural development of the Gran Sasso area was largely controlled by the behaviour of the Anzio-Ancona line. Thus, during the upper Early Pliocene, facies of the Umbrian Basin were overthrust over transitional facies of the Gran Sasso and the central part of the Latium-Abruzzo carbonate platform.

5.4.3 Structural cross-sections

Detailed cross-sections were constructed across the western Gran Sasso in a north-south direction, matching as closely as possible the inferred local thrust transport direction (see section 5.4.5). Sections A and B (figures 77 and 78) are derived from field mapping of the Western Gran Sasso carried out in 1988 (maps are presented in enclosure 2). The southern end of section B has been extended as far as the site of the former Cretaceous shelf-edge, by using field data and interpretation of Carta Geologica d'Italia foglio 140 (Teramo). Section A was further constrained by projecting subsurface data from the L'Aquila-Teramo autostrada tunnel (Cogefar, 1979) onto the southern part of the line of section. The locations of cross-sections A and B are shown in figure 74, whilst the 1:10,000 map of the western Gran Sasso (enclosure 2) summarises the structural mapping carried out in 1988.

5.4.4. Normal faults

Sections were drawn to show late normal faults cutting thrust-related structures, in accordance with field observations. Normal faults remain steep even in the subsurface exposures of the L'Aquila-Teramo autostrada tunnel (Cogefar 1979), and have been drawn as planar structures. The interpretation of Ghisetti and Vezzani (1986a-b, 1988a-b) in which normal faults are listric and sole into a shallow thrust décollement surface is not feasible in this tectonic environment. Models for listric faults, such as the Chevron construction (Verrall, 1982), modified Chevron construction (Williams and Vann, 1987) and the slip-line construction

(Williams and Vann, 1987) produced unrealistic results when applied to the cross-sections. In addition, most large seismogenic normal faults are now thought to remain approximately planar to depths of the same order as the thickness of the seismogenic zone (Jackson, 1987). For these reasons, the normal fault structures are thought to be an entirely new set of structures rather than representing partial reactivation of earlier thrust structures.

The amount of extension in detailed cross-sections A and B (figures 77 and and 78) was determined,* and revealed an overall extension across the area of approximately 14%, whilst across the central portion of the Gran Sasso extension reached 54%.

Displacements on individual normal faults are large, approximately 1-2 km on the Valle Fredda fault (increasing westwards) and one kilometre on the east-west trending fault south of Mt. Corvo and Pizzo Intermesoli.

5.4.5 Thrust displacements

Cross-sections A and B record only small amounts of shortening (less than 15%) based on surface data. The general structural style of the cross-sections, with a large frontal fold structure at the northern end of the area, suggests, however that an underlying low-angle thrust décollement surface must exist, along which the majority of the shortening has taken place. However, no such structure breaks the surface in the area of study, as exemplified by cross-section B in which dips in the flysch sediments gradually decrease on passing further northwards. This is also the case north of Mt. Corvo, ruling out the possibility of a thrust carrying major displacement outcropping immediately north of the mountain as proposed by Ghisetti and Vezzani (1988a, their figure 10a). The space problem produced by the surface dips at this northern end of both sections necessites further shortening at depth, as implied by the

* by line-bε

sections of the Servizio Geologico d'Italia (1963a), Cogefar (1979), and Ghisetti and Vezzani (1983, 1986a-b). Regional seismic interpretations by Mostardini and Merlini (1986) and Bally *et al.*, (1986), along with field studies by Koopman (1983) also present a picture of thin-skinned thrust tectonics, with the major décollement horizon being the Triassic Burano anhydrite. The repetition of the Mesozoic section is necessary in the Gran Sasso area, due to the lack of exposed basement, in common with other areas in central Italy. An indirect piece of evidence for such repitition comes from the Antrodoco I well (50 km west of the Gran Sasso) which penetrated Early Cretaceous pelagic carbonates at 2473 m depth underneath a thick sequence of Late Triassic to Liassic dolomites and anhydrites. This strongly suggests the presence of the Marche pelagic sequence in the footwall of the Latium-Abruzzo overthrust west of the Gran Sasso, with a minimum displacement of 15-20 km (Ghisetti and Vezzani, 1988a). Shortening in the Gran Sasso has been accomodated by means of thrust displacements and thrust-related folds with weakly to moderately well-developed axial-planar cleavage fabrics (figures 79, 81). Locally, tectonic stylolites are present (figure 79b).

Minor thrust-related structures in the study area confirm a northward tectonic transport direction in the area. The axial planes of minor folds (figures 79a, 81) are of shallow, east-west orientation. The hinge lines of major folds have a similar, shallow E-W attitude (see bedding-cleavage data from Sella di Venacquaro, figure 79b). Many minor thrust structures exist, some of which were individually identified by Ghisetti and Vezzani (1988b). In particular, the structure between Cima di Malecosta and Mt. Corvo, labelled by Ghisetti and Vezzani (1988b) as T_5, appears in outcrop to represent a zone of tip folding above a blind thrust of small displacement at depth (figure 80). The thrust cutting the axial plane of the frontal fold (T_7 of Ghisetti and Vezzani, 1983, 1986a-b; figure 77) has a displacement of approximately half a kilometre on the east side of the Valle dell'Rio Arno, reduced to two hundred metres on the west side of the valley, and losing its thrust displacement completely on Mt. Corvo. In view of the minor nature of many of these structures, an attempt has been made in the cross-sections to represent only the major structural features, in order to keep section-balancing as simple as possible. Conventional lithostratigraphic units, mappable in the field, and confirmed by biostratigraphic dating, have been used throughout the study, facilitating comparison with other published regional work and maps. The nomenclature introduced by Ghisetti and Vezzani (1983, 1986a-b) has not been used since erroneous interpretation of the significance of some structures could have led to the generation of a large number of poorly recognisable and correlatable units.

The structural cross-sections confirm the basic north-south continuity of the area from the site of the former shelf-edge to the lower-slope (figure 78 inset). There is some uncertainty in the amount of shortening in the area of the shelf-edge at the south end of section B (figure 78), although this amount is likely to be less than three kilometres if the shallow thrust décollement hypothesis is correct. The distance between the Cenomanian shelf-edge and lower-slope was approximately 25-28 km.

5.4.6 Deformation of sandbodies

Deformation of UpperCretaceous redeposited carbonates on Mt. Corvo is seen in the form of large subvertical kink bands which assist in accomodating deformation produced by the frontal fold (figure 82). The continuity of sandbodies is generally maintained across such structures. More serious disruption of sandbody continuity is caused by large normal faults such as the east-west trending fault south of Mt. Corvo and Pizzo Intermesoli (section 5.4.4). Another problem is the high degree of recrystallisation encountered locally (for example the western part of Mt. Corvo). Such diagenetic changes produced during deformation have completely occluded any remaining porosity in sandbodies in the area (section 3.2).

5.5 Lithofacies

The lithofacies which will be described in detail in this section are those of the Cretaceous to Lower Tertiary series. The descriptions are generally applicable to all stages of the Cretaceous and Lower Tertiary, since most lithofacies are persistent or recurrent throughout this time interval. Jurassic lithofacies will be mentioned briefly, but have been described in detail elsewhere (e.g. Bernoulli, 1967, Chiocchini and Mancinelli, 1978), and these other papers should be consulted for complete sedimentological and biostratigraphic descriptions.

5.5.1 Calcirudite

Calcirudites are typically found in laterally continuous beds (figure 82), although some lenticular forms also occur, usually pinching out within one kilometre. The geometries of these beds will be discussed further in section 5.7.

Cretaceous calcirudites are composed of lithified clasts of skeletal rudistid limestones and poorly-sorted clasts of pelagic micrite and/or wackestone (figure 83). The matrix typically comprises lime mudstone or wackestone with rudist fragments, planktonic and/or benthonic foraminifera and, locally, radiolarians. Jurassic calcirudites are typically composed of clasts and boulder-sized lithoclasts of peloidal limestones (Calcare Massiccio) during the Liassic, and skeletal sponge, echinoderm and algal clasts during the Early Tithonian. In some exposures, sedimentary structures may be present, such as grading and parallel-lamination, but sedimentary structures are generally absent or poorly preserved.

The calcirudite beds are interpreted to be the result of turbidity currents, debris flows and gulley erosion by these flows (see section 4.8.1). Shallow-water-derived clasts are mixed with slope-derived clasts in calcirudites, suggesting that the flows which formed them were responsible for gullying the palaeoslope. Lenticular calcirudites are particularly well-exposed on Mt. S. Franco (figure 84), and clearly infill a deeply incised gulley some 50 metres in depth and one kilometre in width. This is comparable in size to gullies reported from the Recent slope of northern Little Bahama Bank* (see section 5.7). Clasts may have additionally been derived by mass-movements further up-slope, such as slumps and debris-flows (section 5.5.3).

5.5.2 Skeletal Calcarenites

Skeletal calcarenite is an important lithofacies in the Gran Sasso. The facies is chiefly composed of rudist bivalve fragments and subordinate echinoderms, bryozoans, gastropods and red algae, although some beds are very rich in benthonic foraminifera and planktonic foraminifera. Calcarenite beds are both lenticular (figure 85) and laterally continuous, but generally thinner-bedded than calcirudite beds. Graded bedding and planar lamination are common, indicating possible deposition by turbidity currents. Graded Ta and Ta-b (top-cut-out) and Td-e (base-cut-out) calciturbidites are most common. Lime mud is often an important constituent of these beds, which are generally well-sorted.

The Middle and Upper Cretaceous calcarenites are interpreted as being the products of turbidites derived predominantly from coeval rudist buildups.

Jurassic calcarenites are distinctively rich in peloidal and ooid sand-size grains during the Late Liassic to Early Tithonian.

* Harwood and Towers, (1988).

5.5.3 Folded Calcirudites, calcarenites and lime mudstones

Intrastratal soft-sediment deformation of bedding is common throughout the Jurassic and Cretaceous series. Deformation often affects stratal thicknesses between two and six metres (figure 89d), consisting of calcarenites, lime mudstones and wackestones. These packages are sometimes laterally persistent on the scale of one hundred metres or more parallel to the palaeoslope, and may contain folds, which record a consistent northerly downslope direction (figure 86). In one case, on Pizzo Cefalone, the entire Early Aptian series (some fifty metres thick) is deformed in a large translational slide, with a clearly visible basal detachment plane at the top of the Maiolica Formation, above which bedding is deformed into tight overfolds, interpreted as slump folds (figure 86).

Some of the soft-sediment deformation is attributable to slumping, although the deformation of a still-continuous calcarenite bed (figure 89d) appears to be more analogous to the "creep-lobes" described by Harwood and Towers (1988) in their analysis of the lower-slope north of Little Bahama Bank. In the example of figure 89d, creeping of sediment appears to be spatially restricted to areas lying over the margins of the mounded lithofacies described in section 5.5.4.

5.5.4 Lime mudstones and wackestones

These beds generally range from 1 to 20 centimetres in thickness, and may contain planktonic foraminifera and radiolarians. Bioturbation is locally observed.

The beds are interpreted to be produced by settling of decaying planktonic organisms, at times of deep-water origin. Throughout the Cretaceous, a mounded facies can be observed locally intercalated in this lithofacies (figures 82, 87, 89). One example of such a deposit outcrops on the NE crest of Mt. Corvo (figure 89), and is composed predominantly of fine carbonate sand-size grains, The three-dimensional shape of this facies can be observed in an example from the Maiolica Fm. on Pizzo Intermesoli (figure 87). In this outcrop, the facies forms a low-relief mound approximately 20 m high and 400 m across in transverse section (parallel to the strike of the palaeoslope) and ?400 m in longitudinal section (parallel to the dip of the palaeoslope). In both examples above, foresets are visible, with a slip-face direction inclined towards the west (i.e. parallel to the strike of the slope). On Mt. Corvo (figure 89), foresets can be seen passing westward into toesets at the western fringe of the mounded facies.

The mounded facies are possibly the carbonate equivalent of the siliciclastic basin-floor fan (Vail, 1988; Sarg, 1988), recognised in carbonate sequences in the Vercors region of France by Jacquin (1989). This would imply redeposition of platform-derived sand-sized sediment by gravity flows. However, the small areal extent and contour-parallel flow-direction of the mounded facies in the Gran Sasso suggests that bottom currents, reworking slope deposits, may have aided mounded facies formation. In the analysis of cliff-sections in this chapter, the label "bidirectional downlap" (BDD) will be used to describe this facies, as a means of delimiting parts of sections with this distinctive geometry. The possible role played by this facies in determining depositional architecture will be examined in section 5.7.

Previous studies of the Scaglia Formation (Cenomanian to Lower Eocene) (e.g. Colacicchi and Baldanza, 1986) have not noted the presence of such a mounded facies, possibly due to the concentration of studies in the Umbria-Marche basin and not in the region of the palaeoslope.

5.5.5 Sedimentation rates

Crude rates of sediment accumulation for field sections in the Gran Sasso are presented in figure 88. These are based on biostratigraphic dating and sedimentary logs which are reproduced in full in appendix 3 and enclosure 1 respectively. Error bars representing the maximum possible age range of each sample have been plotted against depth in the section. Regression lines have been computed and plotted to show the most likely sedimentation rates during discrete time intervals. Sedimentation rates were clearly variable through the Cretaceous to Early Tertiary, reaching values of between 18 and 33 m/My during the Late Albian (Pizzo Cefalone), and between 40 and 111 m/My in the Middle Cenomanian (Mt. Corvo, Pizzo Intermesoli) and falling to less than 2.5 m/My during the Paleocene (Mt. Corvo I and II). The values for the Late Albian and Middle Cenomanian are comparable to other calciturbidite accumulations, such as the Late Miocene turbidites cored by ODP site 630 (Little Bahama Bank). Values of less than 5 m/My are typical of pelagic carbonates, such as the Paleocene sediments cored by ODP site 627 (S. Blake Plateau- which were suggested as resulting from condensed or punctuated sedimentation).

5.6 Lithofacies associations

5.6.1 Calcirudite/calcarenite dominated series

Some stages of the Cretaceous and Lower Tertiary in the Gran Sasso are dominated by deposition of thick calcirudite and calcarenite beds, with only subordinate lime mudstones and wackestones. Calcarenites may be interspersed with "creep lobe" lithofacies, or translational slides, as described in section 5.5.3 (see figure 89). The calcirudite/calcarenite beds may be lenticular or amalgamated, and rates of deposition are relatively high (see section 5.5.5).

5.6.2 Mounded calcarenite/wackestone/lime mudstones

This facies consists of lime mudstones and wackestones intercalated with thinly-bedded, ?fine-grained calcarenites, and locally lenses of ?fine calcarenites displaying low-angle bedforms (see section 5.5.4). This facies is found throughout the

Cretaceous (see figures 87, 89).

5.6.2 Lime mudstone/wackestone dominated series

The Early Cenomanian and Palaeocene stages were characterised by lime mudstone-dominated deposition, although this lithofacies association occurs elsewhere in the Cretaceous series. Deposition rates of this lithofacies are relatively low (section 5.5.5).Two of the three lithofacies associations can be seen clearly in a single Maastrichtian outcrop on Mt. Corvo, with a stratigraphic thickness of 20 metres (figure 89). Possible controls on sedimentation which gave rise to the distinctive lithofacies associations described in this section are discussed in section 5.9.

5.7 Sediment-body geometries

The calcirudite and calcarenites of Aptian to Cenomanian and Campanian to Early Eocene age outcropping in the Gran Sasso were singled out in particular for studies of carbonate sand-body geometries in order to assess the size and lateral continuity of these important potential hydrocarbon reservoir facies.

5.7.1 Aptian to Cenomanian sandbodies

As mentioned in section 5.5.1, the Early Aptian calcirudite-dominated sequence is in abrupt stratigraphic contact with Barremian nannofossil-bearing limestones of the Maiolica formation in all outcrops observed. The basal bed of the Early Aptian can be traced laterally over distances in excess of two kilometres (for example, figure 95), although local thickness variations do occur. In some localities, (Pizzo Cefalone, Pizzo Intermesoli) the lateral continuity of this sheet-like sand-body is disrupted by sliding and slumping, and slumped, soft-sediment-deformed bedding is interspersed between lenses of the redeposited bed (figures 86, 90).

Further calcirudite beds have been dated as Late Aptian, and on Mt. S. Franco (figure 84) these beds are lenticular (as described in section 5.5.1), possibly having been confined by a previously eroded gulley. The lateral time-equivalent facies on Pizzo Cefalone have sheet-like, laterally continuous geometries. The implication of this may be that carbonate gravity-flows were produced along a broad front on the shelf-edge, but sought any pre-existing topographic depressions on the palaeoslope, thus leaving locally lenticular, laterally-confined deposits, and elsewhere laterally continuous deposits.

Details of the Aptian to Cenomanian sediment body geometries on Pizzo Cefalone and Pizzo Intermesoli are presented in figures 86 and 90 respectively. The east face of Pizzo Intermesoli provides the most complete record of Middle Cretaceous basinal sedimentation in the area. The geometrical relationships between groups of beds have been summarised in three categories, namely *bidirectional downlap* (BDD; see section 5.5.4), *downlap* (DLP) and *onlap* (ONL). These terms will subsequently refer to a group of beds with that particular geometry, distinct from surrounding groups of beds. Each DLP group of beds corresponds to a second-order feature, or turbidite system, as defined by Mutti and Normark (1987).

Where possible, measured sections have been tied to studies of cliff-sections, and in the case of Pizzo Intermesoli this has made it possible to trace specific palaeontologically dated packages of sediment with distinct geometries across the cliff-section. The main features, which can also be recognised in part in the east and south faces of Pizzo Cefalone, are firstly a poorly developed BDD of Lower Aptian age, erosionaly truncated by a DLP and itself covered by ONL, still of Lower Aptian age. The next set of geometries commences with a BDD, followed by DLP, both of Upper Aptian to Lower Albian age. (On Pizzo Cefalone, an ONL is visible also). A further BDD is overlain by DLP correlatable with sediment from the measured section on the south face of Pizzo Intermesoli, dated as belonging to the upper *Rotalipora* *ticinensis* zone of the Upper Albian (for the 30 m interval indicated on figure 90). This group of beds is succeeded by an ONL of uppermost Albian to Lower Cenomanian age. The subsequent BDD is correlatable with sediment dated as belonging to the lower *Rotalipora cushmani* zone, and the overlying DLP also falls within this fossil zone.

5.7.2 Campanian to Lower Eocene sandbodies

The Upper Maastrichtian calcirudite beds exposed on the south face of Mt. Corvo (figure 82) represent a cross-section parallel to the strike of the local palaeoslope. Calcirudite beds are laterally continuous over a horizontal distance in excess of two kilometres, although thickening and thinning is very common. Amalgamated zones (arrowed in figure 82; figure 91) 3-400 metres across and up to 25 metres in thickness pass laterally into discrete thinner beds, interspersed with wackestones and lime mudstones. The amalgamated zone in figure 91 can be seen (when traced eastwards) to be composed of three individual flow events (figure 93). It is suggested that such zones formed in slight depressions in the palaeoslope. Experimental and field observations of sandbodies (e.g. Bridge and Leeder, 1979) predict that channel sandbodies typically stack vertically, seeking topographic lows. This pattern is sometimes complicated by differential compaction, which can result in an incoming sandbody being deposited alongside the previously deposited sandbody. An example of this non-vertical type of stacking is also visible on Mt. Corvo (figure 92). It must be emphasised that the lateral continuity of the sandbodies observed strongly suggests deposition from a broad-fronted gravity-flow, rather than discrete "channels" fed from line sources. Limited outcrop and conditioning induced by siliciclastic models of slope depositional systems (Mullins, 1983b; Mullins *et al.*, 1984) have tempted many carbonate sedimentologists to interpret any lenticular-shaped sandbodies as lobe channel-forms, with little caution. This is particularly true in the Italian geological literature, and may lead to erroneous prediction of the form of subsurface sandbody geometries.

The sandbodies on Mt. Corvo may also be viewed on the east face of the mountain, in a section perpendicular to the strike of the palaeoslope (figure 94). A detailed examination of the geometries exposed in this cliff, coupled with data derived from the south face of Mt. Corvo, has been tied to palaeontological dates obtained from the measured section below the summit of Mt. Corvo (data are indicated on figure 94). Three main sets of BDD, DLP and ONL (Labelled Maa2, Maa2a and Maa3) can be distinguished in the Maastrichtian part of the section. The first set belongs to the Latest Campanian to Early Maastrichtian, whereas the second and third belong to the mid- to Late Maastrichtian. Palaeontological data suggest that the DLP component of the third set lies close to the Cretaceous-Tertiary boundary. A further two sets of BDD, DLP and ONL are visible in the east face of Mt. Corvo, the first of which has been positively dated as Palaeocene by correlation with the nearby measured section. Above this lies a set of BDD, DLP and ONL dated as Lower to Middle Eocene. This in turn is succeeded by a possible BDD of Upper Middle Eocene age.

The depositional architecture of the slope sediments can be seen clearly in the south face of Mt. Corvo (figure 82). Mounded facies (BDD Maa 2) form low-relief accumulations approximately 400 m across (from W to E). The thickest accumulations of calciturbidites in the overlying DLP occur between BDD's. This is clearly seen in the third set of Maastrichtian geometries, where the calciturbidites of DLP Maa 3 are amalgamated and most thickly developed alongside facies of BDD Maa 3. Calciturbidites therefore seek topographic lows created by the depositional geometries of underlying facies, particularly BDD groups of beds. Relief ~~is~~ was reduced as turbidite sedimentation continued, and was reduced still more by ONL groups of beds, only to be produced once more by the next BDD mounded facies. This architectural style was persistent at least from Latest Campanian to Late Eocene times (figure 82).

5.7.3 Depositional models

As discussed in chapter 1, the two popularly used models for interpreting carbonate slope deposits are the slope-apron and submarine fan models. The occurrence of broad-fronted flows on a persistent northerly palaeoslope, with no evidence of a systematic change in slope or current orientation across the area, argues strongly for describing the Gran Sasso sediments as a carbonate base-of-slope apron. The sedimentary features observed (interbedded turbidites and lime mudstones, "creep lobes", slumps) coupled with the penecontemporaneous reworking of material (see section 5.9) are very similar to those found on modern accretionary carbonate slopes, such as Northern Little Bahama Bank (Mullins and Cook, 1986, Harwood and Towers, 1988). The data presented in this chapter is largely in agreement with that of Colacicchi and Baldanza (1986) who applied the carbonate apron concept to the Scaglia Formation of the central Apennines (Cenomanian to Early Eocene), although these authors worked from field outcrops of more limited lateral extent (less than a few hundred metres at best).

5.9 Mesozoic tectonics and sediment-body geometries

Field data from this study (Pizzo Cefalone and Acquare della Formica; figure 9) and data from Bernoulli (1967), Chiocchini and Mancinelli (1978), Castellarin *et al.*, (1978) and Adamoli *et al.*, (1982c) suggest that lateral changes in thickness of sedimentary sections are pronounced, especially during the Jurassic. Bernoulli (1967) demonstrated by use of sections in the Umbria-Marche basin and the Gran Sasso that marked thickness variations occur in a north-south direction from the Latium-Abruzzo carbonate platform in the south to the Umbria-Marche basin in the north. The variations were probably caused by fault-bounded structures produced during the Liassic extensional tectonic phase. A similar pattern is documented by Castellarin *et al.*, (1978). Thickness variations also clearly occur in an east-west direction, in particular between Pizzo Cefalone and Acquare della Formica (section 5.3). A Jurassic normal fault trending in a north-south direction between these two localities may be postulated, downthrown to the west. On the downthrown side of this structure, the Middle Tithonian Terratta Formation, in particular, forms an amalgamated calcirudite body of approximately 170 metres thickness. Figure 95 shows that, in a westward direction away from the structure, this formation forms much thinner discrete beds, suggesting a structural control over the spatial distribution of slope sediments during the Jurassic. Fault-controlled differential subsidence diminished during the Early Cretaceous deposition of the Maiolica Formation (Koopman, 1983), but some outcrops of Aptian to Maastrichtian age display apparent westward onlap relationships (Mt. Corvo, Pizzo Cefalone, figures 82, 95), accompanied by generally thinner-bedded, finer-grained sediments further west (compare the Cenomanian facies of Pizzo Intermesoli and Mt. Corvo, enclosure 1). These relationships could indicate that the Jurassic structure was again active during the Aptian to Maastrichtian stages of the Cretaceous. This Cretaceous tectonic activity would probably be minor (see section 6.7), and the widely cited Cretaceous "tectonic phases" of the Italian literature (Colacicchi *et al.*, 1978, Castellarin *et al.*, 1978, 1982, Baldanza *et al.*, 1982) could be attributed largely to other factors (section 5.9 and chapter 6).

5.9 Depositional Controls

In an effort to understand the temporal as well as spatial distribution of redeposited carbonates in the Gran Sasso, thin sections of samples from measured stratigraphic sections were analysed (see appendix 2 for details) and dated. Biostratigraphic work was carried out using planktonic foraminifera in thin sections, especially keeled *Rotalipora* sp. and *Globotruncana* sp.. Reworked benthonic foraminifera were also dated where present, and the close coincidence between ages obtained from the two groups confirmed the hypothesis that redeposition was dominantly penecontemporaneous in this area (see chapter 2). Calcareous nannofossils were also used to provide a further constraint on the ages of some samples, particularly nannofossil-bearing limestone samples.

Bearing in mind the important basic assumption of penecontemporaneous redeposition, the following sections will describe and discuss reasons for the temporal variations in redeposition in the Gran Sasso.

5.9.1 Bed thickness diagrams

In order to detect fining-upwards and coarsening-upwards trends in the sediments, the vertical sequences analysis method of Ricci-Lucchi (1975) for turbidite series was applied to measured sections (figure 96). By this method, the thickness of the "coarse fraction" (coarser than fine sand grade) of each turbidite bed was plotted sequentially. The coarse fraction only was used to filter out variable thicknesses of pelagic sediment between turbidite beds, which could have caused a great deal of uninterpretable "noise" in the record of redeposition. Fine sand grade was defined as the cut-off since it was impossible to distinguish muddy carbonate sediments with fine sand size grains from pelagic lime mudstones. The maximum grain-size of each turbidite bed was also plotted on the diagrams.

The diagram for Pizzo Intermesoli (figure 96d) shows a marked thickening-upward and coarsening-upward "trend" during the Late Albian. This ends abruptly at the

Albian-Cenomanian boundary to be succeeded by predominantly thinly-bedded facies during the Early Cenomanian. At the base of the *Rotalipora cushmani* zone (Middle Cenomanian) bed thickness increases suddenly then decreases gradually, accompanied by a coarsening upwards "trend". This is followed by further thickening and coarsening-upwards, again in the lower half of the *R. cushmani* zone.

A thickening-upward "trend" is also noticeable in the Late Albian of Pizzo Cefalone, although this is not accompanied by a similar coarsening-upward "trend". The Mt. Corvo II section shows a pronounced thickening and coarsening during the Late Maastrichtian (sediment-geometries described in section 5.7.2). Two kilometres further west on Mt. Corvo I section, (heavily affected by recrystallisation), Maastrichtian bed-thickness trends are more difficult to interpret, and do not suggest a marked thickening "trend" at the end of the Maastrichtian.

Clearly the bed-thickness plots, although they indicate some temporal variation in sedimentation character, are not reliably correlatable from section to section. The methodology of Ricci-Lucchi (1975) may not be helpful in this case since the carbonate slope-apron system does not display the same degree of order as the siliciclastic submarine-fan systems to which it was originally applied. The cycles of coarsening-upward turbidite beds, produced by progradation of inner-fan sediments over those of the outer fan, are not well developed in the carbonates observed in the Gran Sasso. Many complicating variables in the carbonate system, such as carbonate productivity, temperature, salinity, and early lithification (see chapter 1) as well as hydrodynamic differences (carbonate gravity-flows are generally low-efficiency flows, displaying erosional features in close proximity to depositional features, for example figure 82) are responsible for the apparent lack of organisation as depicted by the bed-thickness method. According to

Colacicchi and Baldanza (1986), carbonate gravity-flows in Scaglia limestones (Upper Cretaceous) are generally of lower volume then their siliciclastic counterparts, and cannot be traced for great distances laterally (this study suggests however that some flows can be traced for at least two to three kilometres), so some other criterion is needed in order to interpret the variations in redeposition through time.

5.9.2 Redeposition parameter

The field data obtained are not susceptible to standard statistical procedures, largely due to short-term variations in the thicknesses of lime mud in between turbidite beds. Such variations are of unknown cause, and occur over such a short time-duration that palaeontological dating is insufficiently precise to put a time-scale on them. Consequently, conventional filtering and power-spectral methods cannot be applied to the data. Instead, as a method of identifying times of enhanced redeposition into the basin, the parameter R_d/P was plotted sequentially against bed number for each section (figure 97), where R_d is the thickness of redeposited sediment (coarser than fine sand grade) in a particular bed, and P is the thickness of pelagic sediment in the same bed (fine sand and finer grades). For use of this parameter to be successful, it has to be assumed that the quantity P really represents pelagic sedimentation, or that the effects of erosion and redeposition of pelagic material will tend to cancel each other out.

By comparison of R_d/P and maximum grain size for each bed, it has been possible to identify "redeposition events" of enhanced redeposition from the measured sections. A redeposition event is defined here as being an occurrence of three or more consecutive beds with $R_d/P>0.8$ and maximum grain size of coarse sand or coarser on a Wentworth grain-size scale. Such events have the advantages that; (1) they can readily be identified from field data alone, (2) they filter out "noisy" data, relying on sequential behaviour, such that isolated occurrences such as individual turbidite beds are not considered, and only "major" events are picked out. Figure 98 summarises the main redeposition events identified in the Gran Sasso, along with the sections in which they were identified.

5.9.3 Timing of redeposition events

Using the method outlined in the previous section, it has been possible to identify several redeposition events from measured field sections. These events have been dated as closely as possible using planktonic foraminifera in thin sectin. Redeposition events have been dated as Late Aptian to Early Albian (Upper *G. algeriana* to *T. bejaouensis* zones), Late Albian (firstly, upper *R. ticinensis* zone and, secondly, between the *R. ticinensis* zone and the Albian/Cenomanian boundary), Middle Cenomanian (Lower *R. cushmani* zone), and twice in the Late Maastrichtian (the second event falling close to the Cretaceous/Tertiary boundary). If it is assumed that the rate of production of pelagic sediment (in the sense of section 5.8.2) remains approximately constant through the time intervals considered here, then it is possible to give an estimate for the position in time of a redeposition event, by measuring the proportion of the total thickness of pelagic sediment elapsed since the start of the interval of interest. This procedure may enable better resolution to be obtained than by palaeontological dating alone. By this method, the Middle Cenomanian redeposition event falls at 0.13 My above the base of the *R. cushmani* zone, giving an absolute age for the event (that is, the time at which redeposition is most pronounced) of 94.3 My (timescale of Haq *et al.*, 1987). The second of the two Late Albian events falls at 1.17 My above the Lower *R. ticinensis* zone, yielding an age of 95.6 My. The second of the two Maastrichtian events occurs 6.25 My above the base of the Maastrichtian, corresponding to an absolute age of 67.8 My (timescale of Haq *et al.*, 1987). It should be noticed that, by this method, both sections on Mt. Corvo contain two identifiable redeposition events, where correlation was difficult previously. However, the Middle Cenomanian event cannot be identified in Mt. Corvo I section, and this could indicate that the locus of deposition was further east due to palaeoslope topography (as discussed in section 5.7). The thick redeposited beds of the Early Aptian do not constitute a redeposition event as defined in this section, possibly serving as a reminder that the presence of "redeposition events" is merely a crude first approximation to identify the main inputs of redeposited sediment to the basin from field data. Despite this crudeness, there are several pointers to the true significance of such events, one of which is the enhancement in the visually-estimated proportion of reworked benthonic foraminifera (particularly *Orbitolina* sp.) in redeposited sediments during redeposition events (figure 96). This suggests that whatever process caused the events resulted in enhanced input of platform-derived grains into the basin in redeposited sediments. Other pointers to the nature and significance of redeposition events will be discussed in the next two sections and chapter 6.

5.9.3 Duration of redeposition events

It is clear from palaeontological dating of the section on Pizzo Intermesoli that the frequency of turbidite beds is highly variable (see section 5.6.4). For instance, 21 beds were recorded as being Late Albian in age (1.6 My from *R. ticinensis* zone onwards), compared to only 11 beds of Early Cenomanian age (1.5 My up to the base of the *R. cushmani* zone) and at least 16 beds in the lower half of the *R. cushmani* zone (0.95 My) in the Middle Cenomanian. The redeposition events of the Late Albian and Middle Cenomanian evidently occur at times of increased turbidite frequency, although it is difficult to ascertain how ~~how~~ much time they actually represent. In the strict definition of section 5.9.2, redeposition events occur in geologically very short time periods or instantaneously ~~of time~~, with little or no pelagic sediment deposited in between gravity-flow beds.

5.9.4 Significance of redeposition events

Slope sedimentation during the Cretaceous in the Apennines has been widely attributed to tectonic controls (Colacicchi *et al.*, 1978, Castellarin *et al.*, 1978, Chiocchini *et al.*, 1982, Colacicchi and Baldanza, 1986, Masse and Borgomano, 1987), and these cannot be ruled out as an important factor (see section 4.9), since numerous individual gravity-flows occur randomly throughout the Cretaceous sections in the Gran Sasso. However, such a randomly-operating control is unconvincing as an explanation for the repeated occurrence of redeposition events in the area, as defined in section 5.9.2. The explanation of enhanced redeposition by the action of numerous "weak" tectonic phases ("fasi tettoniche blandi" of the Italian literature) is also unconvincing in the light of the overall subsidence history of the region (chapter 6).

Other types of control over deposition may therefore be operating, such as fluctuations of relative sea-level. Indeed, such sea-level control has been suggested as having been responsible for the widespread Early Cenomanian bauxites of the southern Apennines (Carbone, 1984; section 6.5), and for gravity-flow deposition on the Gargano peninsula (Bosellini and Ferioli, 1988). Research into modern carbonate rimmed-shelves has shown that the maximum frequency of carbonate turbidites occurs during highstands of relative sea-level (Shanumugan and Moiola, 1984, Droxler and Schlager, 1985). The Cretaceous platforms of the southern Apennines can also be regarded as rimmed shelves, fringed by rudist buildups (chapter 1), which allows the thickening upward and coarsening upward trends of the Late Albian and Middle Cenomanian (section 5.9.2) with their accompanying increased turbidite frequency (section 5.9.3) to be interpreted as real features caused by rises in relative sea-level. For the case of the Cenomanian, this is consistent with data from the Latium-Abruzzo carbonate platform, where skeletal carbonate production resumed during the Middle Cenomanian after the hiatus of the Early Cenomanian with associated bauxite formation. The regional significance of the Cretaceous redeposition events identified in the Gran Sasso will be discussed further in Chapter 6.

5.9.5 Sediment geometries and redeposition events

Groups of beds associated with the main redeposition events of the Late Albian, Early Middle Cenomanian and Maastrichtian have downlapping (DLP; progradational) geometries (figures 82, 94). If the main control on deposition were eustatic (see section 6.4 for discussion), then a single cycle of sea-level would comprise a set of BDD, DLP and ONL geometries. One possible interpretation of these geometries which is consistent with what is known about rimmed shelf carbonate systems (section 6.4) would be that BDD mounded facies are deposited during sea level lowstands whilst the platform top is exposed, and this facies is covered by DLP progradational beds as excess sediment is transported off the carbonate platform during sea level rise. The cycle would be completed during the later stages of sea-level rise by sediments with ONL geometries. Although this is not proven to be the response of the carbonate system in the Gran Sasso, progradation during sea-level rise would explain the coarsening upward trends observed in Upper Albian and Middle Cenomanian sediments on Pizzo Intermesoli (section 5.8) and the increase in the proportion of reworked benthonic foraminifera in these same sediments.

If the BDD-DLP-ONL cycles really represent the sedimentary response to cycles of relative sea level, then they may be used to construct a chart showing the anticipated changes in relative sea level (figure 99). On comparison with the eustatic cycles of onlap-offlap of Haq *et al.*, (1987), it is apparent that it is predominantly the major supercycles of these authors which are represented in the basinal sediments of the Gran Sasso. However, for the Maastrichtian, three cycles of BDD-DLP-ONL were recognised from the Gran Sasso sediments, which correspond closely to the number and temporal distribution of onlap-offlap cycles predicted in the eustatic curve.

A further important piece of information which can be gained from the BDD-DLP-ONL cycles in the Gran Sasso if they are interpreted in this way is the influence of relative sea-level on depositional architecture. The laterally offset stacking of lenticular redeposited beds noted from the south face of Mt. Corvo (figure 82) represents a shift in the locus of maximum thickness of accumulation of calciturbidites on the slope. When the basal surface of the lenticular accumulation at the LHS of figure 82 is traced along the cliff face and out across the N-S trending face (figure 94), it is clear that it ~~is~~ belongs to the set of geometries BDD-DLP-ONL Maa 3, whereas the adjacent lenticular, amalgamated accumulation to the RHS (E) belongs to set Maa 2a. If relative sea-level change was the dominant depositional control, then the two lenticular packages must have been formed during different sea level cycles. The locus of thickest turbidite accumulation therefore must have changed as a response to a relative sea-level change. This change has significance whether lowstand or highstand progradation occurred. Since the LHS accumulation (DLP Maa 3) lies over BDD mounded facies, it is suggested that it may have been deposited during a sea-level rise.

By comparing the evidence for slope sediment geometries described in chapter 4 with the evidence presented above, a hierarchy of depositional geometries at different scales can be envisaged. At the smallest scale, internal sediment stacking geometries can be observed within individual groups of beds. In particular, these include amalgamation of turbidite beds and their accumulation within topographic lows on the palaeoslope within DLP groups, and stacking geometries within BDD mounded facies (see figure 82). The timescale of formation of these features is probably confined to part of a single relative sea-level cycle, and the geometries can be observed at a scale of 2-400 m. They therefore correspond to third-order features of Mutti and Normark (1987).

At the next scale of observation, vertical stacking patterns within the slope sediments (over a distance of 1-2 km) can be observed, in which turbidite accumulations seek topographic lows between mounded facies. This type of pattern develops over the time duration of a complete cycle of relative sea level. A still larger order of observation is found in the abandonment of one locus of sedimentation and the shift to a new depocentre on a scale of 3-5 km, leaving laterally offset packages of sediment, each comprising a single third-order sea-level cycle. Such a level of organisation might represent a complete stage or more and could correspond to the second-order features described by Mutti and Normark (1987). Finally, it was noted by inspection of the regional geological map in the Matese area (Carta Geologica d'Italia, f.161 Isernia) that the locus of thickest accummulation of slope sediment on a horizontal scale of approximately 10 km switched at least twice between the Middle Cretaceous and the Middle Eocene, or approximately once every 20-30 My. The scale of observation of this first-order turbidite complex (*sensu* Mutti and Normark, 1987) is of the order of 20-30 km along strike of the palaeoslope. The first (interpretable) slope sediment system to accumulate established in the ?Cenomanian (based on the dating shown on f.161) and lasted until the ?Late Campanian. From

?Late Campanian until the ?Early Eocene, the mapped slope sediments of the Frosolone area accumulated, to be replaced by a new slope sediment system in the ?Middle to Late Eocene. It therefore appears that the active life-span of any particular slope sediment accumulation, at least in the Matese area, was restricted to about 20-30 My. The causes of this largest-order change in the slope-sediment system are not clear. If the hierarchy suggested above is correct, they could perhaps be related to second-order eustatic sea-level fluctuations, although the cause of these variations is itself still a matter of debate. It should be noted that, although a locus of maximum sediment accumulation can be identified, deposition was continuous along the whole length of the slope adjacent to the carbonate platform, and the system ~~therefore~~ may therefore constitiute a carbonate slope apron (*sensu* Mullins and Cook, 1986).

Chapter 6:
Controls on southern Apennine platform-margin anatomy: A synthesis in the framework of the western Tethys Ocean.

6.1 Introduction

This chapter will begin by discussing the sedimentological development of the carbonate platform-margins in southern Italy, summarising data from chapters one to five, and placing this in the context of similar data reported by other authors. The main theme to be developed is an assessment of the likely role played by relative fluctuations of sea-level in controlling lithofacies patterns on the margins.

One of the main aims of Working Group One of the Global Sedimentary Geology Program (GSGP) is "to test the concept that medium and small-scale sequences recorded globally synchronous fluctuations in sea level" by establishing a global network of outcrops and seismic lines. Initially, the project is focussed on the Cretaceous geological record. The second goal of this chapter, then, is to provide data working towards the use of southern Italian outcrops in such a global database. The record of sea-level fluctuations in the southern Apennines has received very little attention until now, and it is hoped to stimulate such work in the future, using a sequence stratigraphic framework by presenting a tentative sequence stratigraphy for the Middle Cretaceous of the region.

The final theme to be developed is that of the overall subsidence histories of the carbonate platforms. Many papers have proposed an extensional tectonic setting for the southern margin of the Tethys Ocean during the Jurassic (for example, Bernoulli and Jenkyns, 1974), but few papers have attempted to quantify the subsidence histories of the platforms from the stratigraphic data available. D'Argenio and Alvarez (1980) made such an attempt, and were able to demonstrate crustal thinning in the region by applying the now little-used "lateral creep" mechanism of Bott (1971, 1973). Ten more years of published stratigraphic data, refined geological timescales, and the widespread use of backstripping techniques in describing crustal subsidence histories have prompted the development here of a first-order model to demonstrate the subsidence of the southern Apennine platforms. The proposed subsidence histories will finally be discussed in the context of current concepts of extensional tectonics, in order to understand better the significance of the many "tectonic phases" proposed in the literature on the region.

6.2 Apennine redeposition

6.2.1 The Gargano Peninsula

The Gargano was initially studied by Pavan and Pirini (1965) during the production of the second edition of Foglio 157 (Monte S. Angelo) of the Carta Geologica d'Italia. The mapping revealed the presence of facies pertaining to carbonate platform, slope, and basin (figure 100a). However, the platform formations recognised were dated as Late Jurassic, whilst those formations belonging to the palaeoslope and basin were dated as Early Cretaceous to Early Tertiary. This basic lack of correlation between the platform and basin domains was overcome by Luperto Sinni and Masse (1984, 1986, 1987) (figure 100b) who demonstrated by detailed palaeontological work the coeval nature of the S. Giovanni Rotondo limestones (platform), Mattinata limestones (slope) and the limestones of Vico del Gargano (basin) during the Early Cretaceous. This was followed by further studies dating the slope sediments, subdivided into the Mattinata limestones (Barremian to Albian), Monte S. Angelo limestones (Cenomanian to Lower Turonian), Navarra limestones (Coniacian to Santonian), Caramanica limestones (Campanian to Palaeocene) and the

Peschici limestones (Eocene) (Masse and Borgomano, 1987; Luperto Sinni *et al.*, 1988). Masse and Borgomano (1987) related the Cretaceous development of the platform-margin to variable amounts of tectonic activity along an east-west trending master-fault, whilst Bosellini and Ferioli (1988) and Bosellini (1989) preferred to account for the sediment-geometries in terms of "catastrophic" processes operating in response to major eustatic events. In particular, Bosellini (1989) interpreted the Monte S. Angelo limestones as constituting a Lower Turonian lowstand wedge (*sensu* Haq *et al.*, 1987). The regional evidence for such a relative sea-level event at the base of the Turonian is the presence of a regional emersion surface on the platforms, with associated bauxite horizons (Crescenti and Vighi, 1970, Istituto di Geologia e Geofisica Università di Napoli, 1978), and this is correlated with an pronounced lowstand interpreted from the relative sea-level curves of Haq *et al.*, (1987). However, study of the Cretaceous succession exposed on the s.s.272 (km 64-66) from Manfredonia to Monte. S. Angelo (enclosure 1), has revealed a four metre thick section of pelagic chalk, laid down in the area of the inferred regional palaeoslope during the ?Early Cenomanian, prior to the onset of deposition of the Mt. S. Angelo limestone in the ?Early Middle Cenomanian. The chalk may suggest a pause in the supply of redeposited carbonates on the margin during the Early Cenomanian. A redeposition event (*sensu* section 5.8.2) of Middle Cenomanian age has been identified from the section by plotting the values of the redeposition parameter (see section 5.9). The Cenomanian to ?Lower Turonian redeposited limestones are overlain by a very thin series of beds including approximately 20 metres of chalk, attributed to the Middle-Late Turonian hiatus on the slope documented by Masse and Borgomano (1987). The chalk section is in turn overlain by redeposited carbonates dated as Latest Turonian to Early Coniacian.

The Cenomanian commencement of deposition of the Monte S. Angelo limestone is in agreement with the dating of Masse and Borgomano (1987), and provides a more regionally consistent picture if the Middle Cenomanian redeposition event on the Gargano is correlated with the event of the same age identified in the Gran Sasso. Although several workers have dated the bauxite horizon on the Apulian platform as Turonian in age (Crescenti and Vighi, 1970, Bárdossy *et al*, 1977, D'Argenio *et al.*, 1986a, Masse and Borgomano, 1987), this does not rule out additionally the possibility of an important emersion of Early Cenomanian age on the Apulian platform. Many Cenomanian bauxite occurrences have been documented in the southern Apennines (Accarie and Beaudoin, 1988, Praturlon and Sirna, 1976, Chiocchini and Mancinelli, 1977). The low sedimentation rates during the Early Cenomanian in the Gran Sasso also add indirect evidence to the argument for Early Cenomanian platform exposure (see section 6.5).

During the Early Turonian, however, relative sea-level is generally interpreted to have reached one of its highest stands of the whole Phanerozoic (Kaufmann, 1977; Vail *et al.*, 1977; Jenkyns, 1985; Haq *et al.*, 1987; but see section 6.7.3). The idea of a lowstand wedge during a time when sea-level was rising according to most relative sea-level curves (for example, Haq *et al.*, 1987) seems unlikely. No lowstand is recorded during the Early Turonian by Haq *et al.*, (1987) as reported by Bosellini and Ferioli, (1988) and Bosellini (1989).

In conclusion, redeposition on the Gargano peninsula was heightened during the Middle Cenomanian, whilst little redeposition took place during the Early Cenomanian and Middle and Late Turonian. Relative sea-level fluctuations may have exerted an influence on the margin (see section 6.6, 6.7.4), whilst syndepositional tectonics cannot be ruled out as an important factor in the long-term (section 6.7).

6.2.2 Maiella Mountains and Marsica

The Maiella Mountains of eastern Abruzzo (figure 5) were the subject of stratigraphic studies by Crescenti *et al.*, (1969). These authors identified the presence of an intact platform-margin, active during the Late Cretaceous. Accarie (1987) and Accarie and Beaudoin (1988) expanded this picture by dating the onlapping redeposited carbonates which overlie Lower to lower Upper Cretaceous platform carbonates above a high-angle unconformity, interpreted as a "palaeofault" surface by Accarie (1987). Redeposition is documented on this margin in the Early Middle Cenomanian following the bauxitiferous hiatus that spans the Middle Albian to Early Cenomanian (inclusive) (see sections 6.3.2, 6.5).

The Marsica region of western Abruzzo has been extensively studied by Colacicchi (1964), Colacicchi and Praturlon (1965a-b) and Colacicchi *et al.*, (1978). Two major depositional supercycles were recognised from the Cretaceous of Marsica by Colacicchi *et al.*, (1978): The first from Neocomian to Cenomanian, and the second from ?Late Cenomanian to Maastrichtian. The former cycle, of slow retreat followed by rapid progradation of the outer shelf, was apparently interrupted by a tectonic event which caused general exposure of the platform and sudden drowning of the eastern (seaward) part of the shelf-edge. The margin shifted westward (shelfwards) by more than ten kilometres after this event. The latter cycle of slow retreat followed by rapid progradation was also interrupted, according to Colacicchi *et al.*, (1978), by the Maastrichtian "tectonic phase", which caused exposure of the platform and drowning of various marginal blocks. Large rockfalls ("megabreccias") were apparently sourced along a master-fault bounding the margin.

Clearly, the sea-level trends used for discussion and comparison by Colacicchi *et al.*, (1978) correspond to the second-order cycles of Haq *et al.*, (1987). Third order sea-level cyclicity was not considered by these authors, although it was discussed by Colacicchi (1987). The evolution of the Marsica margin will be reviewed in the light of evidence for third-order sea-level cycles in sections 6.3 and 6.5.

6.2.3 The Northern Apennines

The carbonate sediments of the northern Apennines are generally considered to have been formed in a deep-water basin (Early Jurassic to Oligocene) developed on thinned continental crust (Bortolotti *et al.*, 1970; Centamore *et al.*, 1980) during a phase of rapid subsidence characterised by block-faulting (Crescenti *et al.*, 1969; Colacicchi *et al.*, 1970; Centamore *et al.*, 1971; Coltorti and Bosellini, 1980; Bice and Stewart, 1985). During the Middle Jurassic to Neocomian, in common with the southern Apennines (section 5.2), regional subsidence is thought to have taken place, and deep-water carbonate sedimentation filled in the irregular pre-existing topography (Cardellini, 1982; Lowrie and Alvarez, 1984). The Aptian to Cenomanian was apparently tectonically quiescent (Montanari *et al.*, 1989), and characterised by rhythmic pelagic deposition in a flat-floored basin (Schwarzacher and Fischer, 1982; De Boer, 1983; Herbert and Fischer, 1985; Montanari, 1985). This apparent tectonic quiescence suggests that any record in the sediment relating to sea-level fluctuations in the region should be particularly clear during these stages (see sections 6.3, 6.4, 6.5, 6.6). From the Early Turonian to Oligocene, however, sedimentary facies and palaeocurrent analyses led Montanari *et al.*, (1989) to the conclusion that new intrabasinal depocentres and structural highs had formed in response to renewed extensional tectonic movements. These authors related conspicuous sedimentary events, such as maxima in turbidite deposition and soft-sediment slumps in the intrabasinal depocentres, to major syndepositional earthquakes of regional extent. Such events are reported to have occurred during the Early Turonian (slump), Coniacian (slump) to Santonian (slump and turbidites), Early Campanian (slump and turbidites), "Middle" Maastrichtian (polarity zone 31R, *G. gansseri* zone; slump and turbidites), Late Danian (slump), Thanetian (slump and turbidites) and Ypresian (slump). The possibility of renewed extensional tectonism in the Apennines during the Late Cretaceous will be discussed in section 6.7.

6.2.4 Tectonic and eustatic controls on carbonate sedimentation

Four major variables control the variation in stratal patterns and lithofacies distributions within carbonate rocks. These include (1) tectonic subsidence, which creates the space where the sediments are deposited; (2) eustatic changes, argued by Vail and Todd (1981) to be the major control over stratal patterns and the distribution of lithofacies; (3) the volume of sediments, which controls palaeo-water depth; and (4) climate, which controls the type of sediments (carbonates are restricted to areas with specific temperature and salinity ranges).

The combination of eustasy and tectonic subsidence produces a relative change of sea level (figure 101). Sarg (1988) states that tectonic subsidence (shown as a linear plot in figure 101) changes slowly with respect to eustasy. The relative change of sea level creates the available space for accomodation of sediments. The thickness of sediments, however, is primarily controlled by tectonic subsidence. Depositional stratal patterns and lithofacies distribution are controlled by the rate of change of sea level. This is expressed by the change of slope of the relative sea-level curve, which is primarily controlled by eustasy (figure 101).

It follows that the major controls on carbonate productivity, platform growth, and facies distribution are short-term eustatic changes superimposed on longer term tectonic changes (i.e. relative changes in sea level). One example of this relationship is given by Hesselbo *et al.*, (in press), from the Wessex basin (U.K.), where candidate sequence boundaries cross the various crustal blocks and are recognisable even during times of relatively rapid crustal extension.

Carbonate platforms associated with sea-level highstands are characterised by relatively thick aggradational-to-progradational geometry, according to Sarg (1988; see section 6.3.1), and can be divided into two types; (1) the *keep-up* carbonate highstand platform, which is interpreted to represent a relatively rapid rate of accumulation that is able to keep pace with periodic rises in relative sea level. Such a platform has a margin characterised by grain-rich, mud-poor lithofacies and non-pervasive submarine cementation; and (2) the *catch-up* carbonate highstand platform, interpreted to represent a relatively slow rate of accumulation that is characterised by micrite-rich parasequences and pervasive early submarine cementation at the platform margin.

Although the progradational geometries of Tethyan carbonate platforms are generally poorly observable (but see Bosellini, 1984; Goldhammer and Harris, 1989), outcrop studies can reveal lithofacies details (chapter 3) and isolate surfaces relating to sea-level excursions. The evidence for such excursions in the southern Apennines is presented in the following sections. The subsidence histories of Apennine platforms will be discussed in section 6.7.

6.3 Cretaceous relative sea-level record

6.3.1 Introduction

Numerous studies have documented the high potential of platform carbonates to record sea-level fluctuations of different orders (Kendall and Schlager, 1981; Read *et al.*, 1986; Sarg and Lehmann, 1986; Grotzinger, 1986). Eberli and Ginsburg (1989) took this concept a stage further by using the onlap/offlap pattern of prograding sequences (formed during the post-Oligocene lateral accretion of Great

Bahama Bank; Eberli and Ginsburg, 1987) for a sequence stratigraphic analysis, and compared it with the eustatic curve developed in the siliciclastic environment (Vail *et al.*, 1977; Haq *et al.*, 1987).

Many studies have suggested, however, that the carbonate environment responds differently to sea-level fluctuations than the siliciclastic environment. Sediment is exported at different stands of sea level into deeper water in the two environments, resulting in the occurrence of basinal fill at different times (Kier and Pilkey, 1971; Mullins, 1983a; Boardmann and Neumann, 1984; Droxler and Schlager, 1985; Austin *et al.*, 1986).

Eberli and Ginsburg (1989) considered for their sequence analysis the onlap/offlap pattern of the prograding sequences along the platform edge rather than the basinal unconformities. The analysis was based on the assumption that the progressive onlapping reflections seen in the seismic record of Great Bahama Bank were produced during a relative rise and highstand of sea-level. The global curve of coastal onlap monitors the progressive encroachment of the coastal deposits and is similarly the record of a relative rise and highstand of sea level (Vail *et al.*, 1977; Haq *et al.*, 1987). Therefore, the two curves can be argued to be the result of the same events and can be correlated.

Correlation of the two curves showed that the two major systems present in the prograding sequences were time equivalent with the youngest supercycle set TEJAS B of Haq *et al.*, (1987). In addition, the number of sequences matched nearly completely the global chart (Haq *et al.*, 1987). The sequence analysis therefore suggested that individual sequences are the result of third-order sea-level fluctuations, and bundles of sequences represent second-order cycles. These results suggested to Eberli and Ginsburg (1989) that sea-level fluctuations are the primary control producing pulses of progradation of the carbonate platform.

Following this line of reasoning, off-bank sediment transport into the deeper basin environment should peak during major episodes of progradation of the carbonate platform. The age of the redeposited sediments resulting from such episodes would give the timing of the major sea-level rises and highstands which postdate major sea-level falls. In order to evaluate the applicability of the processes documented by Eberli and Ginsburg (1989) to the southern Apennine geological record of platform-margin sedimentation, the biostratigraphically determined ages of redeposition events identified in section 5.9.2 have been compared with the eustatic curve of Haq *et al.*, (1987) (figure 98).

6.3.2 Middle Cenomanian

The best dated redeposition event in the southern Apennines is that of the Middle Cenomanian, which falls within the lower half of the *R. cushmani* zone (due to the co-occurrence of *R. cushmani* and *R. appenninica*). This zone commenced at 94.4 My (timescale of Haq *et al.*, 1987) and the lower half of the zone spanned 0.95 My ending at 93.5 My. The major eustatic sequence boundary of the Middle Cenomanian (Haq *et al.*, 1987) therefore falls within the possible period of occurrence of this redeposition event as dated by planktonic foraminifera. This is not thought to necessarily imply lowstand shedding of sediment from the platform however, since major eustatic sea-level falls are also followed by major rises. It is during these rises that carbonate sediments are most likely to be exported into basins in maximal volumes (see above). Since it is not possible to constrain Apennine redeposition palaeontologically to a particular part of any given sea-level cycle, it is important to take into account other evidence (such as sediment geometries) which may provide clues as to the stage of sea-level. Downlapping sediment geometries of this age (section 5.7.1; figures 82, 90) in the Gran Sasso, coupled with a coarsening upwards bed thickness trend and an increase in the proportion of reworked benthonic foraminifera (section 5.8), as well as subsidence considerations (section 6.7.3) suggest that the redeposition event may have taken place during the major sea level rise which would postdate the postulated global sequence boundary of Haq *et al.*, (1987). In order to place the evidence from the Gran Sasso in context, the worldwide evidence for sea level change during the Middle Cenomanian will briefly be reviewed here.

Scott *et al.*, (1988) recognised an intra-Cenomanian sea level rise by making a correlation of three surface and subsurface sections of Lower Cretaceous strata from the Gulf Coast with three comparable sections in Oman. Two events of relative sea-level rise were found to be synchronous in the Gulf Coast basin and the southwestern Arabian platform, and were therefore suggested to represent possible eustatic sea-level rises. One of them, the intra-Cenomanian rise, began at approximately 94.6 My (timescale of Kent and Gradstein, 1985; 93.8 My, timescale of Haq *et al.*, 1987). In Oman, this rise is locally represented by a submarine hardground that formed after drowning of a carbonate shelf (an example of a drowning unconformity, *sensu* Schlager, 1989). In the updip Gulf Coast, mid-Cenomanian paralic and deltaic sediments were deposited upon an Albian-Early Cenomanian shallow carbonate shelf. (In the updip Gulf Coast, the event may be represented by drowning of shallow-water carbonates). A deepening event of Middle Cenomanian age has also been recorded from the Wessex basin (U.K.). In this locality, a Middle Cenomanian "non-sequence" is found at the top of the *Orbirhynchia mantelliana* band (in the *Turrilites costatus* zone of Kennedy, 1969, in Carter and Hart, 1977; Hart, 1980). Sea-level rise in the north Atlantic region has been proposed by Hart and Tarling (1974) during the Middle Cenomanian. Hart

(1980) correlated a mid-Cretaceous sea-level curve by comparing planktonic foraminiferal zones (Robasynski and Caron, 1979) from SE England, SW England, Bornholm, Galicia Bank (DSDP Site 398), Orphan Knoll (DSDP Site 111/111A), Falkland Plateau (DSDP Site 327A), Eastern Indian Ocean (DSDP Site 258) and the Central Pacific (DSDP Site 310A). A good correlation of events in the mid-Cenomanian and Early Turonian was produced. The *Rotalipora cushmani* zone was absent almost worldwide in these deep marine sections, and this hiatus was attributed to a global rise in sea-level during the mid- to Late Cenomanian.

Scott *et al.*, (1988) compared the results of their studies with other published relative sea-level curves for the Early Cretaceous. These include the curves of Kauffmann (1977, 1984), which relate transgressive-regressive cycles with eustatic sea-level changes and periods of intense vulcanism in the Western Interior of the United States, the curves of Vail *et al.*, (1977), which illustrate relative coastal onlap of seismic sequences rather than eustatic curves (Pitman, 1978); the curves of Caldwell, (1984), for the Canadian interior, and of McFarlon (1977) for the Gulf Coast, which were indicated as transgressive-regressive events that only indirectly relate to sea level; and other curves based on water depth from which sea-level changes may be inferred (Rey, 1982; Harris *et al.*, 1984; Longoria, 1984; Flexer *et al.*, 1986). All of these curves show a Late Albian sea-level rise followed by an Early Cenomanian fall. This in turn is followed by sea-level rise during the Middle to Late Cenomanian.

The worldwide examples presented above suggest that the Middle Cenomanian redeposition event recorded in the Gran Sasso sediments can be related to an important eustatic rise in sea level. However, since palaeontological resolution is not sufficient to constrain the redeposition event to a single stage of sea level, and since the sediments cannot in this case be directly traced onto an adjacent carbonate platform, it is not possible to rule out all other alternatives.

In section 6.2.1 the same event was postulated from Early Middle Cenomanian sediments of the Gargano Peninsula. In section 6.2.2 it was noted that redeposition (and by inference, progradation of the platform-margin) commenced in the Early Middle Cenomanian in the Maiella mountains of Eastern Abruzzo (Accarie, 1987; Accarie and Beaudoin, 1988). Retreat of the shelf-edge in Marsica took place during the ?Early Cenomanian (section 6.2.3), and was followed by a new cycle of shelf progradation, previously related by Colacicchi *et al.*, (1978) to a tectonic phase, but by comparison with other areas, it is related here to third-order sea-level cyclicity. (As noted in section 6.2.2, Colacicchi (1987) depicted third order sea level trends for Marsica, but showed differing trends for the inner platform and platform margin during the Middle Cretaceous, and used this result to invoke syndepositional tectonics. Since supposed third-order sea-level trends have to be the same across the complete area, the data presented by Colacicchi (1987) are regarded with caution and the present discussion is based on the data of Colacicchi *et al.*, (1978)).

Schlager (1989) has recently reinterpreted the Mid-Cretaceous unconformity in the Gulf of Mexico, assigned a Cenomanian age by "jump correlation", as a drowning unconformity, in contrast to earlier work by Buffler *et al.*, (1980) who interpreted this surface as a lowstand unconformity. This drowning event was the result of a relative sea-level rise following a major sea-level fall. Such a rise may also have led to the mid-Cretaceous drowning of parts of the southern Apennine platforms (for instance the apparent step-back of the margin reported from Marsica by Colacicchi *et al.*, 1978).

The correlation of the Middle Cenomanian redeposition event of the S. Apennines with a eustatic sea-level rise explains also the observations of Carbone (1984) and others that outer shelf sediments began to prograde seawards, and shelfward into the shelf lagoon, commencing in the Cenomanian, following the main bauxitiferous unconformity of the Middle Cenomanian on the S. Apennine platforms. However, the situation in the southern Apennines may be more complex than the evidence for a straightforward sea-level rise, given above, suggests. Many platforms around the world for instance parts of the Bahamian platforms and those in the Gulf of Mexico (Austin *et al.*, 1986) drowned terminally during the major sea level change of the Middle Cretaceous, In contrast, platforms in the southern Apennines underwent minor drowning and emersion episodes prior to re-establishment in the Late Cretaceous and Early Tertiary. This could suggest that the growth and development of southern Apennine platforms was affected by their local tectonic environment, a hypothesis which will be pursued in section 6.7.

6.3.3 Late Maastrichtian

The second redeposition event identified from the Maastrichtian stage in the Gran Sasso lies close to the Cretaceous-Tertiary boundary. In the Gran Sasso, three thick redeposited beds (locally amalgamated; section 5.6.2) were laid down at this time, and these were succeeded by pelagic sediments during the Early Paleocene. In the Matese mountains, the Cretaceous-Tertiary boundary is represented by a thick redeposited bed (MT2), overlain by Lower Eocene foraminiferal grainstones (Frosolone, Morgia Quadra section, figure 19). The Paleocene is either present as a thin pelagic section or locally absent.

Elsewhere in the S. Apennines, the Maastrichtian record is characterised by redeposition of bioclastic and/or lithoclastic gravity-flow deposits, commonly poorly dateable. In the Maiella mountains of eastern Abruzzo, progradation of bioclastic redeposited sediments occurred shelfwards and basinwards during the Maastrichtian. These sediments were succeeded by argillaceous pelagic sediments during the Early Paleocene in the basin (Accarie, 1987). In the Marsica region, megabreccias of Late Maastrichtian age were reported by Colacicchi *et al.*, (1978), apparently associated with exposure and drowning of some parts of the platform and drowning of other parts (section 6.2.3).

The eustatic curve of Haq *et al.*, (1987) depicts a major sea-level fall in the latest Maastrichtian, followed by a sea-level rise which continued into the Early Paleocene. In a study of Late Cretaceous sea-level changes of New Jersey, Olsson (1988) used palaeoslope models of foraminifera to produce a local sequence stratigraphy. Olsson identified the same sea-level trends as found in sequence TAI.2 of Haq *et al.*, (1987), his proposed sequence extending from the uppermost Cretaceous (*Abathomphalus mayaroensis* zone) into the Early Paleocene (P1 zone). In New Jersey, the greensand of the Hornerstown Formation unconformably overlies a spheroidally weathered surface of the Tinton formation, and a burrowed surface of the New Eygpt Formation.

Donovan *et al.*, (1988) studied the sequence stratigraphy of the K-T transition in the Clayton Formation of Central Alabama, which overlies a sequence boundary, marked by regional truncation of the underlying Prairie Bluff Formation. This sequence boundary was related by these authors to a major eustatic fall in the Late Maastrichtian (67 My, timescale of Haq *et al.*, 1987). The interbedded sandstones and limestones in the Clayton Formation were interpreted as two backstepping marine parasequences deposited on the inner shelf during the subsequent relative rise in sea level. Three iridium anomalies occurred at marine flooding surfaces (interpreted parasequence boundaries) spanning the Late Maastrichtian to Earliest Paleocene in the uppermost Prairie Bluff and basal Clayton Formations.

Donovan *et al.*, (1988) argued for the effectiveness of sea-level changes on the deeper marine record across the K-T boundary, a factor largely discounted by Alvarez *et al.*, (1982). The major eustatic fall in the latest Maastrichtian, marked by the withdrawal of epicontinental seas throughout the globe (Grabau, 1940; Dott and Batten, 1981) and the subsequent eustatic rise had a tremendous effect on global depositional patterns.

In conclusion, we may surmise that the worldwide geological record across the K-T boundary records the effects of an important rise in sea-level. This rise could be the most effective factor which triggered the Late Maastrichtian redeposition event of the southern Apennines.

The comparison of redeposition events in the southern Apennines with eustatic events suggests that a set of onlap-offlap curves (similar to those produced by Eberli and Ginsburg, 1989, for the post-Oligocene sediments of Great Bahama Bank) could be produced from suitable exposures in the S. Apennines in order to test the hypothesis that eustatic sea-level fluctuations also produced pulses of progradation of carbonate platforms worldwide during Cretaceous time.

6.4 Evidence for other sea-level changes

Other field localities in the S. Apennines have yielded data which may be relevant to the hypothesis of sea-level control over carbonate platform sedimentation, although some dated sedimentological features have few available analogous comparisons in the literature on the region. It is felt that the following sections will begin to fill this gap in documentation and interpretation of the sedimentation histories of the Italian platforms.

6.4.1 Umbria pelagic sequence

In a measured section on Mt. Terminilletto (not presented here; Rieti Mts., Umbrian pelagic sequence) two notable bioclastic redeposited beds can be singled out (stratigraphic details are reported in Cantelli *et al.*, (1978). The first of these occurs at the base of the Bathonian to Tithonian section ("calcari selciferi e selci").

The Early Bathonian was a time of relative sea-level rise and highstand following a sea-level fall in the Late Bajocian, according to Haq *et al.*, (1987). A deepening event of Early Bathonian age is also reported by Hallam (1988), recognisable in S. England, the North Sea, NW France, and the Western Interior of the United States. By inference from the hypothesis of Eberli and Ginsburg (1989, see section 6.3.1) it may be supposed that the relative sea-level rise of this age triggered the redeposition of skeletal carbonate sediments into the deep basin, during the progradation of the western edge of the Latium-Abruzzo carbonate platform. Subsequent redeposited beds in this part of the section are characteristically composed of oolite, a common feature of the Tethyan Dogger (Bosellini, 1989). The second well-constrained redeposited bed occurs at the base of the Maiolica Formation, dated as Tithonian by Cantelli *et al.*, (1978). In the overlying ten metres, beds contain associations of *Calpionella alpina* and *C. elliptica* of Tithonian-Berriasian and Early Berriasian age.

The Tithonian-Berriasian boundary is marked by a major sequence boundary, followed by a sea-level rise during the Early Berriasian, on the eustatic curve of Haq *et al.*, (1987). Hallam (1988) also records a global deepening event from the Late Tithonian of eastern and southern England, Poland, the Russian platform, Chile and Argentina. Here again it is possible that redeposition coincided with a deepening of sea-level.

6.4.2 Aptian of the Gran Sasso

The Lower Aptian in the Gran Sasso is marked out by a very abrupt change from Maoilica nannofossil-bearing limestones of Late Tithonian to Early Aptian age to Lower Aptian bioclastic gravity-flow deposits (section 2.4.3). It is suggested that the Early Aptian was a time of progradation of the platform-margin and oversteepening of the palaeoslope, since the entire series (50 m) is affected by a translational glide sheet on Pizzo Cefalone (section 5.5.3). On Pizzo Intermesoli, the presence of chaotic, presumably slumped, facies, of Early Aptian age was observed in contact with the Maiolica formation.*

The earliest sediments dated one metre above the top of the glide sheet on Pizzo Cefalone belong to the *G. algeriana* zone. This suggests that there may have been a hiatus and/or very slow deposition during the latest Early Aptian to the *G. algeriana* zone. Finally, the Upper Aptian to Lower Albian sediments record another redeposition event (section 5.9.2).

Comparing the sediments with the eustatic curve of Haq *et al.*, (1987), a major type 1 sequence boundary falls in the earliest Aptian, followed by a sea-level rise which could have triggered redeposition. This is succeeded in the late Early Aptian to early Late Aptian by a highstand of sea level, during which slow sedimentation would be expected. Finally, at the base of the *G. algeriana* zone on the eustatic curve, a further sea-level fall (sequence boundary) was succeeded by another deepening of sea level, continuing into the earliest Albian. In this example, the sedimentological patterns observed are explained by changes in sea level in a manner consistent with the current knowledge of carbonate-platform responses (Droxler and Schlager, 1985; Austin *et al.*, 1986; Eberli and Ginsburg, 1989).

Scott *et al.*, (1988, section 6.2.1) proposed an intra-Aptian rise in sea-level commencing at 115.8 My (timescale of Kent and Gradstein, 1985; 110.3 My, timescale of Haq *et al.*, (1987). This rise would occur during the time-period of slow pelagic deposition between the Lower and Upper Aptian redeposited series. The conflict

* Similar slumped facies, with a sole surface at the top of the Maiolica Formation are reported from other areas in the Apennines (Arthur and Premoli-Silva, 1982; Bernoulli, pers. comm., 1990).

between the supposed eustatic events of Haq *et al.*, (1987) and Scott *et al.*, (1988) could imply that the sea-level events proposed have only regional significance. (It could also imply that one or both timescales used are incorrect). If the curve of Haq *et al.*, (1987) is correct, then the response of the carbonate system to sea-level change is as would be predicted (i.e. progradation during sea-level rise). The fact that the supposed eustatic events of Haq *et al.*, (1987) rather than the rise proposed by Scott *et al.*, (1988) are more consistent with the local sedimentary record would suggest that the database of Haq *et al.*, (1987) is more weighted towards Western Europe (and may be applicable even in the Tethyan realm), whilst the database of Scott *et al.*, (1988) is derived from the Gulf Coast and Oman. However, if Scott and others assertion of a eustatic rise at 110.3 My is correct, this would imply that the carbonate response in the Gran Sasso is apparently one of slow pelagic sedimentation during a major rise in sea level, a result which is in contrast to other examples discussed here (sections 6.3.1, 6.3.2, 6.3.3, 6.4.1) and elsewhere (Droxler and Schlager, 1985; Eberli and Ginsburg, 1989, for example). The reason for this apparent discrepancy may be partly a function of the distance from the platform to the study area (lower slope). Only a small proportion or no sea-level changes might be expected to affect sedimentation in such relatively basinal settings.

Hallam (1988) has made the point that some sea level excursions during the Jurassic appear to have only regional significance, and this may well be the case during the Aptian as discussed above. This points again to the database used by Haq *et al.*, (1987) being weighted towards particular regions (W. Europe and N. America), rather than having eustatic significance.

6.4.3 Late Albian of the Gran Sasso

The late Albian redeposition event identified in the Gran Sasso (section 5.9.2) took place in the upper *R. ticinensis* zone (i.e. *R. ticinensis* + *Planimolina buxtofi* zone), which lasted from 97.5-97.2 My (timescale of Haq *et al.*, 1987; commencing at 99.5 My, timescale of Kent and Gradstein, 1985). The event falls in coincidence with a transgressive systems tract on the eustatic curve of Haq *et al.*, (1987), during which sea level rose following the major type 1 sequence boundary at the base of the *R. ticinensis* zone (98 My). In section 6.4.2 it was stated that most published global sea level curves show relative deepening during the Late Albian, providing some consistency amongst the data of various groups regarding this stage.

There appear to be two redeposition events recorded from the Late Albian of the Gran Sasso (section 5.9), which, if they could be separately resolved palaeontologically (rather than from redeposition parameter/bed thickness plots), may correspond to the two sequences identified in the supposed global coastal onlap data of Haq *et al.*, (1987). The first event is very precisely dated (see above) and adds strength to the hypothesis that major pulses of carbonate platform progradation occurred during relative sea-level rises.

Other relevant data from the S. Apennines is very sparse, although Masse and Borgomano (1987) mention a change from bioclastic to breccia type redeposition on the eastern margin of the Gargano during the Latest Albian. These deposits include lithoclasts of Berriasian age (see discussion in section 3.2.2). Some clasts are reported by these authors to display examples of vadose diagenesis, suggesting that at times during the Aptian-Albian the shelf-edge was exposed subaerially. The change in style of sedimentation at the end of the Albian is attributed by Masse and Borgomano (1987) to intensified tectonic activity, rather than sea level change.

6.5 S. Apennine carbonate platforms

Important evidence of relative sea level change is provided by the Middle Cretaceous bauxite horizons, widespread in the southern Apennines from Latium-Abruzzo in the north to Caserta (Campania) in the south. The age of the bauxites is generally between Albian and Turonian (Catenacci *et al.*, 1963; Crescenti, 1969a; Crescenti and Vighi, 1970; Sartoni and Crescenti, 1962; Sartoni and Colalongo, 1964), but a good deal of local variation has been reported (figure 102). On the western side of the (Apennine) Abruzzi-Campania platform, the bauxite horizon is intra-Cenomanian, although an additional smaller-scale hiatus occurred close to the Cenomanian-Turonian boundary (Bárdossy *et al.*, 1977; D'Argenio *et al.*, 1986a). On the eastern side of the platform, however, a single stratigraphic gap occurs, purportedly continuous from Albian to Turonian (or Early Senonian) (D'Argenio, 1963, 1970). The stratigraphic gap on the Maiella platform was thought to have a similar duration by D'Argenio *et al.*, (1986a), whereas a minimum gap lasting from Earliest Middle Albian to Early Middle Cenomanian was reported by Accarie (1987). A second, clayey level, above the bauxites in the Maiella has been found by Catenacci (1963), possibly relating to a brief emersion. Bauxite from the Apulian platform has been dated as ?Upper Cenomanian to Turonian (Bárdossy *et al.*, 1977; Crescenti and Vighi, 1970). A main bauxitiferous emersion horizon is overlain by a younger, more argillaceous level, related to a briefer emersion (D'Argenio *et al.*, 1986a).

Karst morphological and lithofacies variations have been interpreted by D'Argenio *et al.*, (1986a) as evidence for a generally higher elevated Apulian platform during the Cretaceous. The spatial distribution of bauxites of slightly different stratigraphic levels in the Abruzzi-Campania platform may also suggest higher elevation of the eastern part of the platform, with its longer stratigraphic gap.

Since the most likely cause of the bauxite horizons is fluctuations in relative sea level, the very long continuous gap reported from the eastern Abruzzi-Campania platform is attributed to erosion of the intervening sediments between sequence boundaries. The Albian bauxites of Abruzzi-Campania and Maiella could be related to the likely relative sea-level fall in the Late Albian (?base of the *R. ticinensis* zone, section 6.4.3). Although no bauxite of this age is recorded from the Apulian platform, the occurrence of Upper Albian breccias with clasts bearing vadose cements (section 6.2.1) indirectly records the exposure of the Apulian platform at this time. In the Maiella mountains, erosion down to the level of the Lowest Middle Albian could have taken place during the major Late Albian sea-level fall. (Erosion would also explain the very abrupt vertical facies transition of ?Late Aptian age on the Maiella platform, (observed during field studies) from subtidal peloidal packstones to kastified sediments with bauxite). The likely Middle Cenomanian sea-level fall (section 6.3.2) would then have caused further erosion of the platform-top down to the previous erosion level, yielding an apparently continuous hiatus from Early Middle Albian to Early Middle Cenomanian. The Middle Cenomanian sea-level fall could also have been responsible for the intra-Cenomanian hiatus on the western part of the Abruzzo-Campania (Apennine) platform. Although again no bauxite is recorded from the Apulian platform during the Early Cenomanian, the section from the palaeoslope on the Gargano (section 6.2.1) contained a chalk horizon of approximately this age, suggesting a hiatus in input of sediment from the adjacent platform. This horizon was overlain by redeposited sediments, as elsewhere in the southern Apennines (section 6.3.2). The eustatic curve of Haq *et al.*, (1987) shows a major type 1 sequence boundary at 90 My, in the Late Turonian, and this event, if real in the Tethyan realm, could have caused the main bauxitiferous emersion horizon in

Apulia (figure 103). This sea-level excursion may have enabled erosion on the eastern Abruzzo-Campania (Apennine) platform to reach the level of the previous hiatus in the Middle Cenomanian, leaving a record of an apparently long, continuous hiatus.

In conclusion, the southern Apennine platforms contain valuable information relating to the local record of fluctuating sea levels during the Cretaceous.

6.6 Towards a Cretaceous sequence stratigraphy

The problem of correlation between the platform, palaeoslope and basin still remains in the southern Apennines. The basinal deposits of the Umbria-Marche basin, with its continuous pelagic Cretaceous record, have been the subject of many classical stratigraphic studies (for example, Alvarez *et al.*, 1977; references in section 5.2.5), whilst data from chapter 5 showed how it was possible to erect a stratigraphy for the Cretaceous of the Gran Sasso (palaeoslope) down to planktonic foraminiferal zonal level, at least in part. The main hindrance to correlation studies is still the poor stratigraphic resolution of the carbonate platforms themselves. However, work by Chiocchini *et al.*, (1984), based on the zonation scheme of Chiocchini and Mancinelli (1977) allows a tentative correlation to be made between the platform, slope and basin for the Aptian to Turonian stages of the Cretaceous. This correlation is partly based on the evidence presented above, relating to the likely timing of major sea level fluctuations in the region (sections 6.2.1, 6.2.2, 6.3.2, 6.3.3, 6.4). A summary of the correlation proposed is presented in figure 103.

Following the definition of Mitchum (1977) of a seismic sequence being defined as "a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities", four main sequences are proposed from the stratigraphic record of the southern Apennines. The first sequence (figure 103) commenced in the Lowest Aptian and ended in the ?lower Upper Aptian. The upper unit of Poggio Pastromelone from the Gargano palaeoslope contains karstified redeposited sediments of Early Aptian age from the Apulian platform (Luperto Sinni and Masse, 1987), strongly suggesting subaerial erosion. On the platform itself, supratidal stromatolitic sediments became increasingly common in the Late Barremian (Luperto Sinni and Masse, 1986). In the Gran Sasso, the faunal diversity of nannofloral communities was drastically reduced in the uppermost two metres of Upper Barremian nannofossil-bearing limestones, below a sharp, often erosional, contact with Lower Aptian bioclastic redeposited carbonates (section 5.6.1). In the Umbria-Marche basin, the Early Aptian sequence boundary generally passes conformably into the transition from the Maiolica formation to the "scisti a fucoidi" (Alvarez *et al.*, 1977). Between the Lower and Upper Aptian sediments of the Latium-Abruzzo platform occur the "*Orbitolina* marls", well known throughout the southern Apennines (De Castro, 1962; Crescenti and Sartoni, 1963; D'Argenio, 1963a-b; Sirna, 1963; Farinacci and Radoicic, 1964) and the Murges (Ricchetti, 1969). In the Aurunci mountains, these are overlain by intraformational conglomerates, locally truncating part of the marl section (Fonte Ottorile; Chiocchini and Mancinelli, 1977; Chiocchini *et al.*, 1984). The *Orbitolina* marls were deposited during the time period represented in the Gran Sasso by a thin pelagic series (section 6.4.2). A stratigraphic gap is suggested at this locality (section 6.4.2) of early Late Aptian age. It is thought that a relative sea level highstand was affecting the region at this time. The intraformational conglomerates above the *Orbitolina* marls could mark the erosion and reworking associated with a major sea-level fall.

The second sequence comprises the ?lower Upper Aptian to lower Upper Albian (figure 103). In the Gran Sasso, the lower part of the sequence reflects a redeposition event (section 5.9), related to rising sea level following the previous major sea-level fall. The development of an extended oxygen minimum zone, possibly indicative of a relative sea-level highstand of Albian age is indicated by the widespread outcrops of anoxic facies in the southern Apennines (for example, the fossil fish beds of Pietraroia on the eastern border of the Latium-Abruzzo platform; D'Argenio, 1963; Catenacci and Manfredini, 1963). In the Umbria-Marche basin a transition took place from the "scisti a fucoidi" to the "scaglia bianca" (Alvarez *et al.*, 1977). The upper boundary of the sequence is marked by the Middle to Upper Albian bauxites of the Maiella and Latium-Abruzzo-Campania platforms (section 6.5), and breccias with vadose cements on the palaeoslope of the Apulian platform (section 6.5). Although erosion makes dating of the hiatus difficult, the local onset of redeposition in the Gran Sasso in the upper *R. ticinensis* zone, strongly suggest that the boundary lies somewhere near the base of the *R. ticinensis* zone.

The third tentative sequence includes the upper Upper Albian to Lower Cenomanian, ending in the early Middle Cenomanian (figure 103). Two redeposition events were identified from the Upper Albian of the Gran Sasso (section 5.9.2), interpreted as the consequence of rising relative sea-level after the major sea-level fall of the Late Albian. Bauxite horizons formed on the western and eastern parts of the Campania-Abruzzo platform, and in the Maiella mountains, dated as Early to Early Middle Cenomanian (section 6.5). In the Aurunci mountains, discontinuous palaeosols and intraformational conglomerates formed during the Early to Early Middle Cenomanian. The onset of the hiatus is difficult to date, and may be partly controlled by differential relief (section 6.5), although the major sea-level fall appears to have occurred in the early Middle Cenomanian, since sediments of this age overlie bauxitiferous/palaeosol-bearing sediments in the Maiella

Mountains and the Aurunci mountains. A brief duration of the sea-level excursion is likely in some areas, for instance, in Apulia, where no bauxite of this age is reported from the platform, and three metres of chalk mark a possible hiatus on the palaeoslope. The regional extent of emersion is confirmed by data from Radoicic, (1987), who reports Upper Albian bauxites from Yugoslavia. The upper boundary of this sequence is thought to trace conformably into the base of the *R. cushmani* zone in the Umbria-Marche basin.

A fourth depositional sequence commenced after the Early/Early Middle Cenomanian hiatus, and lasted until the Late Turonian (figure 103). A redeposition event is recorded in the palaeoslope sediments of the Gran Sasso, interpreted as having been triggered by a relative rise of sea-level following the major sea-level fall of the Early Middle Cenomanian (sections 5.9, 6.3.2). Continued deepening (section 6.3.2) took place up to the Cenomanian-Turonian boundary, the stratigraphic position of the well-known "Bonarelli level" of the Umbria-Marche basin (for example Arthur and Premoli-Silva, 1982). Non-deposition on the Apulian platform during the Turonian is documented by the bauxite horizon (Crescenti and Vighi, 1970), although field observations and published data (Masse and Borgomano, 1987) suggest that the corresponding hiatus in the basin margin was confined to the Middle and Upper Turonian chalk levels. The Turonian bauxites of the eastern Campania-Abruzzo platform and Apulia are tentatively related to the major sequence boundary proposed by Haq *et al.*, (1987) at 89 My in the Late Turonian. Erosion down to the level of the Lower Turonian in Apulia and the ?Middle Cenomanian on the eastern Campania-Abruzzo platform must certainly have accompanied a major sea-level event of approximately this age.

The record of sequences of Late Cretaceous age is difficult to establish. The

Coniacian and Santonian appear to be represented by predominantly pelagic sediments in the southern Apennines. Relative deepening is thought to have taken place during the Campanian, on the basis of a frequently observed black shale horizon in the Molise/ Campania regions (at Carpinone; figure 32, and further south at Mt. Coppe near Benevento; data in appendix 3). Two redeposition events are recorded from the Maastrichtian of the Gran Sasso and redeposition has also been noted from other areas, including the Matese mountains (sections 5.9, 4.8). Much of the platform sediment of this age was destroyed during the events attributed to the Late Maastrichtian sea-level fall (section 6.3.3), although Carbone (1984) reported microkarstic surfaces from redeposited sediments of this age, confirming the exposure of the shelf-edge. The subsequent sea-level rise led to redeposition throughout the southern Apennines (section 6.3.3).

6.7 Subsidence Modelling

6.7.1 Database

In order to place constraints on the Cretaceous tectonic environment of the Southern Italian region, a first- order attempt at modelling the subsidence histories of the southern Apennine carbonate platforms was made. The basic database used was that of D'Argenio and Alvarez, (1980), modified by using more recent stratigraphic data of Accarie, (1987) for the Maiella and that of Luperto Sinni and Masse, (1986) for ~~the~~ Apulia. In addition, data from Chiocchini and Mancinelli (1977) was used to model the subsidence history of the Aurunci Mountains, near Rome. Field data was used to model the subsidence histories of the Umbria-Marche basin in the Gran Sasso, and the East Gargano basin in Apulia. For the reasons outlined earlier, (section 6.5) the mid-Cretaceous hiatus with bauxite was assigned a duration of one million years, during the Early Cenomanian. The timescale adopted during the modelling was that of Haq *et al.* (1987, 1988), due to its widespread current use in the geological literature. However, all subsidence graphs depict error bars in absolute ages, taken as the difference in ages determined by Haq *et al.* (1987) and Kent and Gradstein (1985). Error bars are also shown for palaeontological ages determined during the present study. These bars show the duration of the appropriate planktonic foraminiferal zone or subzone.

These data from the carbonate platforms has been processed seperately to the data for basins, in order to keep the errors in platform data to a minimum. The basin data require additional palaeobathymetric estimates, which introduce an additional variable into backstripping calculations.

Palaeobathymetry of basins in southern Italy was considered to be too poorly constrained to permit use of basinal stratigraphy in modelling, except for the specific examples mentioned above where detailed field sections are available. Stratigraphic data used during modelling is tabulated in appendix 1.

6.7.2 Construction of subsidence curves

Initially, sediment columns were decompacted,* using procedures adopted by Bond and Komintz (1984) for maximum and minimum delithification of fully lithified sediment. Literature data were searched in order to obtain maximum and minimum values of the surface porosity and the exponential coefficient of porosity loss with depth in carbonates. Maximum delithification assumes that all strata were lithified during burial by mechanical compaction, whereas minimum delithification assumes that all carbonate strata were lithified by the addition of a cement that was precipitated early in the burial history of the sediments, and that was derived from an external source (outside the analysed section). Bond and Komintz (1984) employed two different exponential coefficients to simulate maximum delithification, in order to model the

* A computer algorithm to decompact and backstrip sediment columns was kindly supplied by Dr. P.A. Allen (Oxford) to run in BASIC on the Research Machines Nimbus computer. This was adapted to run on the IBM P.C. in compiled BASIC without alteration to the decompaction and backstripping algorithm.

observation that porosity loss is particularly rapid in the upper one kilometre, due to rapid losses of water in loosely consolidated sediment (Rieke and Chilingarian, 1974), followed by a second coefficient to model subsequent more gradual porosity loss. Only one exponential coefficient has been used in the present modelling, since, with the exception of the Apulian platform, the carbonates of the S. Apennines have been buried by variable thicknesses of synorogenic flysch. As a first approximation, the thickness of flysch used in model calculations was set at one kilometre, thus avoiding the necessity of using a second exponential coefficient.

The surface porosity chosen for maximum delithification assumes that all strata are composed of limestone, with an initial porosity of 55% (Schmoker and Halley, 1982), and employs an exponential porosity-depth relationship developed for Pliestocene mixed limestone-dolomite sediments from Florida by Schmoker and Halley (1982):

$$\Phi = xe^{-z/2.498},$$

where Φ is the porosity at any depth in percent, x is the surface porosity in percent, and z is the depth below ground level in km. A similar expression was employed for minimum delithification, substituting a surface porosity for limestone of 20% (Bond and Komintz, 1984), and a porosity/depth coefficient of 1.443km^{-1} (derived from data in Scholle, 1977). An approximation was made by assuming that the depth of post-Eocene overburden on the southern Italian platforms was uniformly one kilometre. The depth of post-Miocene flysch is known to vary within individual flysch depocentres, with depths generally ranging from about 0.6-0.7 to two kilometres. Due to uplift and erosion of the platforms, the maximum depth of burial is not directly measurable, neither do the carbonates contain any useful palaeotemperature indicators, such as abundant fluid inclusions. Some additional compaction must have been experienced by the rocks during thrust compression, although this is assumed to have been relatively short-lived and to have affected sediment columns uniformly. The decompaction process applied was essentially that of Sclater and Christie (1980).

Following decompaction, sediment columns were backstripped to determine the depth to "basement", and thus the subsidence history of the platforms. The depth to true basement, and indeed, the nature of the underlying crust of Italy is still a matter of debate (Lavecchia *et al.*, 1984a, b; Arisi Rota and Fichera, 1985; Bagnoli *et al.*, 1979; Burgassi *et al.*, 1979; Vai, 1979; Bally *et al.*, 1986). For this reason, Airy isostasy, itself an approximation, was assumed throughout, and the "basement" level adopted was the base of the Sinemurian ~~Liassic~~, or as near to this level as the stratigraphy would allow. The Early to Middle Liassic has been widely cited as a time of extensional tectonism and platform-basin differentiation in the Southern Tethyan realm (for example, Bernoulli and Jenkyns, 1974).

Tectonic subsidence, Y, was calculated using the formula:

$$Y = \Phi S^{*}\left(\rho_m - \rho_s / \rho_m - \rho_w\right) + Wd - \Delta SL\left(\rho_w(\Phi - 1) + \rho_m / \rho_m - \rho_w\right);$$

where S^{*} = sediment thickness corrected for lithification, ρ_s = mean bulk density of sediments, ρ_m = mean density of the mantle, ρ_w = mean density of seawater, ΔSL = eustatic change in sea-level relative to its present elevation, Φ = a basement response or weighting function relating sediment and water loads to tectonic subsidence, and Wd = average depth of water in which the unit was deposited. S^{*} was calculated using the empirical maximum and minimum delithification factors (discussed above) The function Φ was set equal to 1, assuming that the subsidence caused by the sedimentary and water loads can be removed using a simple Airy compensation model and that the effects of lateral heat flow and flexure can be ignored. Bond *et al.*, (1988) have shown that this approximation is reasonable so long as it is the form of the subsidence curve produced (termed R1 by these authors) which is of interest, and not the absolute amount of subsidence.

The result of the backstripping calculation is a subsidence curve which incorporates the tectonic subsidence and a eustatic sea-level component (R1 curve). The R1 curve is calculated from the values of the midpoints between the curves for maximum and minimum delithification factors. Since the maximum and minimum delithification factors represent extremes of compaction and cementation respectively, the true value of sediment compaction should lie within the field bounded by these two curves, thus the midpoints are thought, following Bond and Komintz (1984) to be a good first approximation for the true degree of compaction.

The form of the R1 curves was subsequently compared with curves calculated from models that simulate the subsidence of a passive margin during its post-rift (or cooling) stage. The post-rift model curves used for this comparison are calculated from the one-layer stretching model of McKenzie (1978), in which post-rift subsidence is modelled in terms of a cooling lithospheric plate. Studies by Watts (1981) and Keen (1982) have shown that this model is a good approximation of tectonic subsidence in modern passive margins after rifting ends and cooling begins. The model is calibrated for 5 km of oceanic crust (following Steckler, 1981, and Cochran, 1983) and for an equilibrium thermal thickness of the lithosphere of 125 km. These parameters constrain the model ocean-floor curve to be the same as the average age-depth curve for modern ocean floor according to Parsons and Sclater (1977). Crustal parameters used during the calculations are given in appendix 1.

The form of the R1 subsidence of the southern Apennine passive margin is approximately exponential and decays with time (figure 104). The first-order form of the curves resembles the form of the curves calculated from the cooling plate model, although the quality of the match is variable from locality to locality. The general fit of the R1 curves with the model curves is regarded as good evidence that, after correcting for lithification and sediment and water loading, most of the post-rift subsidence was controlled by cooling and thermal contraction of a heated lithospheric plate.

One important feature of the R1 curves for the southern Apennine platforms is the cross-over, observed in all cases, between the predicted model cooling curves and the observed tectonic subsidence calculated from the stratigraphic data. Tectonic subsidence overtakes predicted model subsidence during the Late Cretaceous in all data-sets modelled. The possible explanations for this will be discussed in section section 6.7.6.

6.7.3 Eustatic component of S. Apennine subsidence

If eustatic sea-level changes occurred during the subsidence of the Mesozoic southern Tethyan passive margin, they should be indicated by a misfit between the R1 subsidence curves and curves that can be assumed for post-rift tectonic subsidence (Y) of the margin. The difference between an R1 curve and the best-fit model cooling curve can be regarded as a second reduction of the cumulative cooling curves and is referred to as an R2 subsidence curve by Bond *et al.*, (1988). Bond *et al.*, (1983, 1984, 1988) showed that form of these curves to be very similar for several Early Palaeozoic passive margins in North America, all of which apparently recorded a long term (second-order *sensu* Vail *et al.*, 1977) eustatic cycle during the Cambrian. Bond *et al.*, (1989) showed how repeating short term (2-6 My) cycles could be recognised and correlated in time from the Canadian Rockies to the Great Basin and the Virginia-Tennessee Appalachians again implying a eustatic control. The form of the R2 curve is therefore thought to contain evidence of at least two orders of sea-level change.

Two approaches to the calculation of R2 curves for the southern Apennines have been used. In the first, data from the various platforms have been averaged to produce a mean R2 curve for the Mesozoic of the region. In the second, field data from basin-margin settings in the Gran Sasso and Apulia have been used in order to model the detailed form of subsidence during the Middle Cretaceous, in order to detect evidence for the sea-level changes proposed in sections 6.5 and 6.6.

The mean R2 curve for the S. Apennine platforms (figure 106) has a form which closely resembles that of the long-term (second-order) eustatic curve of Haq *et al.*, (1987) for the Cretaceous. The form of the Jurassic portion of the R2 curve, however, bears little resemblance to the eustatic curve. This could either mean that the eustatic curves of Haq *et al.*, (1987) and Hallam (1988) are only of regional significance, and that the Tethys Ocean experienced an entirely separate relative sea level history, or that the stratigraphic data from the S. Apennines somehow locally weights the R2 curve in favour of events with a short temporal duration. This latter seems likely when the long-term subsidence of the passive-margin is considered. A histogram depicting the average values of the first derivative of the R1 curve (i.e. subsidence rate (Y) + eustatic change (ΔSL)) has been plotted in figure 107. It is clear from this diagram that there is an overall trend from relatively high subsidence rates during the Jurassic to relatively lower rates during the Cretaceous. However, the "peaky" nature of subsidence rates during the Jurassic, and especially obvious during the Cretaceous, suggest that some short-term factor such as sea-level fluctuation may be muting the longer-term tectonic signal. This is not surprising when it is considered that the thickest sections of sediment were probably deposited during rises in sea level (see for example Eberli and Ginsburg, 1989). Such thick sections are often most easily palaeontologically dated, and

* The database on southern Apennine platforms remains sparse due to poor biostratigraphic resolution within the platform carbonates.

therefore the stratigraphic data from the S. Apennine platforms is weighted towards such intervals, which provide the most readily recognisable lithostratigraphic divisions in the field. This observational bias may have weighted the Jurassic data used to compile subsidence histories in favour of short term sea-level-induced excursions in subsidence rate.*

Short term peaks in Jurassic subsidence rates can be identified from figure 107 from the Toarcian, Bajocian and Late Tithonian. Cretaceous short-term peaks have been identified from the Barremian, Early Aptian, Early to Middle Cenomanian, and ?Turonian to Santonian. On the R2 curve (figure 106) the Cretaceous history can be interpreted in terms of a long-term eustatic sea-level rise from the Valanginian to Early Campanian, at which point the highest relative sea level was reached, followed by fall in relative sea level from the Late Campanian to the end of the Maastrichtian. Superimposed on this long term trend are particularly rapid relative sea level rises in the Valanginian, Albian and Early to Middle Cenomanian, and falling sea level in the late Aptian. The long term trend is similar to that proposed by Hallam (1988), Hancock and Kaufmann (1979) and Olssen (1988), although it is at variance with the curve of Haq *et al.*, (1987) which depicts the highest Cretaceous sea level occurring at the Cenomanian- Turonian boundary. The R2 curve for the S. Apennines appears to show rising sea level slowing to a still-stand during the Turonian, followed by subsequent rise until the Campanian. Plots showing subsidence rates for individual localities are shown in figure 108.

The second approach to analysis of R2 subsidence was to model the subsidence of two separate basin margins in the S. Apennines using a combination of literature data and detailed field data. The results of this analysis are shown in figure 109. In the Gran Sasso, the form of the R2 curve suggests sea-level rise during the Early

Aptian, followed by sea-level fall during the Late Aptian and Early Albian. Sea level began to rise again during the upper *R. ticinensis* zone, until the end of the Albian. The Cenomanian began with a fall in relative sea level, until the Early Middle Cenomanian, when sea level rose again during the Lower *R. cushmani* zone. The detailed form of the sea level rises is not smooth, but rather stepwise (figures 109, 110a). Detailed analysis of the first derivative of the R2 curve (i.e. approximating the form of the rate of change of relative sea level) (figure 110c) reveals repeated cyclic variations in gradient during the late Albian and Early Middle Cenomanian. The latter variations appear to have a period of approximately 131,000 ka or less which might suggest that the sea level rise was being "damped" by 100 ka orbital cycles, although the exact period of the variations is beyond the stratigraphic resolution obtainable. If orbital cycles have left a signal in the sediments of the basin margin, this signal is only resolvable during times of relatively rapid sedimentation, when stratigraphic resolution is at its best. The 100 ka and 22 ka cycles have been previously reported from the Carnian to Ladinian carbonate platforms of the Dolomites by Goldhammer *et al.*, (1987) and Goldhammer and Harris (1989). The small relative changes in sea level induced by orbital forcing are further evidence for sea level fluctuations being an important primary control on carbonate platform growth and development.

The maximum rate of sea level change derived from the mean R2 curve for the S. Apennine platforms is approximately 35 mMy^{-1} (Early to Middle Cenomanian) when the quantity $\Delta SL(\rho_m/\rho_m-\rho_w)$ is calculated to give ΔSL using the appropriate parameters. The peak gradient values derived from R2 curves from the basin margins yield peak rates of sea level change of 36 mMy^{-1} (Late Albian) and 24 mMy^{-1} (Early Middle Cenomanian) in very good agreement with the platform data (figure 110b). It should be noted that, although the basin margins do not record the absolute magnitude of the sea level changes (since basinal sediments do not build to sea level to keep pace with the changes), the maximum rate of response to a given sea level change appears to be very similar to that of the platforms. This agreement provides further evidence that sedimentation in both environments was controlled primarily (in the short term) by the same factor, namely sea level cyclicity. Rates of third order sea level change (time averaged) of 3 to 5 cm per 1000 yr have been widely reported as typical values by Haq *et al.*, (1987), Kendall and Schlager (1981), Hine and Steinmetz (1984) and Hancock and Kaufmann (1979). These values are in good agreement with the corrected data from the S. Apennines. In addition, Hine and Steinmetz (1984) have estimated third- order eustatic curves to have amplitudes of 50-75 m, values which are similar to the amplitudes of rises recorded in the R2 curve of figure 106, for instance the approximately 35 m sea level rise of the Early to Middle Cenomanian.

The form of the R2 curve for the Middle Cretaceous of the Gran Sasso has been compared to the form of the R2 curve for the East Gargano basin margin in Apulia (figure 109). A close similarity was observed in the form of the two curves, which both show a stepwise sea level rise during the Late Albian, followed by ?stillstand and/or sea level fall during the Early Cenomanian, and a further stepwise rise during the Early Middle Cenomanian. A stepwise rise during the Early Middle Cenomanian can also be seen in field data from a second separate locality in the Gran Sasso, (Mt. Corvo).

6.7.4. Limitations to subsidence models for the S. Apennines

One of the most critical factors in the matching of tectonic subsidence curves to model cooling curves for a passive margin is the timing of the onset of thermal subsidence, since this determines the time of the starting point for the fit. This factor is of lesser importance when, as in the present case, it is only the form of

R1 subsidence which is of interest, and not the absolute magnitude of the subsidence. A stretching factor, β, derived from such one dimensional modelling would not be of practical use in any case, since it ignores the effects of lateral heat flow and flexure upon the margin, both of which have been shown to be important in determining the overall cooling histories of passive margins (Steckler, 1981, Watts, 1981). It was mentioned in section 6.7.1 that the base of the Sinemurian (201 Ma) was chosen as the time of onset of thermal subsidence in the S. Apennines, since it was at approximately this time that ?fault controlled drowning of parts of the wider Late Triassic platform ended, and the drowned portions began to be onlapped by pelagic carbonates of the Corniola Formation. However, an earlier phase of basin formation during the Late Triassic is widely reported from the region (Ciarapica *et al.*, 1987, Wood, 1981). The Norian Lagonegro basin of the southern Apennines is an example of such a basin, and the lithofacies development undergone by this basin, from continental clastic sediments to shallow marine carbonate sediments and finally to pelagic carbonate and siliceous sediments (Wood, 1981) is an excellent example of a typical passive-margin extensional basin evolution. This type of lithofacies development is lacking from the basins which formed during the Liassic, fragmenting the formerly continuous Late Triassic platform, leaving open the possibility that some mechanism other than lithospheric extension led to their formation. Aigner *et al.*, (1989) showed by computer modelling that it is in principle possible to reduce an extensive carbonate platform to a series of smaller platforms by a purely isostatic mechanism. During a major sea level rise, carbonate production keeps pace with rising sea level only on the margins of the large, isostatically compensated, platform. Subsequently, the isostatic response to the modified load distribution, combined with a fall in sea level, brings two areas into the photic zone, resulting in four isolated platforms.

The Mid-Cretaceous differentiation of the Bahama platform into separate smaller platforms with intervening basins as the result of a major (intra-Cenomanian) sea level rise could be interpreted in this way (for example Schlager, 1989). If such an isostatic mechanism operated in the S. Apennines during the Liassic, then the thermal subsidence being modelled is that resulting from Late Triassic rifting in the region. Even if this were the case, the probable effects of finite rifting time (Cochran, 1983) would be such that the major part of the thermal subsidence of the S. Tethyan passive margin took place during or after the Middle Liassic (approximately 15 My after commencement of Triassic rifting). In order to test this hypothesis, the thicknesses of Late Triassic strata were included in subsidence calculations where possible, with the result that a marked change in gradient of the R1 curve was observed prior to the Liassic. This was taken to indicate the predominance of fault-controlled subsidence prior to this time.

The choice of crustal parameters can influence the form of the subsidence to some extent, for instance, changing the decay constant of cooling of the lithospheric plate changes the quality of the fit of R1 curves to model cooling curves (Bond *et al.*, 1989) although the actual form of the deviations from the R1 curve was shown by these authors not to be significantly affected. Since the amplitudes of R1 curves are poorly constrained (see figure 104), the decay constant for the modern ocean floor (62.8 My) is as valid as any other, and the amplitudes of deviations from the R1 curves are thus somewhat model dependent. This provides a further error bar on the magnitudes of eustatic changes inferred from the modelling. The insulating effects of cold sediment deposited on a passive margin, which could potentially retard cooling of the lithospheric plate and mimic variations from the R1 curve, was thought to be insignificant by Bond *et al.*, (1989), since similar variations were observed in sections containing widely differing sediment thicknesses from the Great Basin. This would also seem to be the case in the southern Apennines, although more detailed sections need to be analysed in order to fully discount this effect.

The exact form of subsidence curves in the S. Apennines is still difficult to evaluate, and there is a need for more accessibly-published, well-dated and accurately measured stratigraphic sections from the region, in order to reduce the weighting of R1 and R2 curves to short-lived events. More work is also needed to constrain the palaeobathymetry of pelagic basins in the region. Lack of reliable palaeobathymetric estimates introduces large error bars into the form of the subsidence curves for the basins, especially during the Jurassic, when water depths were probably increasing in most areas (see data of D'Argenio and Alvarez, 1980).

The sediment porosity-depth relationships used probably exert the biggest influence on the shape of the R1 curves produced during modelling (Bond and Komintz, 1984), although, as discussed in section 6.7.2, the use of a mean decompaction value derived from the maximum and minimum limits of delithification should yield an R1 curve within the actual range of decompaction needed.

One of the principal advantages of the computer modelling over traditional methods of sedimentological analysis was the ability to critically assess the reported geological history of some areas by interactive programing. A good example of this is the interpretation of the subsidence data for the east Gargano basin. Using the published stratigraphic data of D'Argenio and Alvarez (1980) (derived from Vezzani, 1975), the age of basin formation in the area was Early Cretaceous. However, the misfit between the R1 subsidence curve for the margin and the best-fit model cooling curve was significantly reduced when the data from the local geological map (Carta Geologica d'Italia foglio 157, Mt. S. Angelo) and the borehole Peschici 1 (AGIP Mineraria, 1961) were reinterpreted as suggesting basin formation during the Liassic. This interpretation is consistent with the occurrence of deep-water facies, containing pelagic bivalves and radiolaria, of Early to Middle Jurassic age in the Peschici 1 borehole (Martinis and Pavan, 1967). A Liassic age of basin formation is also more consistent with the regional geological picture of Middle Liassic basin formation (see section 6.7.2)

6.7.5 Influence of local tectonics

One other piece of evidence from the subsidence curves comes from the curves for the Matese Mountains. Here, the Cretaceous section at Pietraroia is much thinner than that of the Northeastern Matese (localities in figure 32). At Pietraroia, virtually no tectonic subsidence occurred during the Cretaceous, whereas steady subsidence continued in the Northeastern Matese, with a slight acceleration in the Late Cretaceous. The differential subsidence between these two localities (figure 105) implies Cretaceous extensional fault movements, possibly due to a renewed heat input into the region. The amount of differential subsidence observed requires a rotation of the pre-Cretaceous subtratum of approximately 5°, about 2.5° each being due to tectonic tilting and sediment loading. Using the methodology of Jackson *et al.*, (1988), around 500 m of footwall uplift would be predicted for a rotated extensional tilt-block thirty kilometres across, with initial fault orientations of sixty degrees to the horizontal (see appendix 2). This tilt-block dimension and degree of uplift is of the right order of magnitude to explain the puzzling amount of uplift and erosion implicit in the relationship of underlying platform facies to the Senonian unconformity in the Matese (see section 4.9). Field data and palaeontological results from this area imply the formation of a platform-margin during the Jurassic (section 4.6), and probably during the Liassic. This allows the possibility that the Cretaceous fault movements in the area were reactivating earlier Liassic structures. Such movements could be the result of small amounts of additional lithospheric heat input, with β values as low as 1.05 in the example described above from the Matese mountains (appendix 2). Increased lateral heat input into the region has been inferred from studies of the Northern Apennines (see below) during the Upper Cretaceous, and such effects would largely explain the differences in the total amount of subsidence and form of R1 curves for the region (figure 104), for which the best-fit exponential model cooling curves yield a 2σ of ± 0.20. The local variations in total subsidence strongly argue for the important influence of lateral heat flow effects in determining the detailed cooling history of the passive margin, and also provide justification for averaging the platform subsidence data to produce the subsidence rate graph of figure 107 and the mean R2 curve for the region. Using such an averaging procedure minimises the effects of local tectonic movements on the subsidence data.

In summary, footwall uplift during reactivation of Jurassic extensional tilt-blocks provides a possible mechanism to explain the erosional relief (up to 1500 metres crude sediment thickness) commonly observed beneath the Senonian unconformity in both Italy and Yugoslavia.

6.7.6. Regional tectonic context of Apennine subsidence

The end of the Early Cretaceous (Albian to Cenomanian) may have been a time of renewed lateral heat input into the region, caused by nearby opening of the eastern Mediterranean and the postulated eastward propagation of the Western Mediterranean into the Apulian region during the Aptian to Albian (Dercourt *et al.*, 1986).

As noted in section 6.7.2, observed tectonic subsidence was greater than predicted model subsidence in all data-sets from the southern Apennines during the Late Cretaceous. This systematic misfit is thought to be significant, and may indicate renewed crustal extension in the region during the Late Cretaceous. The exact timing of the onset of this renewed extension is difficult to ascertain, since it is somewhat model dependent, but by inspection of the R1 curves it is most likely to have occurred during the Cenomanian or Turonian stages. Such a date would be compatible with the timing of the major change in plate motion between Europe and Africa, during which Africa began its northward motion (Dewey *et al.*, 1989). This changeover in plate–motions could ultimately have been responsible for the change in tectonic environment in the Apennines during the Late Cretaceous.

A similar acceleration in subsidence rates has been proposed from the Early Turonian to Eocene of the northern Apennine pelagic basin (Montanari *et al.*, 1989; section 6.2.4). Apparently, new intrabasinal depocentres and structural highs formed in this basin during the Early Turonian, controlled by reactivation of the pre-existing pattern of buried Jurassic normal faults which formed during the passive-margin phase of the Western Tethys, following a time of tectonic quiescence during the Aptian to Cenomanian. The tectonic activity which controlled the sedimentary and topographic development of the northern Apennine Scaglia Rossa basin was thought by Montanari *et al.*, (1989) to be the result of the distant effects of the regional plate tectonic configuration in that part of the Tethys Ocean, in particular, the eo-Alpine deformational events which were occurring in the Eastern Alps at the same time as subduction commenced in the western part of the northern Apennines. Subsidence of the Scaglia Rossa basin, however, was thought to be directly due to oceanic subduction along the Apennines orogenic front, which would have caused further stretching of a previously faulted and thinned continental crust, prior to the continent-continent collision between the Adriatic (African) plate and the Corso-Sardinian (European) plate. Pre-alpine tectonic activity may have also triggered the "seismite" events noted in the southern Apennines (section 4.8.3) and could have contributed to shelf-edge collapse events (for example in the Late Maastrichtian; section 4.8) in combination with processes induced by relative lowstands of sea-level. Locally accelerated subsidence in the southern Apennines (section 6.7.5) during the Late Cretaceous may have been promoted by the initiation of subduction in the northern Apennines, although the present stratigraphic database makes it difficult to discriminate between a Late Cretaceous event and a possible acceleration in the Barremian-Aptian due to ocean spreading in the area of the present Western Mediterranean*. Neither of these possibilities, however, is compatible with the Cenomanian "tectonic phase" proposed by some authors (for example Colacicchi *et al.*, 1978). In view of this incompatibility and the reported tectonic quiescence in the northern Apennines during the Aptian to Cenomanian, events during the Cenomanian (exposure and drowning of parts of the shelf-edge) are much more consistent with the widely reported third-order fluctuations of relative sea-level during this stage. Features peviously attributed to Cenomanian tectonics, such as the step-back of certain S. Apennine platform margins (for example, Marsica; Colacicchi, 1987) can be predicted as the consequence of sea-level change during this stage. Scaturo *et al.*, (1989) in computer simulations of the Devonian Judy Creek reef complex of the western Canada Alberta basin derived an empirical formula showing backstepping distance, X, to be a function of sea-level rise, Z, and platform slope, Y, such that:

$$X(Z,Y) = (1 - \exp(-w*Z)) + \exp(-Y/p);$$

where Z is the ratio of carbonate growth rate to rate of sea-level rise, and p and w are user-defined scaling constants. If p and w are set to equal one, then for a value of Z of 0.33 and a platform slope of 0.1°, the backstepping distance predicted would be 1.19 km. This value is calculated from time-averaged values of 20 mMy^{-1}

* Dercourt *et al.*, (1986), M. Daly (B.P. Structural Studies Group) pers. comm., 1989.

for carbonate growth potential and 60 mMy^{-1} for the rate of the Middle Cenomanian sea-level rise. Since the scaling factors are not known in this case, the equation cannot be applied to predict the responses of Apennine platforms, except to illustrate the point that backstepping can occur without recourse to tectonic movements.

Bond *et al.*, (1989) point out (figure 111) that as the rate of lithospheric cooling slows, unconformities will become more common at sequence boundaries, and will be of increasing duration. This effect would explain the pronounced emersion of S. Apennine platforms during the Middle Cretaceous, as the Liassic thermal anomaly had decayed considerably by this time.

Due to the lack of stratigraphic resolution currently available in the southern Apennine database, it seems most plausible to attribute the local accelerations in subsidence rates in the region to the Late Cretaceous onset of subduction along the Apennine front, by comparison with the much better constrained data from the northern Apennines.

Chapter 7: Conclusions

The aims of this thesis were to study in detail different parts of Cretaceous carbonate platform-margins in the southern Apennines and to combine these data in order to make inferences about the behaviour of the platform system as a whole through geological time. Of particular interest were:

(1) the lithofacies, sediment-body geometries and organisation ("anatomy") of slope sediment systems. Was it possible to make a "physical stratigraphy" for these deposits, in an analogous way to the method used in interpretation of reflection seismic records?

(2) controls on the redeposition of sediment into the slope system, specifically the possible roles of relative sea-level fluctuations and local tectonic activity (allocyclicity) versus autocyclicity in carbonate turbidite systems, and;

(3) the response of the carbonate platform system as a whole to possible mechanisms affecting sediment production rates. For instance, was the response of the platforms the same as that of the slope system at particular times, and was the behaviour of southern Apennine platforms in any way "special" or different from that of other Cretaceous carbonate platforms?

7.1 Initial approach

The first approach to the problems of interest presented above was to undertake field mapping of a small, well-exposed area of slope sediments in order to describe their geometries and sedimentology. Synsedimentary tectonic activity might be detectable from mappable facies transitions (an approach used successfully in siliciclastic systems by Leeder, 1987) or even exhumed palaeofaults (figure 20c-d). The type of slope profile and slope sediment organisation might be mappable by tracing facies laterally in the direction of the former carbonate platform. The Upper Cretaceous to Early Tertiary slope facies of the eastern margin of the Apennine platform (figure 5) in the Frosolone area (figure 32) were chosen for this exercise. The detailed results of mapping at 1:10,000 scale are presented in chapter 4.

It became apparent at an early stage that the mappable lithoclastic calcirudite beds exposed at Frosolone gave an important clue to the behaviour of the carbonate platform system as a whole during the Late Cretaceous, since they contained a variety of lithoclasts with a wide range of ages (from Upper Jurassic to Uppermost Cretaceous). On further field investigation and compilation of published data (figure 21), it was found that erosional episodes were characteristic of all platform margins exposed in the southern Apennines, and furthermore, that they occurred repeatedly throughout Cretaceous time, in the ?Early Hauterivian, Early Aptian, Late Albian, Middle Cenomanian, ?Early Campanian and Maastrichtian stages.

The recognition of the major facies change which took place close to the Cretacous-Tertiary boundary, coupled with palaeontological data presented by Pironon (1980), enabled the construction of detailed restored cross-sections showing the sediment geometries of the major lithoclastic calcirudite beds in the mapped area at Frosolone (figures 49, 50). These sections demonstrated the lenticular shape and amalgamation geometries of the beds in a direction perpendicular to mean palaeoflow on a horizontal distance of 5-7 km (figure 51). Field studies also indicated the presence of a 100-150 m section of time-equivalent facies onlapping ?Upper Triassic to Lower Cretaceous platform facies in the adjacent Matese mountains. Such an onlap relationship must indicate large-scale uplift and erosion of the platform prior to Campanian-Maastrichtian times. Unfortunately, the sediment geometries in the Matese-Frosolone area (downlap, onlap, *et cetera*) were not observable at the scale of the reflection seismic tool, so an alternative approach had to be taken in order to assess the possible role of local tectonics in modifying the behaviour of the platform-margin during the Late Cretaceous to Early Tertiary. The search for large-scale continuous exposures of Cretaceous slope sequences led to further fieldwork in the Gran Sasso d'Italia.

7.2 Physical stratigraphy and redeposition in the Gran Sasso d'Italia

Mapping at 1:10,000 scale in the Gran Sasso d'Italia (enclosure 2) , coupled with interpretation of cliff-sections tied to measured stratigraphic sections for time-control, enabled the recognition of lithofacies and the grouping of these into three major lithofacies associations, each characterised by a distinctive depositional geometry. These were:

(1) calcareous turbidites with subordinate interbedded wackestone and lime mudstones, organised in *downlapping* depositional packages (DLP);

(2) predominantly fine-grained calcareous turbidites, wackestones and lime mudstones, reworked into mounded facies (approximately 400 x 400 x 10 m) displaying low-angle foreset geometries indicating slope-contour parallel flow, and having *bidirectional downlapping* geometries (BDD) and;

(3) thinly-bedded dominantly fine-grained wackestone and lime mudstone facies organised into *onlapping* depositional packages (ONL).

Sedimentological features of the sediments included poorly-developed coarsening-upwards- and thickening-upwards- trends in some DLP groups of beds (figure 96), and both vertical and laterally-offset stacking patterns of major amalgamated, lenticular calcareous turbidite beds. These beds could be observed to seek topographic lows between relief generated by groups of beds with BDD geometry.

Establishing time-control on the sedimentological features observed in the Gran Sasso became of critical importance, both to interpreting the depositional architecture and correlating between sections, and to allow interpretations to be made in relation to the depositional controls affecting slope sedimentation. To this end, collaborative work was carried out in association withthe Stratigraphy Branch of British Petroleum Research International Limited, Sunbury-on-Thames. The results of this work are presented in chapter 2. Briefly, dating by means of planktonic foraminifera in thin sections suggested that reworking of sediment was contemporaneous in the area (within the limits of palaeontological dating). This hypothesis was strengthened by age determinations made using reworked benthonic foraminifera, calcareous algae and nannoflora within the same thin sections, all of which gave dates in good agreement with the planktonic species. On this basis, times of particularly enhanced redeposition (redeposition "events"), identifiable as downlapping packages of thick calcareous turbidites in the field (figures 82, 86, 90, 95) were dated as Early Aptian, Latest Aptian to Earliest Albian, Late Albian, Early Middle Cenomanian and Late Maastrichtian in age.

By tying measured sections with their palaeontological dates to cliff-sections with their observed geometries, it was possible to identify several cycles of the geometries BDD-DLP-ONL and to place these within the Cretaceous time-frame (figures 82, 86 90, 94). Particularly notable are three well-developed cycles observed in both N-S and E-W sections (parallel and perpendicular to the palaeoslope) on Mt. Corvo, one of which developed in Late Campanian to Early Maastrichtian times, and the other two in Late and Latest Maastrichtian times respectively.

7.3 Depositional controls and sediment architecture

Recent research into modern rimmed carbonate shelves (summarised in chapter 1) has shown that the export of newly-produced carbonate sediment (i.e. contemporaneous sediment) into basins as calcareous turbidites is at a maximum during relative sea-level highstands (Droxler and Schlager, 1985). It has also been shown that such carbonate platform systems are extremely sensitive to fluctuations of relative sea-level (Eberli and Ginsburg, 1989). With this in mind, field and published data from southern Apennine platforms and basins were critically re-examined to see if a consistent pattern emerged. Two immediate difficulties with this approach presented themselves:

(1) platform, slope and basin exposures are almost always separated and discontinuous in the southern Apennines, making direct lateral correlation of important events very difficult or impossible, and;

(2) events associated with possible third-order relative sea-level fluctuations had a time-duration much shorter than the limits of palaeontological resolution obtainable from the region.

The first difficulty was overcome partially by examination of regional structural data, which showed ~~that~~, for the Matese-Frosolone and Gran Sasso areas, at least, that the platform facies adjacent to presently exposed slope facies belonged to the same palaeogeographic/structural unit, without major internal deformation. Therefore, data relating to events on the carbonate platforms in these areas could be compared to data from the slopes with some confidence in these cases. The second problem is more serious, and the approach taken was to date as closely as possible events from the slope facies and to compare these with the dates of events from the platforms in the region and published data. Two further methods of study were possible; firstly to divide the physical events on the slope into cycles using the sediment geometries, and to place these into the locally determined timeframe (see above); and secondly, to study the compositional variations in the sediments which might show systematic changes through time in an analogous way to sediments from modern platforms (see section 1.3).

The results of the construction of physical stratigraphy within the dated time-frame (see above) allowed a tentative comparison to be made between the major BDD-DLP-ONL cycles of the Gran Sasso and certain major eustatic events (Haq *et al.*, 1987). In particular, the major redeposition events noted above appear to have a close temporal relationship to some of the major eustatic sequence boundaries of Haq *et al.*, (1987). A notable coincidence was alluded to in section 5.9.5 between the three Maastrichtian cycles of BDD-DLP-ONL and the three Maastrichtian eustatic cycles of Haq *et al.*, (1987). However, a close examination showed that redeposition events in the Gran Sasso are characterised by downlapping geometries which overlie sediments with bidirectional downlapping geometries, and are themselves overlain by onlapping sediments. The downlapping sediments were contemporaneously reworked (see above) and preliminary data suggest that the proportion of reworked benthonic foraminifera increases upwards locally during redeposition events. These data therefore are more amenable to interpretation as the products of "highstand shedding" during major sea-level rises which closely postdated major eustatic relative sea-level falls.

By contrast, sedimentological data from the mapped lithoclastic calcirudites on the slope in the Frosolone area, in particular the lithoclastic composition with derived clasts representing a wide range of ages, suggest that an origin by erosion during relative lowstands of sea-level is more likely in that area. In common with the Gran Sasso (see below; section 4.9) three depositional sequences can be postulated when the mappable beds are traced from their onlap (with erosional truncation) onto the platform downslope to their correlative conformities within the slope sediments at Frosolone.

Interpretation of the Cretaceous southern Apennine platforms as being sensitive to sea-level fluctuations is further encouraged by the similar temporal response of sediment production on the Apennine platforms and slopes as interpreted from subsidence data (section 6.7), coupled with the close temporal coincidence of events of platform erosion, platform exposure, redeposition and erosional truncation within slope sediments (figure 112). By correlating such events, four tentative depositional sequences were recognised from the Middle Cretaceous (*sensu* Mitchum, 1977). These spanned the Earliest Aptian to ?early Late Aptian, ?early Late Aptian to early Late Albian, latest Late Albian/Early Cenomanian to early Middle Cenomanian, and early Middle Cenomanian to ?Late Turonian respectively.

The presence of cyclicity in slope sediments related to relative sea-level oscillations has also allowed an interpretation of slope sediment architecture to be made. Laterally offset stacking of amalgamated calcareous turbidite beds on Mt. Corvo could be explained by the fact that the two bedding packages in this case form part of two separate geometrically-defined depositional packages (BDD-DLP-ONL), each of which might be the product of a third-order cycle of relative sea-level (see above). Shifting of the locus of maximum sediment accumulation took place as a new cycle commenced and new slope relief formed as mounded facies. This second-order (*sensu* Mutti and Normark, 1987) organisation was observed to operate on a scale of 4-5 km over a time-span of 1-3 My (section 5.9.5). The models derived from studies of outcrops at this scale in the Gran Sasso made it possible to return to the data from the Matese area, and to recognise from field mapping and f.161 Isernia (Carta Geologica d'Italia) evidence for a longer term, first-order carbonate turbidite complex (*sensu* Mutti and Normark, 1987) containing individual depocentres between 10 and 15 km in length (parallel to the platform margin) with an active life-span of between 20 and 30 My. It is possible that the switch from one depocentre to another may mark the commencement of a new second-order relative sea-level cycle.

Therefore, it may be concluded that, despite continuous carbonate production along the length of the carbonate platform-margin (mappable basinal formations are laterally continuous throughout the area), local foci for sedimentation can be recognised.

7.4 Apennine subsidence

Published data, up to the most recently available, were used in a one-dimensional modelling exercise, incorporating an Airy isostatic compensation model, in order to deduce the thermal cooling histories of localities in the Apennines presumed to have been sited on the southern passive margin of the Mesozoic Tethys Ocean (section 6.7). When suitable corrections were made for sediment loading and compaction, first-order (R1) curves of tectonic (thermal) subsidence were compared with model cooling curves (*sensu* McKenzie, 1978) as a means of interpreting the subsidence history of the passive margin.

R1 curves for the Apennines displayed a general form in reasonable agreement with the model curves, with relatively high Jurassic subsidence rates declining during the Early Cretaceous. However, almost all R1 curves cross the predicted model curves during Late Cretaceous time, a feature which may suggest renewed thermal input into the region (renewed crustal extension). The average time of cross-over lies in the Cenomanian or Turonian stages. An alternative possibility to explain the shape of the R1 curves would be that the Cretaceous sea-level rise continued to cause sufficient additional subsidence to keep the observed subsidence values higher than predicted model values until Latest Cretaceous to Early Tertiary times.

The field data obtained in the Matese Mountains and consideration of the local geological map (f.161 Isernia) and stratigraphic data (chapter 4) clearly show an unconformity between Campanian-Maastrichtian slope facies and ?Upper Triassic, Jurassic and Lower Cretaceous platform facies. Calculations of footwall uplift (appendix

2) and consideration of the field data are consistent with the hypothesis of unconformity generation by the uplift and erosion associated with rotation of a large (approximately 30 km square) extensional fault block. Published stratigraphic data suggest that differential subsidence in the area had already commenced by the end of the Early Cretaceous. Data presented in chapter 4 demonstrate the creation of a platform margin in the Matese area during the Jurassic (?Liassic) by fragmentation of a larger Late Triassic platform. If this had occurred by means of a regional phase of extensional tectonism (evidence for such a phase is discussed in section 6.7.5) then the fault movements of the Late Cretaceous could have taken place by reactivation of Jurassic structures. The pattern of Late Cretaceous unconformities in both Italy and Yugoslavia with their associated large amounts of erosion might best be explained by renewed extensional tectonics. A possible cause of renewed extension in the Apennines could be the onset of Apennine subduction to the north of the region during the Late Cretaceous, connected to early Alpine orogenesis.

A second reduction (R2) of the subsidence curves for Apennine platforms has been attempted to try and gain data relating to the form of eustatic variations in the region (section 6.7). The Jurassic portion of the average R2 curve is difficult to interpret (figure 106), but the Cretaceous portion shows marked upturns (more subsidence then predicted by simple thermal subsidence) during the Early Aptian, Albian and Early to Middle Cenomanian.

The Jurassic portion of the R2 curve is probably dominated by the local tectonic signal (differential subsidence of fault blocks) although the shape of the Cretaceous portion of the curve (particularly during the Aptian to Turonian stages) is in good agreement with the shape that would be predicted from the interpretation of the regional geology into sea-level mediated depositional sequences (section 6.6; see above).

A further method of deducing the eustatic component of Apennine subsidence was the construction of R1 and R2 curves for the slopes in the Gran Sasso and Apulia (Gargano peninsula) using a combination of field and published data, and assuming a minimum bathymetry (section 6.7.2). The shape of the R2 curves for the two slopes was broadly similar (figure 109) and similar to that of the platforms, with marked upturns in the Early Aptian, Late Albian and Early Middle Cenomanian (figure 109).

Despite the many limitations and assumptions involved in one-dimensional subsidence modelling (section 6.7.4), the similar features of the platform and basin curves are interpreted as being the product of a common control on deposition. The deviations from steady thermal subsidence may best be explained by changes of relative sea level, a conclusion in agreement with the interpretation of the sedimentology and depositional geometries of slope sediments (chapters 4 and 5).

7.5 Future studies

A promising avenue of further research might be to examine the detailed compositional variations in slope sediments. In modern carbonates such information has been used to distinguish the stage of relative sea-level (Haak and Schlager, 1989). If such information could be gained from Cretaceous slope sediments by closely-spaced sampling of measured sections (beyond the logistical scope of the present project), it might be combined with data presented here concerning depositional geometries to clarify the nature of controls on sedimentation (sea-level versus tectonic control; highstand versus lowstand export of sediment into the slope environment).

The tentative depositional sequences referred to in section 6.6 based on regional stratigraphic data could be investigated in the field by studying the detailed depositional geometries of carbonate platform sediments from the southern Apennines, especially at the crucial interface with the slope itself. Critical surfaces bounding sequences could be examined petrographically and isotopically to gain additional evidence for changes in the sedimentary environment.

Published data from platform interiors in the southern Apennines lacks any sequence stratigraphic interpretation, and it should be possible to re-examine some such areas in this way. Improved time-control of platform sediments would also be desirable, although the sparse microfaunas present make this a long-term task.

The subsidence models presented in this thesis might be improved if they could incorporate proprietary borehole data, although few commercial boreholes have penetrated Mesozoic carbonates in the Apennines. Further field stratigraphic data from future studies could readily be incorporated into the data-set, and more sophisticated modelling, allowing for finite rifting times and two-dimensional subsidence modelling along restored cross-section profiles (which are becoming better constrained as seismic reflection processing techniques improve) might then be justified.

The phase of Late Cretaceous renewed crustal extension alluded to in section 6.7.6 could be studied further by checking Cretaceous field exposures other then those already mentioned for structural relationships (rotation of bedding, erosion of structural highs). Sediments associated with such features could be dated to constrain better the timing of onset of renewed differential subsidence and fault movements.

A final promising avenue of research lies in the investigation of zoned carbonate cements by PIXE analysis (section 3.3.2). It is envisaged that the PIXE technique could be combined with isotopic data to provide a clearer picture of the extent and evolution of diagenetic fluid systems. If the data from Gargano dolomites were added to and combined with isotopic and PIXE data from calcites, it might be possible to produce predictive models which estimate the likely aerial extent and continuity of late-stage secondary porosity in carbonate slope systems.

Appendix 1: Subsidence modelling data

Table A1: Crustal Parameters.

Values of model parameters are after Steckler, (1981), Cochran, (1983).

Parameter	Symbol	Value
Lithospheric thickness	l	125 km
Crustal thickness[a]	t_c	31.2 km
Crustal density	ρ_c	2.8 g cm^{-3}
Mantle density	ρ_m	3.33 g cm^{-3}
Sediment density	ρ_s	varies with depth
Seawater density	ρ_w	1.03 g cm^{-3}
Coefficient of thermal expansion[a]	α	3.4×10^{-5} $^{\circ}C^{-1}$
Asthenospheric temperature	T_0	1333 $^{\circ}$C
Thermal diffusivity of lithosphere	K	0.008 cm^2 s^{-1}
Thermal conductivity of lithosphere	K	0.0075 cal cm^{-1} s^{-1} $^{\circ}$C
Lithospheric time constant of thermal decay	τ	62.7 m.y.

[a] The values of these parameters have been chosen so that old (125 km thick) continental lithosphere at sea level is in isostatic balance with oceanic lithosphere containing a 5-km-thick crust which has a ridge crest depth of 2500 m and subsides toward a final depth of 6400 m.

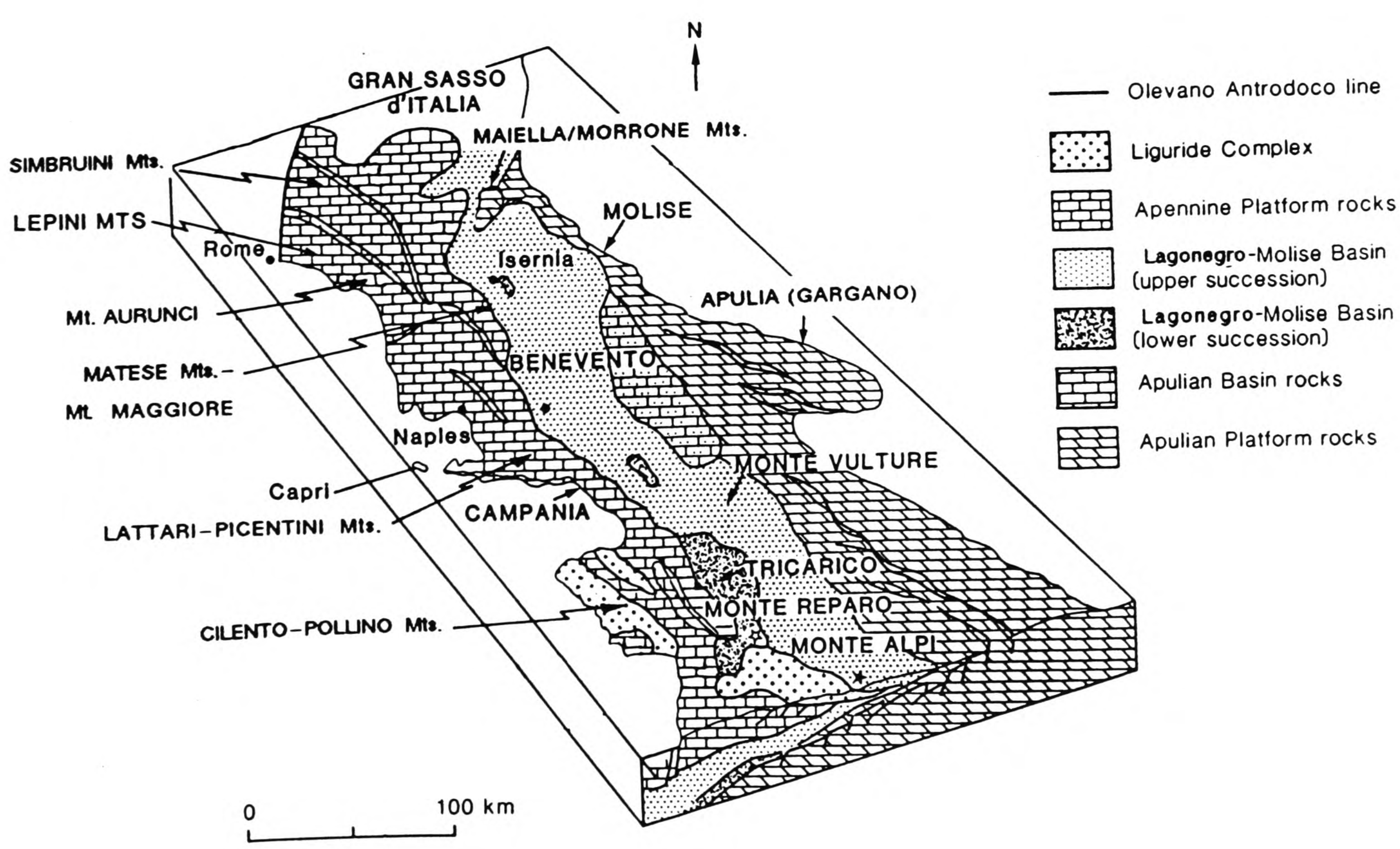
The density of limestone was assumed for calculations to be 2.65 g cm^{-3}.

Details of other parameters used during modelling are given in section 6.7 of the text.

AGE (Ma)	SERIES or STAGE	LITHOLOGY and ENVIRONMENT	STRATIGRAPHIC UNIT	DEPTH (Km)
66.5	Upper Cretaceous	Back–reef lagoon to open shelf rudistid–bearing carbonates	Calcari a Rudiste	0.000
96	Lower Cretaceous	Back–reef lagoon limestones and minor dolomitic intercalations		1.000
131	Dogger–Malm	as above		1.400
179	Liassic (Sinemurian to Toarcian)	as above	Livello a Lithiotis (pp)	2.050
201				2.350

Intermediate (Abruzzi–Campania) carbonate platform (northern part, Simbruini mountains)

Data from Devoto (1967), Devoto and Praturlon (1973), and Parotto and Praturlon (1975), in D'Argenio and Alvarez, 1980



AGE (Ma)	SERIES or STAGE	LITHOLOGY and ENVIRONMENT	STRATIGRAPHIC UNIT	DEPTH (Km)
66.5	Upper Cretaceous	back-reef lagoon to open shelf rudistid-bearing carbonates	Calcari a Rudiste	0.000
95		Bauxite and/or breccias		0.200
96	Lower Cretaceous	Back-reef lagoon limestones with minor dolomitic intercalations		0.201
131	Malm			0.651
152	Dogger			0.900
179	Liassic (Sinemurian to Toarcian)		Livello a Lithiotis (pp.)	1.350
201				1.600

Intermediate (Abruzzi–Campania) carbonate platform
(southern part, Matese–Monte Maggiore)

Data from Catenacci and others (1963) and D'Argenio (1963, 1967), in D'Argenio and Alvarez, 1980

AGE (Ma)	SERIES or STAGE	LITHOLOGY and ENVIRONMENT	STRATIGRAPHIC UNIT	DEPTH (Km)
78	Upper Cretaceous	Back-reef lagoon to open shelf rudistid-bearing carbonates	Altamura limestone	0.000
95		Bauxite		0.854
96	Upper Aptian to Albian	Back-reef lagoon and supratidal carbonates	Bari limestone (pp.)	0.855
110	Barremian to Lower Aptian		Membre a Requieniidae	1.135
116.5	Valanginian to Hauterivian	As above (rarely oolitic limestones)	Membre loferitique	1.435
128	Berriasian	Back-reef lagoon (rarely open shelf or supratidal) limestones	Membre de Borgo Celano	1.525
134		Skeletal limestones with Ellipsactinia, corals and algae		1.755
	Jurassic		Monte Sacro limestone	
201			?thrust repetition of Jurassic	4.900

External (Apulia) carbonate platform
(northern Murges and Gargano peninsula)

Data from Vezzani (1975), in D'Argenio and Alvarez, 1980, Luperto Sinni and Masse (1986, 1987)

AGE (Ma)	SERIES or STAGE	LITHOLOGY and ENVIRONMENT	STRATIGRAPHIC UNIT	DEPTH (Km)
66.5	Upper Cretaceous	Back-reef lagoon to open shelf rudistid-bearing carbonates	Calcari a Rudiste	0.000
96	Lower Cretaceous	Back-reef lagoon carbonates and marls	Marne ad Orbitolina (pp.)	0.600
131	Dogger to Malm	Back-reef lagoon (rarely open-shelf) carbonates	Livello a Cladocoropsis (pp.)	0.950
179	Liassic (Sinemurian to Toarcian)	back-reef lagoon carbonates	Livello a Lithiotis (pp.)	1.300
201	Hettangian			(1.803)
210				2050

Internal (Latium-Campania-Lucanla) carbonate platform (central part, Lattari-Picentini mountains)

Data from De Castro (1962), Scandone and Sgrosso (1965), and D'Argenio (unpublished data), in D'Argenio and Alvarez (1980)

AGE (Ma)	SERIES or STAGE	LITHOLOGY and ENVIRONMENT	STRATIGRAPHIC UNIT	DEPTH (Km)
39.4	Upper Palaeocene to Eocene	Open shelf carbonates		0.000
63		Bauxite		0.185
64	Upper Cretaceous to Lower Palaeocene	Open shelf and back-reef lagoon carbonates		0.186
95		Bauxite		0.685
96	Lower Cretaceous	Open shelf, back-reef and intertidal carbonates with rare palaeosols		0.686
131	Malm	Back-reef lagoon carbonates		1.185
152	Dogger	as above		2.075
179	Upper Lias	as above		2.995
186	Sinemurian to Pliensbachian	as above		3.225
201				(3.725)

External ? (Apulia) carbonate platform
(northern part, Maiella mountains)

Data from Crescenti (1969), in D'Argenio and Alvarez, 1980, and Accarie (1988)

AGE (Ma)	SERIES or STAGE	LITHOLOGY and ENVIRONMENT	STRATIGRAPHIC UNIT	DEPTH (Km)
54	Palaeocene	Open shelf and back-reef lagoon carbonates		0.000
66.5	Upper Cretaceous	Back-reef lagoon to open shelf rudistid-bearing carbonates	Calcari a Rudiste	0.050
96	Lower Cretaceous	Back-reef lagoon carbonates and marls, biolithites in upper part	Marne ad Orbitolina (pp.)	1.050
131	Dogger to Malm	Back-reef lagoon (rarely open shelf) carbonates	Livello a Cladocoropsis (pp.)	1.700
179	Liassic (Sinemurian to Toarcian)	Back-reef lagoon carbonates	Livello a Lithiotis (pp.)	2.350
201	Hettangian			(2.563)
210				2650

Internal (Latium–Campania–Lucania) carbonate platform (northern part, Lepini mountains)

Data from Parotto and Praturlon (1975), in D'Argenio and Alvarez, 1980

AGE (Ma)	SERIES or STAGE	LITHOLOGY and ENVIRONMENT	STRATIGRAPHIC UNIT	DEPTH (Km)
54	Upper Palaeocene	Back-reef lagoon to open shelf Mollusk-bearing carbonates		0.000
60.2	Campanian to Lower Palaeocene	Back-reef lagoon to open shelf Rudistid-bearing limestones and minor dolomitic intercalations	Calcari a Rudiste	0.020
84	Turonian to Santonian			0.080
92	Middle to Upper Cenomanian			0.730
94.5	Lower Cenomanian	Back-reef lagoon lmestones and dolomites with thin palaeosols		0.830
96	Albian	Back-reef lagoon limestones and dolomites		0.980
108	Aptian		Marne ad Orbitolina (pp.)	1.140
113	Neocomian (pp.) to Aptian	As above		1.340
128	Portlandian to Neocomian (pp.)	Back-reef lagoon dolomitic limestones		1.440
136	Bathonian to Kimmeridgian	Back-reef lagoon limestones with minor dolomitic intercalations	Livello a Claricoropsis (pp.)	1.840
165	Bajocian	Back-reef lagoon to open-shelf oolitic limestones		2.240
171	Aalenian			2.390
179	Upper Sinemurian to Toarcian	Skeletal buildup to back-reef carbonates	Livello a Lithiotis (pp.)	2.450
197.5	Lower Sinemurian	Back-reef lagoon dolomites and limestones		2.800
201				2.864

Internal (Latium–Campania–Lucania) carbonate platform (northern part, Aurunci Mountains)

Data from Chiocchini and Mancinelli (1977)

AGE (Ma)	SERIES or STAGE	LITHOLOGY and ENVIRONMENT	STRATIGRAPHIC UNIT	DEPTH (Km)
54	Upper Cretaceous to Palaeocene	Back–reef lagoon to open shelf rudistid–bearing carbonates	Calcari a Rudiste	0.000
96	Lower Cretaceous	Back–reef lagoon carbonates and marls	Marne ad Orbitolina (pp)	0.800
131	Malm	Back–reef lagoon carbonates	Livello a Cladocoropsis (pp)	1.250
152	Dogger	back–reef lagoon carbonates		1.700
179	Liassic (Sinemurian to Toarcian)	back–reef lagoon carbonates	Livello a Lithiotis (pp)	2.450
201	Hettangian	as above		(2.663)
210				2.750

Internal (Latium–Campania–Lucania) carbonate platform (southern part, Cilento and Pollino mountains)

Data from Parotto and Praturlon (1975) in D'Argenio and Alvarez, 1980

LOCALITY	Mean exponential	Maximum exponential	Minimum exponential	Sum square of residuals	Cross-over date (Ma)
Apulia (Gargano Peninsula)	3.623	4.000	2.113	0.029	80.8
Monte Aurunci	1.752	2.153	1.489	0.235	95.3
Maiella/Morrone Mts.	2.154	3.181	1.710	0.036	99.7*
Cilento/Pollino Mts.	1.699	2.043	1.462	0.001	91.9
Lattari/Picentini Mts.	1.458	1.618	1.326	0.043	83.9
Lepini Mts.	1.633	1.913	1.429	0.202	86.5
Simbruini Mts.	1.554	1.780	1.381	0.090	87.0
Matese Mts. (northeast)	1.517	1.711	1.363	0.055	108.7
Matese Mts. (D'Argenio and Alvarez, 1980)	1.441	1.589	1.318	0.015	111.2
Matese Mts. (Pietraoia)	1.378	1.480	1.273	0.008	86.9

Appendix 2: Calculation of footwall uplift.

A2.1 Calculation of footwall uplift

The calculation presented here follows the method of Jackson *et al.*, (1988).

Table A2: Parameters used to calculate initial subsidence, S_1.

Parameter	Symbol	Value
Thickness of lithosphere	a	125 km
Thickness of crust	t_c	30 km
Density of mantle (at 0°C)	ρ_m	3.35 g cm^{-3}
Density of crust (at 0°C)	ρ_c	2.78 g cm^{-3}
Density of seawater	ρ_w	1.03 g cm^{-3}
Density of (carbonate) sediments	ρ_s	2.65 g cm^{-3}
Density of mantle (asthenosphere) at 1333°C	ρ_a	calculated from ρ_m and α
Coefficient of thermal expansion	α	3.28×10^{-5} °C^{-1}
Temperature of asthenosphere	T_1	1333°C

The amount of uplift to be calculated is for an initial fault spacing, d, of 30 km, with an initial fault plane dip. Θ_0. of 60°. which will undergo a 5° rotation (rotation angle ψ = 5°) to a final dip, Θ_1, of 55°.

With this initial configuration, the amplitude of sawtooth topography between adjacent fault blocks is given by the quantity F, where

$F = d \sin \psi$

i.e. $F = 30 \sin 5°$

i.e. $F = 2.61$ km

The amount of extension, β, is given by

$\beta \sin \Theta_1 = \sin \Theta_0$

In this case, $\beta = \sin 60° / \sin 55°$

i.e. $\beta = 1.057$

The initial overall subsidence, S_1, is given by the expression

$$S_1 = \frac{a\left[(\rho_m - \rho_c)\frac{t_c}{a}\left(1 - \frac{\alpha T_1}{2}\frac{t_c}{a}\right) - \frac{\alpha T_1}{2}\rho_m\right]}{\rho_m(1 - \alpha T_1)}(1 - 1/\beta) \qquad (1)$$

Using the values of parameters given above this reduces to

$$S_1 = 2.46(1 - 1/\beta)$$

so here $S_1 = 2.46(1 - 1/1.057)$

$= 0.133$ km

The additional subsidence due to sediment loading, σ, is given by

$$\sigma = F\left(\frac{\rho_a}{\rho_s}\right) - y - \sqrt{F\frac{\rho_a}{\rho_s}\left(F\frac{\rho_a}{\rho_s} - 2y\right)} \qquad \textbf{(2)}$$

where $y = \frac{F}{2} + S_1$

i.e. $y = 1.440$ km

so, substituting values of ρ_s and ρ_a given above into equation **(2)** yields a value of

$\sigma = 0.707$ km

From the above calculations, the magnitude of uplift of the footwall crests, U, is

$$U = \frac{F}{2} - S_1 - \sigma$$

i.e. $U = 1.307 - 0.133 - 0.707$

$U = 0.468 \approx 0.470$ km

A2.2 Discussion

This amount of uplift is the amount that would be predicted from the Cretaceous stratigraphic record in the Matese mountains. Stratigraphic data from Pietraoia and the Northeastern Matese (Cestari *et al.*, 1975; localities in figure 32) yield approximately 0.690-0.720 km of differential subsidence in Cretaceous strata when suitable correction has been made for sediment compaction (see section 6.7). Since the two localities are approximately 10 km apart (figure 32) and are not thought to be separated by any major tectonic structures (section 4.5), this amount of differential subsidence corresponds to a rotation of the pre-Cretaceous substratum of between 4-5°. For this reason, a value of 5° rotation between initial and final fault dips was chosen. About 50% of this rotation is due to a tectonic tilt, and 50% is caused by sediment loading. The surface expression of renewed Late Cretaceous crustal extension in the southern Apennines is therefore small (≈2-2.5°) rotations of large normal faults.

with extension values, β in the range β = 1.05-1.15. The fault block under examination in this example is likely to have formed during the Jurassic (?Liassic) rather than in the Cretaceous since new field evidence (chapter 4; in agreement with D'Argenio *et al.*, 1986b) has demonstrated the existence of a platform-margin in the area adjacent to and to the north of the Matese mountains during the Jurassic and Early Cretaceous, in an area that was formerly part of a broader carbonate platform. Many authors have put forward evidence for Jurassic crustal extension in the southern Tethyan area (see section 6.7.2 and references therein), and the most likely reason for the formation of a platform-margin at this time is by means of extensional tilt-block formation. The 30 km size (fault spacing) of the Matese mountains fault-block is derived from Late Cretaceous to Early Tertiary sedimentary facies and palaeocurrent patterns in the area observed during field studies and by examination of f.161 (Isernia) of the Carta Geologica d'Italia, and data from Pironon (1980) (see section 4.9). Cross-section 10 of Mostardini and Merlini (1986; figure 36) shows a present-day major normal fault structure in approximately the position of the inferred southern boundary of the Mesozoic Matese mountains fault block. The thickness of the Triassic-Early Jurassic shown on this section changes abruptly across this structure, suggesting that this was in fact the site of an important Mesozoic fault.

The true size of the fault block depends on how much Apennine thrust shortening has taken place across the area. A recent structural interpretation of the frontal zone of the Apennine thrust belt in the Molise district (Cello *et al.*, 1989; figure 36), based on both field and seismic evidence, shows a relatively simple ramp anticline-type structure at the surface in the Matese mountains, cut by listric faults at depth. This interpretation is very similar to that shown in cross-section 10 of Mostardini and Merlini, (1986) through the Matese mountains, again based on borehole and extensive regional seismic coverage. These two data lend some confidence to field observations from the area (chapter 4) which lead to the interpretation of the local structure as a single major thrust sheet, preserving a more-or-less intact Mesozoic carbonate platform-to basin transition, albeit strongly modified by Miocene to Recent normal faults.

Erosion of large amounts of sediment by a footwall uplift mechanism could explain in large part the enigmatic unconformities of the Late Cretaceous which are so common in both Italy and Yugoslavia, and are associated with large amounts of erosion of older strata (section 6.7.5). In the Matese mountains, stratigraphic data and subsidence modelling suggest that erosion took place between Late Aptian-Early Albian (when differential subsidence commenced) and Late Campanian times (when onlapping sediments began to cover the eroded platform surface), implying a minimum rate of footwall uplift of approximately 13-16 mmy^{-1}. Stratigraphic data and facies patterns from other areas in the southern Apennines, particularly the Maiella mountains, could also be interpreted in a similar way. The Maiella mountains formed an isolated structural high (tilt-block crest?) surrounded by carbonate slopes during the Late Cretaceous (Accarie, 1987). Subsidence modelling of this area (section 6.7; figure 104c) show a different form of subsidence for the Cretaceous as compared with other areas. A cross-over between tectonic subsidence (calculated from stratigraphic data) and subsidence predicted from simple stratching models occurs, in common with other areas. However, the data from the Maiella show consistently less subsidence than predicted by the best-fit model cooling curve, the opposite situation to other areas modelled. This could be explained by the sampling of stratigraphic data for the Maiella (from the presently exposed Mesozoic platform carbonates) from a position on what geological map and field studies (Accarie, 1987) suggest could have been a structural high forming part of a large extensional tilt-block structure, which, although slowly subsiding, was uplifted relative to surrounding areas and therefore records less tectonic subsidence than predicted by simple thermal cooling models. This example serves as a caution to interpretation of one-dimensional subsidence modelling data from a single locality, and every effort has been made to make a true regional interpretation (section 6.7) by averaging subsidence data from several areas in order to eliminate the effects of local differential subsidence.

Appendix 3: Micropalaeontology and Nannofloral Studies.

Micropalaeontological and nannofloral analyses were undertaken in collaboration with the Stratigraphy Branch, British Petroleum Research International Limited, Sunbury-upon-Thames. Drs. M.D. Simmons and A.A.H. Wonders kindly undertook micropalaeontological work, whilst J. Pearce carried out nannofloral determinations.

A3.1 Micropalaeontology

Conventional 30µm unpolished thin-sections mounted on glass with epoxy resin, both stained and unstained, with and without coverslips, were used for analysis. Uncovered specimens were coated with emersion oil before analysis. Staining was carried out using the method described by Dickson (1963) for a combined stain of Alizarin Red-S and Potassium Ferricyanide. By this mehod, calcite stains in shades of pink, dolomite remains uncoloured, and ferroan dolomite is coloured blue. A Nikon microscope with Nikon UFX 100 photographic attachment were used for viewing specimens with x40, x100 and x400 total magnification. Ilford FP4 100ASA black and white print film was used for photography.

A3.2 Nannofloral analysis

Specimens for analysis were crushed and mounted on glass slides by suspension in aqueous solution and smearing onto the slide surface. Observation was by means of a Nikon microscope with x400 and x512 total magnification. Photomicrographs were taken with a Nikon camera using Kodak Technical Pan 100ASA black and white print film.

Micropalaeontological and Nannofossil results

(Analysis carried out by Dr. M.D. Simmons and J. Pearce)

Overall age of each specimen is indicated next to the specimen number. Sample localities in the Matese mountains and Gran Sasso are indicated in figures 32, 74. For localities in Campania, see Carta Geologica d'Italia f.161 (Isernia), f.162 (Campobasso), f.173 (Benevento). The Maiella mountains are covered by f.147 (Lanciano), Rieti mountains by f.139 (L'Aquila), and the Gargano by f.157 (Mt. S. Angelo). Sample numbers relate to measured sections (enclosure 1).

Locality/No.	Microfossils	Age	Zone
Gran Sasso d'Italia			
Mt. Corvo			
8.111	Early Cenomanian?		
	Rotalipora sp.	Late Albian to Cenomanian	
	Preglobotruncana sp.	Early to Middle Cenomanian	
8.112	Middle Cenomanian		
	Rotalipora monsolvensis/		*R. cushmani*
	Rotalipora cushmani		
	Rotalipora appenninica	Middle Cenomanian	
	Orbitolina conica		
8.113	*Orbitolina* sp.	Middle Cenomanian	
8.114	Middle Cenomanian		
	Rotalipora sp.	Late Albian to Cenomanian	
	Orbitolina sp.	Middle Cenomanian	
8.115	*Orbitolina* sp.	Middle Cenomanian	
8.116	Middle to late Cenomanian		
	Rotalipora sp.- *R. cushmani* gp.		
	Preglobotruncana gibba	Middle to Late Cenomanian	
8.117		Cenomanian	
8.118	*Rotalipora* sp.	Cenomanian	
8.120	Santonian to Coniacian (lower *G. Elevata* zone)		
	Globotruncana sp.		
	Marginotruncana coronata	Santonian to Coniacian	top *H. helvetica* to lower *G. elevata*
	Globotruncana linneiana gp.	Upper Turonian to Maastrichtian	*D. asymetrica* or younger
	Rotalipora sp.		
8.121	Campanian		
	Rotalipora linneiana gp.		
	Globotruncanita sp.	Campanian to Maastrichtian	
	Pseudotextularia sp.		
nannoflora			

	Watznaueria barnesae	Coniacian to Maastrichtian	
	Cretarhabdus crenulatus	assemblage	
	Micula staurophora		
	Discorhabdus ignotus		
	Cribosphaera ehrenbergi		
	Lithraphidites carniolensis		
8.122	*Orbitoides media*	Early late Campanian	*G. stuartiformis* to middle *G. subspinosa*
8.125	Upper Maastrichtian (middle to upper *G. gansseri* to top *A. mayaroensis*)		
	Contusatruncana (=*Globotruncana*) *contusa* (=*Rosita contusa*)	Maastrichtian	middle to upper *G. gansseri* to top *A. mayaroensis*
	Globotruncana linneiana sp.		*D. asymetrica* to *A. mayaroensis*
	Globotruncanita sp.		
	Globotruncana bulloides	Early to Middle Maastrichtian	top *D. asymetrica* to *G. gansseri*
	Siderolites sp.	Maastrichtian	
8.127	Late Maastrichtian		
	Orbitoides sp.	Late Campanian to Maastrichtian	
	Orbitoides apiculata?	Late Maastrichtian	*G. stuarti* to *G. mayaroensis*
	Globotruncanita sp.		
	Upper Maastrichtian (middle to upper *G. gansseri* to top *A. mayaroensis*)		
8.129	?Early Palaeocene-K/T boundary		
	Siderolites sp.	Maastrichtian	
	Discocyclina sp.	?Palaeocene to Eocene	
	Orbitoides sp.	Upper Cretaceous (?Maastrichtian)	
	Siderolites calcitropoides sp.	Maastrichtian	
	Miliolid sp.		
8.130	Late Palaeocene (P3-P4)		
	Morozzovella sp.	Early Palaeocene to Late Eocene	
	Morozovella angulata?	Late Palaeocene	P3A to P4
	Planorotalites sp.		
nannoflora			
	Coccolithus pelagicus	Eocene assemblage	
	Placolith (indet.)		
	Sphenolithus sp.		
	Chiasmolithus solitus		
	Ericsonia formosa		

Pizzo d'Intermesoli

8.133	Albian		
	Ticinella sp. (*T. primula*?)	Albian to Late Albian	*T. primula* to *R. ticinensis*
	Hedbergella sp.	Barremian to Cenomanian	
	Orbitolina sp.		
	Ticinella primula?		*T. primula* to *R. ticinensis*
8.134	*Preglobotruncana* sp.+*Ticinella* sp.= Middle to Late Albian		
	breggiensis+*buxtofi* = lower *buxtofi* zone (upper *R. ticinensis* zone)		
	Biticinella sp.		
	Rotalipora ticinensis-Rotalipora subticinensis transition forms		upper *R. subticinsensis* to lower *R. ticinensis*
	Biticinella breggiensis	Late Albian	
	Planomalina buxtofi?		upper *R. ticinensis* to *R. appenninica*
	Hedbergella planispira	Early Aptian to Early Coniacian	upper *S. cabri* to *D. primitiva*
	Preglobotruncana sp.?		
	Radiolaria		
8.135	Within *ticinensis* zone (lower half of *buxtofi* zone) (Middle to Early Late Albian)		
	Pseudothalmanninella (=*Rotalipora*) *ticinensis* gp.		lower *buxtofi* zone?
	Miliola nezzazata		
	Hedbergella sp.		
	Orbitolina sp.		
8.136	Late Albian		
	Orbitolina sp.		
	Orbitolina subconcava	Late Albian	
	Orbitolina cuvillieri	Late Albian	
8.137	Middle Cenomanian		
	Hedbergella simplex		
	Preglobotruncana sp.		
	Rotalipora sp. (sensu stricto)		
	Rotalipora appenninica		base of *R. cushmani* zone/top of *R. reicheli* zone.
	Rotalipora cushmani gp.		*R. cushmani*
	Rotalipora-Ticinella transition forms		
	Ticinella subticinensis		
	Orbitolina sp.	Middle Cenomanian or older	
8.138	Middle Cenomanian or older		
	Rotalipora cushmani gp.		

	Preglobotruncana sp.		
	Favusella sp.	Middle Cenomanian or older	
	Rotalipora appenninica		*R. appenninica* to middle *R. cushmani*
	Thalmaninella (=*Rotalipora*) sp.		
	Orbitolina sp.		
8.139		Middle Cenomanian	
8.140	*Rotalipora* sp.	Middle to Late Cenomanian?	
8.141	*Marginotruncana* sp.	Turonian or younger	
nannoflora			
	Watznaueria barnesae	Bajocian to Maastrichtian	
8.142	*Globotruncanita elevata?*	Santonian to Campanian	
8.143	*Globotruncana linneiana* gp.	Santonian or younger	
8.144	Middle Cenomanian		
	Rotalipora cushmani gp.	Late Cenomanian	
	Orbitolina conica	Early to Middle Cenomanian	

(ascending order 139, 144, 143, 141, 142, 140)

Mt. Corvo II

8.157	Early Maastrichtian		
	Heterohelix sp.	Maastrichtian	
	Globotruncanita sp.		
	Siderolites sp.		
	Globotruncana sp.		
8.158	Early Maastrichtian		
	Orbitoides sp.		
	Siderolites calcitrapoides	Latest Campanian to Early Maastrichtian	
	Globotruncanita sp.		
	Globotruncana sp. (advanced)		
8.159	"Middle" to Late Maastrichtian		
8.159	*Globotruncana* sp.		
	Planoglobulina sp. (=*Sigalia*)	"Middle" to Late Maastrichtian	
8.160	Late Maastrichtian		
	Globotruncana sp. (advanced)		
	Rosita sp.		middle to upper *G. gansseri* to *A. mayaroensis*
8.161	*Orbitoides apiculata*	"Middle" Maastrichtian?	*G. stuarti* to *G. mayaroensis*
8.163	*Omphalocyclus macroporus*	Early to "Middle" Maastrichtian	as 161
	Globotruncanita sp.		
8.164	Maastrichtian		
	Siderolites sp.		
	Orbitoides sp.	Maastrichtian	

	Discocyclina sp.	Tertiary?
	Red algae	
8.165	Early Palaeocene?	
	Globotruncanita sp.	"Middle" Maastrichtian
	Sigalia sp.	Maastrichtian
	Early Palaeocene?	
8.166	Eocene	
	Dictyoconus sp.	
	Distichoplax biserialis (alga)	latest Palaeocene to early Eocene
	Lithothamnium sp. (alga)	
	Rotalia sp.	
	Morozovella sp. (primitive forms)	
	Planorolites sp. (*P. chapmanii* gp.)	P3 to P6
	Bacillogypsinoides sp.	Eocene
	Subbotinia sp.	
	Globorotalia sp. (*G. pusilla* gp.)	Late Palaeocene
8.167	Early to Middle Eocene	
	Nummulites sp.	Tertiary
	Aveolina sp.	
	Orbitolites sp.	Early to Middle Eocene
8.168	Uppermost Middle Eocene/Lowermost Late Eocene (P13-P14)	
	Turborotalia sp.	
	Nummulites sp.	Latest Middle to Earliest Late Eocene
	Assilina sp.	Middle Eocene or older
	Turborotalia cerroazulensis	Latest Middle Eocene
	Discocyclina sp.	

Pizzo Cefalone

PC244	*Cayeuxia* sp. (alga)	Late Jurassic to Early Cretaceous
PC249	Bajocian-Maastrichtian nannoflora	
	Cyclagelosphaera margerelii	
	Watznaueria barnesae	
	Parhabdolithus embergeri	
PC261	Early Aptian association	
	Palorbitolina lenticularis	Late Barremian to Early Aptian
	Pseudocyclammina vasconica	Valanginian to Early Aptian
PC262	Cretaceous (Berriasian-Maastrichtian) nannoflora	
	Watznaueria barnesae	
	Cretarhabdus angustiforatus	
PC264	Aptian	
	Orbitolina sp.	Late Barremian to Cenomanian
	Bryozoan	

	Favosella sp.		
	Hedbergella sp.	Aptian	
PC266	Early Cretaceous		
	Lithocodium aggregatum (alga) (=*Bacinella* sp.)		
	Palaeodyctioconus sp.?		
	Orbitolinopsis sp.	Early Cretaceous	
PC267	Late Aptian		
	Hedbergella trochoidea	Late Aptian	upper *G. algeriana* to *T. bejaouensis*
	Hedbergella sp.		
nannoflora			
	Watznaueria barnesae		
	Lithastrinus planus		
Albian-Cenomanian?			
PC268	*Orbitolina* sp.		
	Red Algae		
PC269	Earliest Albian		
	Hedbergella sp.		
	Ticinella bejaouensis? (primitive)	Early Albian	
	Orbitolinopsis sp.	Aptian to Albian	
PC270	*R. breggiensis/R. subticinensis* zones		
	Orbitolina sp.	Late Albian to Early Cenomanian	
	Hedbergella sp.		
	Ticinella (advanced)-*Rotalipora* (primitive) transition forms	Late Albian	*R. breggiensis/ R. subticinensis* boundary
PC271	Late Albian		
	Orbitolina sp. (advanced)	Late Albian	
	Ticinella sp. (primitive *Rotalipora* sp.?)		
PC272	Late Albian		
	Orbitolina sp.		
	Hedbergella sp.		
	Ticinella sp.	Late Albian	

nannofossils

8.100 Berriasian-Maastrichtian assemblage
Watznaueria barnesae
Lithraphidites carniolensis
Cretarhabdus crenulatus

8.101 Barremian-Early Aptian (probably Early Aptian)
Nannoconus steinmanni
Watznaueria barnesae

Micrantholithus obtusus
Lithraphidites carniolensis
Parhabdolithus embergeri
Cyclagelosphaera margereli

Acquare delle Formica

nannoflora
8.259 Bajocian-Maastrichtian
Watznaueria barnesae
Nannoconus sp.
8.260 Late Jurassic to Early Cretaceous
Cayeuxia sp. — Late Jurassic to Aptian/Albian
nannoflora
Watznaueria barnesae — Bajocian to Maastrichtian
8.257 Late Barremian
Orbitolina sp. — Barremian to Cenomanian
Palaeodictyconus balkanensis — Late Barremian

Mt. S. Franco

SF227		Early Aptian to Albian	
SF228	*Coptocampylodon fontis* (alga)	Barremian to Aptian	
SF229	Aptian		
	Coptocampylodon fontis (alga)	Barremian to Aptian	
	Hedbergella sp. (simple forms)		
	Charentia cuvillieri	Aptian to Albian	
SF230	*Trochoidea* sp.	Late Aptian	
SF231	Aptian		
	Wetherodella sp.	Aptian	
	Lithocodium sp. (alga)		
SF232	Late Aptian		
	Orbitolina sp.		
	Hedbergella trochoides	Late Aptian	Upper *G. algeriana* to *T. bejaouensis*
SF235	*Orbitolina* sp.	Late Barremian to Early Cenomanian	

Sella di Mt. Corvo

8.107 Early Miocene. Aquitainian to Burdigalian?
8.107 *Miogypsina* sp.
Lepidocyclina sp.

Pizzo Camarda

nannoflora
8.218 *Coccolithus pelagicus* — Tertiary
8.220 Eocene assemblage
Coccolithus pelagicus

Sphenolithus spp.
Calcispheres
Chiasmolithus solitus
Sphenolithus radians
T. crassus?

8.222 Middle Eocene?
Coccolithus pelagicus
Sphenolithus sp.
T. crassus

8.229 Tertiary + reworked Cretaceous
Watznaueria barnesae (reworked)
Reticulofenestra sp.

Valle dell'Rio Arno

8.272 Berriasian to Maastrichtian
Watznaueria barnesae
Nannoconus sp.
Lithraphidites carniolensis

Matese Mountains

La Gallinola

8.77	*Miliola* sp.	
8.79	*Discorbia* sp.	
8.81	*Miliola* sp.	
8.82	*Lithocodium* sp. (alga)	Cenomanian or older

Mt. Croce

8.56	*Globotruncana lineiana* gp.	Campanian to Middle Maastrichtian
8.59	*Discorbia* sp.	
	Miliola sp.	
8.60	*Haplophragmoides* sp. (primitive)	Late Jurassic to Early Cretaceous
8.61	Campanian	
	Orbitoides sp.	Campanian to Maastrichtian
	Orbitolina sp.	Early to Middle Cretaceous
8.62	*Orbitoides* sp.	Campanian
8.63	*Late Palaeocene to Early Eocene assemblage	
	Distichoplax biserialis (red alga)	Palaeocene to Eocene
	Discocyclina sp.	
	Ascilina sp.*	
	Orbitoides sp.	Campanian to Maastrichtian
	Alveolina sp.*	
	Morozovella angulata gp.*	

nannoflora

8.14 Tertiary
Dictyoccoccites sp.
Reticulofenestra sp.
8.15 Miocene to Early Pliocene
Reticulofenestra pseudoumbilica
Reticulofenestra minuta Miocene to Early Pliocene
8.17 Early Miocene-Early Pliocene assemblage (Early to Middle Miocene NN6-8?)
Calcidiscus macintyrei
Reticulofenestra minuta
Reticulofenestra pseudoumbilica
Coccolithus pelagicus
Helicosphaera carteri
Sphenolithus sp.
Geminilithella jafari
Discoaster brouweri
Geminilithella rotula
8.18 Early Miocene to Early Pliocene (NN4-NN15) (Early Tortonian or older)
Reticulofenestra pseudoumbilica
R. minuta
Coccolithus pelagicus
Helicosphaera carteri
Calcidiscus macintyrei
Calcispheres
8.305 Miocene (NN4-11) + reworked Palaeocene to Oligocene and Cretaceous
Scyphosphaera lagena
Helicosphaera carteri
Reticulofenestra pseudoumbilica
Coccolithus pelagicus
Calcidiscus macintyrei
Watznaueria barnesae (reworked)
Dictyococcites bisectus (reworked)

Mt. Valle Diamante
8.41 *Cayeuxia piae* (alga) Late Jurassic

Frosolone
8.87 Early Eocene
Alveolina schwagerii Early Eocene
Nummulites sp.
SCA I 27.9
Morozovella sp. Middle to Late Palaeocene
2.10 II *Siderolites calcitropoides* Maastrichtian
2.10 III Eocene + Late Jurassic to Early Cretaceous reworking
Trocholina conica (lithoclast) Late Jurassic

3.10 II	*Miliola* sp.	
	Calcareous algae	
4.10 I	Eocene	
WET2 28.9	Eocene	
	Lithothamnium sp. (alga)	
	Rotalia sp.	
	Chapmaninae sp.	Eocene
28.9+	*Globigerina* sp.	Eocene
XLN2 30.9		
	Cayeuxia sp. (alga)	Late Jurassic to Early Cretaceous
29.9 III	Eocene to Oligocene	
DOL1 30.9	Eocene + Cretaceous reworking	
	Globergerinopsis sp.	Eocene
DOL2 2.10		
	Siderolites sp.	Early Maastrichtian

Macchiagodena

7.51	Maastrichtian + Early Cretaceous reworking	
	Orbitoides sp.	Maastrichtian
	Miliola sp. (lithoclast)	

S. Angelo in Griotte

7.132	Barremian to Aptian (lithoclast)	
	Triploporella sp. (calcareous alga)	
	Cuneola sp.	
7.133	*Orbitoides* sp.	Late Cretaceous
7.138	*Trocholina* sp.	Late Jurassic
7.140	*Orbitoides* sp.	Maastrichtian

S. Polo Matese

SPM294	Cenomanian?	
	Orbitolina sp.	
	Numuloculina sp.	Cenomanian?
SPM295	(Neptunian dyke)	Basal Middle Miocene
SPM296	*Orbitolina* sp.	Middle Cretaceous
SPM297	Aptian-Albian?	
	Cuneolina laurentii/ camposaurii	Valanginian to Late Albian
SPM300	*Orbitolina conica*	Early Cenomanian

Pesche

P68	*Trocholina* sp.	Triassic to Cretaceous
P80	Late Berriasian to Early Hauterivian?	
	nannoflora	
	Watznaueria barnesae	

Cruciellipsis cuvillieri
Rucinolithus sp.

P83 Late Jurassic
Trocholina umbo? (lithoclast) — Kimmeridgian to Tithonian
Cayeuxia moldavici — Kimmeridgian to Tithonian

P84 *Calpionella* sp. (=Tintinnids) — Tithonian to Valanginian

nannoflora

8.5 *Watznaueria barnesae* — Bajocian to Maastrichtian

8.6 *Watznaueria barnesae* — Bajocian to Maastrichtian
Placoliths (indet.)

8.94b Berriasian-Campanian assemblage
Watznaueria barnesae
Lithraphidites carniolensis
Maniuitella pemmatoidea
Biscutum ellipticum

8.299 *Watznaueria barnesae* — Bajocian to Maastrichtian

Carpinone

87.66 *Lithocodium* sp. (reworked alga) — Latest Jurassic to Early Cretaceous

Morgue Quadra (Frosolone)

MQ103 *Trocholina* sp.
Miliola sp.
Red algae

MQ104 Late Jurassic to Early Cretaceous lithoclasts
Cayeuxia sp. — Tithonian to Kimmeridgian

Campitello Matese

7.10 IV *Cayeuxia* sp. — Late Jurassic to Early Cretaceous

Pietraoia

PT3 *Miliola* sp. (reworked)

10.10 III *Trocholina elongina*
Trocholina gigantea
Trocholina alpina

10.10 V Late Cretaceous
Dasyclina sclumbergeri — Late Cretaceous
Miliola sp. (reworked)

10.10 VI *Globotruncana* sp. — Late Cretaceous

Miranda

8.7 *Watznaueria barnesae* — Bajocian to Maastrichtian

Campania

Mt. Coppe

nannoflora

8.89 Campanian assemblage
Microrhabulus decoratus
Quadrum trifidum
Cretarhabdus crenulatus
Micula staurophora
Lithraphidites carniolensis
Cribrosphaera ehrenbergi
Eiffellithus turnzeiffeli
Predizcosphaera cretacea
Watznawaria barnesae
Broinsonia parca
Arkhangelskiella cymbiformis
Biscutum ellipticum
Ahmeuerella octoradiata
Calculites ovalis
Lucianorhabdus maleformis
Ceratolithoides aculeus
Quadrum gartneri

Mt. Camposauro

MC11.10 I	Barremian to Aptian	
	Orbitolinopsis sp.	
	Miliola sp.	
	Orbitolina sp.	
	Cayeuxia sp. (alga)	Early Cretaceous
	Bacinella sp. (alga)	Early Cretaceous
15.9 I	Early Cretaceous	

Maiella Mountains

Maiella West Wall

8.27	*Salpingoporella dinarica* (alga)	Late Aptian or older
8.26	*Miliola* sp.	
	Textularia sp. (simple forms)	

Rieti Mountains

Mt. Terminillo

T149 Bajocian to Albian
nannoflora
Watznaueria barnesae

Watznaueria britannica

Mt. Valloni (Rieti Mts.)

RV215	Bajocian to Kimmeridgian nannoflora *Watznaueria barnesae* *Crepidolithus crassus*	

Gargano Peninsula

MAT1 16.9	*Hedbergella* sp.	
MAT2 16.9	Cenomanian? *Orbitolina* sp. Calcareous algae	
MSA IV 25.9		Turonian or younger
MSA 18.9	*Orbitolina* sp.	Late Barremian to Aptian?
MSA DR	*Orbitoides* sp.	Late Cretaceous
MA2	Late Cretaceous	

References

ABBOTS, F. V., 1988. Controls on contrasting sandbody architectures in resedimented oolitic units from rift systems of the Mediterranean Jurassic. In: *Abstracts of Am. Ass. Petrol. Geol. Mediterranean Basins Conference,* Nice, September 25-28, 1988.

ACCARIE, H., 1987. Dynamiques sedimentaire et structurale au passage plate-forme/ bassin. Les facies carbonatés Crétacés et Tertiaires: Massif de la Maiella (Abruzzes, Italie). *Thèse doctorale,* Ecole des Mines de Paris, Mémoires des Sciences de la Terre, **5**, 162pp..

ACCARIE, H., AND BEAUDOIN, B., 1988. Dynamique de la transition plate-forme/ bassin en domaine carbonaté: Le Crétacé supérieur du massif de la Maiella (Abruzzes, Italie). *C. R. Acad. Sci. Paris,* t.**307**, Série II, 1245-1250.

ACCORDI, G., CARBONE, F., AND SIRNA, G., 1982. Relationships among tectonic setting, substratum, and benthonic communities in the Upper Cretaceous of Northeastern Matese (Molise, Italy). *Geol. Romana,* **21**, 755-793.

ACCORDI, G., CARBONE, F., AND SIRNA, G., 1987. Presenza di Senoniano a rudiste lungo il margine Aquilano del Gran Sasso. *Rend. Soc. Geol. It.,* **10**, 79-82.

ADAMOLI, L., BERTINI, T., CHIOCCHINI, M., DEIANA, G., MANCINELLI, A., PIERUCCINI, U., AND ROMANO, A., 1978. Ricerche geologiche sul Mesozoico del Gran Sasso d'Italia (Abruzzo). II. Evoluzione tettonico-sedimentaria dal Trias superiore al Cretaceo inferiore dell'area compresa tra il Corno Grande e S. Stefano di Sessano (F. 140 Teramo). *Studi Geologici Camerti,* **4**, 7-17.

ADAMOLI, L., BERTINI, T., CHIOCCHINI, M., DEIANA, G., MANCINELLI, A., PIERUCCINI, U., AND ROMANO, A., 1982a. Ricerche geologiche sul Gran Sasso d'Italia (Abruzzo). V. Evoluzione tettonico-sedimentaria dal Trias superiore al Cretaceo inferiore dell'area compresa tra M. Camicia e Ofena (F. 140 Teramo). *Studi Geologici Camerti*, **7**, 89-95.

ADAMOLI, L., BERTINI, T., DEIANA, G., PIERUCCINI, U., AND ROMANO, A., 1982b. Ricerche geologiche sul Gran Sasso d'Italia (Abruzzo). VI. Primi risultati dello studio strutturale della catena del Gran Sasso d'Italia (F. 140 Teramo). *Studi Geologici Camerti*, **7**, 97-103.

ADAMOLI, L., MANGANELLI, V., PIERUCCINI, U., AND ROMANO, A., 1982c. Richerche geologiche sul Gran Sasso d'Italia (Abruzzo). VII. La zona tra Valle Fredda e Valle dell'Inferno (Provv. di L'Aquila e Teramo). *Studi Geologici Camerti*, **7**, 105-113.

ADDY, S.K. AND BUFFLER, R.T., 1984. Seismic stratigraphy of shelf and slope, northeastern Gulf of Mexico. *Bull. Am. Ass. Petrol. Geol.* **68**, 1782-1789.

AGUAYO, C.J.E., BASANEZ, L.M.S, BELLO, M.R., PIMIENTA, L.M., AND SOSA, P.A., 1985. Tectonic evolution and sedimentary environments during the Mesozoic at Reforma- Jalpa area, southeast Mexico. In: *Deep-Water Carbonates: Buildups, Turbidites, Debris Flows, and Chalks* (Eds. Crevello, P.D., and Harris, P.M.), *Soc. Econ. Paleont. Miner. Core Workshop*, **6**, 249-265.

AIGNER, T., DOYLE, M., LAWRENCE, D., EPTING, M., AND VAN VILIET, A., 1989. Quantitative modeling of carbonate platforms: Some examples. In: Controls on carbonate platform and basin development (Eds. Crevello, P.D., *et al.*), *Spec. Publ. Soc. Econ. Paleont. Miner.* **44**, 27-37.

ALBERTI, A., 1953. Osservazioni preliminari sulla geologia dell'Appennino centrale, Foglio 139 (L'Aquila) e Foglio 140 (Teramo). *Boll. Serv. Geol. It.*, **75**, 638-643.

ALBERTI, A., 1954. Nota preliminare sul rilevamento geologico dell'Appennino abruzzese: Foglio 140 Teramo III SW e SE (Gran Sasso d'Italia). *Boll. Serv. Geol d'It.*, **76**, 407-411.

ALBERTI, A., 1956. Nota preliminari sul rilevamento geologico dell'Appennino abruzzese (F.140 Teramo)(Campagna Geologica 1955). *Boll. Serv. Geol. d'It.*, **78**, 353-355.

ALBERTI, A., 1957. Sul rilevamento geologico in Abruzzo: F.140 Teramo. *Boll. Serv. Geol. d'It.*, **79**, 385-391.

ALESSANDRI, D., SCANDONE, P., AND SCARSELLA, F., 1968. Il Trias della parete orientale del Corno Grande (Gran Sasso d'Italia). *Boll. Soc. Nat. Napoli*, **77**, 239-246.

ALVAREZ, W., ALVAREZ, L.W., ASARO, F., AND MICHEL, H.V., 1982. Current status of the impact theory for the terminal Cretaceous extinction. In: Geological Implications of Impacts of large asteroids and comets on the Earth (Eds. Silber, L.T., and Schultz, P.H.), *Geol. Soc. Am. Spec. Paper* **190**, 305-316.

ALVAREZ, W., ARTHUR, M.A., FISCHER, A.G., LOWRIE, W., NAPOLEONE, G., AND PREMOLI-SILVA, I., 1977. Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy. V. Type section for the Late Cretaceous-Paleocene reversal time scale. *Bull. Geol. Soc. Am.*, **88**, 383-389.

ARISI ROTA, F., AND FICHERA, R., 1985. Magnetic interpretation connected to "geomagnetic provinces": The Italian case history. 47th Meeting European Association of Exploration Geophysicists (preprint).

ARTHUR, M.A., AND FISCHER, A.G., 1977. The Gubbio section. I. Lithostratigraphy and sedimentology. *Bull. Geol. Soc. Am.*, **88**, 367-371.

ARTHUR, M.A., AND PREMOLI-SILVA, I., 1982. Development of widespread organic carbon-rich strata in the Mediterranean Tethys. In: Nature and Origin of Cretaceous Carbon-Rich Facies (Eds. Schlanger, S.O., and Cita, M.B.), 6-54, Academic Press, London.

AUSTIN, J.A., Jr., SCHLAGER, W., PALMER, A.A., *et al.*, 1986. Bahamas. *Proc. Init. Repts. (Pt. A) O.D.P.*, **101**, Texas A and M University, College Station, 591pp..

BAGNOLI, G., GIANELLI, G., PUXEDDU, M., RAU SQUARCI, P., AND TONGIORGI, M., 1979. A tentative reconstruction of the Tuscan basement. *Mem. Soc. Geol. It.*, **20**, 99-116.

BALDACCI, L., AND CANAVARI, M., 1884. La regione centrale del Gran Sasso d'Italia. *Boll. Com. Geol. It.*, **15**, 345-359.

BALDANZA, A., COLACICCHI, R., AND PARISI, G., 1982. Controllo tettonico sulla deposizione dei livelli detritici nella Scaglia Cretaceo-Paleocenica (Umbria Orientale). *Rend. Soc. Geol. It.*, **5**, 11-14.

BALLY, A.W., 1954. Geologische Untersuchengen in den SE Abruzzen. Zürich, Bühler Buchdruck, 289pp..

BALLY, A.W., BURBI, L., COOPER, AND GHELARDONI, R., 1986. Balanced sections and seismic reflection profiles across the central Apennines. *Mem. Soc. Geol. It.*, **35**, 257-310.

BARBERA, C., 1967. Memorie geomorfologiche dell'Italia centro-meridionale: 2-Ammoniti giurassiche del Gran Sasso e dell'Aquilano. *Atti. Acc. Sc. Fis. Nat.*, **3**, 227-313.

BARDOSSY, G.Y., BONI, M., DALL'AGLIO, M., D'ARGENIO, B., AND PANTO, G.Y., 1977. Bauxites of peninsular Italy: Composition, origin and geotectonic significance. Bauxites of peninsular Italy: Composition, origin, and geotectonic significance. In: Karst Bauxites (ed. Bárdossy, G.Y.). *Monograph series on mineral deposits* **15**, 1-61, Gebr. Borntraeger, Berlin, 441pp..

BARNOLAS-CORTINAS, A., (Ed.), 1984. Sedimentologia del Jurasico de Mallorca. Excursion Guide Book, Palma de Mallorca, 263pp..

BARRATTOLO, F., 1980. Su alcune nuove Triploporelle (Alghe verdi, Dasicladacae) del Cretacico inferiore dell'Appennino campano. *Boll. Soc. Nat. Napoli*, **89**, 97-167.

BARRATOLO, F., AND PUGLIESE, A., 1987. Il Mesozoico dell'Isola di Capri. *Quaderni*

* BAUMGARTNER, P.O., 1987. Age and genesis of Tethyan Jurassic Radiolarites. *Eclogae Geol. Helv.* **80**, 831-879.

dell'Accademia Pontaniana, **8**, 6-37.

BATHURST, R.G.C., 1975. Carbonate sediments and their diagenesis. *Developments in Sedimentology* **12**, Elsevier, New York, 685pp.

* BEHRMANN, R.B., 1936. Die Faltenbögen des Apennins und ihre palaogeogaphische Entwicklung. *Abh. Gesellschaften Göttingen*, Math.-Phys. Klasse III Folge, **15**, 1-126.

BEHRMANN, R.B., 1958. Die Geotektonische Entwiklung Des Appennin-Systems. *Geotektonische Forschungen*, **12**, 99pp., Stuttgart.

BENEO, E., 1949. Tentativo di sintesi tettonica dell'Italia peninsulare e insulare. *Boll. Soc. Geol. d'It.*, **68**, 80pp..

BERNOULLI, D., 1967. Probleme der Resedimentation im Jura Wertgriechenlands und des Zentralen Apennin. *Verb. Naturf. Ges. Basel*, **78**, 35-54.

BERNOULLI, D., 1972. North Atlantic and Mediterranean Mesozoic facies: A comparison. *Init. Repts. Deep Sea Drill. Proj.*, **11**, 801-871.

BERNOULLI, D., AND JENKYNS, H.C., 1974. Alpine, Mediterranean and central Atlantic Mesozoic facies in relation to the early evolution of the Tethys. In: *Modern and Ancient Geosynclinal Sedimentation* (Eds. Dott, R.H., and Shaver, R.H.), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **19**, 129-160.

BERNOULLI, D., KALIN, O., AND PATACCA, E., 1979. A sunken continental margin of the Mesozoic Tethys: The Northern and Central Apennines. In: *Symposium "Sedimentation Jurassique W. Europèen", A.S.F. Publ. Spec.*, **1**, 197-210.

BERNOULLI, D., AND WEISSERT, H., 1987. The upper Hawasina nappes in the central Oman Mountains. Stratigraphy, palinspastics and sequence of nappe emplacement. *Geodinamica Acta*, **1**, 47-58.

BICE, D.M., AND STEWART, K.G., 1985. Ancient erosional grooves on exhumed bypass margins of carbonate platforms: Examples from the Apennines. *Geology*,

13, 565-568.

BOARDMAN, M.R., AND NEUMANN, A.C., 1984. Sources of periplatform carbonates: Northwest Providence Channel, Bahamas. *Jour. Sedim. Petrol.*, **54**, 1110-1123.

BOARDMAN, M.R., NEUMANN, A.C., BAKER, P.A., DULIN, L.A., KENTER, R.J., HUNTER, G.E., AND KIEFER, K.B., 1986. Banktop responses to Quaternary fluctuations in sea-level recorded in periplatform sediments. *Geology*, **14**, 28-31.

BOARDMAN, D.R. II., AND MALINKY, J.M., 1985. Glacial-eustatic control on Virgilian cyclothems in north central Texas. *Am. Ass. Petrol. Geol. Southwest Section Transactions* 13-23.

BOND, G.C., AND KOMINTZ, M.A., 1984. Construction of tectonic subsidence curves for the Early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup and crustal thinning. *Bull. Geol. Soc. Am.*, **95**, 155-193.

BOND, G.C., KOMINTZ, M.A., AND DEVLIN, W.J., 1983. Thermal subsidence and eustasy in the Lower Paleozoic miogeocline of western North America. *Nature*, **306**, 775-779.

BOND, G.C., KOMINTZ, M.A., AND GROTZINGER, J.P., 1988. Cambro-Ordovician eustasy: evidence from geophysical modelling of subsidence in Cordilleran and Appalachian passive margins. In: New perspectives in basin analysis (Eds. Kleinspehn, K.L., and Paola, C.), 129-150, Springer-Verlag, New York, 453pp..

BOND, G.C., KOMINZ, M.A., STECKLER, M.S., AND GROTZINGER, J.P., 1989. Role of thermal subsidence, flexure, and eustasy in the evolution of Early Paleozoic passive-margin carbonate platforms. In: Controls on carbonate platform and basin development (Eds. Crevello, P.D., *et al.*), *Spec. Publ. Soc. Econ. Paleont. Miner.* **44**, 39-61.

BORTOLOTTI, V.P., PASSERINI, P., SAGRI, M., AND SESTINI, G., 1970. The miogeosynclinal sequences. In: Development of the northern Apennines geosyncline (Ed. Sestini, G.), *Sedim. Geol.*, **4**, 341-444.

BOSELLINI, A., 1984. Progradation geometries of carbonate platforms: Examples from the Triassic of the Dolomites, northern Italy. *Sedimentology* **31**, 1-24.

BOSELLINI, A., 1989. Dynamics of Tethyan carbonate platforms. In: Controls on carbonate platform and basin development, (eds. Crevello, P.D., *et al.*), *Soc. Econ. Paleont. Miner. Spec. Publ.* **44**, 3-13.

BOSELLINI, A., FAZZUOLI, M., MASETTI, D., MATTAVELLI, L., AND SARTI, M., 1981a. Le torbiditi oolitiche della Falda Toscana (Giurassico medio-superiore): Provenienza e implicazioni tettoniche. *Rivista Italiana Paleontologia e Stratigrafia*, **87**, 177-192.

BOSELLINI, A., AND FERIOLI, G.L., 1988. Sequenze deposizionali e discordanze nel Gargano meridionale. *Atti 74th Congr. Geol. It.*, vol.**A**, 49-54.

BOSELLINI, A., MASETTI, D., AND SARTI, M., 1981b. A Jurassic "Tongue of the Ocean" infilled with oolitic sands: The Belluno Trough, Venetian Alps, Italy. *Marine Geology*, **44**, 59-95.

~~BOSELLINI, A., MASETTI, D., AND SARTI, M., 1981b. A Jurassic "Tongue of the Ocean" infilled with oolitic sands: The Belluno Trough, Venetian Alps, Italy. *Marine Geology*, **44**, 59-95.~~

BOSELLINI, A., AND WINTERER, E.L., 1975. Pelagic limestone and radiolarite of the Tethyan Mesozoic: A genetic model. *Geology*, **3**, 279-282.

BOSI, C., AND BERTINI, T., 1970. Geologia della media Valle dell'Aterno. *Mem. Soc. Geol. It.*, **9**, 719-777.

BOTT, M.H.P., 1971. Evolution of young continental margins and formation of shelf basins. *Tectonophysics*, **11**, 319-327.

BOTT, M.H.P., 1973. Shelf subsidence in relation to the evolution of young continental margins. In: Implications of continental drift to the earth sciences (Eds. Tarling, D.H., and Runcorn, S.K.), vol.2, 675-683, Academic Press, London.

BRIDGE, J.S., AND LEEDER, M.R., 1979. A simulation model of alluvial stratigraphy. *Sedimentology*, **26**, 617-644.

BUFFLER, R.T., SCHLAGER, W., AND LEG 77 SCIENTIFIC PARTY, 1984. *Init. Repts. D.S.D.P.* U.S. Government Printing Office, Washington D.C., **77**, 747 pp.

BUFFLER, R.T., WATKINS, J.S., SHAUB, F.J., AND WORZEL, J.L., 1980. Structure and early geologic history of the deep central Gulf of Mexico. In: The origin of the Gulf of Mexico and the Central North Atlantic (Ed. Pilger, R.H., Jr.), Proceedings of a symposium at Louisiana State University, 3-16.

BURGASSI, P.D., COSTANTINI, A., DELL'AGNELLO, L., LAZAROTTO, A., AND SANDRELLI, F., 1979. Esame dei rapporti fra le formazioni metamorfiche del basamento nella Toscana a sud dell'Arno. *Mem. Soc. Geol. It.*, **20**, 123-133.

CACCIAMALI, G.B., 1924. Carreggiamenti nell'Appennino abruzzese-campano. *Boll. Soc. Geol. It.*, **43**, 128-138.

CALDWELL, W.G.E., 1984. Early Cretaceous transgressions and regressions in the Southern Interior plains. In: The Mesozoic of Middle North America: *Can. Soc. Petrol. Geol. Mem.* **9**, 173-203.

CALEMBERT, L., CATALANO, P.G., CONATO, V., LAMBRECHT, L., AND MOJOIE, A., 1972a. Observation dans le massif du Gran Sasso (Apennin Central). *C. R. Acad. Sci. Paris*, **274**, 2013-2015.

CALEMBERT, L., CATALANO, P.G., CONATO, V., LAMBRECHT, L., AND MOJOIE, A., 1972b. Le sondage de Fontari dans le massif du Gran Sasso. *C. R. Acad. Sci. Paris*, **274**, 3065-3068.

CANAVARI, P., 1881. Un'escursione al Gran Sasso. *Proc. Verb. Soc. Tosc. Sc. Nat.*, 267.

CANAVARI, P., 1885. I Fossili del Lias inferiore del Gran Sasso. *Atti. Soc. Tosc. Sc. Nat.*, **7**, 1-21.

CANTELLI, C., CASTELLARIN, A., AND PRATURLON, A., 1978. Tettonismo giurassico lungo "l'Ancona-Anzio" nel settore M. Terminillo-Antrodoco. *Geologica Romana*, **17**, 161-189.

CARANNANTE, G., CARBONE, F., CATENNACI, V., AND SIMONE, L., 1978. I carbonati triassici dei Monti Aurunci: Facies deposizionali e diagenetiche. *Boll. Soc. Geol. It.*, **97**, 687-698.

CARANNANTE, G., AND SIMONE, L., 1986. "Temperate" versus "tropical" Cretaceous carbonate platforms in Italy. *Rend. Soc. Geol. It.*, **9**, 153-157.

CARBONE, F., 1984. Evoluzione tettonico-sedimentaria delle unita' carbonatiche centroappenniniche durante il Meso-Cenozoico. *C.N.R. Centro di Studio per la Geologia dell'Italia centrale*, Rome, 34pp..

CARBONE, F., AND SIRNA, G., 1981. Upper Cretaceous reef models from Rocca di Cave and adjacent areas in Latium, central Italy. *Soc. Econ. Paleont. Miner. Spec. Publ.* **30**, 427-445.

CARDELLINI, S., 1982. La formazione della "Maiolica" nelle Marche settentrionali: I. Rilevamento formazionale e biostratigrafia delle aree campione; II. Correlazioni regionali. Università degl studi di Urbino, Istituto di Geologia, Laurea Thesis, 231pp..

CARTER, D.J., AND HART, M.B., 1977. Aspects of mid-Cretaceous stratigraphical micropalaeontology. *Bull. British Museum (Natural History), Geology series*, **29**, 1-135.

CASSETTI, M., 1893. Appunti geologici sul Matese. *Boll. Com. Geol. d'It.*, **24**, 329-342.

CASSETTI, M., 1894. Relazione sui lavorieseguiti nella Valle del Volturno nell' anno 1893. *Boll. Com. Geol. d'It.*, **25**, 258-274.

CASSETTI, M., 1895. Osservazioni geologiche eseguite l'anno 1894 in alcune parti dell'Appennino meridionale. *Boll. Com. Geol. d'It.*, **26**, 329-345.

CASSETTI, M., 1898. Rilevamento geologico nell'Abruzzo Aquilano ed in terra di lavoro eseguito nel 1897. *Boll. Com. Geol. d'It.*, **29**, 122-138.

CASTELLARIN, A., COLACICCHI, R., AND PRATURLON, A., 1978. Fasi distensive, trascorrenze e sovrascorrrimenti lungo la "Linea Ancona-Anzio" dal Lias medio al Pliocene. *Geologica Romana*, **17**, 161-189.

CASTELLARIN, A., COLACICCHI, R., PRATURLON, R., AND CANTELLI, C., 1982. The Jurassic- Lower Pliocene history of the Ancona-Anzio line (Central Italy). *Mem. Soc. Geol. It.*, **24**, 325-336.

CATALISANO, S., 1938. Stato attuale delle conoscenze geologiche sul Gran Sasso d'Italia. *Boll. Soc. Geol. It.*, **57**, 155-173.

CATENACCI, E., AND MANFREDINI, M., 1963. Osservazioni stratigrafiche sulla Civita di Pietraroia (Benevento). *Boll. Soc. Geol. It.*, **82**, 65-92.

CATENACCI, E., DE CASTRO, P., AND SGROSSO, I., 1963. Complessi guida nel Mesozoico del Matese orientale. *Mem. Soc. Geol. It.*, **4**, 837-856.

CELLO, G., TORTORICI, L., MARTINI, N., AND PALTRINIERI, W., 1989. Structural styles in the frontal zones of the southern Apennines, Italy: an example of from the Molise district. *Tectonics* **8**, 753-768.

CENTAMORE, E., CHIOCCHINI, M., DEIANA, G., MICARELLI, A., AND PIERUCCINI, U., 1971. Contributo alla conoscenza del Giurassico dell'Appennino umbro-marchigiano. *Studi Geologici Camerti*, **1**, 7-89.

CENTAMORE, E., CHIOCCHINI, M., JACOBACCI, A., MANFREDINI, M., AND

* CESTARI, G., MALFERRARI, N., MANFREDINI, M., AND ZATTINI, N., 1975. Note illustrative della Carta Geologica d'Italia alla scala 1: 100,000, Foglio 162 (Campobasso). *Servizio Geologico d'Italia*, Rome.

MANGANELLI, V., 1980. The evolution of the Umbrian-Marchean Basin in the Apennine section of the Alpine orogenic belt (central Italy). In: Memoires Bureau da la Recherche Geologique et de Minieres (Eds. Cogne, J., and Slansky, M.), **108**, 298-305.

* CHANNELL, J.E.T., D'ARGENIO, B., AND HORVATH, F., 1979. Adria, the African promontory in Mesozoic mediterranean paleogeography. *Earth Sci. Rev.*, **15**, 218-292.

CHIOCCHINI, M., 1977. Richerche geologiche sul Gran Sasso d'Italia (Abruzzo). I. Facies di margine della piattaforma carbonatica durante il Lias medio e superiore nei pressi di S. Stefano di Sessanio (F.140 Teramo). *Studi Geologici Camerti*, **3**, 165-173.

CHIOCCHINI, M., DEIANA, G., MANCINELLI, A., PIERUCCINI, U., AND ROMANO, A., 1982. Schema dell'evoluzione paleogeografica dell'area del Gran Sasso d'Italia durante il Trias superiore-Cretaceo inferiore. *Rend. Soc. Geol. It.*, **5**, 35-38.

CHIOCCHINI, M., AND MANCINELLI, A., 1977. Microbiostratigrafia del Mesozoico in facies di piattaforma carbonatica dei Monti Aurunci (Lazio Meridionale). *Studi Geologici Camerti*, **3**, 109-152.

CHIOCCHINI, M., AND MANCINELLI, A., 1978. Richerche geologiche sul Mesozoico del Gran Sasso d'Italia (Abruzzo). III. Correlazioni microbiostratigrafiche tra facies di margine della piattaforma carbonatica e facies pelagiche del Giurassico e Cretaceo Inferiore. *Studi Geologici Camerti*, **4**, 19-36.

CHIOCCHINI, M., MANCINELLI, A., AND ROMANO, A., 1984. Stratigraphic distribution of benthic Foraminifera in the Aptian, Albian and Cenomanian carbonate sequences of the Aurunci and Ausoni mountains (southern Lazio, Italy). *Benthos 83; Second Int. Symp. Benthic Foraminifera*, Pau, April 1983, 167-181.

CHIOCCHINI, M., MOLINARI PAGANELLI, V., AND ZUCCARI, A., 1976. Aperçu sur la biostratigaphie des sédiments carbonatés de plate-forme du Latium centre méridional (Italie). Prémière partie: Crétacé. *Atti VII Coll. Afric. Micropaleontologia,* Nigeria.

CIARAPICA, G., CIRILLI, S., D'ARGENIO, B., MARSELLA, E., PASSERI, L., AND ZANINETTI, L., 1987. Late Triassic open and euxinic basins in Italy. *Rend. Soc. Geol. It.,* **9**, 157-166.

CLERMONTE, J., 1977. La bordure abruzzaise sud-orientale et la Haut Molise: Histoire sédimentaire et tectonique comparée. *Riv. Ital. Paleont. Strat.,* **83**, 21-102.

CLERMONTE, J., 1982. Evoluzione paléogéographique et structurale de l'Italie centro-méridionale durant l'Alpin. Notion de promontoire apulien. *Sciences de la Terre,* **25**, 39-64, Nancy.

CLERMONTE, J., AND PIRONON, B., 1979. La plate-forme campano-abruzzaise de la Meta au Matese (Italie méridionale): Différenciations au Paléogènne et au Miocene, structures, relations avec les formations molisanes. *Bull. Soc. Géol. France,* **7**, t.21, 737-743.

COCCO, E., 1971. Note illustrative della Carta Geologica d'Italia. Foglio **161** (Isernia). Servizio Geologico d'Italia, Rome.

COCHRAN, J.R., 1983. Effects of finite rifting times on the development of sedimentary basins. *Earth and Planetary Science Letters,* **66**, 289-302.

COGEFAR, 1979. Gran Sasso: Il traforo autostradale. Cogefar S.p.A., 267pp..

COLACICCHI, R., 1964. La facies di transizione della Marsica nord-orientale. I. Serie della Serra Sparvera e della Rocca di Chiarano. *Geologica Romana,* **3**, 93-124.

COLACICCHI, R., 1966. Le caracteristiche della facies abruzzese alla luce delle moderne indagini geologiche. *Mem. Soc. Geol. It.,* **5**, 35-38.

COLACICCHI, R., 1987. Sedimentation on a carbonate platform as controlled by sea level changes and tectonic movements. *Mem. Soc. Geol. It.*, **40**, 199-208.

COLACICCHI, R., AND BALDANZA, A., 1986. Carbonate turbidites in a Mesozoic pelagic basin: Scaglia formation, Apennines. Comparison with siliciclastic depositional models. *Sedimentary Geology*, **48**, 81-105.

COLACICCHI, R., PASSERI, L., AND PIALLI, G., 1970. Nuovi dati sul Giurese della Marsica nord-orientale. *Mem. Soc. Geol. It.*, **9**, 839-874.

COLACICCHI, R., AND PIALLI, G., 1967. Dati a conferma di una lacuna dovuta ad emersione nel Giurese del Monte Cucco (Apennino umbro). *Boll. Soc. Geol. It.*, **86**, 179-194.

COLACICCHI, R., PIALLI, G., AND PRATURLON, 1978. Arretramento tettonico del margine di un piattaforma carbonatica e produzione di brecce e megabrecce: L'esempio della Marsica (Appennino centrale). *Quad. Fac. Ing. Univ. Ancona*, **21**, 295-327.

COLACICCHI, R., AND PRATURLON, A., 1965a. Stratigraphical and palaeogeographical investigations on the Mesozoic shelf-edge facies in Eastern Marsica (central Apennines, Italy). *Geologica Romana*, **4**, 89-118.

COLACICCHI, R., AND PRATURLON, A., 1965b. Il problema delle facies nel Giurese della Marsica nord-orientale. *Boll. Soc. Geol. It.*, **84**, 55-66.

COLLINSON, J.D., AND THOMPSON, D.B., 1982. Sedimentary Structures. George Allen and Unwin, London, 194pp..

COLTORTI, M., AND BOSELLINI, A., 1980. Sedimentazione e tettonica nel Giurassico della dorsale Marchigiana. *Studi Geologici Camerti*, **6**, 189-316.

COOK, H.E., 1979. Ancient continental slope sequences and their value in understanding modern slope development. In: *Geology of Continental Slopes*, (Eds. Doyle, L.S., and Pilkey, O.H.), *Soc. Econ. Paleont. Miner. Spec. Publ.* **27**, 287-305.

COOK, H.E., AND EGBERT, R.M., 1981. Carbonate submarine fan facies along a Paleozoic prograding continental margin, western United States (abs.). *Bull. Am. Assoc. Petrol. Geol.*, **65**, 913.

COOK, H.E., AND ENOS, P., 1977. Deep-water carbonate environments- an introduction. In: *Deep-water Carbonate Environments*, (Eds. Cook, H.E., and Enos, P.), *Soc. Econ. Paleont. Miner. Spec. Publ.* **25**, 1-3.

COOK, H.E., HINE, A.C., AND MULLINS, H.T., 1983. Platform-margin and deep water carbonates. *Soc. Econ. Paleont. Miner. Short Course* **12**.

COOK, H.E., AND MULLINS, H.T., 1983. Basin margin environment. In: Carbonate Depositional Environments, (Eds. Scholle, P.A., Bebout, D.G., and Moore, C.H.), *Am. Assoc. Petrol. Geol. Memoir* **33**, 540-617.

COOK, H.E., McDANIEL, P.N., MOUNTJOY, E.W., AND PRAY, L.C., 1972. Allochthonous carbonate debris flows at Devonian bank ("reef") margins, Alberta, Canada. *Bull. Can. Petrol. Geol.*, **20**, 439-497.

CORSO, W., 1988. Development of the Early Cretaceous northwest Florida carbonate platform. *Unpublished Ph.D. Dissertation* University of Texas at Austin, 180 pp.

CORTESE, E., 1926. Studi e ricerche in Campania, Puglia, Calabria e Sicilia (per la ricerca del petrolio). *Mem. Descritt. Carta Geologica d'Italia* **20**, 125-168.

CRESCENTI, U., 1969a. Biostratigrafia delle facies mesozoiche dell'Appennino centrale: Correlazioni. *Geologica Romana*, **7**, 15-40.

CRESCENTI, U., 1969b. Stratigrafia della serie calcarea dal Lias al Miocene nella regione marchigiano-abruzzaise. Parte I-Descrizione delle serie stratigrafiche. *Mem. Soc. Geol. It.*, **8**, 155-204.

CRESCENTI, U., CROSTELLA, A., DONZELLI, G., AND RAFFI, G., 1969. Stratigrafia della serie calcarea dal Lias al Miocene nella regione marchigiano-abruzzese. Parte II-Litostratigrafia, biostratigrafia, paleogeografia. *Mem. Soc. Geol. It.*, **8**, 343-420.

CRESCENTI, U., AND SARTONI, S., 1963. Sintesi biostratigrafica del Mesozoico dell' Italia meridionale. *Mem. Soc. Geol. It.*, **4**, 685-692.

CRESCENTI, U., AND VIGHI, L., 1970. Risultati delle ricerche eseguite sulle formazione bauxitiche del Casertano e del Matese, in Campania. *Mem. Soc. Geol. It.* **9**, 401-434.

D'ANDREA, M., AND URGERA, A., 1986. Correlazione stratigrafiche ed alcune considerazioni paleogeografiche sul Mesozoico del Monti della Meta (Appennino centro-meridionale) *Mem. Soc. Geol. It.*, **35**, 27-32.

D'ARGENIO, B., 1963a. I calcari ad Ittioliti del Cretacico inferiore del Matese. *Acc. Sc. Fis. Mat. Napoli.*, **4**, s.3, n.4, 63pp., Napoli.

D'ARGENIO, B., 1963b. Linee isopiche e strutturali cretaciche persistenti nell'Appennino Campano. *Rend. Acc. Sc. Fis. Mat.*, s. IV. **80**, 367-393, Napoli.

D'ARGENIO, B., 1970. Central and southern Italy Cretaceous bauxites - stratigraphy and paleogeography. *Ann. Inst. Geol. Publici Hung.* **54**, 221-233.

D'ARGENIO, B., AND ALVAREZ, W., 1980. Stratigraphic evidence for crustal thickness changes on the southern Tethyan margin during the Alpine cycle. *Bull. Geol. Soc. Am.*, **91**, part I, 681-689; part II, 2558-2587 (microfiche).

D'ARGENIO, B., DE CASTRO, P., CESARE, E., AND SIMONE, L., 1975. Bahamian and Apenninic limestones of identical lithofacies and age. *Bull. Am. Assoc. Petrol. Geol.*, **59**, 524-533.

D'ARGENIO, B., MINDSZENTY, A., BARDOSSY, G.Y., JUHASZ, E., AND BONI, M., 1986a. Bauxites of southern Italy revisited. *Rend. Soc. Geol. It.*, **9**, 263-268.

D'ARGENIO, B., ORTOLANI, F., AND PESCATORE, T., 1986b. Geology of the Southern

Apennines. A brief outline. Proc. Int. Symp. on: Engineering geology problems in seismic areas. Bari, 31pp. (preprint).

D'ARGENIO, B., PESCATORE, T., AND SCANDONE, P., 1975. Structural pattern of the Campania-Lucania Apennines. In: *Structural Model of Italy* (Eds. Ogniben, L., Parotto, M., AND Praturlon, A., *Quaderni de "La Ricerca Scientifica", Cons. Naz. Ric.*, Rome, **90**, 313-327.

DE BOER, P.L., 1983. Aspects of Middle Cretaceous pelagic sedimentation in southern Europe. *Geologica Ultraiectina*, **31**, 1-112.

DE CASTRO, P., 1962. Nuove osservazioni sul livello ad Orbitoline in Campania (Nota preliminare). *Boll. Soc. Nat. Napoli*, **71**, 103-135.

DE LORENZO, G., 1937. Geologia dell'Italia meridionale. N. ed. a cura di G. D'Erasmo Ed. *Politecnica*, Napoli.

DEMANGEOT, J., 1952. L'arc Abruzzaise extern, étude tectonique. *La Ricerca Scientifica*, **6**, 904-939.

DEMANGEOT, J., 1965. Géomorphologie des Abruzzes adriatiques. *Mem. et Doc. C.N.R.S.*, 403pp..

DE NOCERA, S., 1973. Il nannoplankton calcareo degli scisti ad Aptici e della Maiolica del Pizzo Cefalone (Gran Sasso d'Italia). *Boll. Soc. Nat. Napoli*, **82**, 53-76.

DERCOURT, J., ZONENSHAIN, L.P., RICOU, L.E., KAZMIN, V.G., LE PICHON, X., KNIPPER, A.L., GRANGJACQUET, C., SBORTSHIKOV, I.M., GEYSSANT, J., LEPVRIER, C., PECHERSKY, D.H., BOULIN, J., SIBUET, J.C., SAVOSTIN, L.A., SOROKHTIN, O., WESTPHSAL, M., BAZHENOV, M.L., LAUER, J.P., AND BIJU-DUVAL, B., 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. In: Evolution of the Tethys (Eds. Aubouin, J., Le Pichon, X., and Monin, A.S.), *Tectonophysics*, **123**, 241-315.

DE ROSA, C., 1976. Osservazioni su *Salpingoporella exilis* (Dragastan) 1971. *Boll. Soc. Geol. Napoli*, **85**, 205-230.

DEVOTO, G., 1963. La serie stratigrafica di Monte S. Croce (Venafro). *Mem. Soc. Geol. It.*, **4**, 761-765.

DEVOTO, G., 1964. Zone ad Alveolinidae nel Cretaceo e Paleocene del Lazio ed Abruzzo centro-meridionale. *Geol. Romana*, **3**, 405-409.

DEWEY, J.F., HELMAN, M.L., TURCO, E., HUTTON, D.W.H., AND KNOTT, S.D., 1989. Kinematics of the Western Mediterranean. *Geol. Soc. Lond. Spec. Publ.* **45**, *Alpine Tectonics* (Eds. Coward, M.P., Dietrich, D., and Park, R.G.), 265-283.

DOLAN, J.F., 1989. Eustatic and tectonic controls on deposition of hybrid siliciclastic/ carbonate basinal cycles: Discussion with examples. *Bull. Am. Ass. Petrol. Geol.* **73**, 1233-1246.

DONOVAN, A.D., BAUM, G.R., BLECHSCHMIDT, G.L., LOUTIT, T.S., PFLUM, C.E., AND VAIL, P.R., 1988. Sequence stratigraphic setting of the Cretaceous-Tertiary boundary in Central Alabama. In: Sea-level changes: An integrated approach (Eds. Wilgus, C.K., *et al.*), *Soc. Econ. Paleont. Miner. Spec. Publ.* **42**, 299-308.

DOTT, R.H., AND BATTEN, R.G, 1981. Evolution of the Earth. McGraw-Hill, New York, 573pp..

DROXLER, A.W., AND SCHLAGER, W., 1985. Glacial versus interglacial sedimentation rates and turbidite frequency in the Bahamas. *Geology*, **13**, 799-802.

EBERLI, G.P., 1987. Carbonate turbidite sequences deposited in rift-basins of the Jurassic Tethys Ocean (Eastern Alps. Switzerland). *Sedimentology*, **34**, 363-388.

EBERLI, G.P., (in press) Calcareous turbidites and their relationship to sea-level fluctuations and tectonism. In: *Cycles and events in Stratigraphy* (Eds. Einsele, G., Ricken, W., Seilacher, A.)

EBERLI, G.P., AND GINSBURG, R.N., 1987. Segmentation and coalescence of

Cenozoic carbonate platforms, northwestern Great Bahama Bank. *Geology*, **15**, 75-79.

EBERLI, G.P., AND GINSBURG, R.N., 1989. Cenozoic progradation of northwest Great Bahama Bank, a record of lateral platform growth and sea-level fluctuations. In: Controls on carbonate platform and basin development (Eds. Crevello, P.D., *et al.*) *Soc. Econ. Paleont. Miner., Spec. Publ.* **44**, 339-351.

ENOS, P., 1974. Reefs, platforms and basins of the Middle Cretaceous in Northeast Mexico. *Bull. Am. Assoc. Petrol. Geol.*, **58**, 800-809.

ENOS, P., 1977. Tamabra limestone of the Poza Rica trend, Cretaceous, Mexico. In: Deep-water carbonate environments (Eds. Cook, H.E., and Enos, P.), *Spec. Publs. Soc. Econ. Paleont. Miner.*, **25**, 273-314.

ENOS, P., 1985. Cretaceous debris reservoirs, Poza Rica field, Veracruz, Mexico. In: Carbonate petroleum reservoirs, a case book (Eds. Roehl, P.O., and Choquette, P.W.), Springer-Verlag, New York, 455-469.

ENOS, P., 1988. Evolution of pore space in the Poza Rica trend (Mid-Cretaceous), Mexico. *Sedimentology*, **35**, 287-326.

ENOS, P., AND MOORE, C.H., 1983. Fore-reef slope environment. In: Carbonate Depositional Environments, (Eds. Scholle, P.A., Bebout, D.G., and Moore, C.H.), *Am. Assoc. Petrol. Geol. Memoir* **33**, 508-537.

EVANS, J., AND KENDALL, C.G.H., 1977. An interpretation of the depositional setting of some deep- water Jurassic carbonates of the central High Atlas mountains, Morocco. In: *Deep-water carbonate environments* (Eds. Cook, H.E., and Enos, P.) *Soc. Econ. Paleont. Miner. Spec. Publ.* **25**, 249-261.

FARINACCI, A., AND RADOICIC, R., 1964. Correlazioni tra serie giuresi e cretacee dell' Appennino centrale e delle Dinardi esterne. *La Ricerca Scientifica*, **34**, 269-300.

FITTIPALDI, U., 1900. Gastropodi del calcare turoniano di S. Polo Matese

(Campobasso). *Atti. R. Acc. Sc. Napoli*, s.2, **10**, no.5.

FLEXER, A., ROSENFIELD, A., LIPSON-BENITAH, S., AND HONIGSTEIN, A., 1986. Relative sea level changes during the Cretaceous in Israel. *Bull. Am. Assoc. Petrol. Geol.*, **70**, 1685-1699.

FLORES, V.Q., 1978. Paleosedimentologia en la zona de Sitio Grande-Sabancuy. *Petroleo Internacional*, **26**, 44-48.

FRASER, D.G., WATT, F., GRIME, G.W., AND TAKACS, J., 1984. Direct determination of strontium enrichment on grain boundaries in a garnet lherzolite xenolith by proton microprobe analysis. *Nature*, **312**, 352-354.

FRASER, D.G., FELTHAM, D.J., AND WHITEMAN, M.I., 1989. High resolution scanning proton microprobe studies of micron-scale trace element zoning in a secondary dolomite: Implications for studies of redox behaviour in dolomites. Thematic volume on the analysis and interpretation of zoned carbonate cements, *Sedimentary Geology* **65**, 223-232.

GHISETTI, F., AND VEZZANI, L., 1983. Deformazioni pellicolari mioceniche e plioceniche nei domini strutturali esterni dell'Appennino centro-meridionale (Maiella ed arco Morrone-Gran Sasso). *Mem. Soc. Geol. It.*, **26**, 563-577.

GHISETTI, F., AND VEZZANI, L., 1986a. Assetto geometrico ed evoluzione strutturale della catena del Gran Sasso tra Vado di Siella e Vado di Corno. *Boll. Soc. Geol. It.*, **105**, 131-171.

GHISETTI, F., AND VEZZANI, L., 1986b. Carta geologica del gruppo M. Siella-M. Camicia- M. Prena-M. Brancastello (Gran Sasso d'Italia). Scale 1:15,000, explanatory notes on the rear, S. EL. CA., Firenze.

GHISETTI, F., AND VEZZANI, L., 1988a. Geometric and kinematic complexities in the Marche-Abruzzi external zones (Central Apennines, Italy). *Geologische Rundschau*,

77, 63-78.

GHISETTI, F., AND VEZZANI, L., 1988b. Relazioni strutturali tra il fronte della piattaforma carbonatica Laziale-Abruzzese e i domini pelagici Umbri, Marchigiani e Molisani. *Atti 74th Congresso Soc. Geol. It.*, **B**, 243-250.

GINSBURG, R.N., *et al.*, 1986. The global sedimentary geology program - Report of an International Workshop, Fisher Island, Florida.

GOLDHAMMER, R., DUNN, P.A., AND HARDIE, L.A., 1987. High frequency glacio-eustatic oscillations with Milankovitch characteristics recorded in northern Italy. *Amer. J. Sci.*, **287**, 853-892.

GOLDHAMMER, R., AND HARRIS, M.T., 1989. Eustatic controls on the stratigraphy and geometry of the Latemar buildup (Middle Triassic), the Dolomites of northern Italy. In: Controls on carbonate platform and basin development (Eds. Crevello, P.D., *et al.*), *Spec. Publ. Soc. Econ. Paleont. Miner.* **44**, 323-338.

GRABAU, A.W., 1940. The rhythm of the Earth. Henri Vetch, Peking, 561pp..

GROTZINGER, J.P., 1986. Cyclicity and paleoenvironmental dynamics, Rocknest platform, northwest Canada. *Bull. Geol. Soc. Am.*, **97**, 1208-1231.

GROVER, G., AND READ, J.F., 1983. Paleoaquifer and deep burial cements defined by regional cathodoluminescence patterns, Middle Ordovician of Central Virginia. *Bull. Am. Assoc. Petrol. Geol.*, **67**, 1275-1303.

GRZYBOWSKI, J., 1921. Contributo agli studi sulla struttura geologica dell'Italia meridionale. *Boll. Soc. Geol. It.*, **40**, 85-97.

GULLO, M., AND VITALE, F.P., 1987. The "megabreccia event" in the Upper Cretaceous-Eocene "Scaglia" of western Sicily. *Rend. Soc. Geol. It.*, **9**, 195-202.

HAAK, A.B., AND SCHLAGER, W., 1989. Compositional variations in calciturbidites due to sea-level fluctuations, late Quaternary, Bahamas. *Geol. Rundschau,* **78**, 477-486.

HALLAM, A., 1984. Pre-Quaternary sea-level changes. *Ann. Rev. Earth Planet. Sci.*, **12**, 205-243.

HALLAM, A., 1988. A reevaluation of Jurassic eustasy in the light of new data and the revised EXXON curve. In: Sea-level changes: An integrated approach (Eds. Wilgus, C.K., *et al.*), *Soc. Econ. Paleont. Miner. Spec. Publ.* **42**, 261-273.

HANCOCK, J.M., AND KAUFFMAN, E.G., 1979. The great transgressions of the late Cretaceous. *J. Geol. Soc. London*, **136**, 175-186.

HANSEN, E., 1965. Methods of deducing slip line orientations from the geometry of folds. *Yb. Carnegie Instn. Wash.*, **65**, 387-405.

HAQ, B.U., HARDENBOL, J., AND VAIL, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, **235**, 1156-1167.

HAQ, B.U., HARDENBOL, J., AND VAIL, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea level change. In: Sea-level changes: An integrated approach (Eds. Wilgus, C.K. *et al.*), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **42**, 71-108.

HARRIS, M.T. 1988. Margin and foreslope deposits of the Latemar carbonate buildup (Middle Triassic), the Dolomites, northern Italy. *Unpublished Ph.D. thesis*. The John Hopkins University, 473 pp.

HARRIS, P.M., SEIGLIE, G.A., AND SCHNEIDERMANN, N., 1984. Regional unconformities and depositional cycles, Cretaceous of the Arabian Peninsula. In: Interregional Unconformities and Hydrocarbon accumulation (Ed. Schlee, J.S.), *Am. Assoc. Petrol. Geol. Mem.* **36**, 67-80.

HART, M.B., 1980a. The recognition of mid-Cretaceous sea-level changes by means of Foraminifera. *Cretaceous Research*, **1**, 289-297.

HART, M.B., 1980b. A water depth model for the evolution of the planktonic Foraminiferida. *Nature*, **286**, 252-254.

HART, M.B., AND TARLING, D.H., 1974. Cenomanian palaeogeography of the North Atlantic and possible mid-Cenomanian eustatic movements and their implications. *Palaeogrogr., Palaeoclimat., Palaeoecology,* **15**, 95-108.

HARWOOD, G.M., AND TOWERS, P.A., 1988. Seismic sedimentologic interpretation of a carbonate slope, north margin of Little Bahama Bank. In: Austin, J.A., Jr., Schlager, W., *et al.*, 1988, *Proceedings of the Ocean Drilling Program, Scientific Results,* **101**, 263-277.

HERBERT, T.D., AND FISCHER, A.G., 1985. High-resolution history of carbonate and silica accumulation rates in a mid-Cretaceous pelagic core. Geological Society of America, Abstracts with Programs, **17**, 608.

HESSELBO, S., COE, A.L., AND JENKYNS, H.C., 1989. Recognition and documentation of depositional sequences from outcrop: An example from the Aptian and Albian on the eastern margin of the Wessex Basin. *Jl. Geol. Soc. Lond.* (in press).

HILL, K.C., AND HAYWOOD, A.B., 1988. Structural constraints on the Tertiary plate tectonic evolution of Italy. *Mar. Petrol. Geol.*, **5**, 2-16.

HINE, A.C., AND STEINMETZ, J.C., 1984. Cay Sal Bank, Bahamas-A partially drowned carbonate platform. *Marine Geology,* **59**, 135-164.

HOBSON, J.P., CALDWELL, C.D., AND TOOMEY, D.F., 1985. Early Permian deep-water allochthonous limestone facies and reservoir, West Texas. *Bull. Am. Assoc. Petrol. Geol.,* **69**, 2130-2147.

HUMPHREY, J.D., AND QUINN, T.M., 1989. Coastal mixing-zone dolomite, forward modelling, and massive dolomitization of platform-margin carbonates. *Jour. Sedim. Petrol.,* **59**, 438-454.

IETTO, A., 1964. Osservazioni geologiche su alcune zone del Matese (Appennino Campano). *Boll. Soc. Nat. Napoli,* **72**, 112-116.

IETTO, A., 1969. Assetto strutturale e ricostruzione paleogeografica del Matese Occidentale (Appennino Meridionale). *Mem. Soc. Nat. Napoli*, **78**, 441-471.

ISTITUTO DI GEOLOGIA E GEOFISICA UNIVERSITA DI NAPOLI, 1978. Processi paleocarsi e neocarsi e loro importanza economica nell'Italia Meridionale: Guida alle escursioni, 210pp..

JACKSON, J.A., 1987. Active normal faulting and crustal extension. In: *Continental Extensional Tectonics* (Eds. Coward, M.P., Dewey, J.F., Hancock. P.L.), *Geol. Soc. Spec. Publ.* **28**, 3-17.

JACKSON, J.A., WHITE, N.J., GARFUNKEL, Z., AND ANDERSON, H., 1988. Relations between normal-fault geometry, tilting and vertical motions in extensional terrains: An example from the southern Gulf of Suez. *Jour. Struct. Geol.*, **10**, 155-170.

JACQUIN, T., 1989. Sequence stratigraphy in the southern Vercors (Hauterivian-Barremian). *Field trip guide, Universite de Bourgogne/I.F.P.*, 1989.

JENKYNS, H.C., 1985. The Early Toarcian and Cenomanian-Turonian anoxic events in Europe: comparisons and contrasts. *Geol. Rund.* **74**, 505-518.

JENKYNS, H.C., AND WINTERER, E.L., 1982. Palaeoceanography of Mesozoic ribbon radiolarites. *Earth and Planetary Science Letters*, **60**, 351-375.

JONES, O.T., 1940. The geology of the Colwyn Bay district: Study of submarine slumping during the Salopian Period. *Q. Jl. geol. Soc. Lond.*, **95**, 335-382.

KAUFFMAN, E.G., 1977. Geological and biological overview: Western Interior Cretaceous basin. *The Mountain Geologist*, **14**, 75-99.

KAUFFMAN, E.G., 1984. Paleobiography and evolutionary response dynamic in the Cretaceous Western Interior seaway of North America. *Geol. Assoc. Can. Spec. Paper* **27**, 273-306.

KEEN, C.E., 1982. The continental margins of eastern Canada: A review. In:

Dynamics of passive margins (Ed. Scrutton, R.A.), *American Geophysical Union, Geodynamics series*, **6**, 45-58.

KENDALL, C.G.St.G, AND SCHLAGER, W., 1981. Carbonates and relative changes in sea level. *Marine Geology*, **44**, 181-212.

KENT, D.V., AND GRADSTEIN, F.M., 1985. A Cretaceous and Jurassic geochronology. *Bull. Geol. Soc. Am.*, **96**, 1419-1427.

KIER, J.S., AND PILKEY, O.H., 1971. The influence of sea-level changes on sediment carbonate mineralogy, Tongue of the Ocean, Bahamas. *Marine Geology*, **11**, 189-200.

KNOTT, S.D., 1988. Structure, sedimentology and petrology of an ophiolitic flysch terrain in Calabria, south Italy. *Unpublished D. Phil. Thesis*, University of Oxford, 152pp.

KOOPMAN, A., 1983. Detachment tectonics in the Central Apennines, Italy. *Geol. Ultraiectina*, **30**, 1-155, Utrecht.

LAVECCHIA, G., MINELLI, G., AND PIALLI, G., 1984a. L'Apennino umbro-marchigiano: Tettonica distensiva e ipotesi di sismogenesi. *Boll. Soc. Geol. It.*, **103**, 467-476.

LAVECCHIA, G., MINELLI, G., BIELLA, G., CONVERSINI, P., DEMARTIN, M., LOZEJ. A., MAISTRELLO, M., SCARASCIA, S., AND TABACCO, I., 1984b. Primi resultati del profilo sismico a rifrazione Perugia-Frontone. *Boll. Soc. Geol. It.*, **103**, 447-466.

LAZZARI, A., 1950. Sulla tettonica del massicio del Matese (Provincia di Benevento e Campobasso)-note preliminare. *Contr. Sc. Geol.* **1**, 112-114, suppl. a *La Ricerca Scientifica*, C.N.R., Rome.

LEEDER, M., 1987. Sediment deformation structures and the palaeotectonic analysis of sedimentary basins, with a case study from the Carboniferous of northern England. In: *Deformation of Sediments and Sedimentary rocks* (Eds. Jones, M.E., and Preston, R.M.F.) *Geol. Soc. Spec. Publ.* **29**, 137-146.

LONGORIA, J.F., 1984. Mesozoic tectonostratigraphic domains in east-central Mexico. *Geol. Ass. Can. Spec. Paper* **27**, 65-76.

LOTTI, B., 1926. Descrizione geologica dell'Umbria. *Mem. descr. Carta Geol. d'It.* **21**, 1-320.

LOWRIE, W., AND ALVAREZ, W., 1984. Lower Cretaceous magnetic stratigraphy in Umbrian pelagic limestones. *Earth and Planetary Science Letters*, **71**, 315-328.

LUPERTO SINNI, E., AND MASSE, J.P., 1984. Données nouvelles sur la micropaléontologie et la stratigraphie de la partie basale du "calcari di Bari" (Crétacé inférieur) dans la région des Murges (Italie méridionale). *Riv. It. Paleont. Strat.*, **90**, 331-374.

LUPERTO SINNI, E., AND MASSE, J.P., 1986. Données nouvelles sur la stratigraphie des calcaires du Crétacé inférieur du Gargano (Italie méridionale). *Riv. It. Paleont. Strat.*, **92**, 33-66.

LUPERTO SINNI, E., AND MASSE, J.P., 1987. Données nouvelles sur la stratigraphie et la mircopaléontologie des séries carbonatées de talus et de bassin du Crétacé inférieur du Gargano (Italie méridionale). *Riv. It. Paleont. Strat.*, **93**, 347-378.

LUPERTO SINNI, E., MASSE, J.P., AND BORGOMANO, J., 1988. Le correlazioni stratigrafiche tra le serie cretacee delle Murge e del Gargano (Italia Meridionale). *Atti 74th Congr. Geol. It.*, vol.**B**, 293-297.

LUTERBACHER, H.P., AND PREMOLI-SILVA, I., 1964. Biostratigrafia del limite Cretaceo-Terziario nell'Appennino Centrale. *Riv. Ital. Paleont. Strat.*, **40**, 67-128.

MANFREDINI, M., 1958. Relazione preliminare sui rilevamento geologico del Foglio Teramo (Catena del Gran Sasso fra Vado di Corno e Vado Ferruccio). *Boll. Serv. Geol. It.*, **79**, 393-396.

MANFREDINI, M., 1963. Schema dell'evoluzione tettonica della Peninsola Italiana.

Boll. Serv. Geol. It., **84**, 101-130.

MANFREDINI, M., 1964. Osservazioni geologiche sul bordo interno della depressione Molisano-Sannitica (Italia meridionale). *Mem. Soc. Geol. It.*, **4**, 959-975.

MANFREDINI, M., 1975a. Lineamenti geologici della Catena del Gran Sasso d'Italia (L'Aquila). *Boll. Soc. Geol. It.*, **76**, 69-78.

MANFREDINI, M., 1975b. Lineamenti della Catena del Gran Sasso d'Italia. Estr. da AA.VV. Club Alpino Italiano, sezione di L'Aquila: Omaggio al Gran Sasso, 91-96.

MARSELLA, E., AND PAPPONE, G., 1987. Sediment gravity flows on a Mesozoic carbonate slope. Monti della Maddalena (southern Apennines). *Rend. Soc. Geol. It.* **9**, 219-224.

MARTINIS, B., AND PAVAN, G., 1967. Note illustrative della Carta Geologica d'Italia alla scala 1:100,000, Foglio 157, Monte Sant'Angelo. *Serv. Geol. d'It.*, Rome, 56pp..

MARTINIS, B., AND PIERI, M., 1964. Alcune notizie sulla Formazione Evaporitica del Triassico superiore nell'Italia centrale e meridionale. *Mem. Soc. Geol. It.*, **4**, 649-678.

MASSE, J.P., AND BORGOMANO, J., 1987. Un modèle de transition plate-forme-bassin carbonaté contrôlé par des phénomènes tectoniques: le Crétacé du Gargano (Italie méridionale). *C. R. Acad. Sci. Paris*, t.**304**, série II, 521-526.

MASSE, J.P., AND PHILIP, J., 1981. Cretaceous coral-rudist buildups of France. In: *European fossil reef models* (Ed. Toomey D.F.), *Soc. Econ. Paleont. Miner. Spec. Publ.* **30**, 399-426.

MATTHEWS, R.K., AND FROLICH, C., 1987. Forward modelling of bank-margin carbonate diagenesis. *Geology*, **15**, 673-676.

McFARLON, E., Jr., 1977. Lower Cretaceous sedimentary facies and sea level changes, U.S. Gulf Coast. University of Texas at Austin, Bureau of Economic

Geology, Report of Investigations No.89, 5-11.

McKENZIE, D.P., 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, **40**, 25-32.

MEYERS, W.J., 1974. Carbonate cement stratigraphy of the Lake Valley Formation (Mississipian) Sacramento Mountains, New Mexico. *Jour. Sedim. Petrol.*, **44**, 837-861.

MEYERS, W.J., 1978. Carbonate cements: their regional distribution and interpretation in Mississipian limestones of southeastern New Mexico. *Sedimentology*, **25**, 371-400.

MEYERS, W.J., GRAMS, J., AND HEMMING, G., 1988. Covariations of trace elements in Mississipian calcite cement: Implications for CL and causes of zoning. B.S.R.G. Meeting on the analysis and interpretation of zoned calcite cements, book of abstracts.

MICARELLI, A., POTETTI, M., AND CHIOCCHINI, M., 1977. Ricerche microbiostratigrafiche sulla Maiolica della regione umbro-marchigiana. *Studi Geologici Camerti*, **3**, 57-86.

MIGLIORINI, C.I., 1950. Suddivisione geografica dell'Appennino per uso geografico. Una proposta. *Boll. Soc. Geol. It.*, **70**, 95-96.

MITCHUM. R.M. Jr., 1977. Part 11, glossary of terms used in Seismic stratigraphy. In: *Seismic Stratigraphy- Applications to Hydrocarbon Exploration* (Ed. Payton, C.E.), *Mem. Am. Ass. Petrol. Geol.* **26**, 205-212.

MONTANARI, A., 1985. Cenomanian anoxic foreslope inferred from turbiditic cherts in the pelagic basin of the northern Apennines, Italy. Geological Society of America, Abstracts with Programs, **17**, 667.

MONTANARI, A., CHAN, L.S., AND ALVAREZ, W., 1989. Synsedimentary tectonics in the Late Cretaceous-Early Tertiary pelagic basin of the northern Apennines, Italy. In: Controls on carbonate platform and basin development (Eds. Crevello, P.D., *et al.*), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **44**, 379-399.

MORETTI, A., 1951. Notizie geologiche e morfologiche sul gruppo del Gran Sasso d'Italia. *Boll. Serv. Geol. It.*, **71**, 77-111.

MOSTARDINI, F., AND MERLINI, S., 1986. Appennino centro-meridionale: Sezione geologiche e proposta di modello strutturale. *Mem. Soc. Geol. It*, **35**, 177-202.

MULLINS, H.T., 1983a. Comment on "Eustatic control of turbidites and winnowed turbidites". *Geology*, **11**, 57-58.

MULLINS, H.T., 1983b. Base-of-slope carbonate aprons: An alternative to the submarine fan model. *Bull. Am. Assoc. Petrol. Geol.*, **67**, 521.

MULLINS, H.T., BOARDMAN, M.R., AND NEUMANN, A.C., 1978. Echo character of off-platform carbonates. *Mar. Geol.*, **32**, 251-268.

MULLINS, H.T., LYNTS, G.W., NEUMANN, A.C., AND BALL, M.M., 1978. Characteristics of deep Bahama channels in relation to hydrocarbon potential. *Bull. Am. Ass. Petrol. Geol.* **62**, 693-704.

MULLINS, H.T., AND COOK, H.E., 1986. Carbonate apron models: Alternatives to the submarine fan model for paleoenvironmental analysis and hydrocarbon exploration. *Sedimentary Geology*, **48**, 37-79.

MULLINS, H.T., HEATH, K.C., VAN BUREN, M., AND NEWTON, C.R., 1984. Anatomy of a modern open-ocean carbonate slope: Northern Little Bahama Bank. *Sedimentology*, **31**, 141-168.

MULLINS, H.T., AND HINE, A.C., 1989. Scalloped bank margins: Beginning of the end for carbonate platforms? *Geology*, **17**, 30-33.

MULLINS, H.T., AND NEUMANN, A.C., 1979. Deep carbonate bank margin structure and sedimentation in the northern Bahamas. In: *Geology of Continental Slopes*, (Eds. Doyle, L.S., and Pilkey, O.H.), *Soc. Econ. Paleont. Miner. Spec. Publ.*, **27**, 165-192.

MUTTI, E., AND NORMARK, W., 1987. Comparing examples of Modernand Ancient Turbidite Systems: Problems and concepts. In: *Marine Clastic Sedimentology* (Eds. Leggett, J.K., and Zuffa, G.G.), 1-38. Graham and Trotman.

MUTTI, E., RICCHI LUCCHI, F., SEGURET, M., AND ZANZUCCHI, G., 1984. Seismoturbidites: A new group of resedimented deposits. *Marine Geology*, **55**, 103-116.

NEGRETTI, G.C., 1957. Appunti sulla evoluzione paleogeografica della Valle Latina settentrionale dal Cretaceo superiore al Miocene superiore, con particolare riguardo alla trasgrassione miocenica. *Pubbl. Ist. Geol. Paleont. Univ. Roma*, A.6, **27**, Rome, 27pp.

OGNIBEN, L., 1969. Schema introduttivo alla geologia del confine calabro-lucano. *Mem. Soc. Geol. It.*, **9**, 453-763.

OGNIBEN, L., 1985. Relazione sul modello geodinamico "conservativo" della regione italiana. *Commisione ENEA-ENEL per lo studio dei problemi sismici connessi con la realizzazione di impianti nucleari*, E.N.E.A., 357pp..

OLSSEN, R.K., 1988, Foraminiferal modeling of sea-level change. In: Sea-level changes: An integrated approach (Eds. Wilgus, C.K., *et al.*), *Soc. Econ. Paleont. Miner. Spec. Publ.* **42**, 289-297.

PAROTTO, M., 1980. Apennin Central. In: Introduction à la géologie générale d'Italie. *26th Congr. Géol. Int.*, Paris, 257-311.

PAROTTO, M., AND PRATURLON, A., 1975. Geological summary of the Central Apennines. In: *Structural Model of Italy, Quad. de "La Ricerca Scientifica"*, **90**, 257-311.

PARSONS, B., AND SCLATER, J.G., 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. *J. Geophys. Res.*, **82**, 803-828.

PASSERI, L., 1977. Sedimentologia e ricostruzioni paleogeografiche nel Trias superiore dell'Appennino centrosettentrionale. *Boll. Soc. Geol. It.*, **95**, 601-618.

PAULL, C.K., AND NEUMANN, A.C., 1987. Continental margin brine seeps: Their geological consequences. *Geology*, **15**, 545-548.

PAVAN, G., AND PIRINI, C., 1965. Stratigrafia del foglio 157 "Monte San Angelo". *Boll. Serv. Geol. It.*, **86**, 123-189.

PESCATORE, T., 1963. Affiorimenti di flysch cretacico nell'alta Valle del Volturno (Alto Molise). *Mem. Soc. Geol. It.*, **4**, 791-800.

PESCATORE, T., 1964. Rapporti tra depressione molisano-sannitica e Appennino calcareo. *Boll. Soc. Nat. Napoli*, **82**, 213-227.

PESCATORE, T., 1965. Richerche geologiche sulla depressione Molisano-Sannitica. *Atti. Accad. Fis. Mat. Napoli*, **5**, 101-145.

PESCATORE, T., 1978. Evoluzione del Bacino Irpino (Italia meridionale) durante il Miocene. *Boll. Serv. Geol. It.*, **97**, 783-805.

PESCATORE, T., AND TRAMUTOLI, M., 1980. I rapporti tra i depositi del Bacino di Lagonegro e del Bacino Irpino nella media valle del Basento (Lucania). *Rend. Accad. Fis. Mat. Napoli*, **47**.

PIERI, M., 1966. Tentativo di ricostruzione paleogeografico-strutturale dell'Italia centro-meridionale. *Geol. Romana*, **5**, 407-424.

PIRONON, B., 1980. La notion de zone de transition en bordure orientale de la plate-forme campano-abruzzaise de la Meta au Matese (Italie centro-méridionale). *Thèse 3e Cycle*, Nancy, 175pp..

PITMAN, W.C. 1978. Relationship between eustacy and stratigraphic sequences of passive margins. *Bull. Geol. Soc. Am.* **89**, 1389-1403.

PRATURLON, A., 1964. Calcareous algae from Jurassic-Cretaceous limestones of the central Apennines (southern Latium-Abruzzi). *Geol. Romana*, **3**, 171-202.

PRATURLON, A., 1966a. Algal assemblages from Lias to Paleocene in southern

Latium-Abruzzi: A review. *Boll. Soc. Geol. It.*, **85**, 167-194.

PRATURLON, A., 1966b. Heteroporella lepina, new dasyclad species from Upper Cenomanian-Lower Turonian of Central Apennines. *Boll. Soc. Paleont. It.*, **5**, 202-205.

PRATURLON, A., 1968. Note illustrative della carte geologica d'Italia, Foglio 152, Sora. *Serv. Geol. d'It.*, 76pp..

PRATURLON, A., and SIRNA, G., 1976. Ulteriori dati sul margine Cenomaniano della piattaforma carbonatica laziale-abruzzese. *Geologica Romana*, **15**, 83-111.

PREMOLI-SILVA, I., AND PAGGI, L., 1977. Cretaceous through Paleocene biostratigraphy of the pelagic sequence at Gubbio, Italy. *Mem. Soc. Geol. It.*, **15**, 21-32.

PRICE, I., 1977. Facies distribution and interpretation of primary cherts in a Mesozoic continental margin succession, Othris, Greece. *Sedimentary Geology*, **18**, 321-335.

RADOICIC, R., 1987. Bauxites of the internal Dinarides: Stratigraphy and facies of bedrock and cover (Bosnia-Metohija sector). *Rend. Soc. Geol. It.*, **9**, 277-281.

RAMSAY, J.G., AND HUBER, M.I., 1983. The Techniques of Modem Structural Geology, Volume 1, Strain Analysis. Academic Press, London, 307 pp.

READ, J.F., 1982. Carbonate platforms of passive (extensional) continental margins: types, characteristics and evolution. *Tectonophysics* **81**, 195-212.

READ, J.F., 1985. Carbonate platform facies models. *Bull. Am. Ass. Petrol. Geol.* **69**, 1-21.

READ, J.F., GROTZINGER, J.P., BOVA, J.A., AND KOERSCHNER, W.F., 1986. Models for generation of carbonate cycles. *Geology*, **14**, 109-144.

RENZ, O., 1936. Stratigrapische und mikropalaeontologische Untersuchung der Scaglia (Obere Kreide-Tertiar) im Zentralen Apennin. *Eclogae Geol. Helv.*, **29**, 1-149.

RENZ, O., 1951. Ricerche stratigrafiche e micropaleontologiche sulla Scaglia (Cretaceo superiore-Terziario) dell'Appennino centrale. *Mem. Descritt. Carta Geologica D'Italia,* **29**, 1-173.

REY, J., 1982. Dynamique et paléoenvironnements du Bassin Mésozoique d'Estremadure (Portugal), au Crétacé Inférieur. *Cretaceous Research,* **3**, 103-111.

RICCHETTI, G., 1969. Calcari con Orbitoline, nuovo livello guida del Cretaceo nelle Murge baresi. *Boll. Soc. Geol. It.* **88**, 321-328.

RICCI LUCCHI, F., 1975. Depositional cycles in two turbidite formations of the northern Apennines. *J. Sedim. Petrol.* **45**, 1-43.

RIEKE, H.H., III, AND CHILINGARIAN, G.V., 1974. Compaction of argillaceous sediments, Elsevier, Amsterdam, 424pp..

ROBASZYNSKI, F., AND CARON, M., 1979. Atlas of mid-Cretaceous planktonic foraminifera (Boreal sea and Tethys). *Cah. Micropal., C.N.R.S.,* Paris, 185pp..

ROVERETO, G., 1927. Sur les charriages de l'Appennin Central et Meridional. *C. R. Soc. Géol. Fr.,* **9**, 100-112.

RUIZ-ORTIZ, P.A., 1983. A carbonate submarine fan in a fault-controlled basin of the Upper Jurassic, Betic Cordillera, southern Spain. *Sedimentology,* **30**, 33-48.

SACCO, F., 1907. Il gruppo del Gran Sasso d'Italia. *Mem. R. Accad. Sci. Torino,* **s.2, 59**, 61-88.

SACCO, F., 1910. L'Appennino meridionale. *Boll. Soc. Geol. It.,* **29**, 287-368.

SACCO, F., 1912. La geotettonica dell'Appennino meridionale. *Boll. Geol. Soc. It.,* **30**, 379-387.

SACCO, F., 1935. Le direttrici tettoniche dell'Appennino. Nota I e II. *Rend. Acc. Lincei. Cl. Sc. Fis. Nat.,* **22**, 371-375 and 551-553.

SALMOIRAGHI, F., 1881. Alcuni appunti geologici sullo Appennino fra Napoli e

Foggia. *Boll Com. Geol. d'It.*, **12**, 96-113.

SANTIAGO, A.J., 1980. Giant oil fields of the southern zone- Mexico. In: *Giant Oil and Gas Fields of the Decade 1968-1978*, (Ed. Halbouty, M.T.), *Am. Assoc. Petrol. Geol. Memoir* **30**, 339-385.

SARG, J.F., 1988. Carbonate sequence stratigraphy. In: Sea-level changes: An integrated approach (Eds. Wilgus, C.K., *et al.*), *Soc. Econ. Paleont. Miner. Spec. Publ.* **42**, 155-182.

SARG., J.F., AND LEHMANN, P.J., 1986. Lower-Middle Guadalupian facies and stratigraphy San Andres/Grayburg formations, Permian Basin, Guadalupe Mountains, New Mexico. In: Field Trip guidebook, San Andres/Grayburg Formations, Guadalupe Mountains, New Mexico and Texas: Permian Basin Section, Society of Economic Paleontologists and Mineralogists Publication, 25-86.

SCANDONE, P., 1967. Studi di geologia lucana: La serie calcareo-silico-marnosa e i suoi rapporti con l'Appennino calcareo. *Boll. Soc. Natur. Napoli,* **76**, 1-175.

SCANDONE, P., 1972. Studi di geologia lucana: La serie calcareo-silico-marnosa e note illustrative. *Boll. Soc. Natur. Napoli,* **81**, 225-300.

SCANDONE, P., SGROSSO, I., AND BRUNI, I., 1963. Appunti di geologia sul Monte Bulgheria (Salerno). *Boll. Soc. Nat. Napoli,* **72**.

SCANDONE, P., GIUNTA, G., AND LIGUORI, V., 1974. The connection between the Apulia and Sahara continental margins in the southern Apennines and Sicily. *Mem. Soc. Geol. It.*, **13**, 317-323.

SCARSELLA, F., 1951. Sulla zona d'incontro dell'Umbria e dell'Abruzzo. *Boll. Serv. Geol. It.,* **71**, 155-165.

SCARSELLA, F., 1953. Relazione preliminare sui rilevamenti geologici fatti durante il 1953 nei fogli L'Aquila, Teramo, Civitavecchia, Ariano Irpino. *Boll. Serv. Geol d'It.*,

75, 795-807.

SCARSELLA, F., 1954. Relazione preliminare sul rilevamento geologico fatto nelle tavolette 140 III NO e NE (Gran Sasso d'Italia) durante la campagna estiva del 1954. *Boll. Serv. Geol. d'It.*, **76**, 571-574.

SCARSELLA, F., 1955a. Calcari titoniani a *Calpionella alpina* nel Giurassico coralligeno del Gran Sasso d'Italia. *Boll. Serv. Geol. It.*, **77**, 327-332.

SCARSELLA, F., 1955b. Di un lembo di Paleogene trasgressivo sul Lias inferiore della vetta del Corno Grande (Gran Sasso d'Italia). *Boll. Serv. d'It.*, **77**, 573-578.

SCARSELLA, F., 1957. Il rilevamento geologico del Gran Sasso d'Italia. *Boll. Soc. Geol. It.*, **76**, 64-68.

SCARSELLA, F., 1958. Filoni sedimentari nel calcare massiccio hetangiano del Corno Grande (Gran Sasso d'Italia). *Boll. Soc. Geol. It.*, **78**, 15-28.

SCARSELLA, F., 1959. 80th riunione estiva della Società Geologica Italiana. L'Aquila 13-19 Sett. 1959. Guida alle escursioni.

SCARSELLA, F., AND MANFREDINI, M., 1955. Relazione preliminare sul rilevamento geologico del gruppo del Matese. *Boll. Serv. Geol. It.*, **76**, 575-579.

SCATURO, D.M., STROBEL, J.S., KENDALL, C.G.ST.C., WENDTE, J.C., BISWAS, G., BEZDEK, J., AND CANNON, R., 1989. Judy Creek: A case study for a two-dimensional sediment deposition simulation. In: Controls on carbonate platform and basin development (Eds. Crevello, P.D., *et al.*), *Spec. Publ. Soc. Econ. Paleont. Miner.* **44**, 63-76.

SCHLAGER, W., 1981. The paradox of drowned reefs and carbonate platforms. *Bull. Geol. Soc. Am.*, **92**, 197-211.

SCHLAGER, W., BUFFLER, R.T., ANGSTADT, D., AND PHAIR, R. 1984. Geologic history of the southeastern Gulf of Mexico. In: Buffler. R.T., *et al.*, *Init. Repts. D.S.D.P.* **77**, 715-738.

SCHLAGER, W., 1989. Drowning unconformities on carbonate platforms. In: Controls on carbonate platform and basin development (Eds. Crevello, P.D., *et al.*), *Soc. Econ. Paleont. Miner. Spec. Publ.* **44**, 15-25.

SCHLAGER, W., AND PHILIP, J., 1989. Cretaceous carbonate platforms. Position paper, Working Group 4, Global Sedimentary Geology Program, Miami, Florida, 15pp..

SCHMOKER, J.W., AND HALLEY, R.B., 1982. Carbonate porosity versus depth: A predictable relation for south Florida. *Am. Assoc. Petrol. Geol. Bull.*, **66**, 2561-2570.

SCHOLLE, P.A., 1977. Chalk diagenesis and its relation to petroleum exploration: Oil from chalks- a modern miracle? *Bull. Am. Assoc. Petrol. Geol.*, **61**, 982-1009.

SCHWARZACHER, W., AND FISCHER, A.G., 1982. Limestone bedding and perturbations of the earth's orbit. In: Cyclic and event stratification (Eds. Einsele, G., and Seilacher, A.), 72-95, Springer-Verlag, Berlin.

SCLATER, J.G., AND CHRISTIE, P.A.F., 1980. Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the Central North Sea basin. *J. Geophys. Res.*, **85**, 3711-3773.

SCOTT, R.W., FROST, S.H., AND SHAFFER, B.L., 1988. Early Cretaceous sea-level curves, Gulf Coast and Southeastern Arabia. In: Sea-level changes: An integrated approach (Eds. Wilgus, C.K., *et al.*), *Soc. Econ. Paleont. Miner. Spec. Publ.* **42**, 275-284.

SEARLE, M.P., JAMES, N.P., CALON, T.J., AND SMEWING, J.D., 1983. Sedimentological and structural evolution of the Arabian continental margin in the Musandam Mountains and Dibba Zone, United Arab Emirates. *Bull. Geol. Soc. Am.*, **94**, 1381-1400.

SEGURET, M., LABAUME, P., AND MADARINGA, R., 1984. Eocene seismicity in the Pyrenees from megaturbidites of the South Pyrenean Basin (Spain). *Marine Geology*, **55**, 117-131.

SELLI, R., 1957. Sulla trasgressione del Miocene della Italia meridionale. *Gior. di Geol.*, s.2, **26**, 1-54.

SELLI, R., 1962. Il Paleogene nel quadro della geologia dell'Italia centro-meridionale. *Mem. Soc. Geol. It.*, **3**, 737-789.

SERVIZIO GEOLOGICO D'ITALIA, 1955. Carta Geologica d'Italia in scala 1:100,000. Foglio 139 L'Aquila.

SERVIZIO GEOLOGICO D'ITALIA, 1963a. Carta Geologica d'Italia in scala 1:100,000. Foglio 140 Teramo.

SERVIZIO GEOLOGICO D'ITALIA, 1963b. Carta Geologica d'Italia alla scala 1:25,000 Foglio 157 "Monte San Angelo".

SERVIZIO GEOLOGICO D'ITALIA, 1971. Carta Geologica d'Italia alla scala 1:100,000. Fogli 161 (Isernia), 162 (Campobasso), Rome.

SGROSSO, I., 1963. La trasgressione miocenica nel Matese centrale. *Boll. Soc. Nat. Napoli*, **72**, 150-153.

SGROSSO, I., 1964. La serie stratigrafica di Serra delle Macchietelle in relazione ad alcune caratteristiche della tettonica del Matese. *Boll. Soc. Nat. Napoli*, **73**, 186-194.

SGROSSO, I., AND TORRE, M., 1968. Su alcuni affioramenti terziari dei dintorni di Monteroduni (Matese). *Boll. Soc. Nat. Napoli*, **77**, 131-158.

SHANMUGAN, G., AND MOIOLA, R.J., 1982. Eustatic control of turbidites and winnowed turbidites. *Geology*, **10**, 231-235.

SHANMUGAN, G., AND MOIOLA, R.J., 1984. Eustatic control of calciclastic turbidites. *Mar. Geol.*, **44**, 1-24.

SIGNORINI, R., 1962. Osservazioni geologiche nell'alto Molise. *Boll. Soc. Geol. It.*, **80**, 215-224.

SIGNORINI, R., AND DEVOTO, G., 1962. Il Paleogene nell'alto Molise. *Mem. Soc. Geol. It.*, **3**, 461-511.

SIRNA, G., 1963. Aptian Charophyta of southern Latium. *Geol. Romana* **2**, 279-290.

SPALLETTA, C., AND VAI, G.B., 1984. Upper Devonian intraclast parabreccias interpreted as seismites. *Marine Geology*, **55**, 133-144.

STECKLER, M.S., 1981. Thermal and mechanical evolution of Atlantic-type margins. Unpublished PhD. Dissertation, Columbia University, New York, 261pp..

SWINCHATT, J.P., 1967. Formation of large-scale cross-bedding in a carbonate unit. *Sedimentology* **8**, 93-120.

TENORE, G., 1872. Saggio dell'industria mineraria e sulla costituzione geologica della provincia. *La scienza e l'arte dello ing. arch.*, **3**, n.1, Napoli.

THIEDE, J., 1981. Reworked neritic fossils in Upper Mesozoic and Cenozoic central Pacific deep-sea sediments monitor sea-level changes. *Science* **211**, 1422-1424.

UFFICIO GEOLOGICO, 1934. Carta geologica d'Italia, scala 1:100,000, f.**161** (Isernia), Roma.

VAI, G.B., 1979. Paleozoico e basamento in Italia. Aggiornamenti e problemi. *Mem. Geol. Soc. It.*, **20**, 1-464.

VAIL, P.R., 1988. Seismic stratigraphy interpretation procedure. In: *Atlas of seismic stratigraphy Volume 1*, (Ed., Bally, A.W.), *Am. Ass. Petrol. Geol. Studies in Geology* **27**, 1-10.

VAIL, P.R., MITCHUM, R.M., AND THOMPSON, S., 1977. Seismic stratigraphy and global changes of sea-level. Part IV. Global cycles of relative sea level change. In: Seismic stratigraphy-Applications to hydrocarbon exploration (ed. Payton, C.E.), *Mem. Am. Assoc. Petrol. Geol.*, **26**, 63-81.

VAIL, P.R., AND TODD, R.G., 1981. North Sea Jurassic unconformities, chronostratigraphy, and sea-level changes from seismic stratigraphy. In: Proceedings, Petroleum Geology of the Continental Shelf, Northwest Europe Conference, London (Eds., Illing, L.V., and Hobson, G.D.), 216-235, Heydon and Sons.

VALLARIO, A., 1964. Osservazioni geologiche nella zona di Capriati al Volturno (Caserta). *Boll. Soc. Nat. Napoli*, **72**, 132-137.

VECSEI, A. AND EBERLI, G.P., 1989. Depositional geometry of prograding carbonate sands along the upper slope of Maiella carbonate platform (Central Italy). *Abstracts 10th Regional Meeting on Sedimentology, Int. Ass. Sediment.*, 244-245.

VERRALL, P., 1982. *Structural Interpretation with Applications to North Sea Problems.* Course notes No. 3, J.A.P.E.C..

VEZZANI, L., 1975. Lithostratigraphic complexes and evidence for tectonic phases in the Molise-Puglia-Lucania Apennines. In: Structural Model of Italy, *Quaderni de "La Ricerca Scientifica"*, **90**, 329-363, Rome.

VINIEGRA, O.F., 1981. Great carbonate bank of Yucatan, southern Mexico. *J. Petrol. Geol.*, **3**, 247-278.

WATT, F., AND GRIME, G.W., 1987. Principles and Applications of High Energy Microbeams. Adam Hilger, 399pp..

WATTS, A.B., 1981. The U.S. Atlantic continental margin: Subsidence history, crustal structure and thermal evolution. In: Geology of Passive Continental Margins: History, Structure and Sedimentologic Record. *Am. Assoc. Petrol. Geol. Education Course Note Series* **19**, chapter 2, 75pp..

WATTS, K.F., 1988. Triassic carbonate submarine fans along the Arabian platform margin, Sumeini Group, Oman. *Sedimentology*, **35**, 43-72.

WATTS, K.F., AND GARRISON, R.E., 1986. Sumeini Group, Oman- Evolution of a Mesozoic carbonate slope on a south Tethyan continental margin. *Sedimentary Geology*,

48, 107-168.

WINKER, C.D., AND BUFFLER, R.T., 1988. Paleogeographic evolution of early deep-water Gulf of Mexico and margins, Jurassic to Middle Cretaceous (Comanchean). *Bull. Am. Ass. Petrol. Geol.* **72**, 318-346.

WRIGHT, V.P., AND WILSON, R.C.L., 1984. A carbonate submarine-fan sequence from the Jurassic of Portugal. *Jour. Sedim. Petrol.*, **54**, 394-412.

WHITEMAN, M.I., 1988. The development of the former Molise basin margin in the Isernia-Campobasso region. *Atti 74th Congresso Soc. Geol. It.*, **vol.A**, 521-528.

WILLIAMS, G.D., AND VANN, I., 1987. The geometry of listric normal faults and deformation in their hangingwalls. *Jour. Struct. Geol.*, **9**, 789-797.

WILSON, J.L., 1975. Carbonate Facies in Geologic History. Springer-Verlag, New York, 471pp..

WINTERER, E.L., AND BOSELLINI, A., 1981. Subsidence and sedimentation on Jurassic passive continental margin, southern Alps, Italy. *Bull. Am. Assoc. Petrol. Geol.*, **65**, 394-421.

WONDERS, A.A.H., 1977. The major phases of movement of the Northern Apennine autochton and the eugeosynclinal stratigraphy of the Northern Apennines. *Mem. Soc. Geol. It.*, **15**, 91-94.

WONDERS, A.A.H., 1978. Middle and Late Cretaceous pelagic sediments of the Umbrian Sequence in the central Apennines. *Koninklijke Nederlandse Akademie van Wetenschappen*, series B, **82**, 171-205.

WOOD, A.W., 1981. Extensional tectonics and the birth of the Lagonegro Basin (southern Italian Apennines). *N. Jb. Paleont. Abh.*, **161**, 93-131.

WOODCOCK, N.H., 1979. The use of slump structures as palaeoslope orientation estimators. *Sedimentology*, **26**, 83-99.

WRIGHT, V.P., AND WILSON, R.C.L., 1984. A carbonate submarine-fan sequence from the Jurassic of Portugal. *Jour. Sedim. Petrol.*, **54**, 394-412.

YOSE, L.Y., AND HELLER, P.L., 1989. Sea-level control of mixed-carbonate-siliciclastic, gravity-flow deposition: Lower part of the Keeler Canyon Formation (Pennsylvanian), southeastern California. *Bull. Geol. Soc. Am.*, **101**, 427-439.

ZACCARA, G., AND MAINO, A., 1957. Rilievo gravimetrico dell'Italia centro-meridionale (Lucania, Molise e Campania-Abruzzi). *Boll. Serv. Geol. It.*, **78**, 789-794.

ZACCARA, G., AND MAINO, A., 1958. Carta gravimetrica d'Italia. Relievo della Campania, del Lazio e dello Abruzzo occidentale. *Boll. Serv. Geol. It.*, **79**, 479-488.

ZAMPARELLI, V., 1964. La successsioni stratigrafia dal Giurassico superiore al Cretaceo medio nel versante meridionale di Pizzo Cefalone (Gran Sasso d'Italia). *Boll. Soc. Nat. Napoli*, **72**, 161-167.

ZAMPARELLI, V., 1966. Le microfacies cretaceo-eoceniche nella serie di Rio Arno (Gran Sasso d'Italia). *Boll. Soc. Nat. Napoli*, **75**, 553-560.

ZANFRA, S., 1963. Osservazioni micropaleontologiche della serie di terreni dal Cretaceo medio al Miocene inferiore sul bordo orientale del massiccio del Matese (Italia meridionale). *Mem. Soc. Geol. It.*, **4**, 1-7.