HYDROLOGICAL IMPLICATIONS

OF

STABLE ISOTOPE DETERMINATIONS

IN U.K.WATERS

(with special reference to the Malham area,

North Yorkshire, and the Lambourn area, Berkshire)



VOLUME 2

by

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in the School of Geography, Oxford

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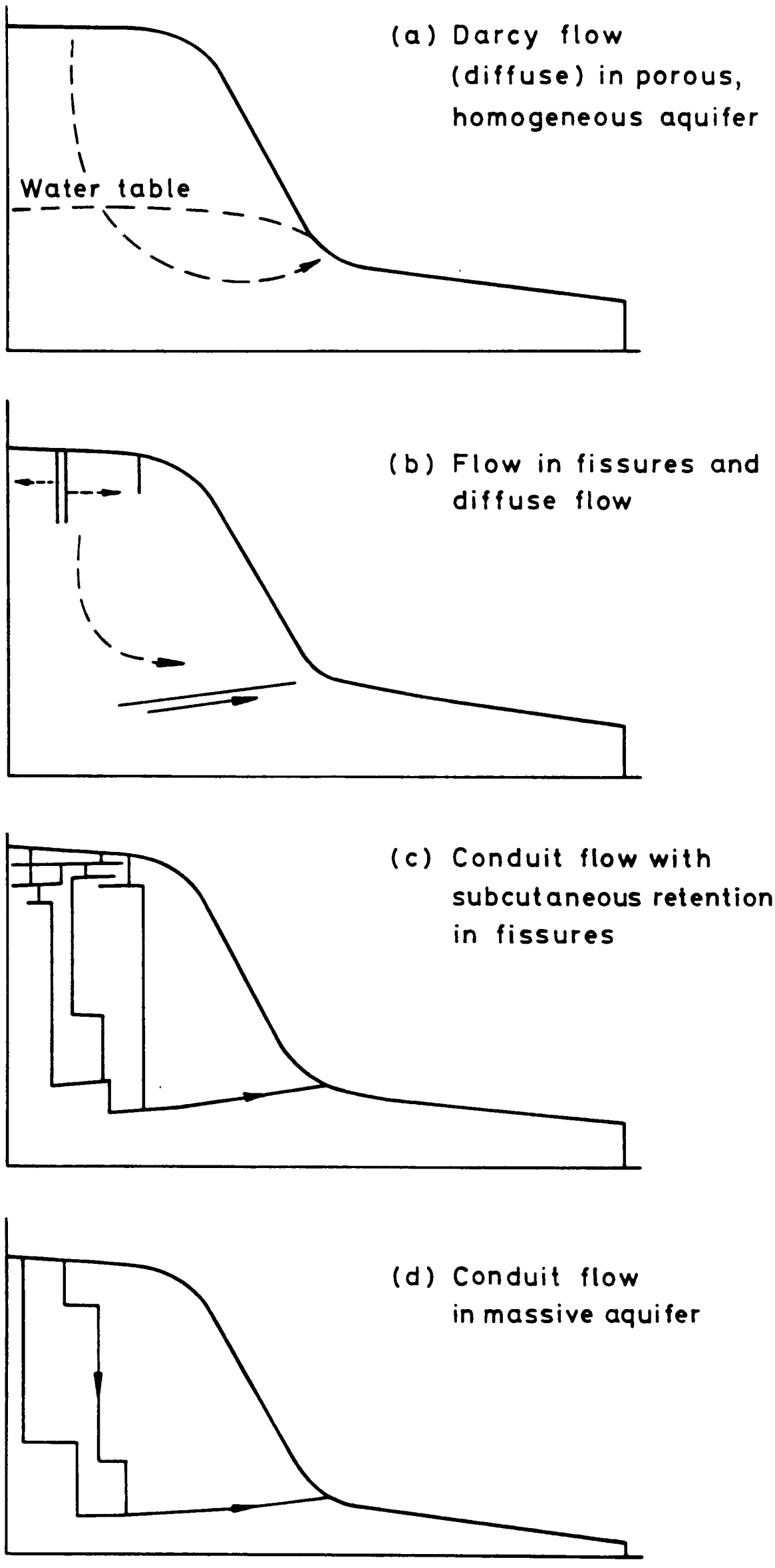


Fig. 1.1 The spectrum of flow regimes observed in limestone aquifers (modified from SHUSTER & WHITE, 1971)

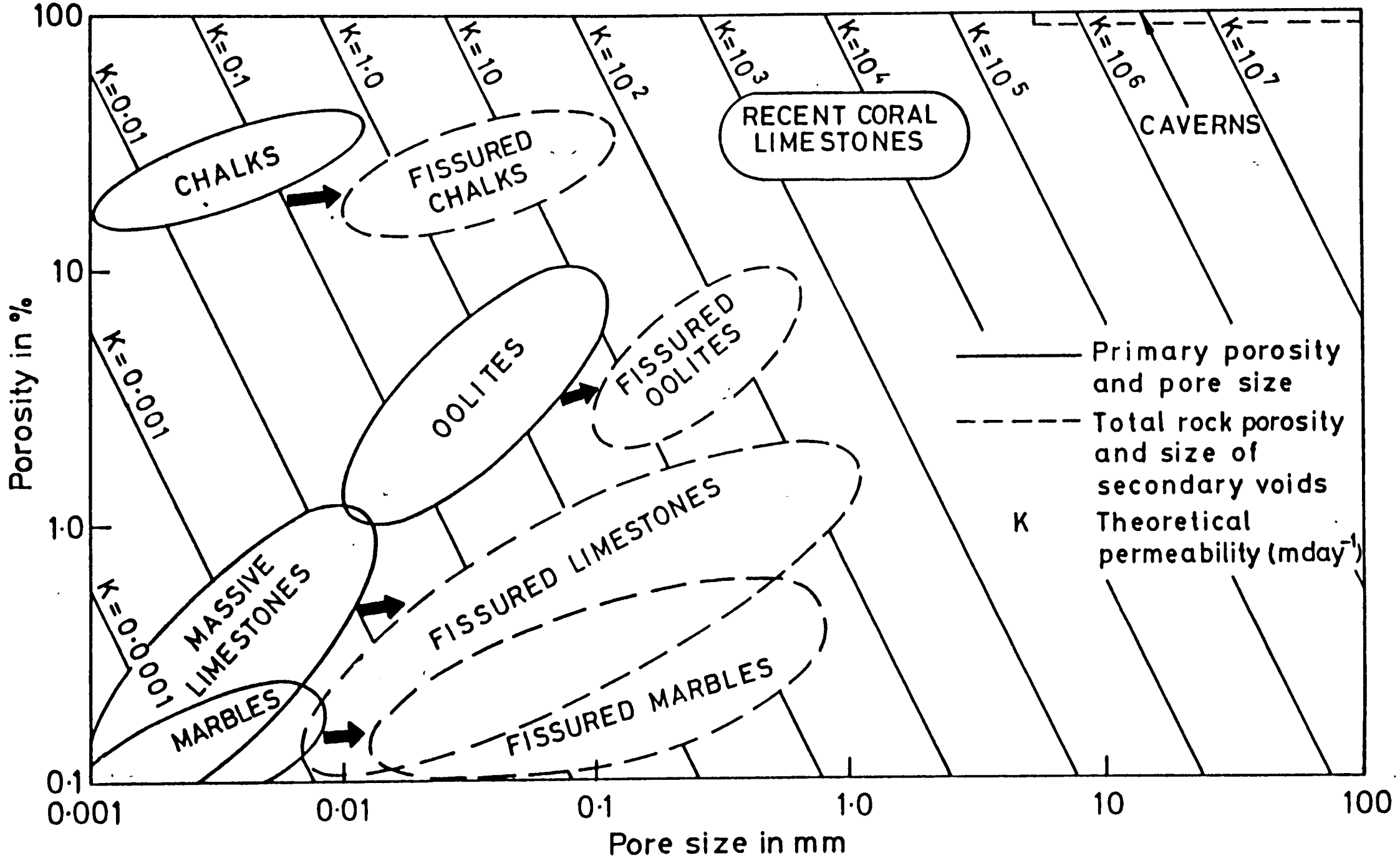


Fig. 1.2 Primary and secondary porosity, pore size and permeability of limestone aquifers (Source: D.I. SMITH et al., 1976)

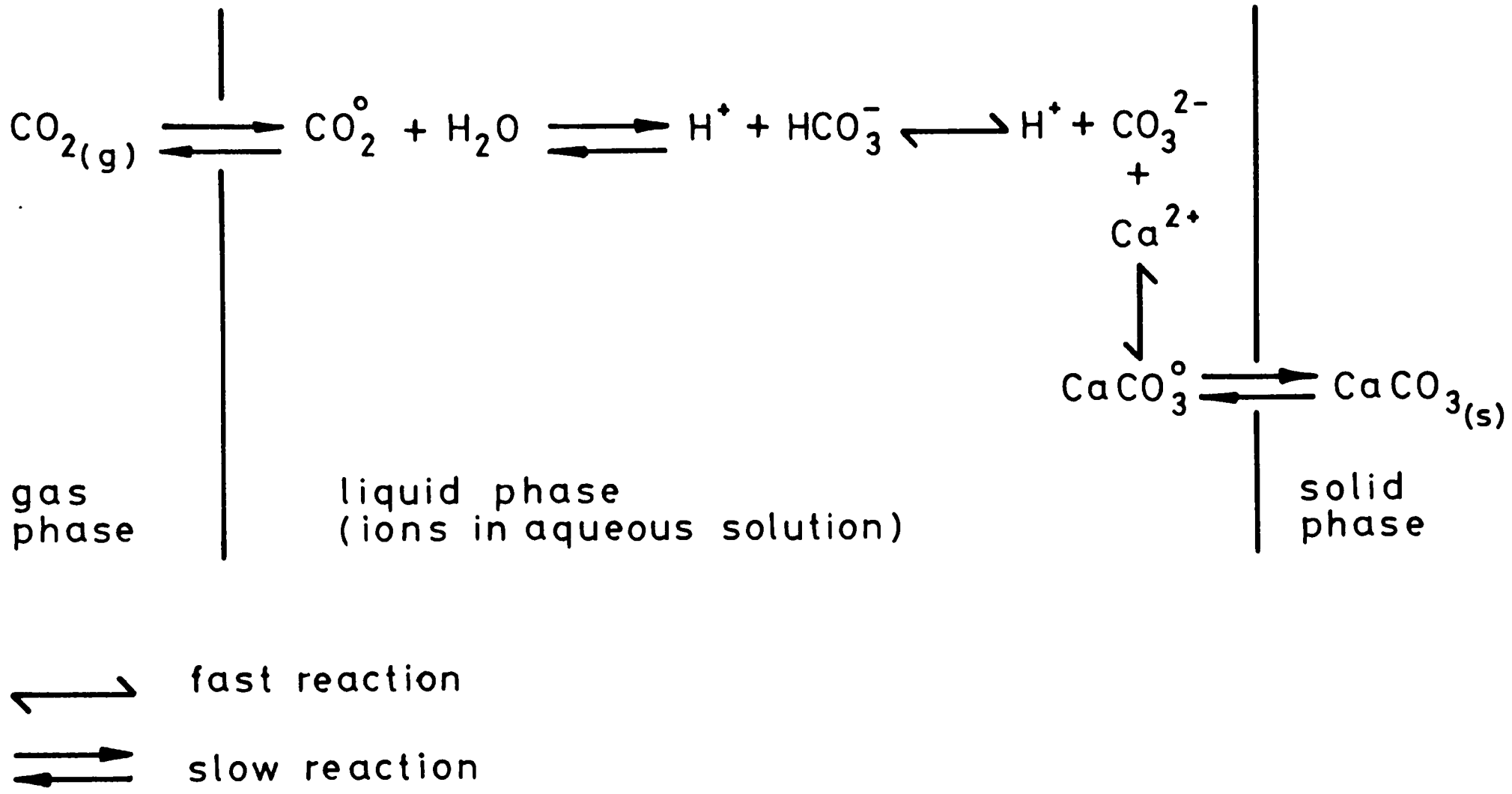
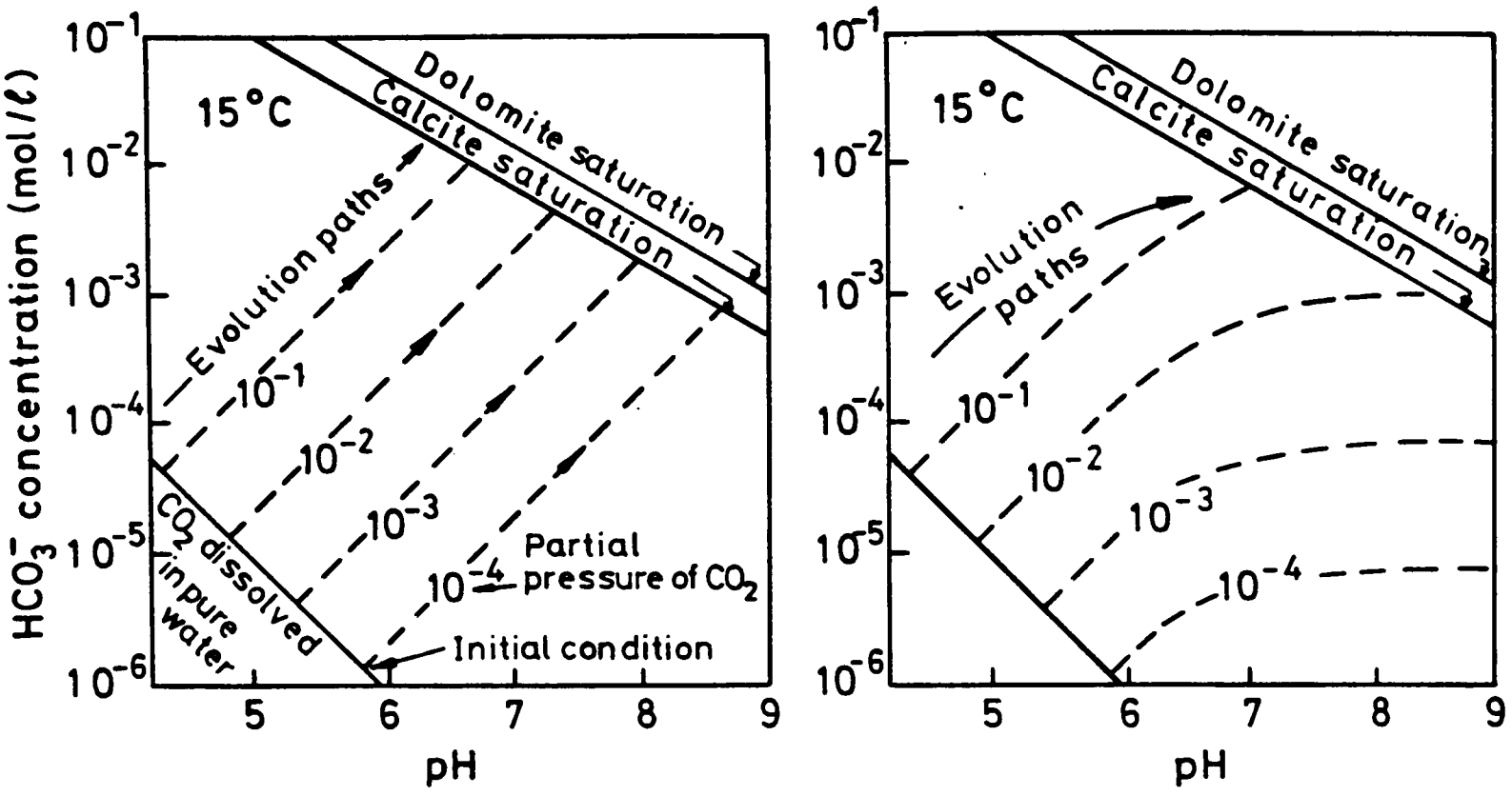
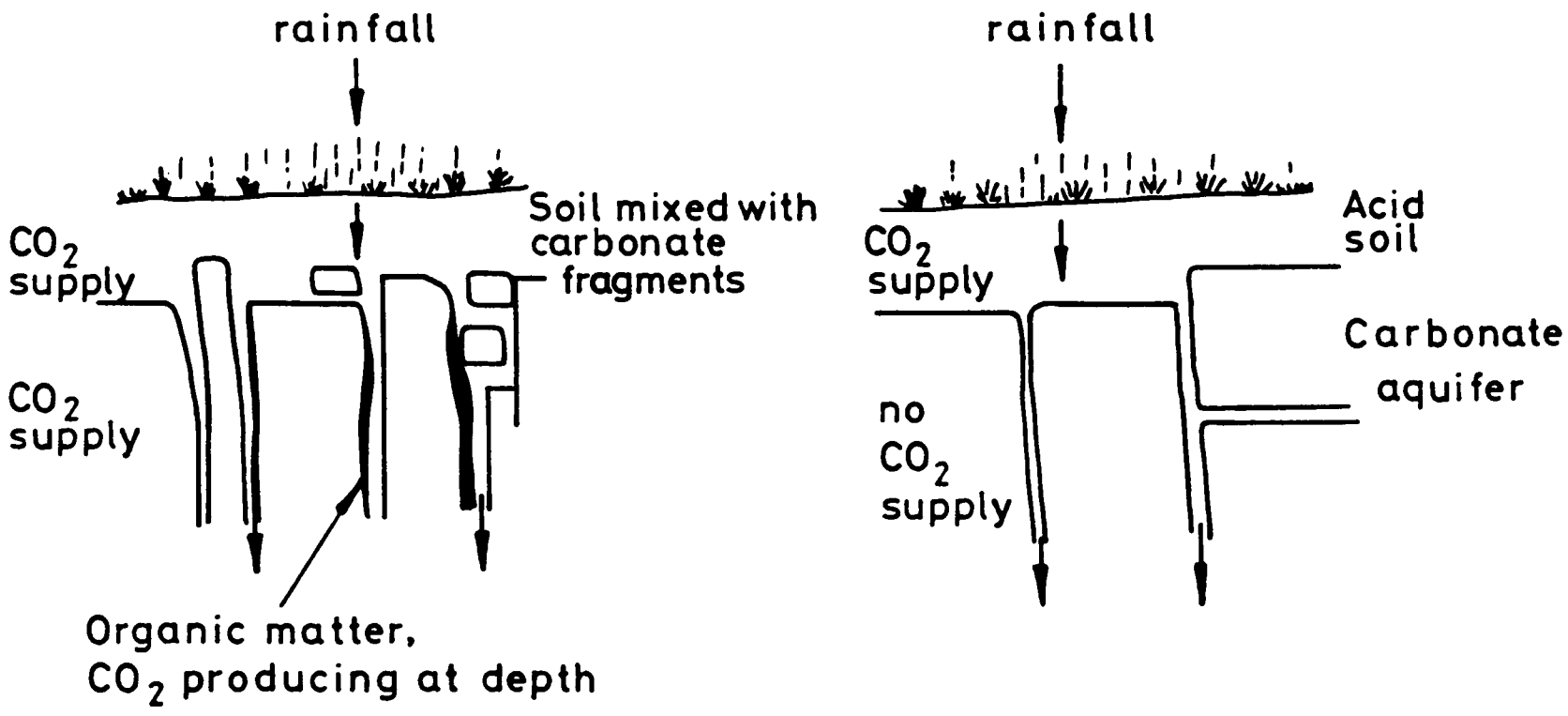


Fig. 1.3 Simplified chemical equilibria of the $CaCO_3$-H_2O-CO_2 system (after PICKNETT et al., 1976)



(a) Open system dissolution (b) Closed system dissolution

CHEMICAL EVOLUTION



(c) Open system dissolution (d) Closed system dissolution

SCHEMATIC RECHARGE CHARACTERITICS

Fig. 1.4 Chemical evolution (source FREEZE & CHERRY, 1979) and schematic recharge characteristics, in open system (a, c) and closed system (b, d) carbonate rock dissolution by carbonic acid

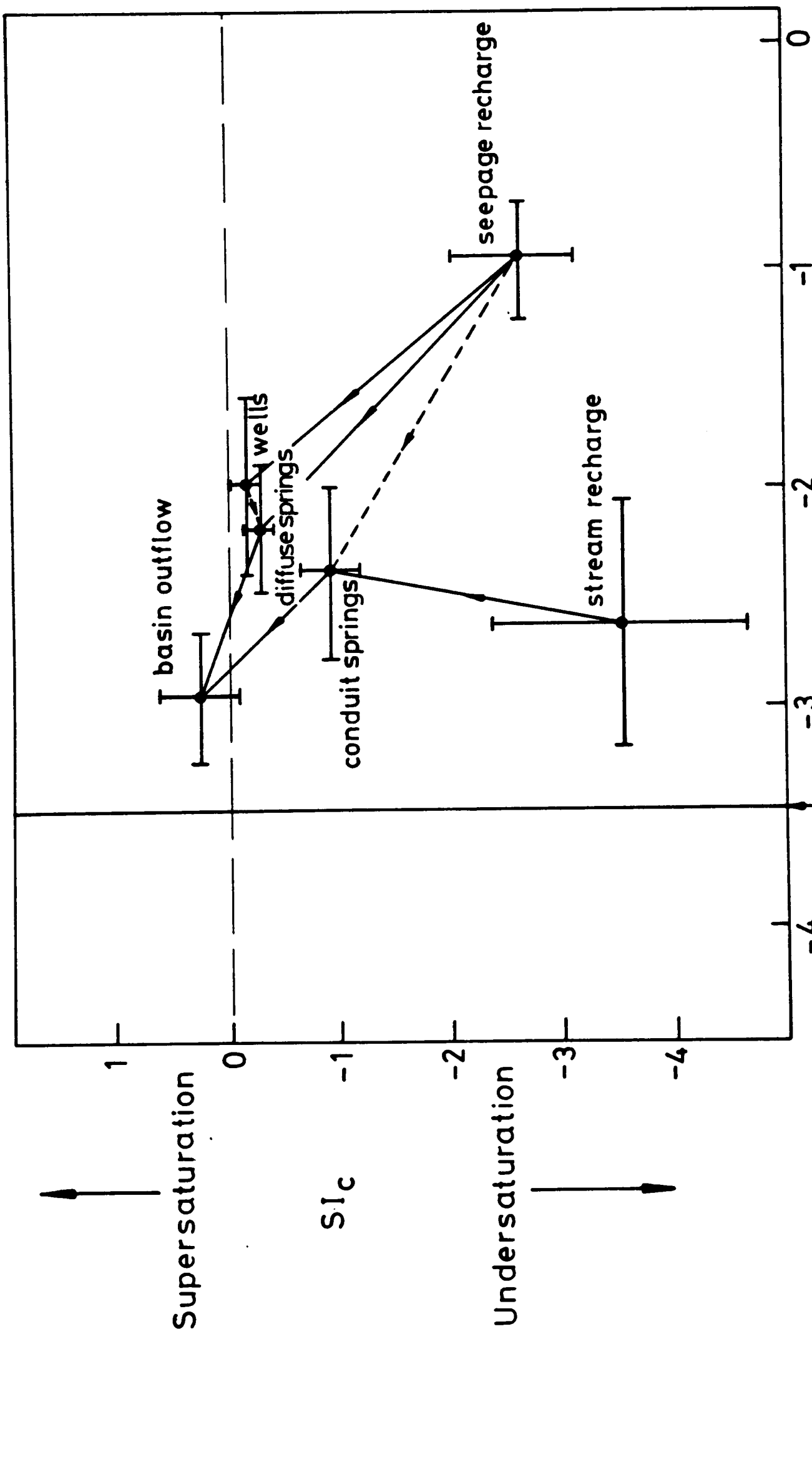
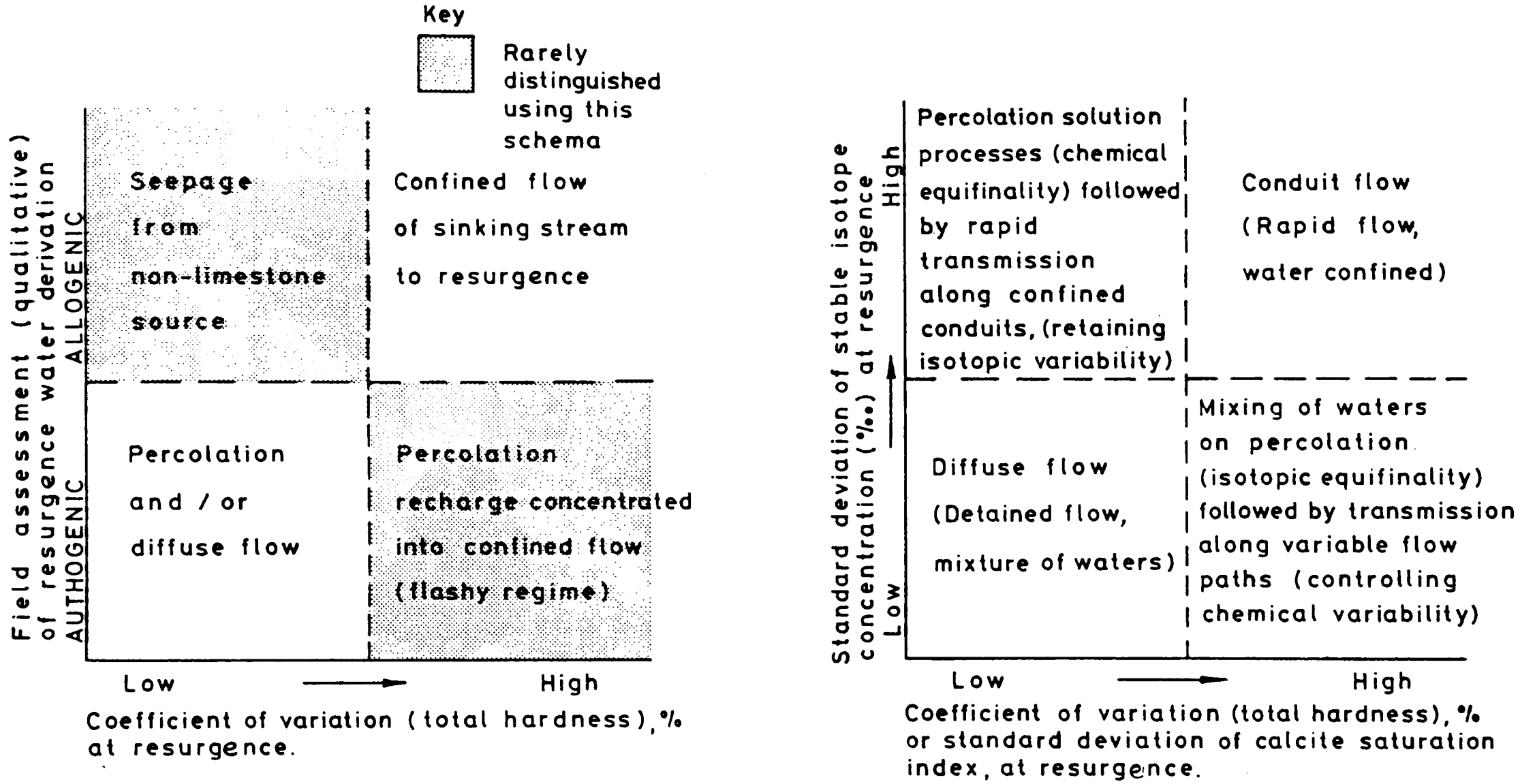


Fig. 1.5 Classification of karst waters according to mean and standard deviation (at 1σ) of the saturation index with respect to calcite (SI_c) and equilibrium partial pressure of carbon dioxide (pCO_2) (Source: DRAKE & HARMON, 1973)



(a) Semi-descriptive schema.

(b) Inferential schema (tentative)

Fig. 1.6 The use of hydrological indices to distinguish flow regimes in limestone aquifers; (a) Semi-descriptive schema using chemical data and field assessment of water derivation; (b) Inferential schema making use of stable isotopes together with chemical data

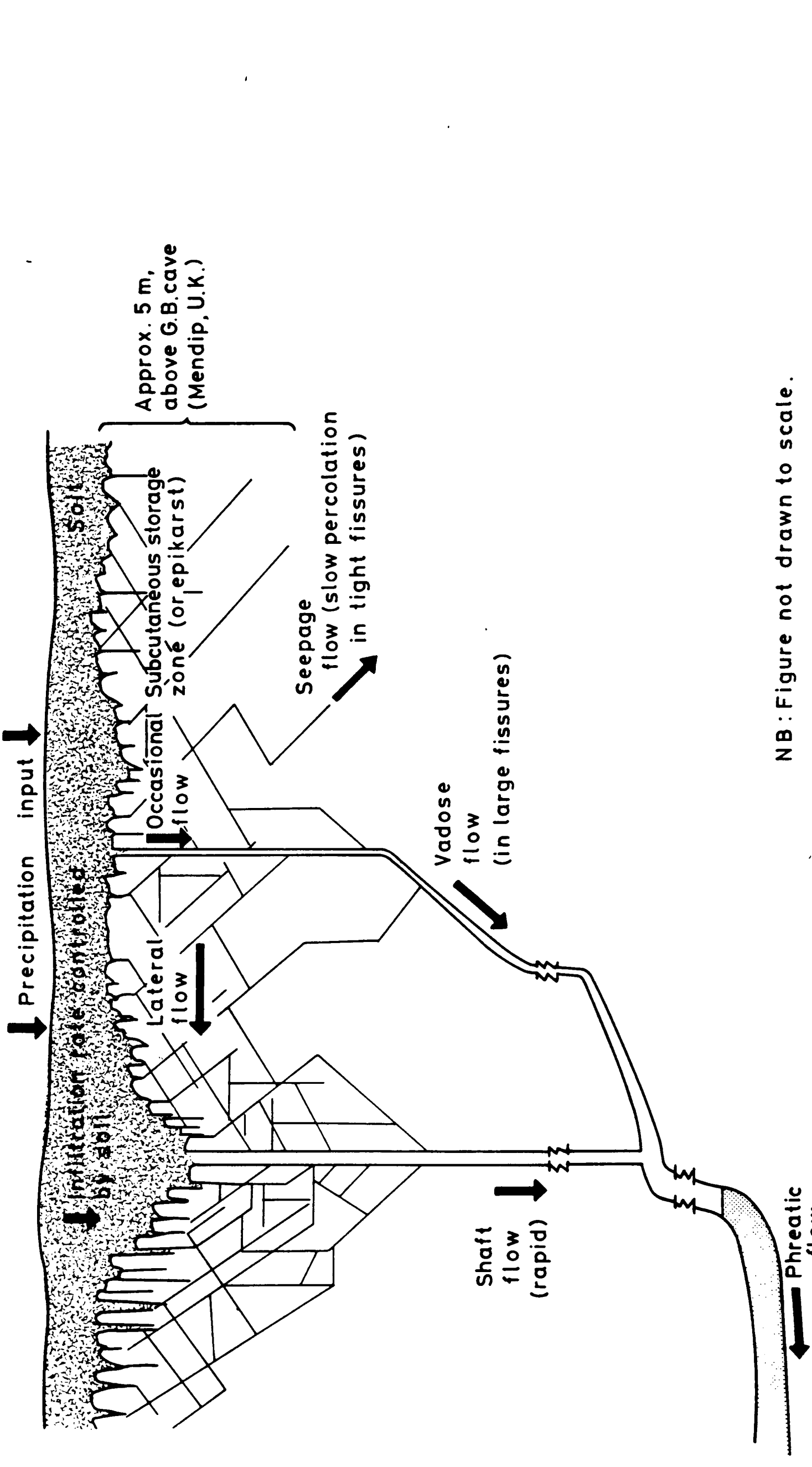


Fig. 1.7 Storage and recharge characteristics in the karstified limestone aquifer of the Mendip Hills, U.K., inferred from studies in the unsaturated zone (after FRIEDRICH, 1981)

NB: Figure not drawn to scale.

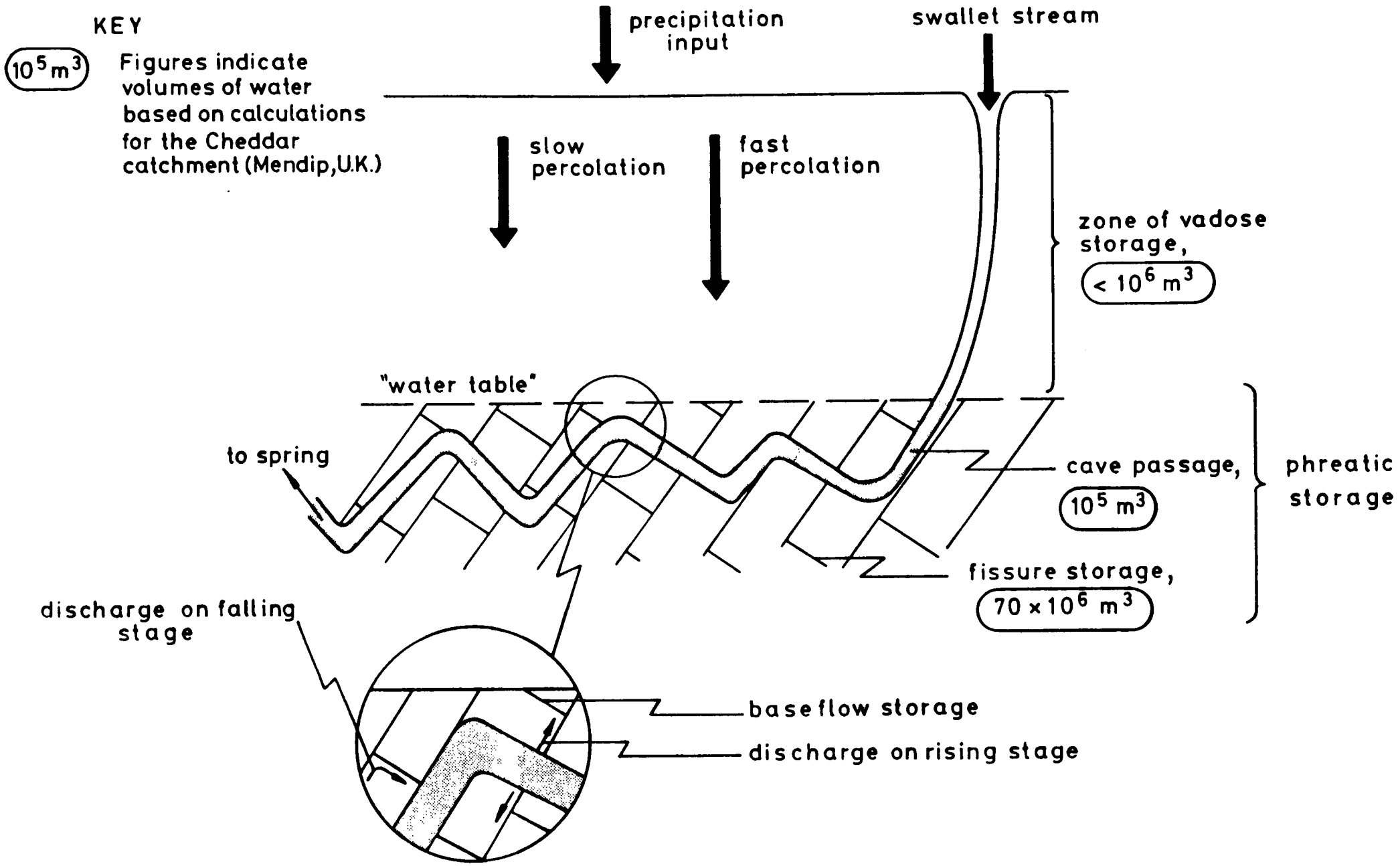
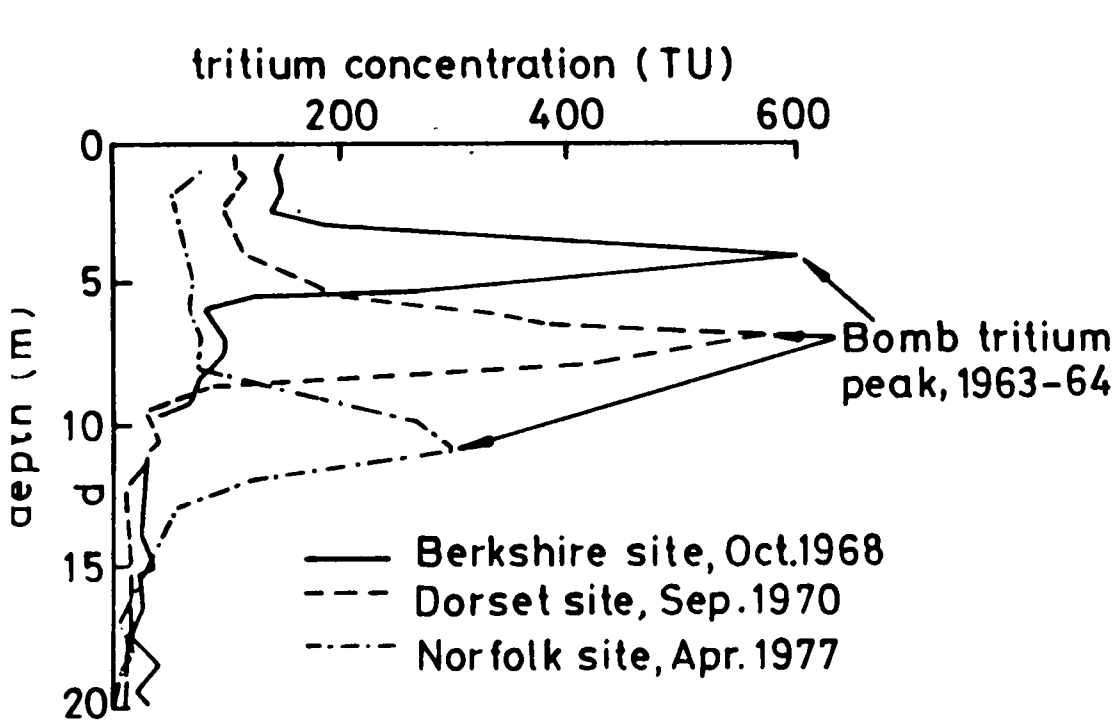
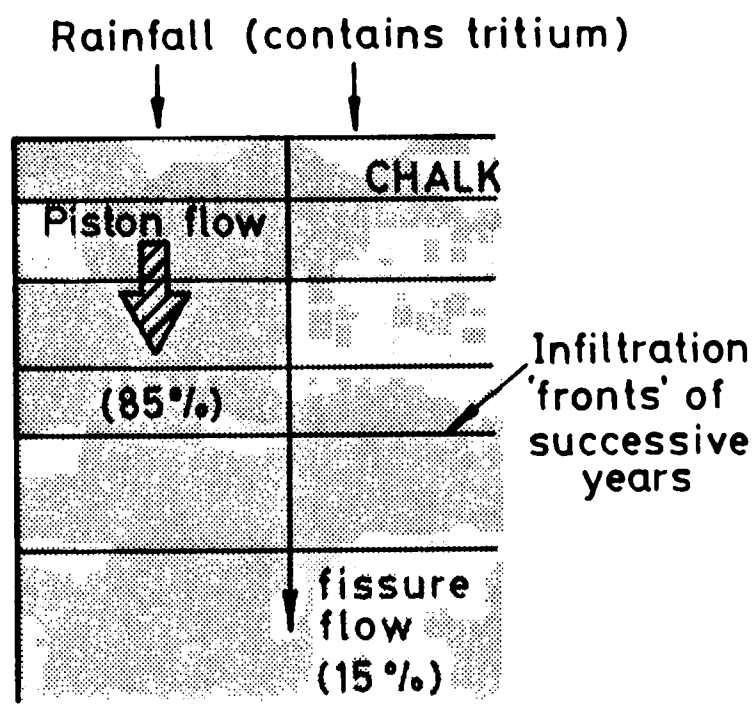


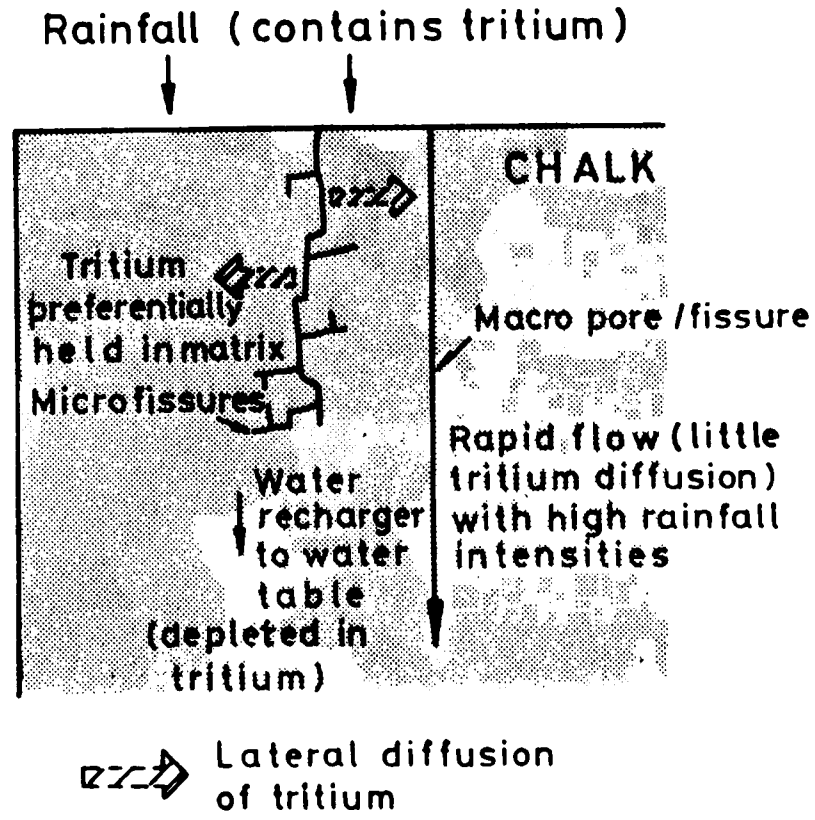
Fig. 1.8 Storage and recharge characteristics in the karstified limestone aquifer of the Mendip Hills, U.K., inferred by ATKINSON (1971) from tracing and hydrograph studies



a) Selected tritium profiles measured in chalk of the unsaturated zone from FOSTER & SMITH-CARRINGTON (1980)



(b) Model of SMITH et al, (1970)



(c) Model of FOSTER & SMITH-CARRINGTON (1980)

Fig. 1.9 Recharge characteristics in the unsaturated zone of a Chalk aquifer, inferred from tritium investigations of interstitial waters (Sources: SMITH et al., 1970; FOSTER & SMITH-CARRINGTON, 1980)

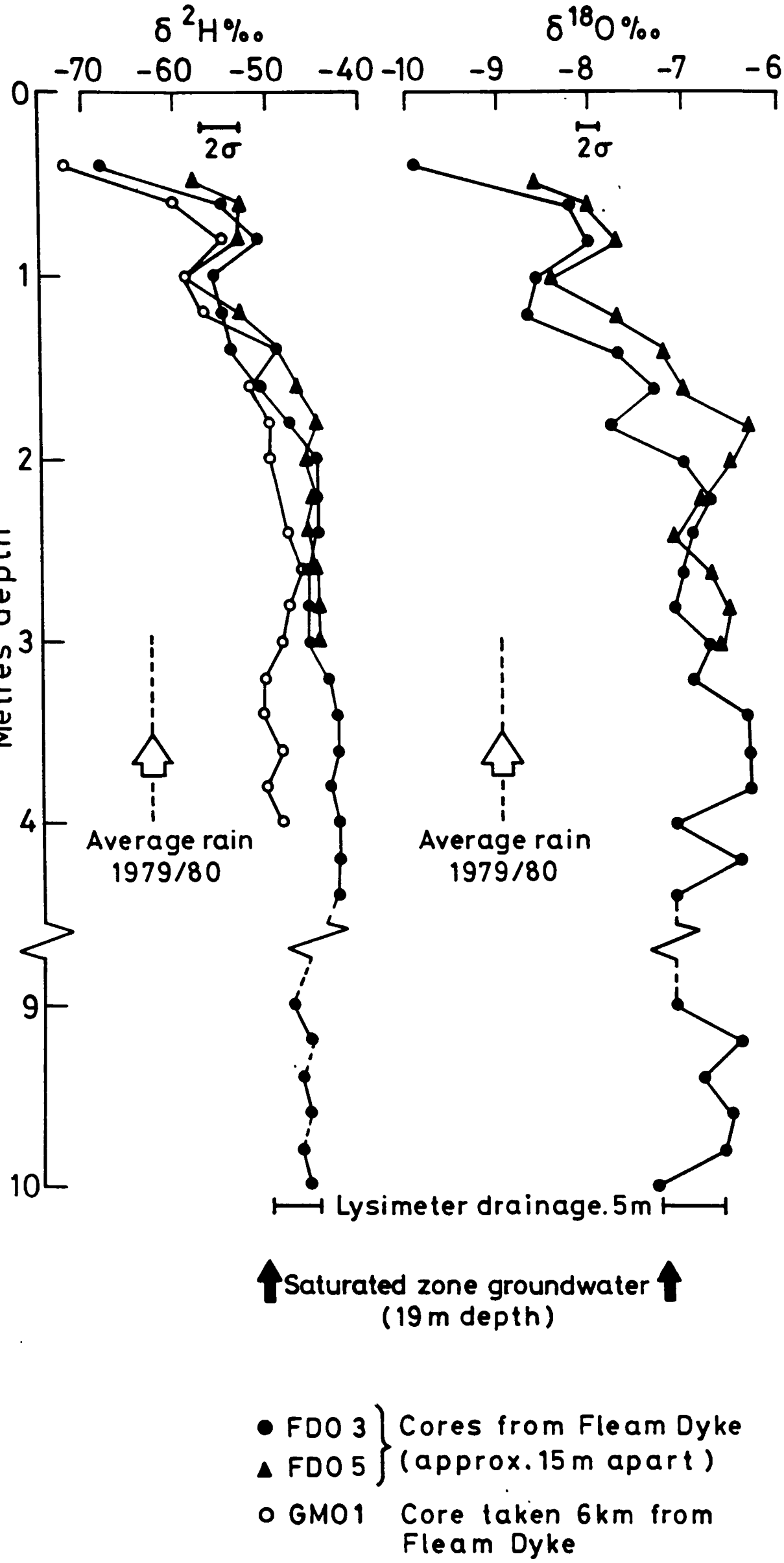


Fig. 1.10 Stable isotope composition of lysimeter drainage and groundwater, and isotopic profiles of interstitial waters in the Chalk unsaturated zone, at Fleam Dyke, Cambridgeshire, U.K. (Source: BATH et al., 1982)

ISOTOPES OF OXYGEN Nucleus*	Comments	AVERAGE TERRESTRIAL ABUNDANCE (%)
8 P 8 N	Relative atomic mass 16 (^{16}O) Stable	99·76
8 P 9 N	Relative atomic mass 17 (^{17}O) Stable	0·037
8 P 10 N	Relative atomic mass 18 (^{18}O) Stable	0·1

ISOTOPES OF HYDROGEN		
1 P	Relative atomic mass 1 (^{1}H) Stable	99·984
1 P 1 N	Relative atomic mass 2 (^{2}H or D) Stable	0·015
1 P 2 N	Relative atomic mass 3 (^{3}H or T) β Radioactive $t_{1/2}$ = 12·35 years	10^{-14} to 10^{-16}

ISOTOPES OF CARBON		
6 P 6 N	Relative atomic mass 12 (^{12}C) Stable	98·89
6 P 7 N	Relative atomic mass 13 (^{13}C) Stable	1·11
6 P 8 N	Relative atomic mass 14 (^{14}C) β Radioactive $t_{1/2}$ = 5730 years	$\sim 10^{-11}$

*P = proton

N = neutron

Fig. 2.1 The atomic composition and average terrestrial abundance of the isotopes of oxygen, hydrogen and carbon

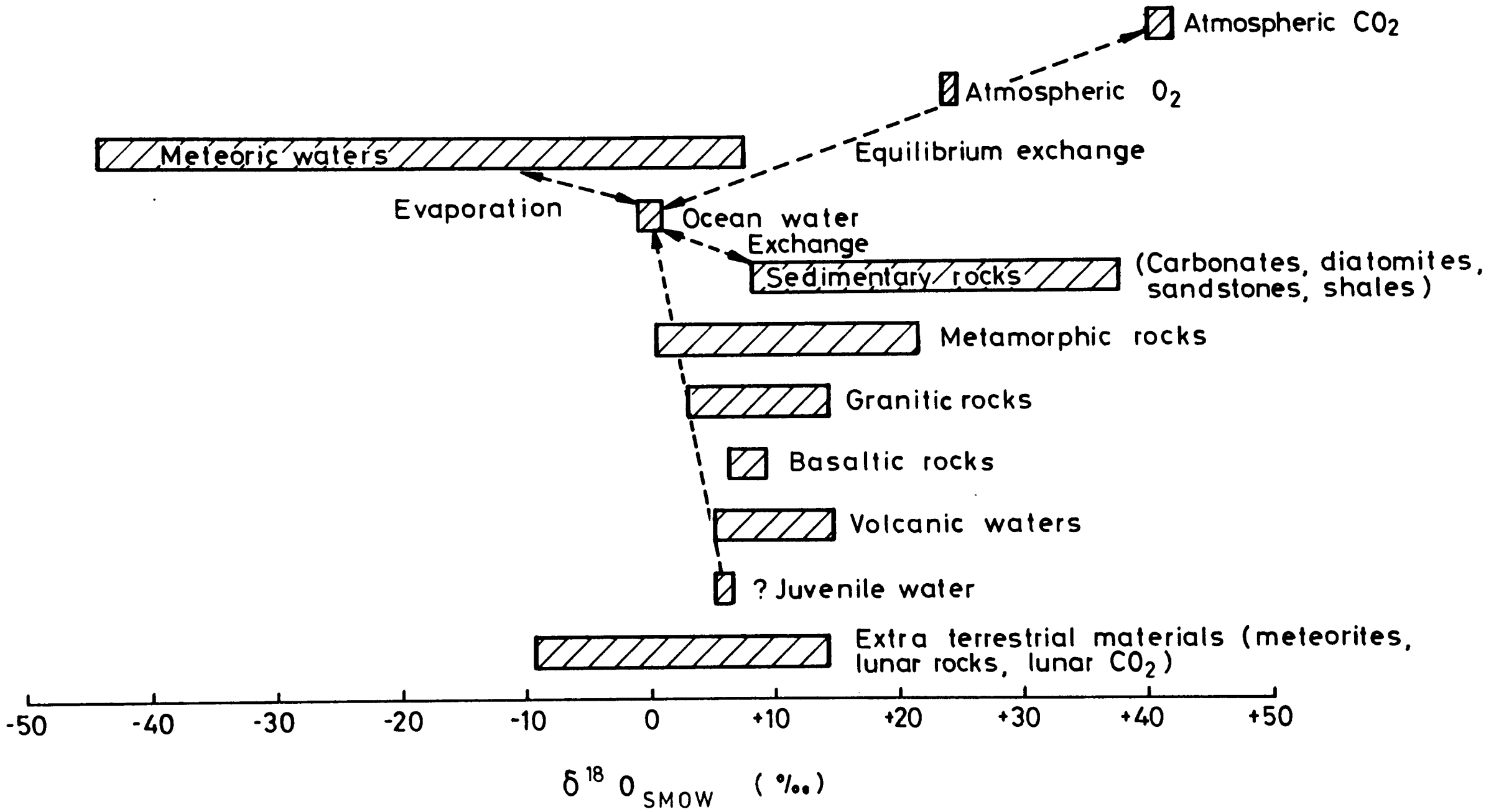


Fig. 2.2 The distribution of oxygen isotopes in natural materials (Sources: HOEFS, 1973; FERRONSKY & POLYAKOV, 1982)

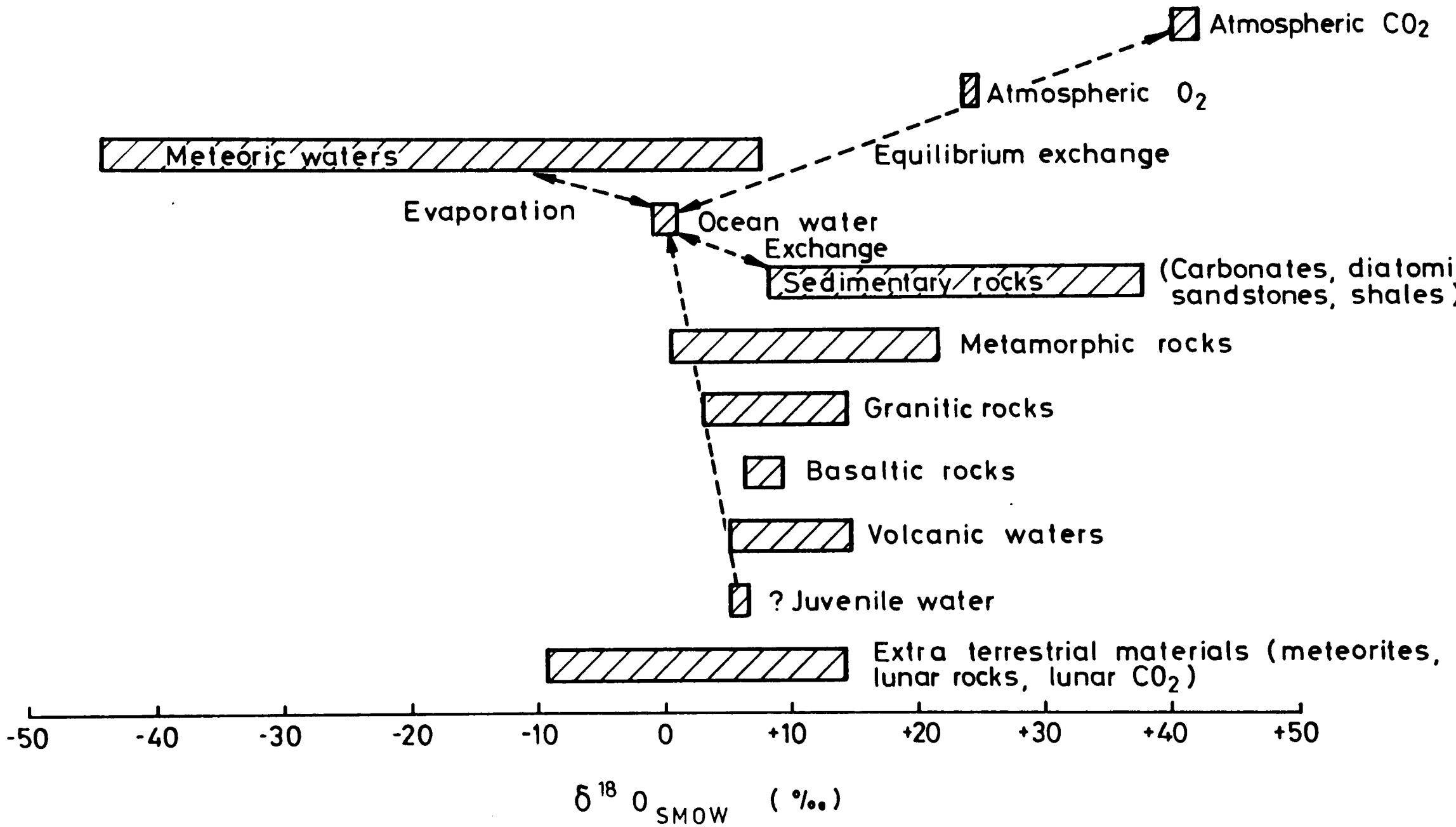


Fig. 2.3 The distribution of hydrogen isotopes in natural materials (Sources: HOEFS, 1973; FERRONSKY & POLYAKOV, 1982)

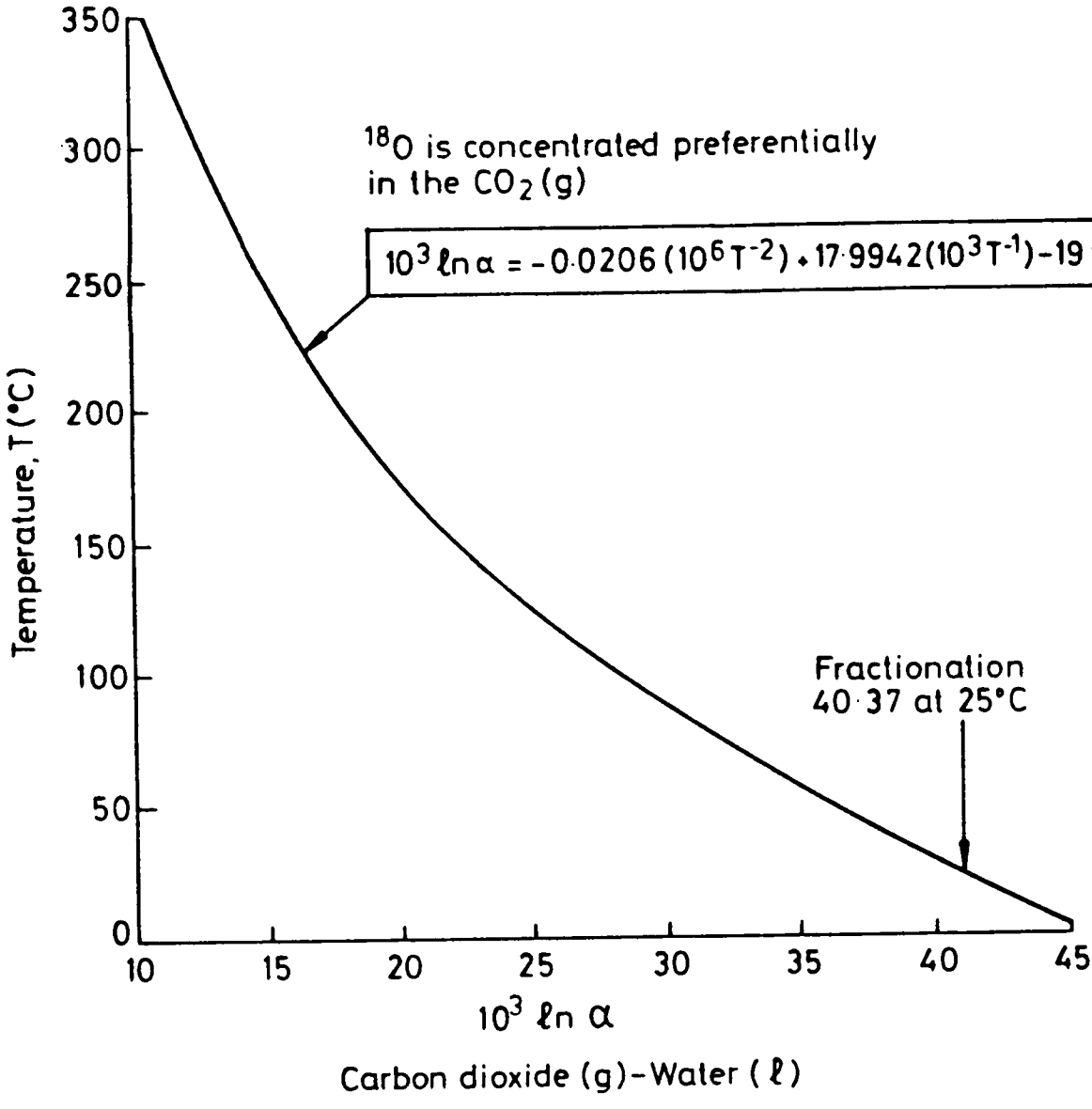
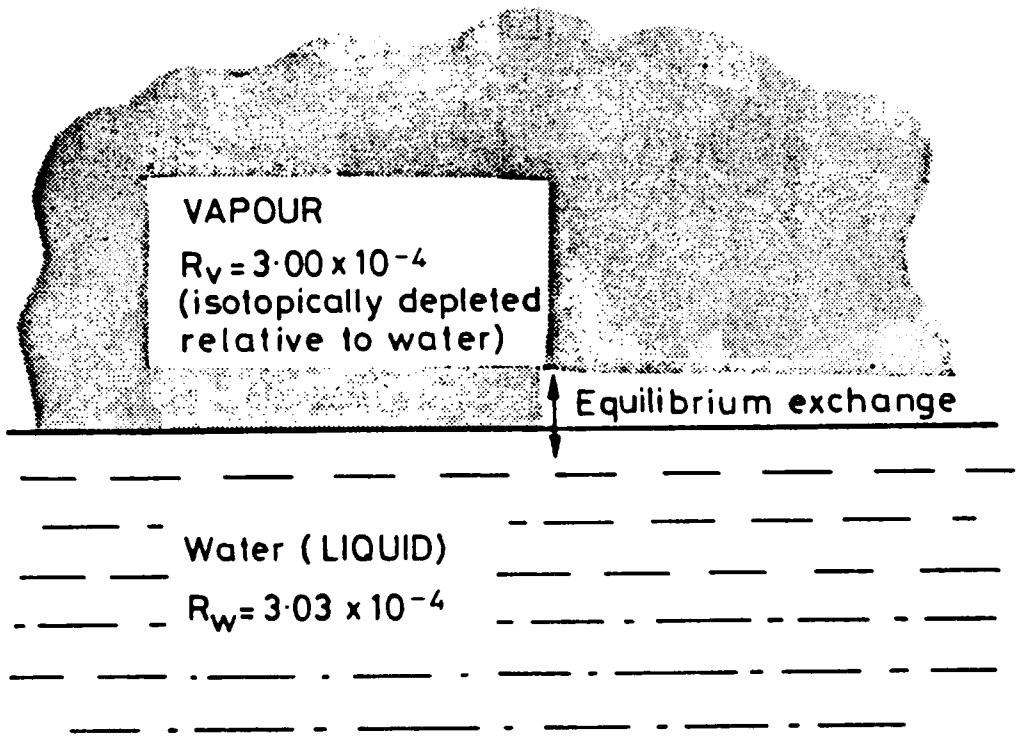


Fig. 2.4 The temperature dependence of the fractionation factor, α, in the equilibrium exchange of oxygen isotopes between CO_2 and water (Source: FRIEDMAN & O'NEIL, 1977)



where R values express the ratios $^{18}O/^{16}O$

Fractionation factor, $\alpha_{water-vapour} = \frac{R_w}{R_v} = \frac{3.03 \times 10^{-4}}{3.00 \times 10^{-4}} \simeq \underline{1.010}$

Fig. 2.5 Equilibrium fractionation of oxygen isotopes, between water vapour and water(liquid) in a 'closed' system

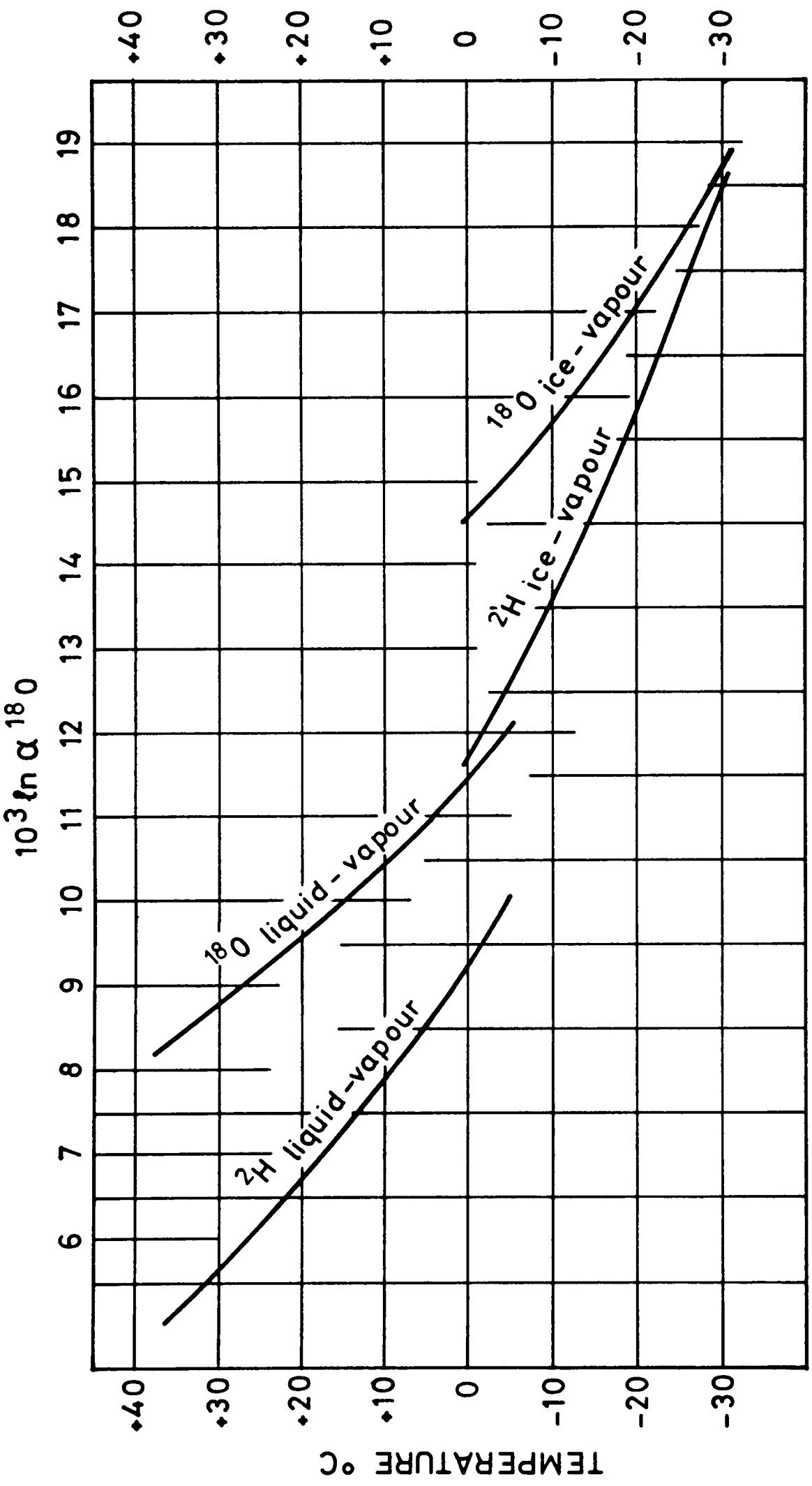
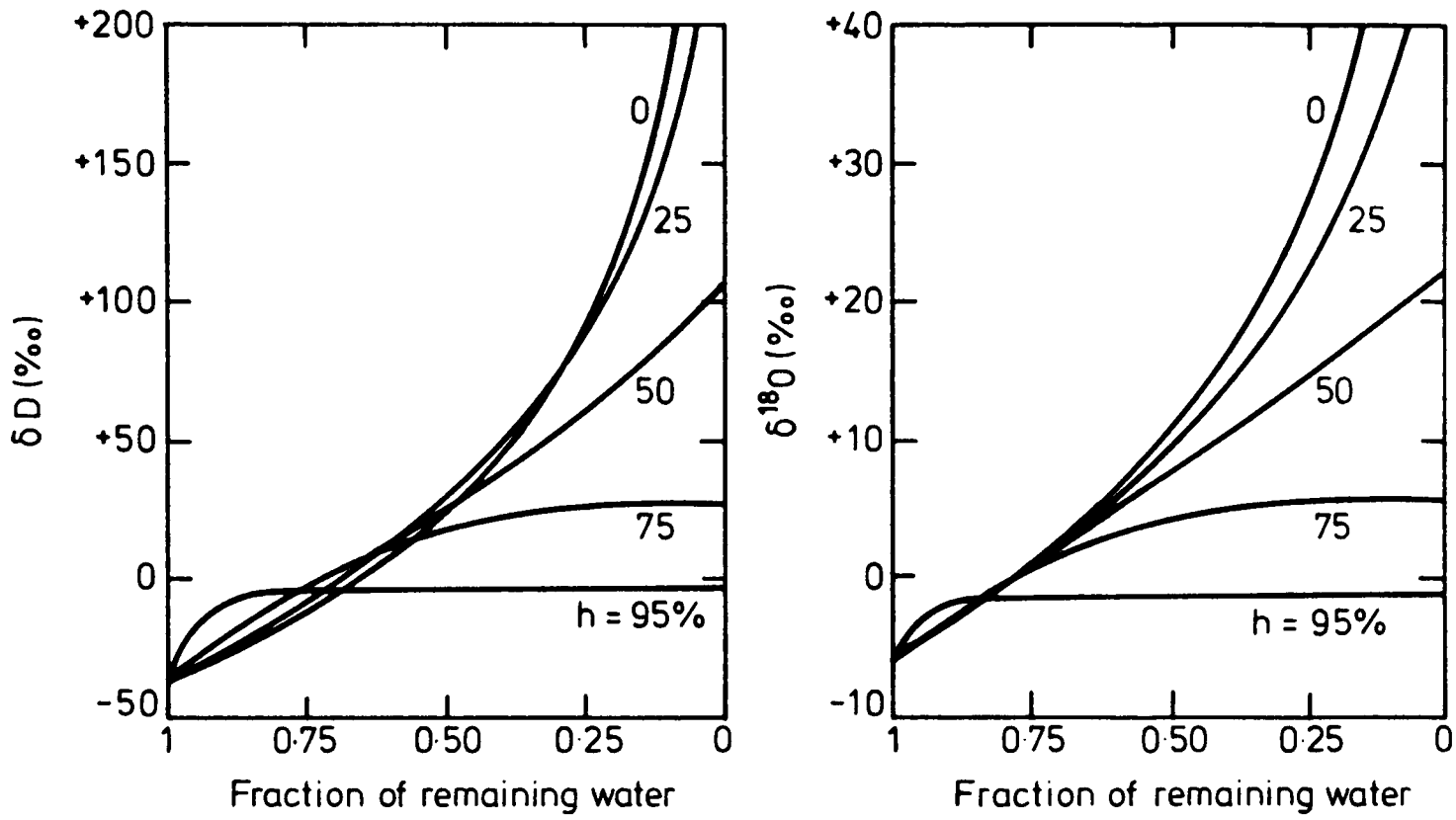


Fig. 2.6 The temperature dependence of the fractionation factors of oxygen and hydrogen isotopes, for the water systems of liquid-vapour and ice-vapour (Source: FRITZ & FONTES, 1980, p.7)



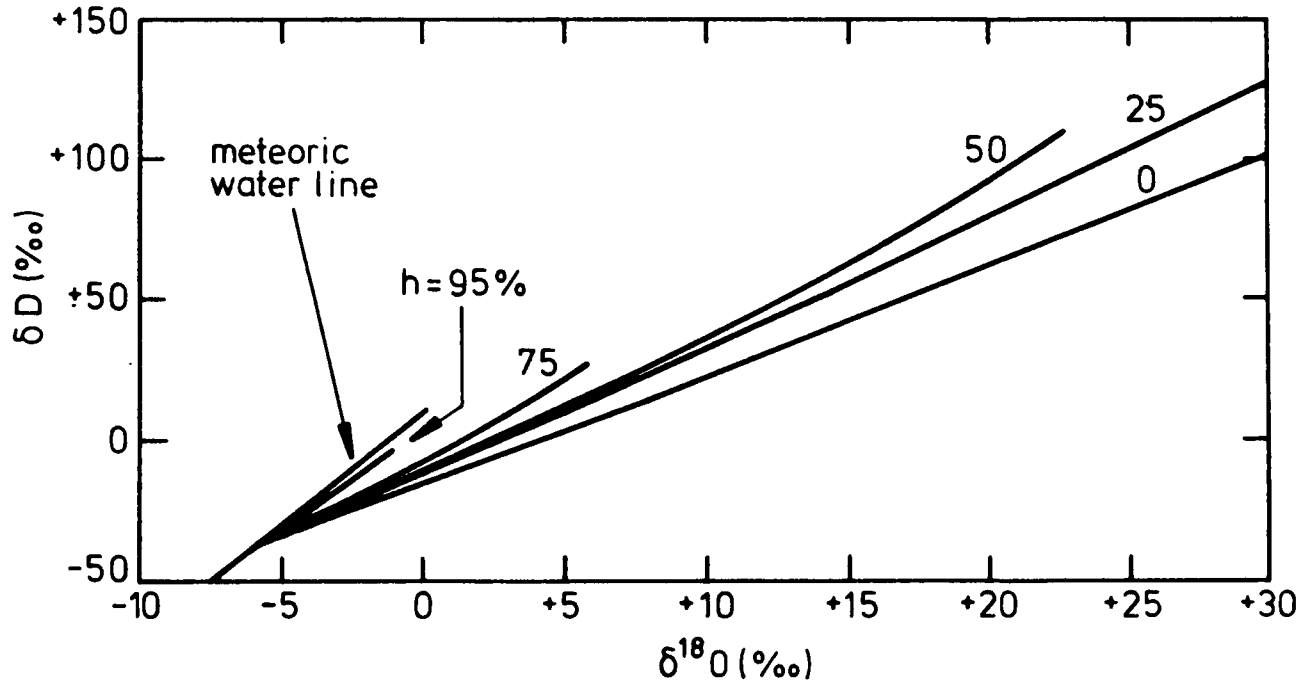


Fig. 2.7 Isotopic composition of evaporating water beneath different relative humidities (h), illustrating the lowering of slope $\delta^{18}O - \delta D$ to below 8. The following conditions apply: initial isotopic composition of water, $-6‰(\delta^{18}O)$, $-38‰(\delta D)$; isotopic composition of atmospheric moisture, $-12‰(\delta^{18}O)$, $-86‰(\delta D)$. The Meteoric Water Line has a slope of 8. (Source: GILATH & GONFIANTINI, 1983)

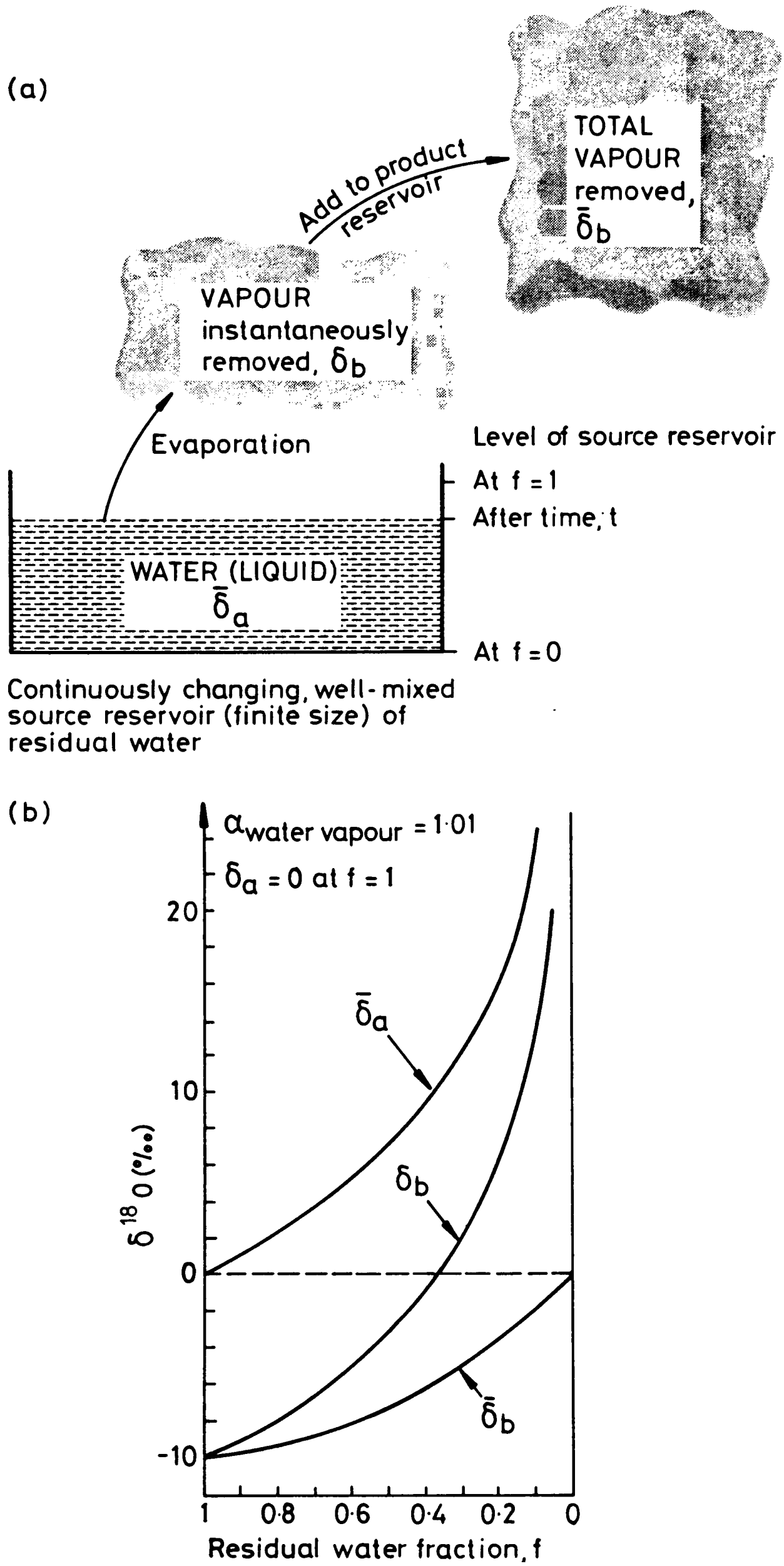


Fig. 2.8 Non-equilibrium fractionation between product and reactant reservoirs in an 'open' system: (a) schematic diagram of evaporation, with removal of vapour; (b) plot of the changing $\delta^{18}O$ compositions of the system components, with continuing evaporation

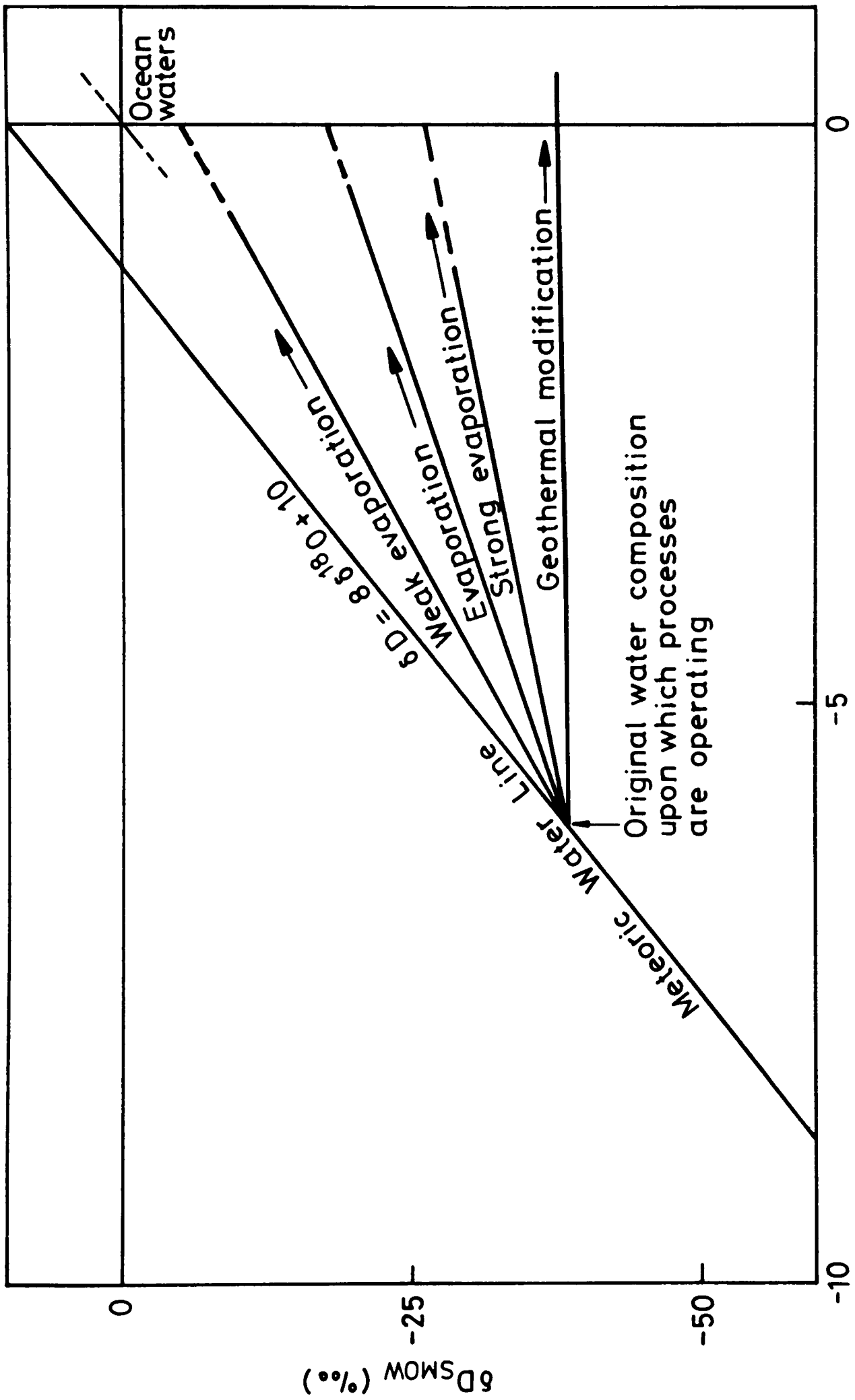


Fig. 2.9 Loci of $\delta^{18}O$- δD compositions of a hypothetical water undergoing evaporation or geothermal modification, illustrating the development of a slope less than 8 in the natural environment

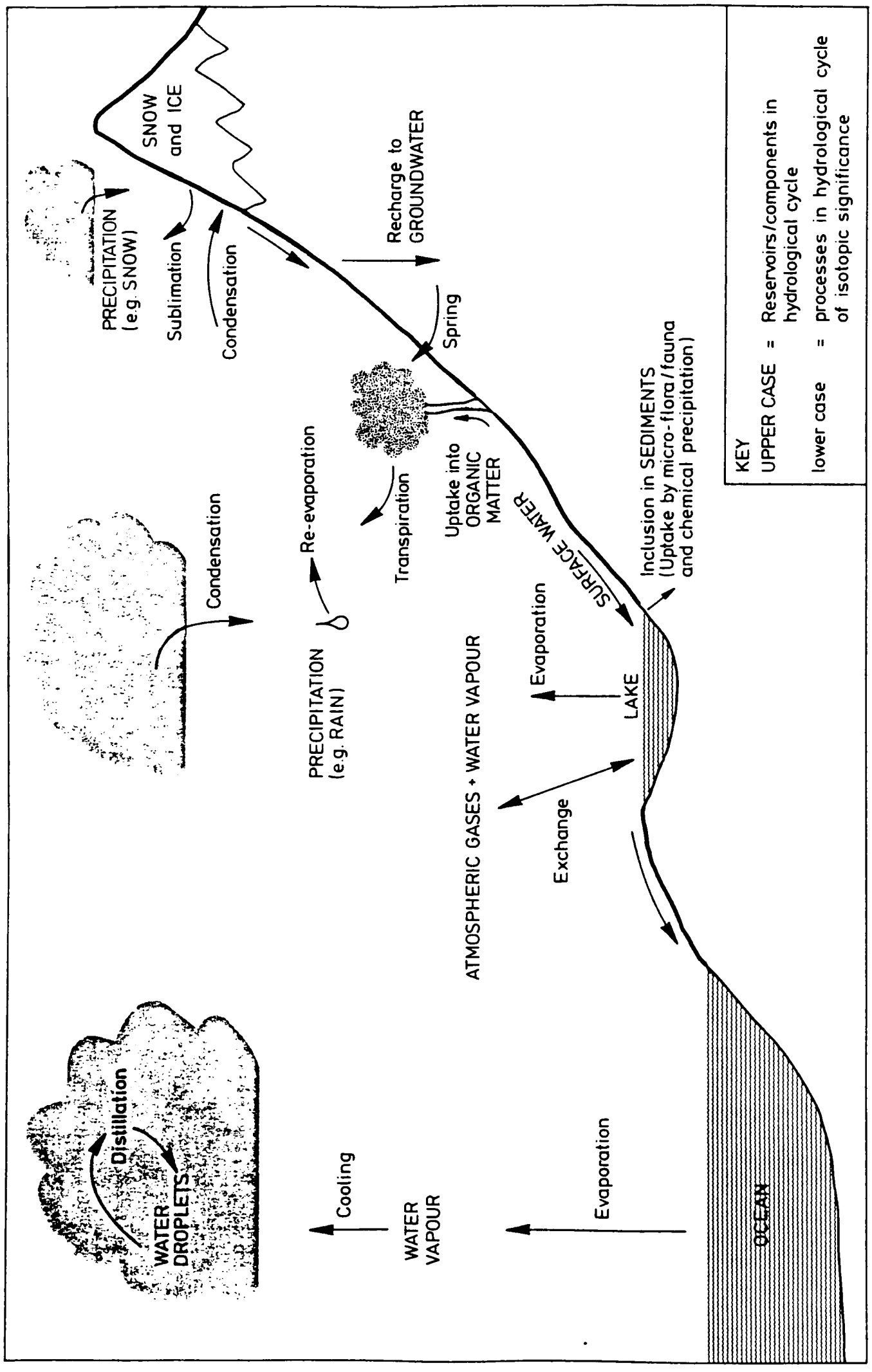


Fig. 2.10 Schematic diagram of the hydrological cycle, showing the reservoirs in which water may be held, and the processes of isotopic significance for stable isotope hydrology

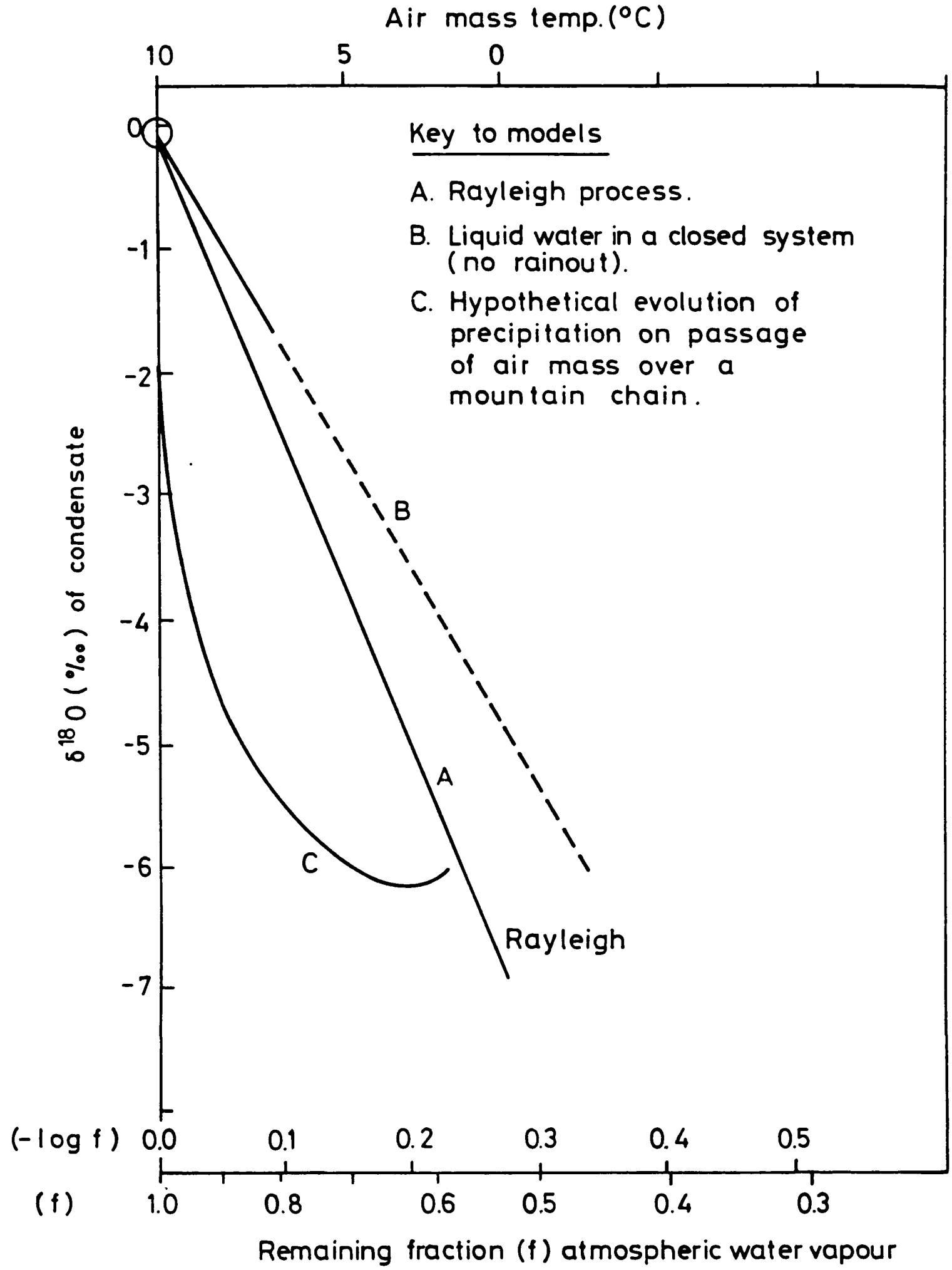


Fig. 2.11 Change in the $\delta^{18}O$ composition of precipitation as a result of rainout (models A and C) and of liquid water in a closed system (model B) (Source : GAT & DANSGAARD, 1972)

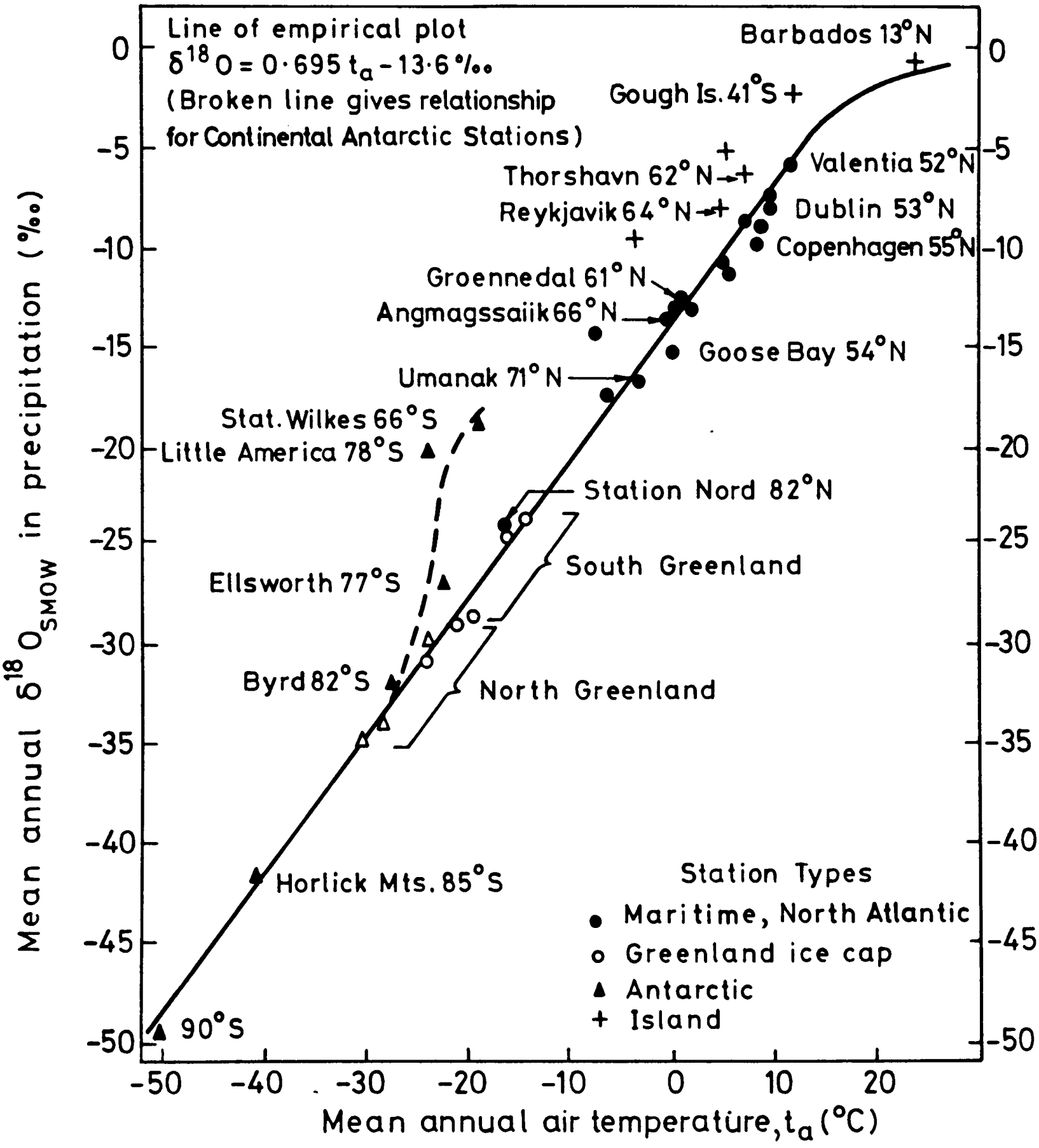


Fig. 2.12 Plot of the mean annual $\delta^{18}O$ in precipitation as a function of temperature, for stations bordering the Atlantic Ocean (after DANSGAARD, 1964)

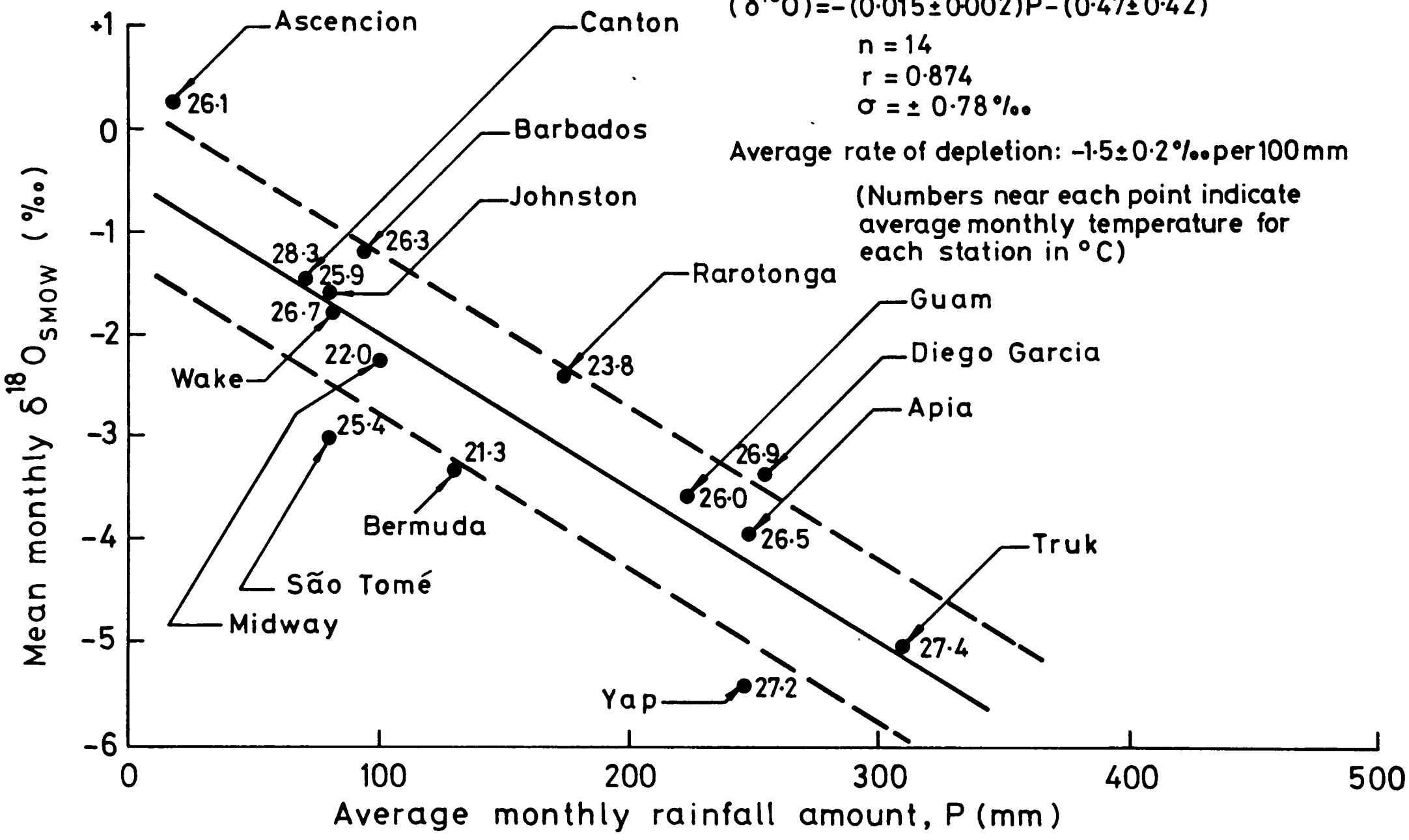


Fig. 2.13 Plot of the mean monthly $\delta^{18}O$ in precipitation against mean monthly rainfall, for tropical stations, illustrating the 'amount effect' (Source: YURTSEVER & GAT, 1981)

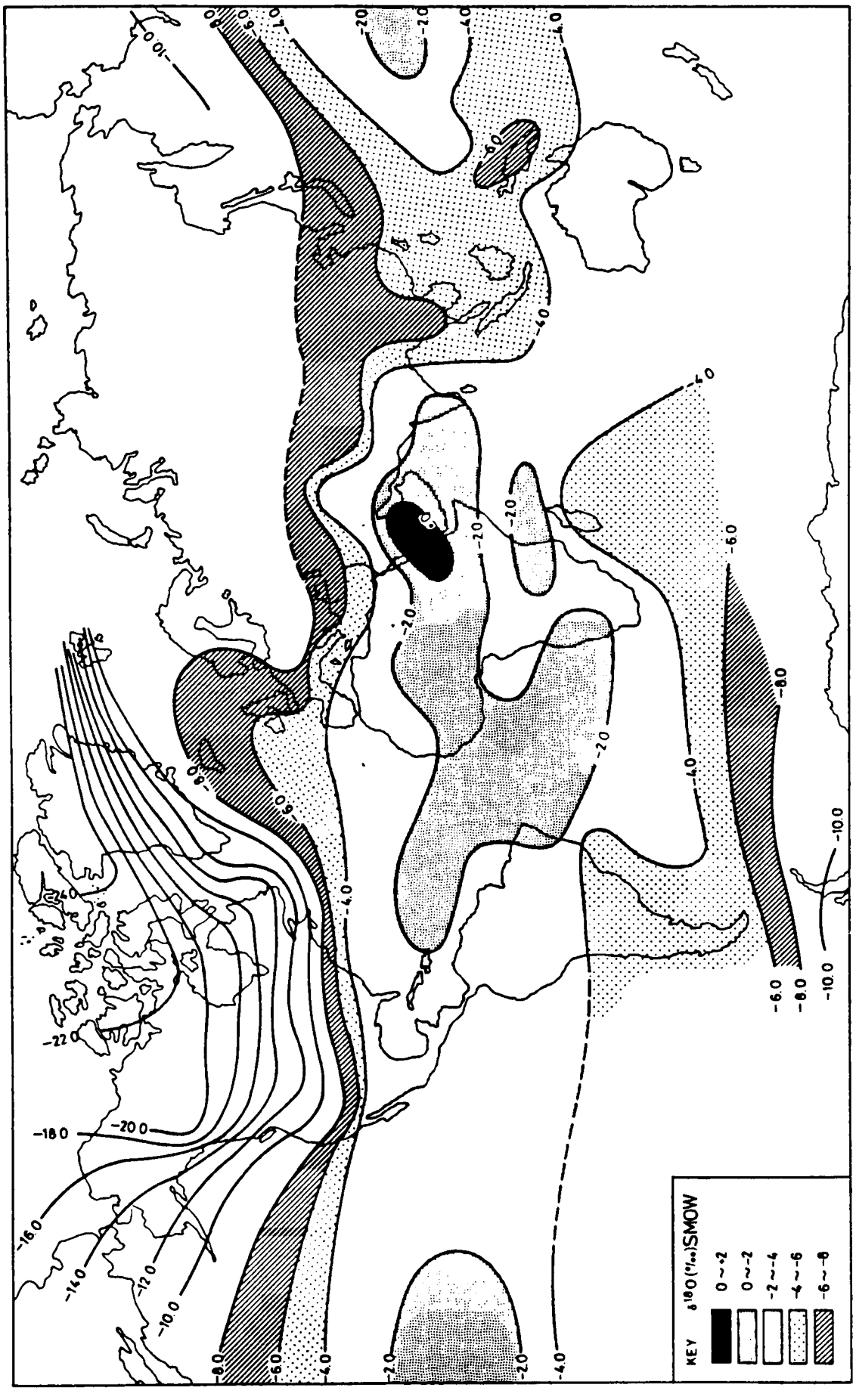


Fig. 2.14 The global pattern of mean annual $\delta^{18}O$ in precipitation, showing the 'latitude effect'
(Source: YURTSEVER & GAT, 1981)

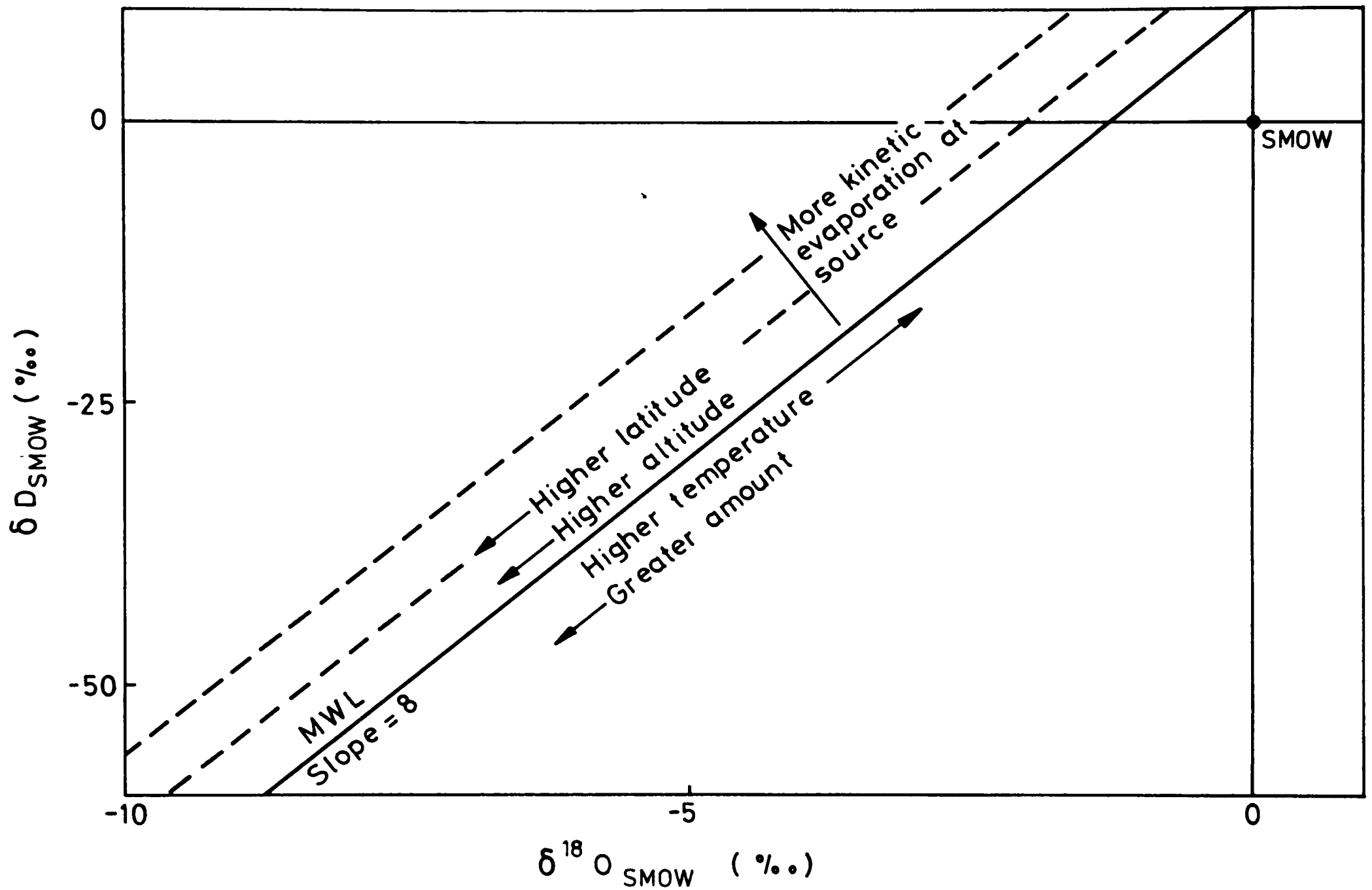


Fig. 2.15 Variations of $\delta^{18}O$- δD isotopic composition along the Meteoric Water Line according to the isotope 'effects' in precipitation, and the shift in locus according to kinetic evaporation of a water at its source (MWL = Meteoric Water Line)

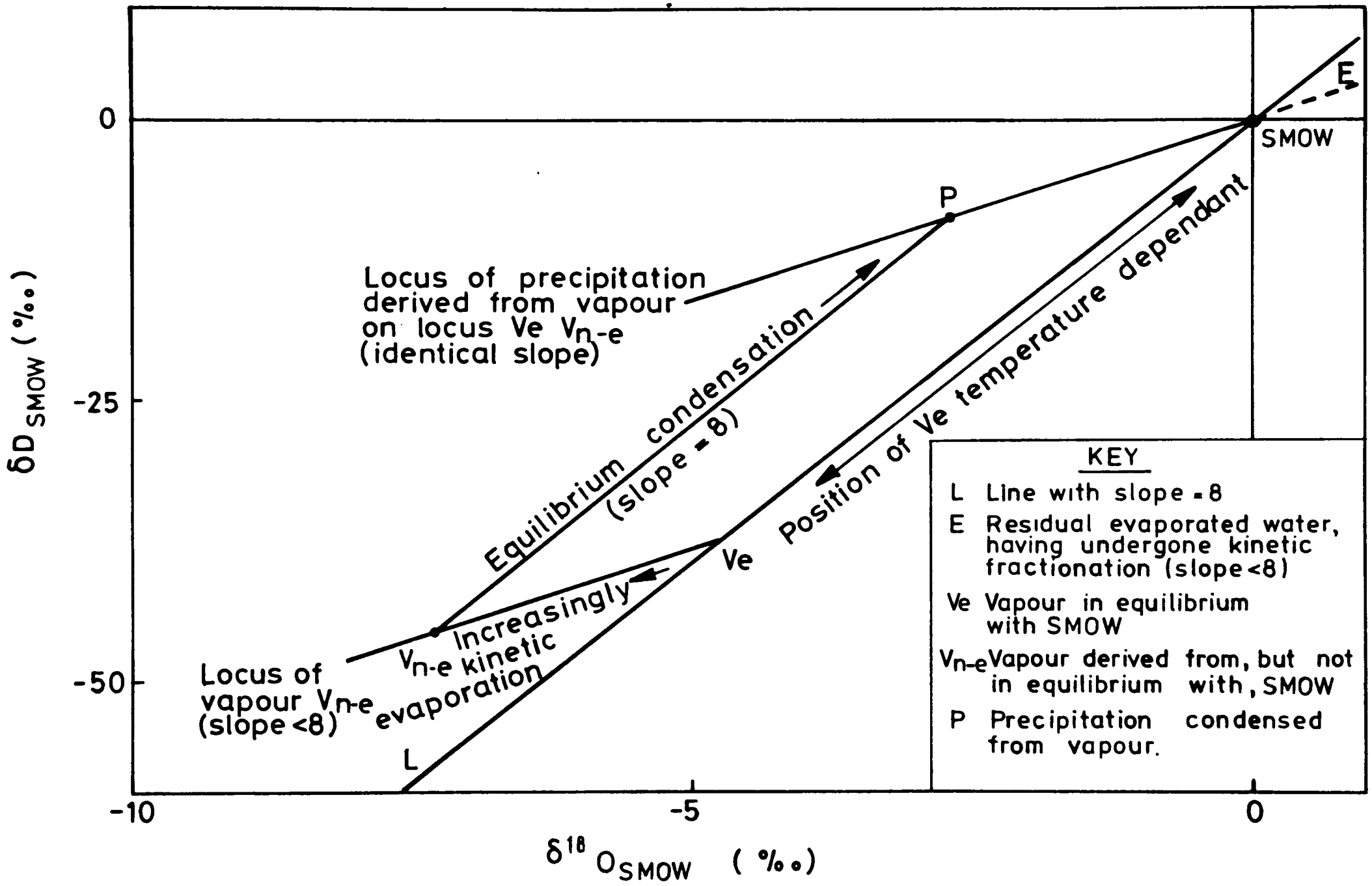


Fig. 2.16 $\delta^{18}O$- δD plot to show the production of a d-excess in precipitation, P, from the kinetic evaporation of a limited water body (derived from SMOW)

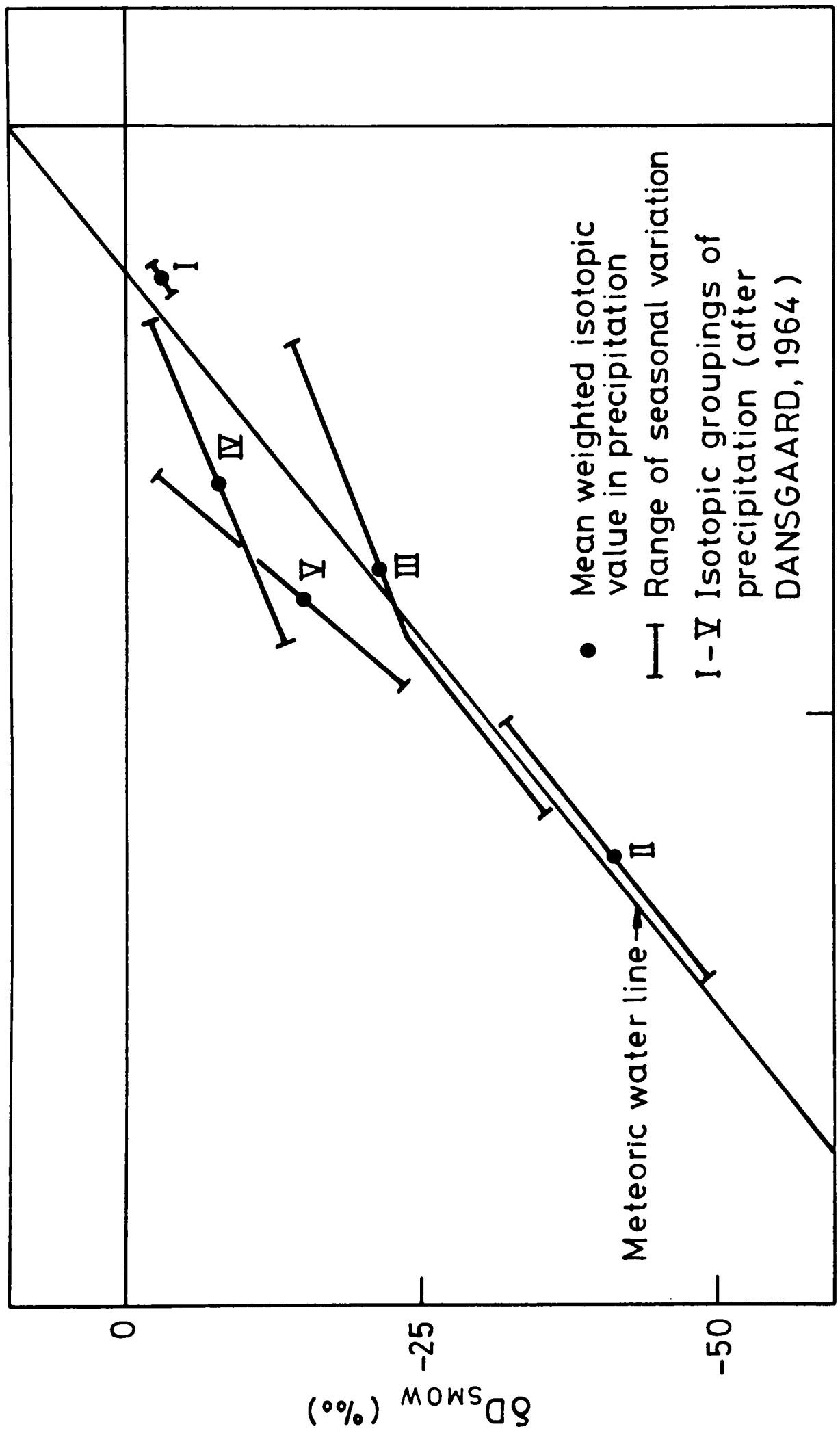


Fig. 2.17 Seasonal variations and mean $\delta^{18}O$- δD composition of rainfall at hypothetical stations in isotopic groupings (I-V) of precipitation. [For explanation of groupings, see table 2.6]

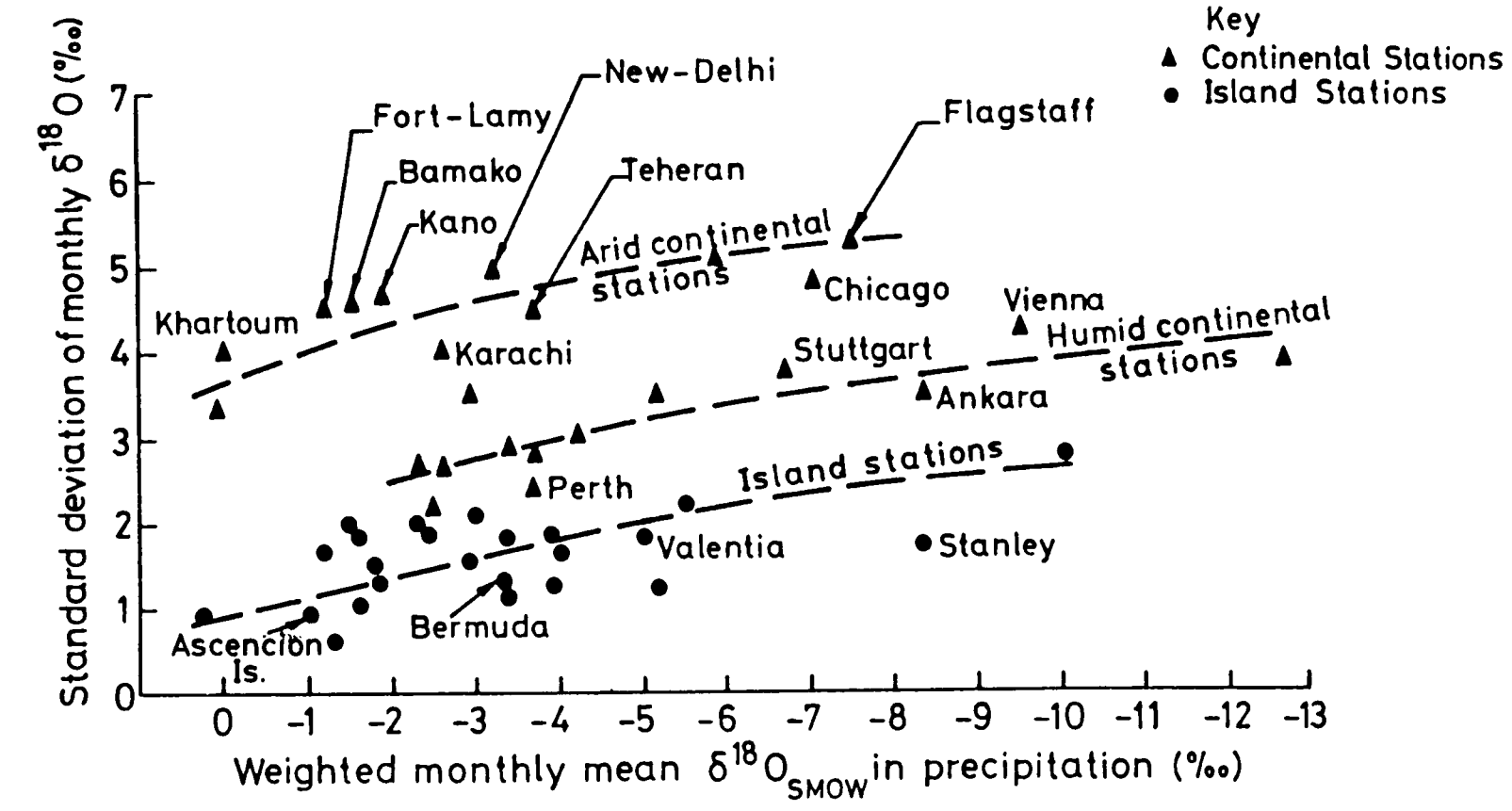


Fig. 2.18 The relationship between weighted monthly mean $\delta^{18}O$ and the standard deviation of monthly $\delta^{18}O$ in precipitation, for IAEA/WMO network stations (Source: YURTSEVER & GAT, 1981)

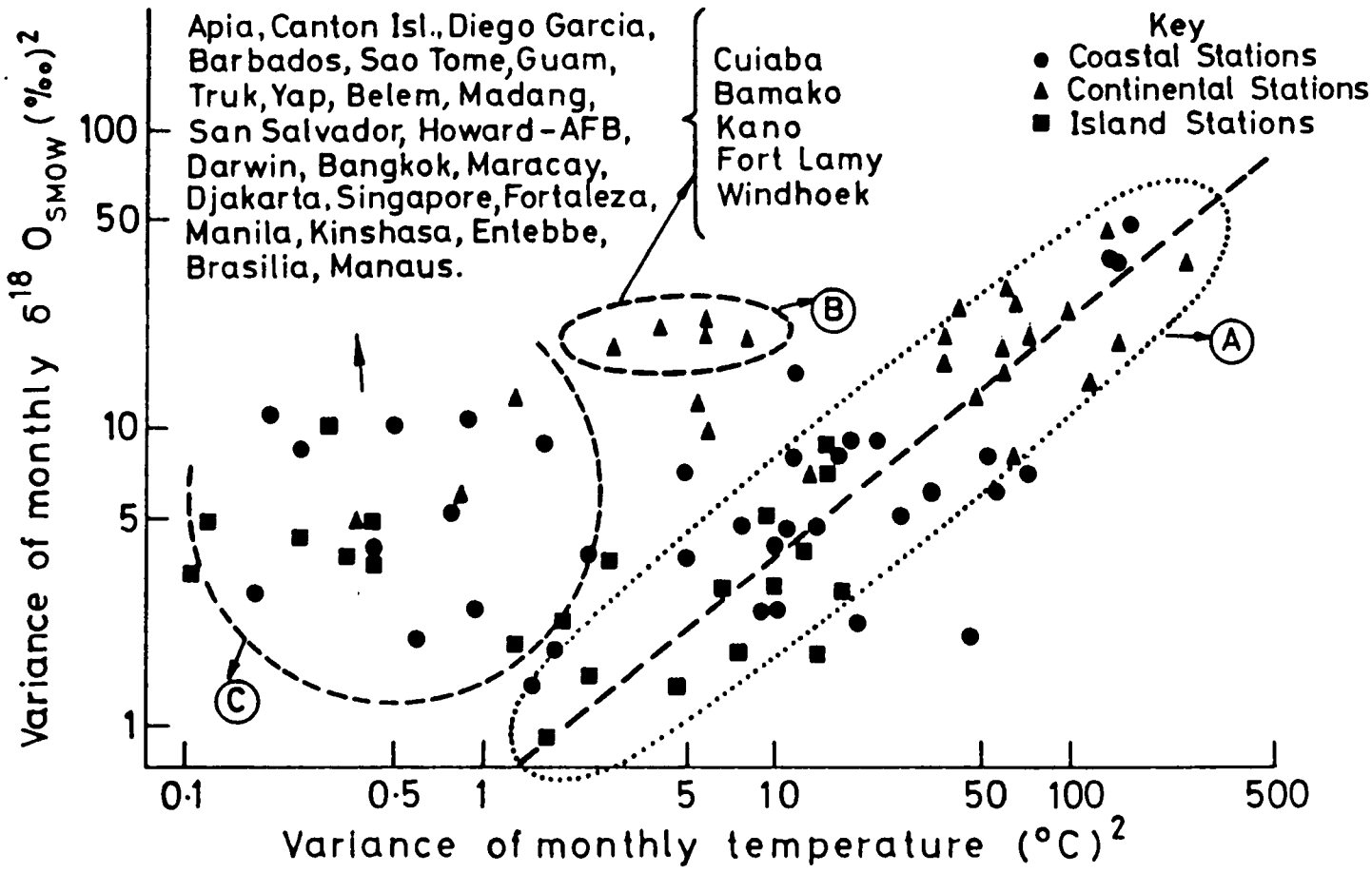


Fig. 2.19 The relationship between variances of monthly temperature and of monthly $\delta^{18}O$ in precipitation, for IAEA/WMO network stations (Source: YURTSEVER & GAT, 1981)

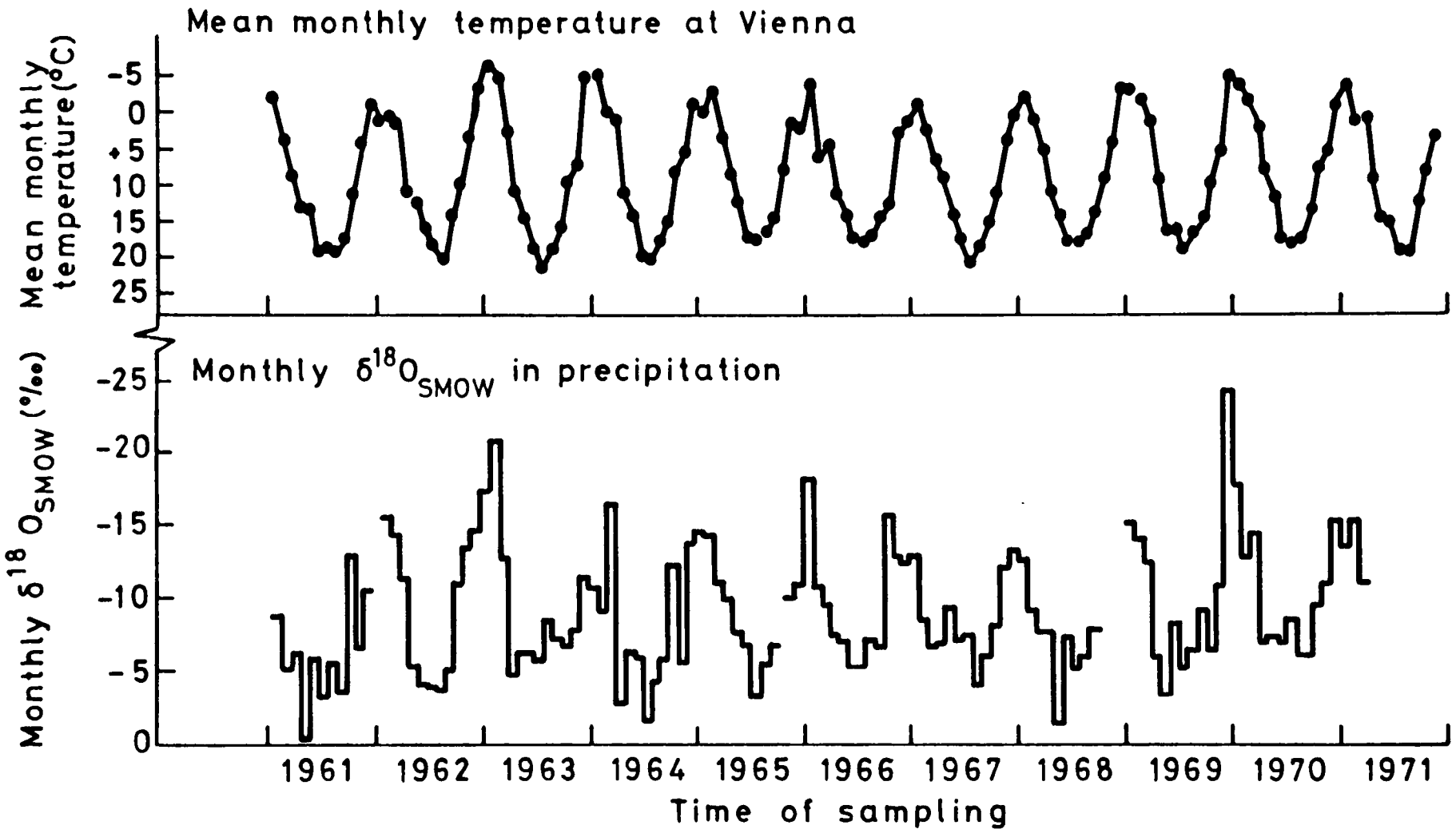
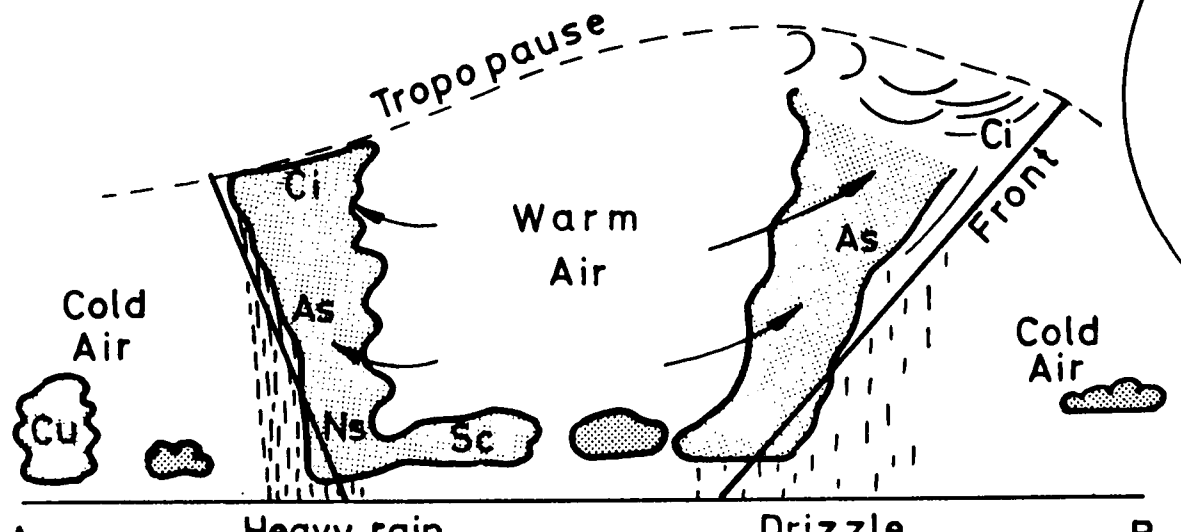
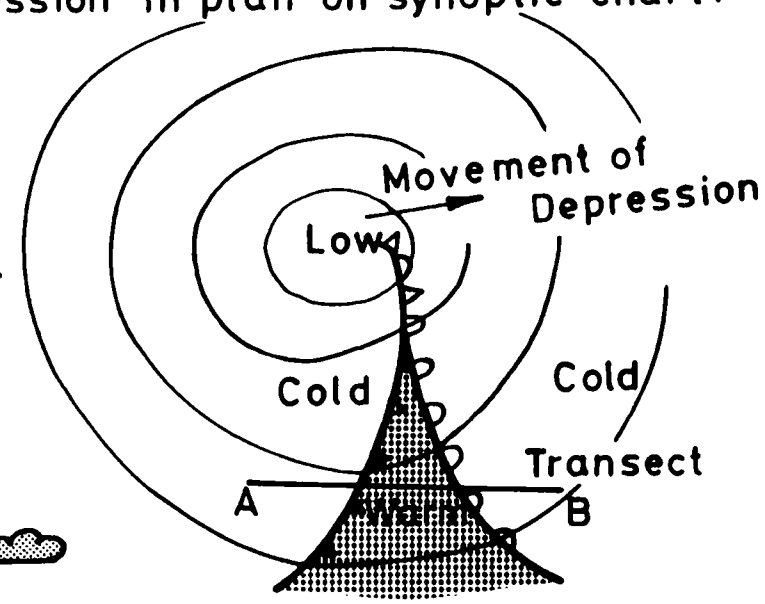


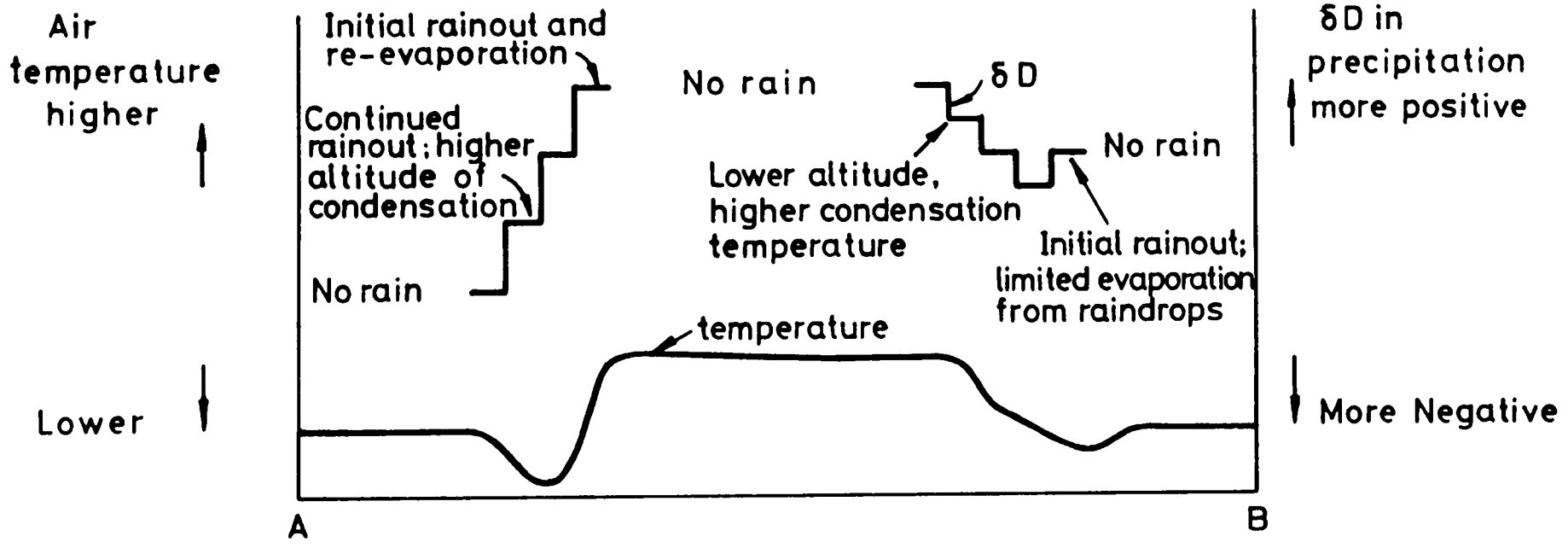
Fig. 2.20 Seasonal variations of temperature and of $\delta^{18}O$ in precipitation, in Vienna (Source: YURTSEVER & GAT, 1981)

(a) Section through fronts of mid-latitude depression (after BARRY AND CHORLEY, 1976).



(b) Depression in plan on synoptic chart.





Key to cloud types in (a)

Ci Cirrus
As Altostratus
Sc Stratocumulus
Ns Nimbostrasus
Cu Cumulus

(c) Hypothetical temperature and δD variation associated with frontal system.

Fig. 2.21 A simple model of variations in δD in rainfall and in temperature, associated with the passage of a frontal system: (a) in section, (b) in plan view

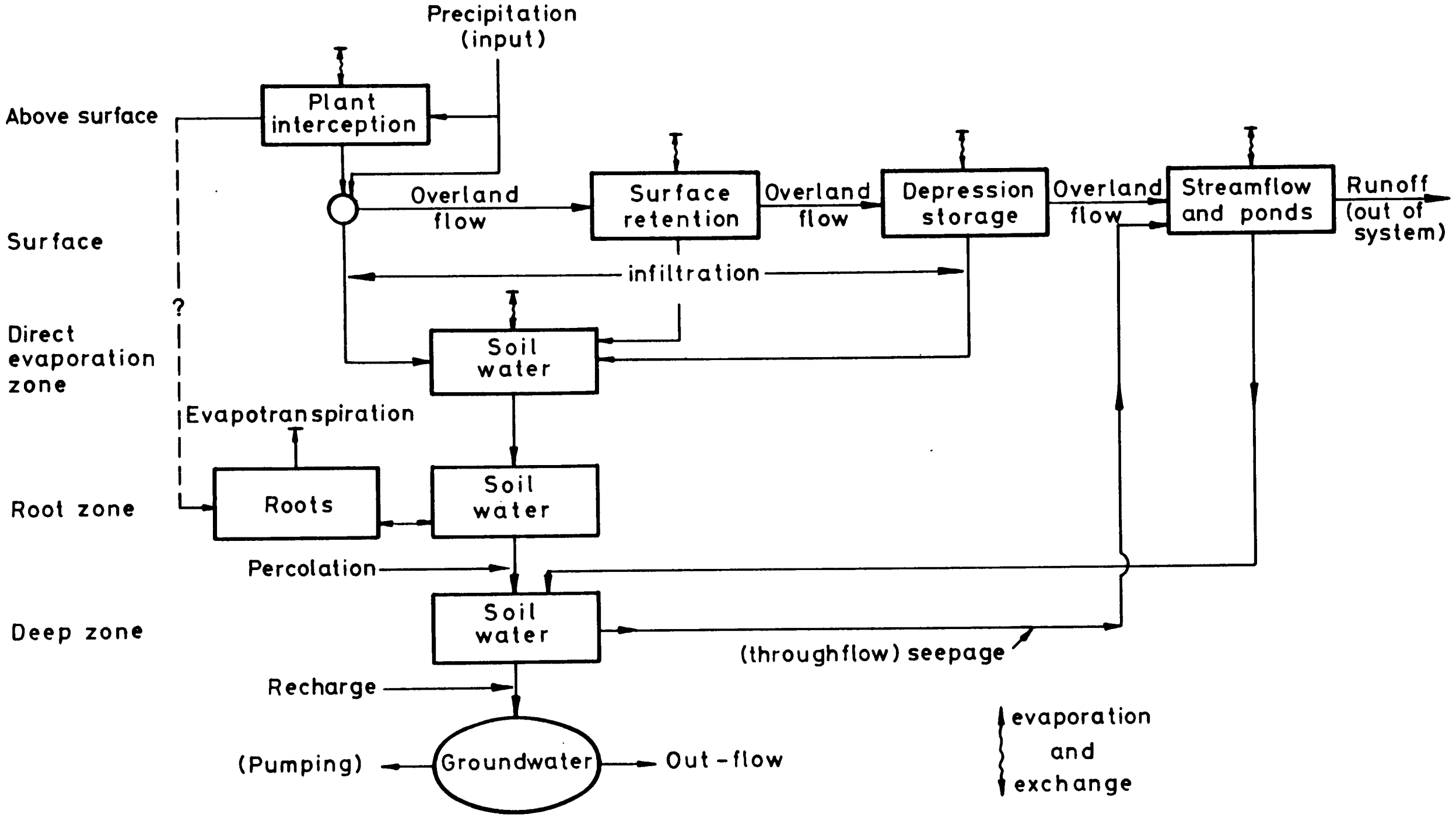


Fig. 2.22 Isotopic fractionation (caused by evaporation and exchange), and mixing of water, in the recharge and runoff processes (Source: GAT & TZUR, 1967)

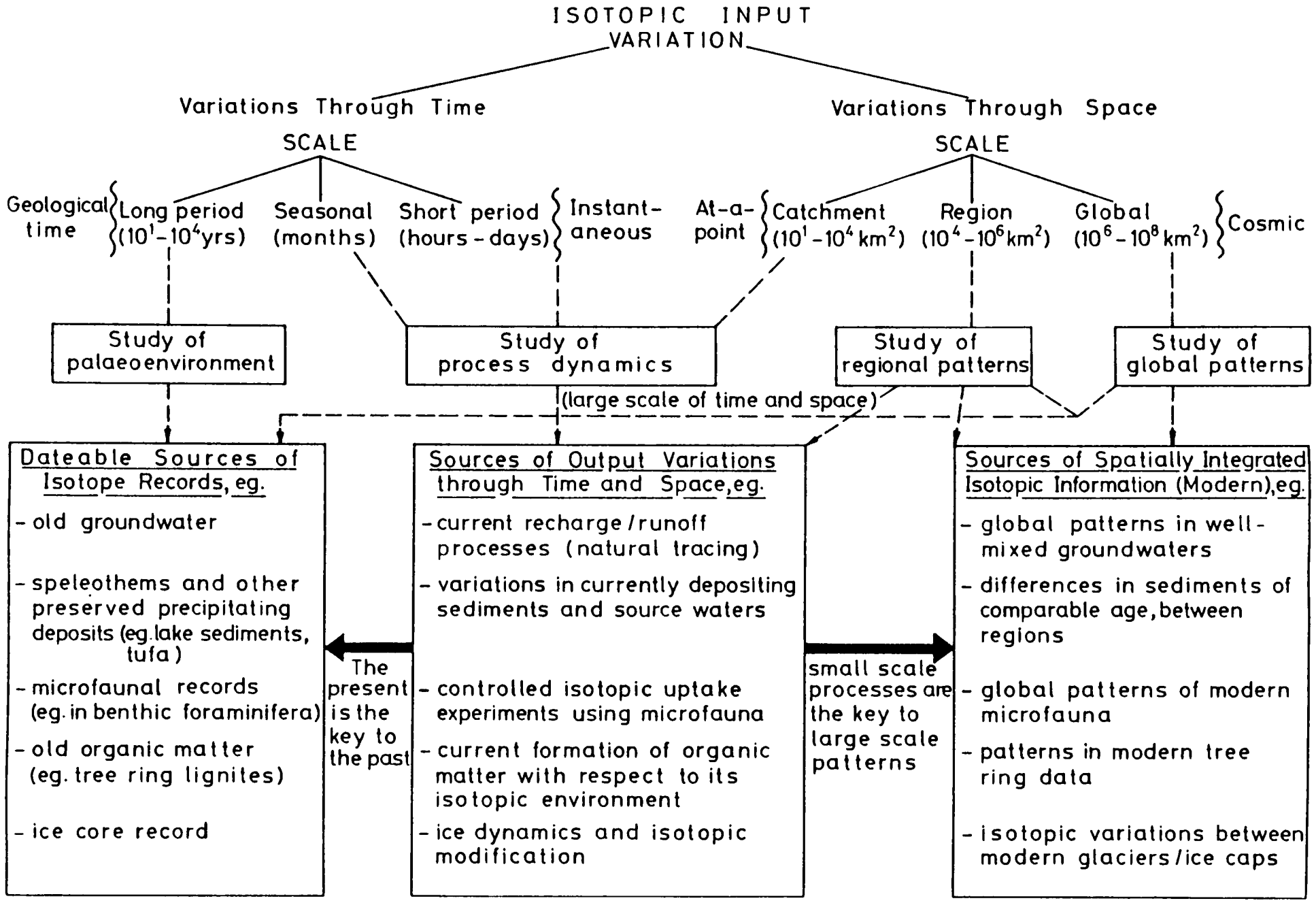
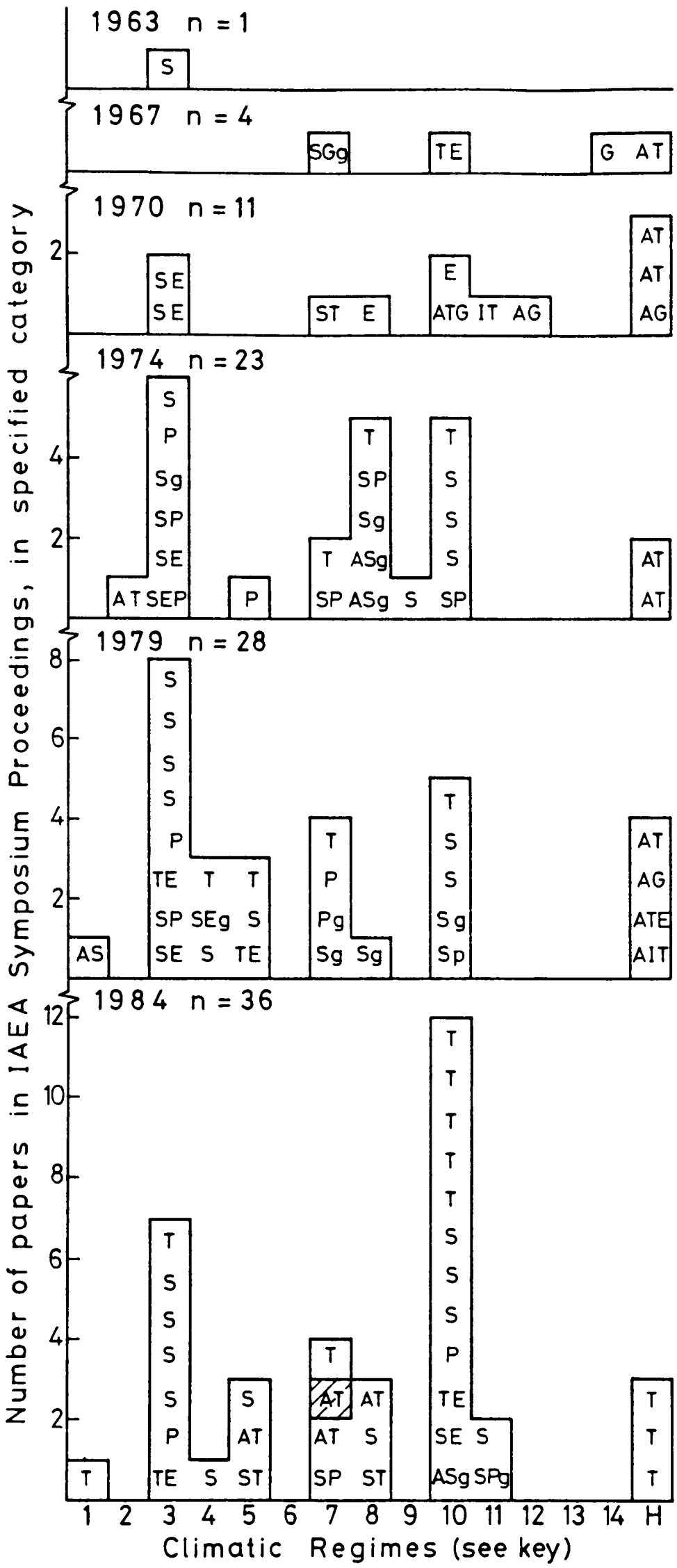


Fig. 2.23 The scales of study in isotope hydrology and its neighbouring disciplines



KEY

CLIMATES (after STRAHLER, 1969)

Low latitude climates

1 Wet equatorial
2 Trade-wind littoral
3 Tropical desert and steppe
4 West coast desert
5 Tropical savanna

Mid-latitude climates

6 Humid subtropical
7 Maritime west coast
8 Mediterranean
9 Mid-latitude desert and steppe
10 Humid continental

High latitude climates

11 Continental subarctic
12 Marine subarctic
13 Tundra
14 Icecap

H Major highland areas (climatic zonation with altitude)

STABLE ISOTOPE APPLICATIONS IN HYDROLOGY

A Application dependent upon 'altitude effect'

I Investigation of isotopic input in precipitation, per se

S Identification of water source (whole water bodies)

T Tracing of water, by matching input and output

E Evaporation studies

P Palaeoenvironmental /palaeowater studies

G Glaciological investigations (including snow pack development)

g Geothermal waters identified

▨ This study

Categories A and I are only included in conjunction with other aspects of stable isotope applications; most tracing studies (T) include an assessment of isotopic input in precipitation

Fig. 2.24 Classification through time of papers presented at IAEA Symposia, according to area climate and the category of application of the stable isotopes, in hydrological studies (1963- 1984)

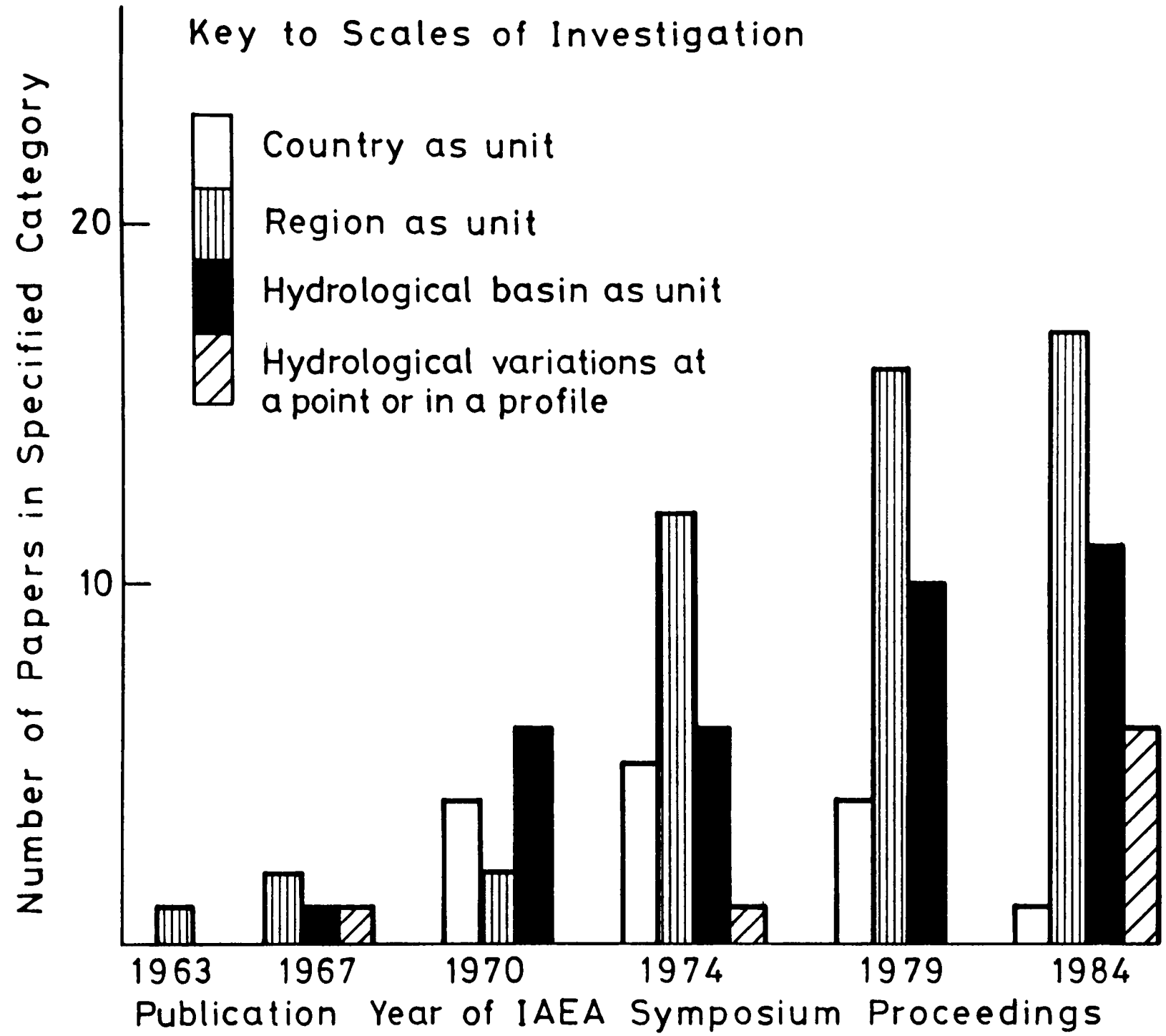


Fig. 2.25 Classification, according to the scale of investigation, of isotope hydrology studies published in proceedings of IAEA Symposia (1963- 1984)

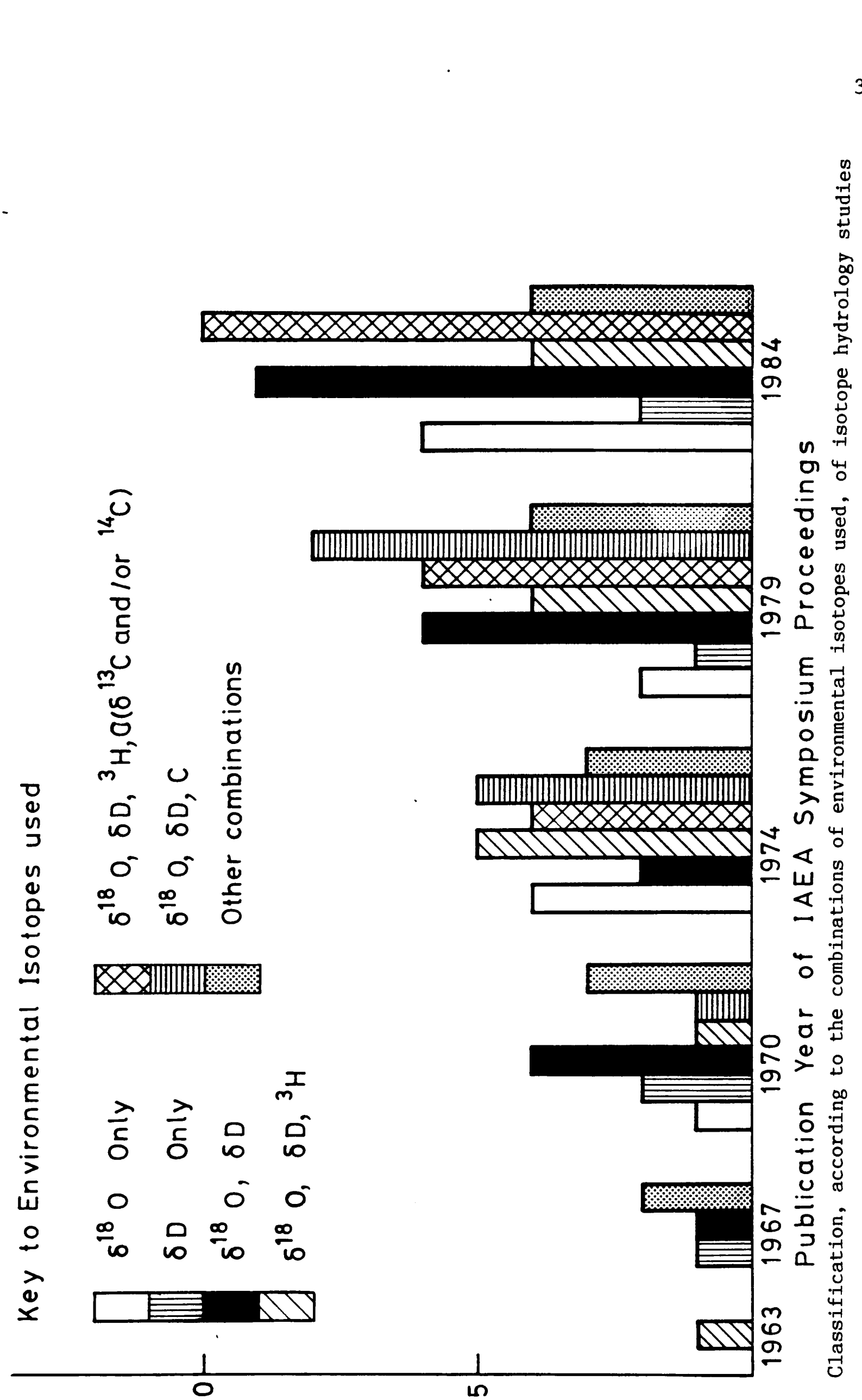


Fig. 2.26 Classification, according to the combinations of environmental isotopes used, of isotope hydrology studies published in proceedings of IAEA Symposia (1963– 1984)

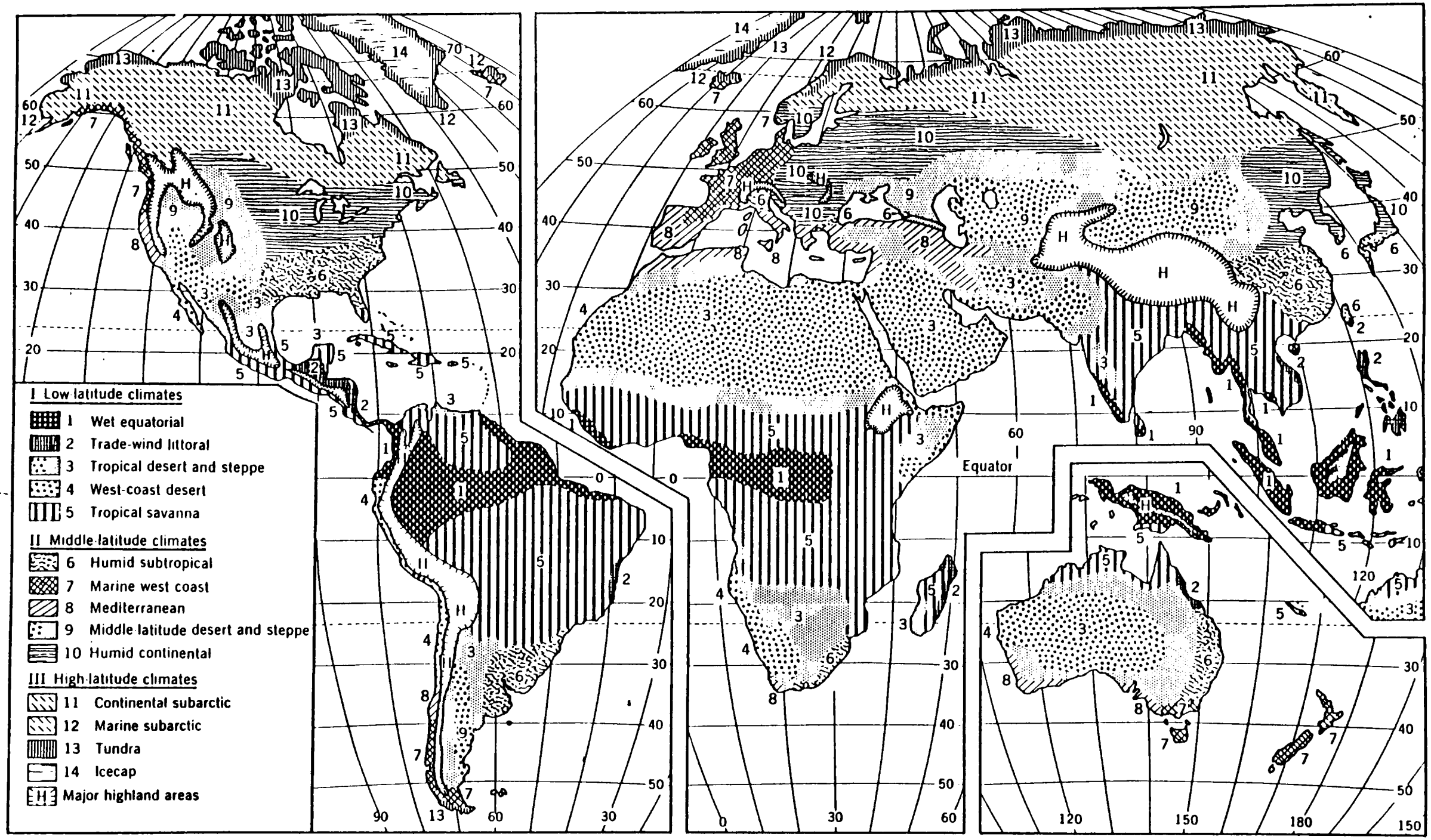


Fig. 2.27 The classification of climates by STRAHLER (1969)

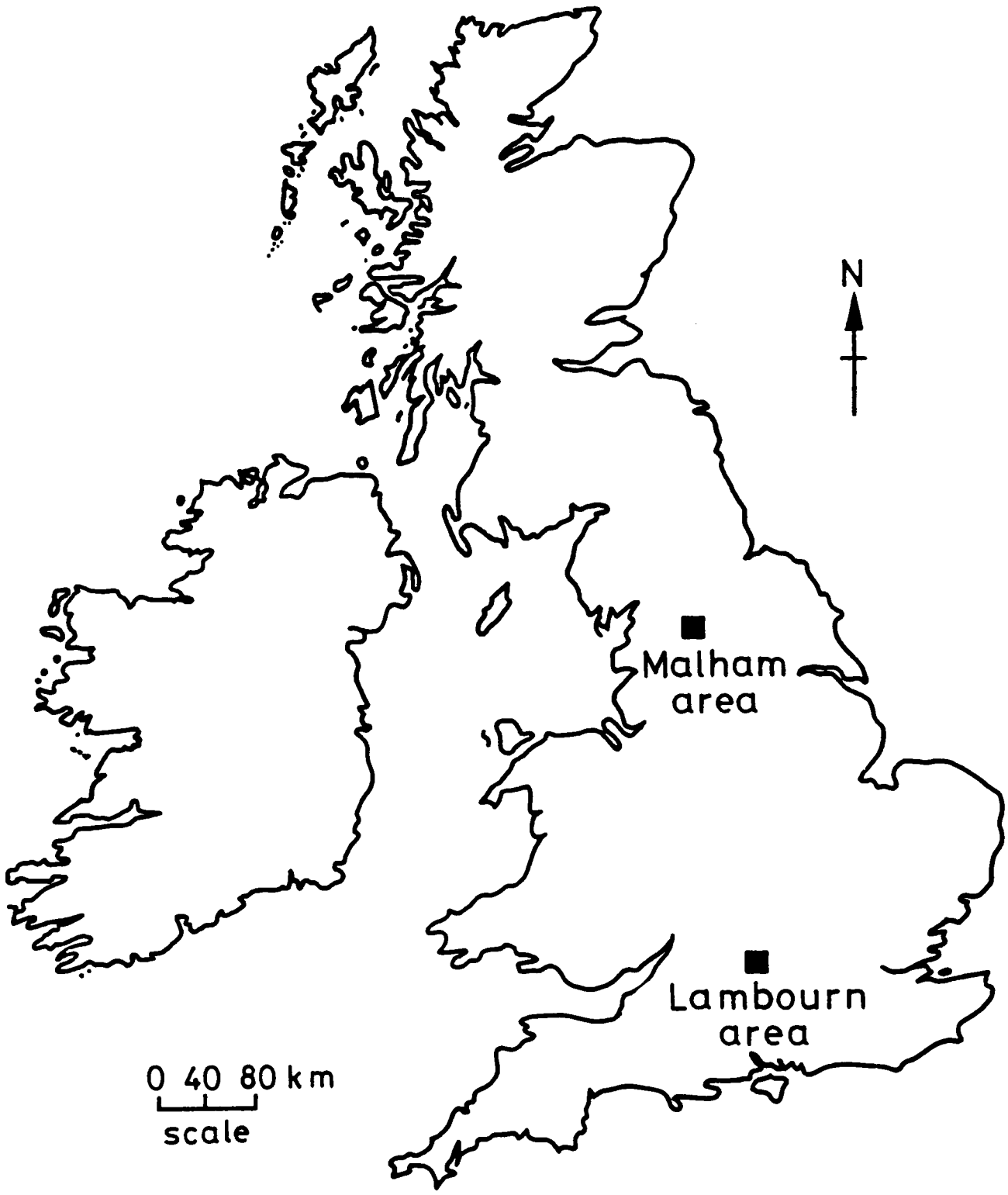


Fig. 3.1 Location of the Malham and Lambourn study areas in the U.K.

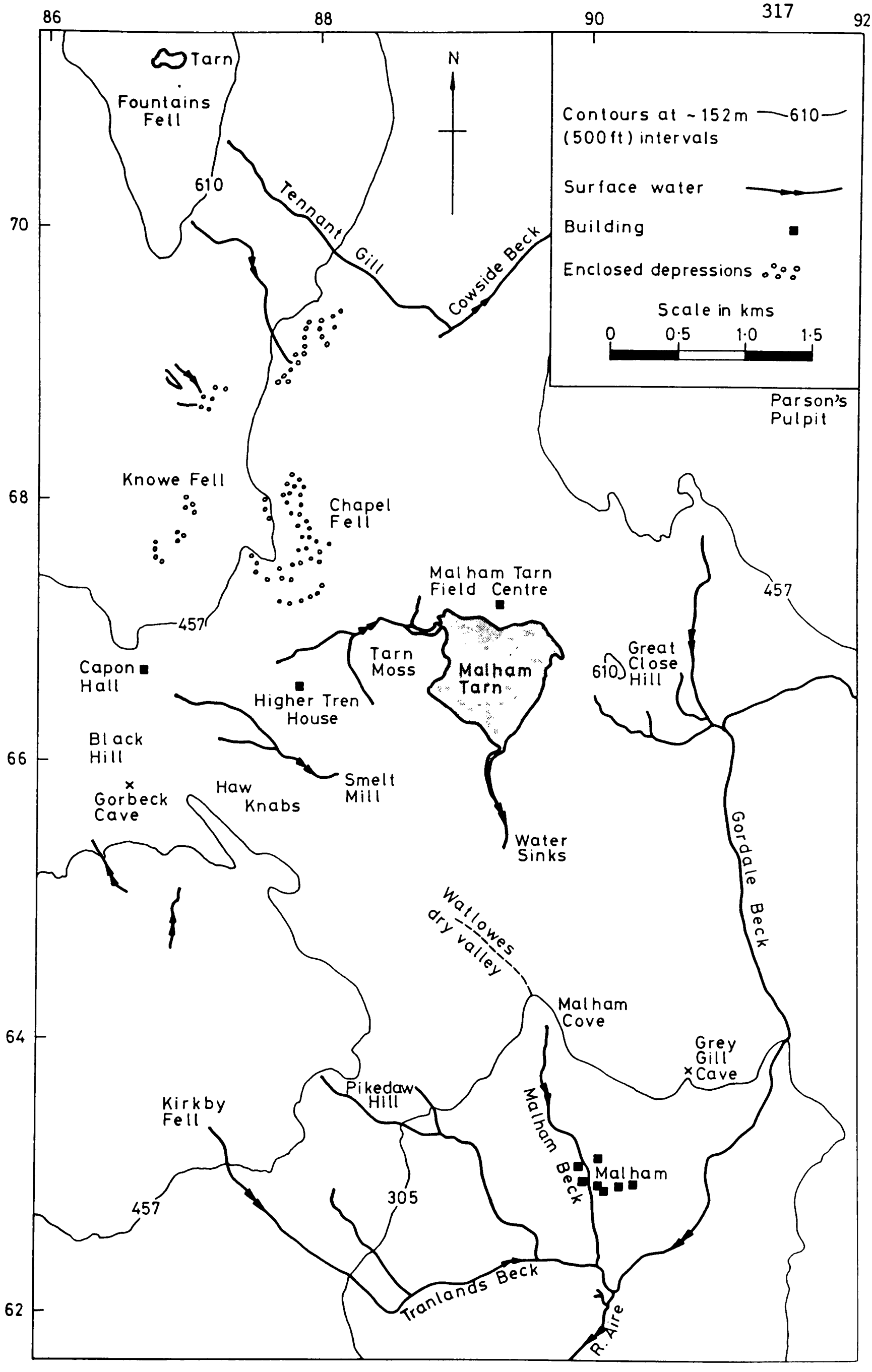


Fig. 3.2 Drainage and relief of the Malham area

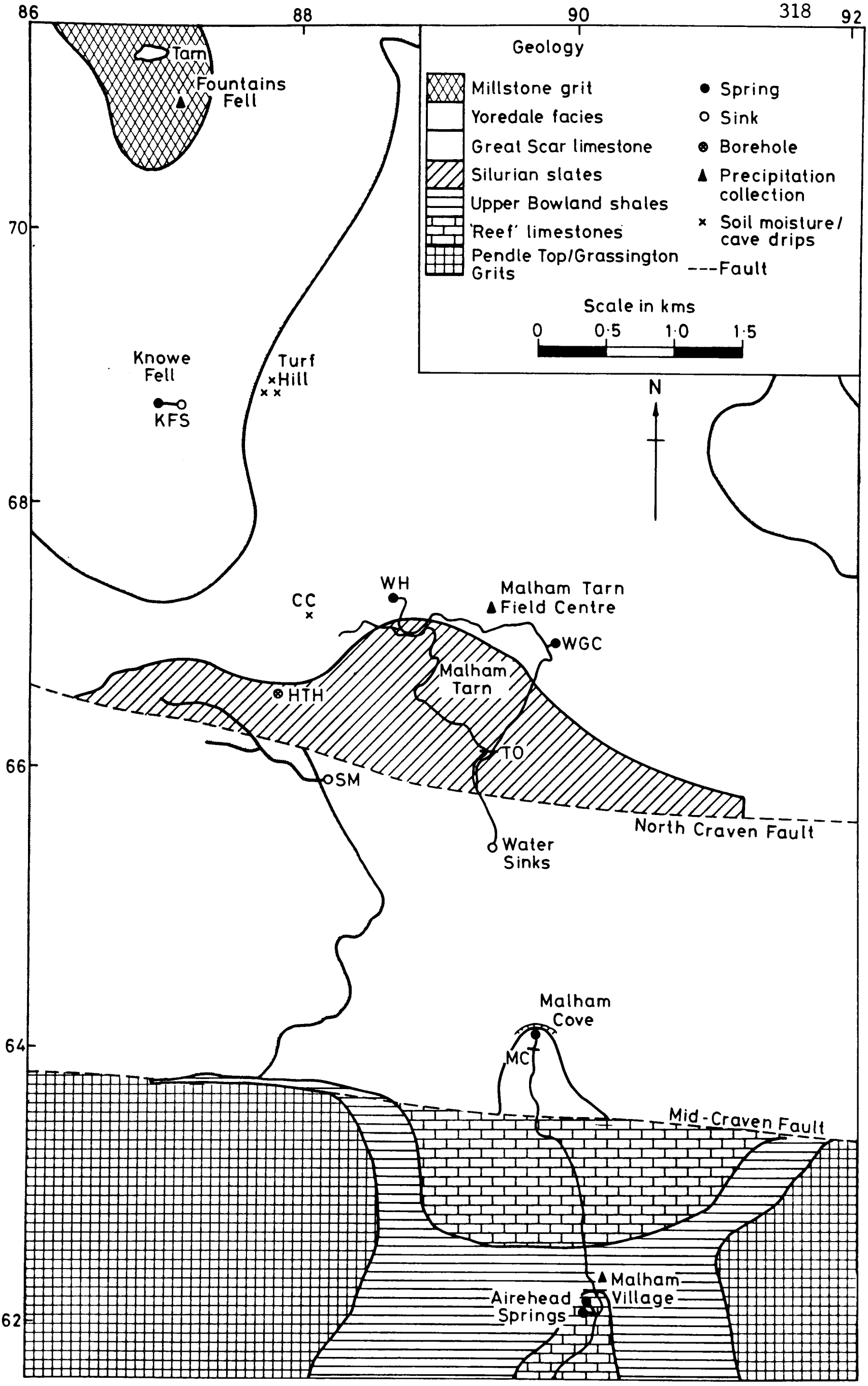


Fig. 3.3 Geology and sampling locations in the Malham area; for site abbreviations see section 3.2.1(e)
(Sources: O'CONNOR, 1964; SMITH & ATKINSON, 1977)

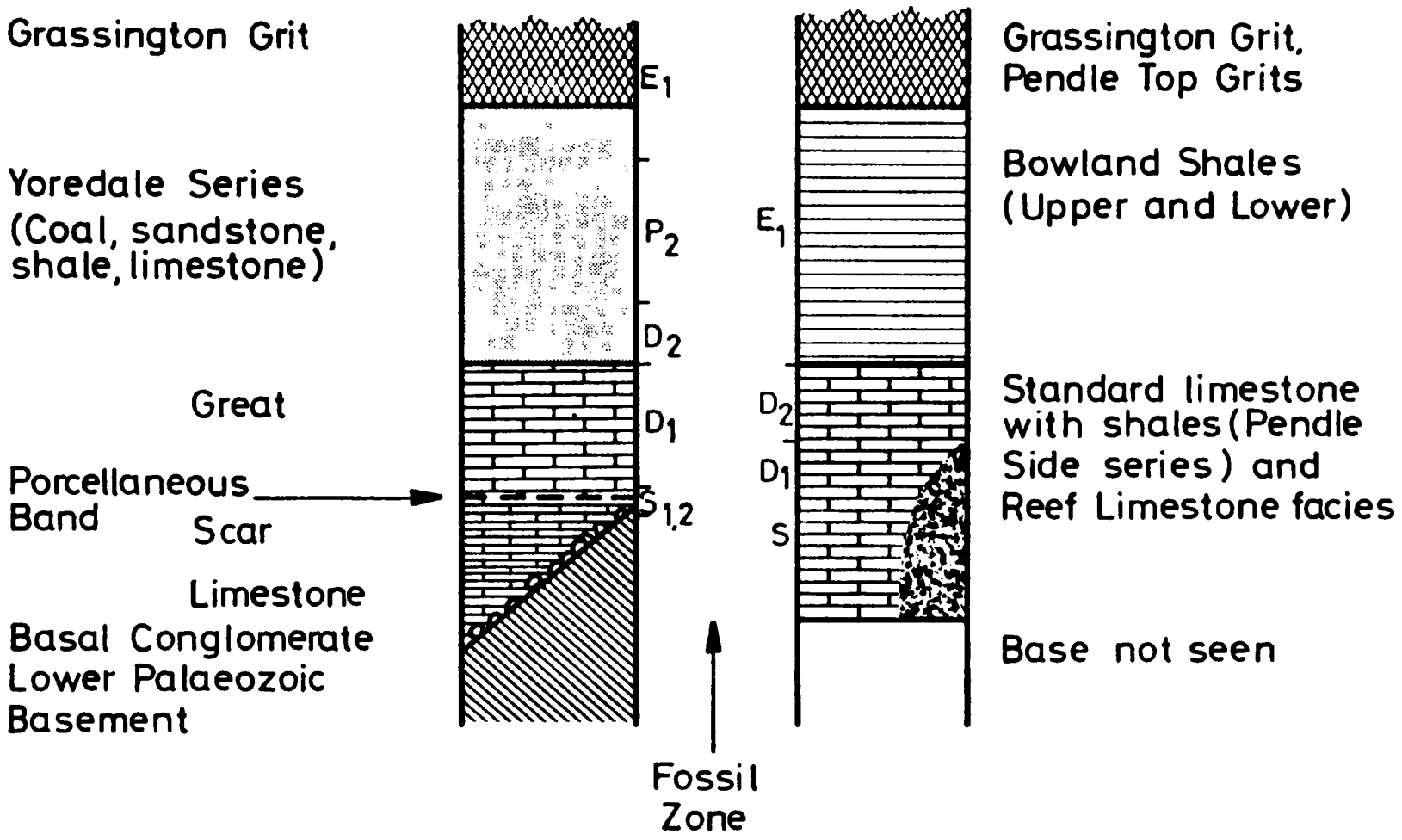


Fig. 3.4 Correlation of stratigraphy North and South of the Mid-Craven Fault (Sources: O'CONNOR, 1964; WALTHAM, 1974, p.28)

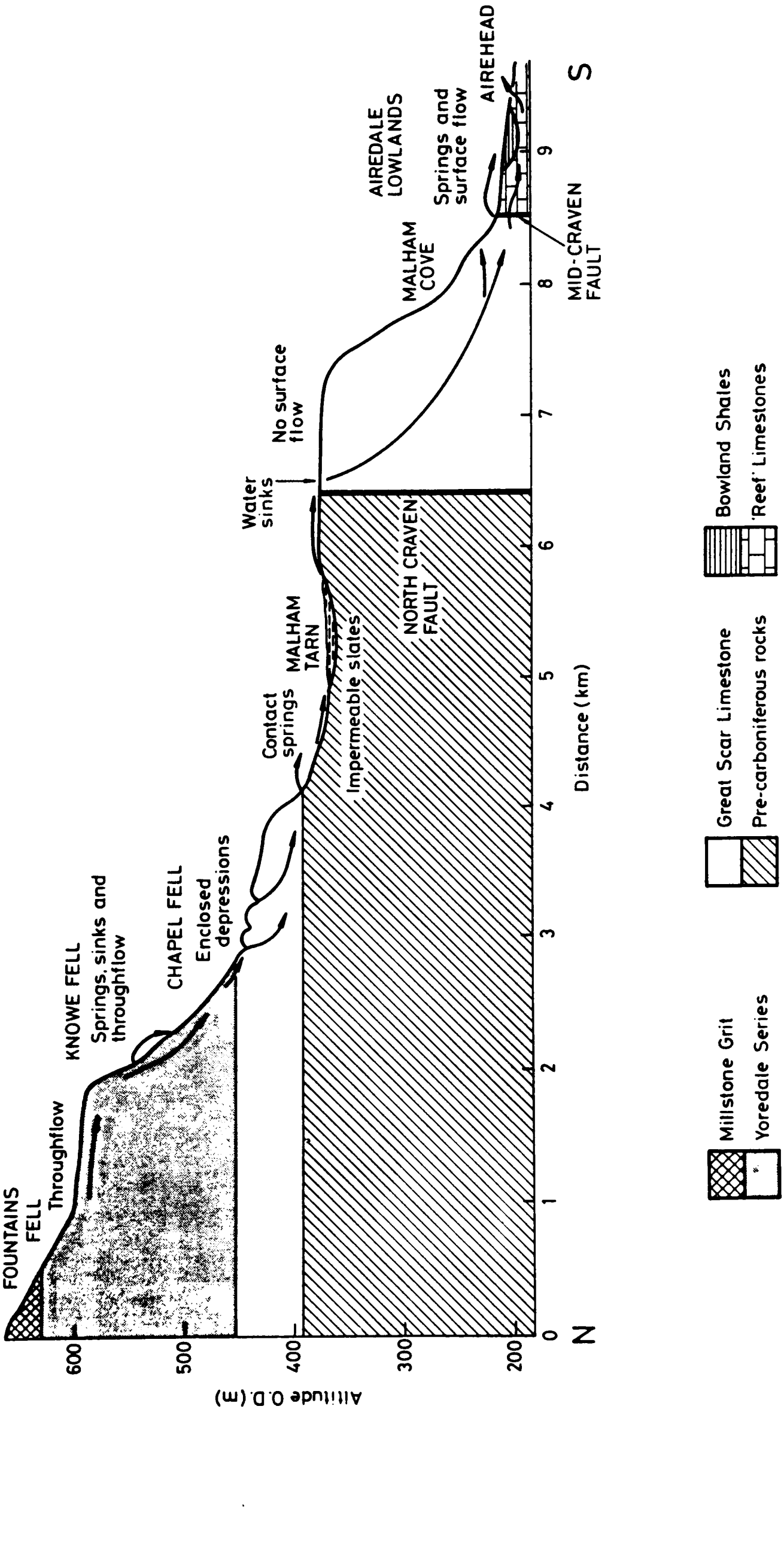


Fig. 3.5 The cascading hydrological system of the Malham area

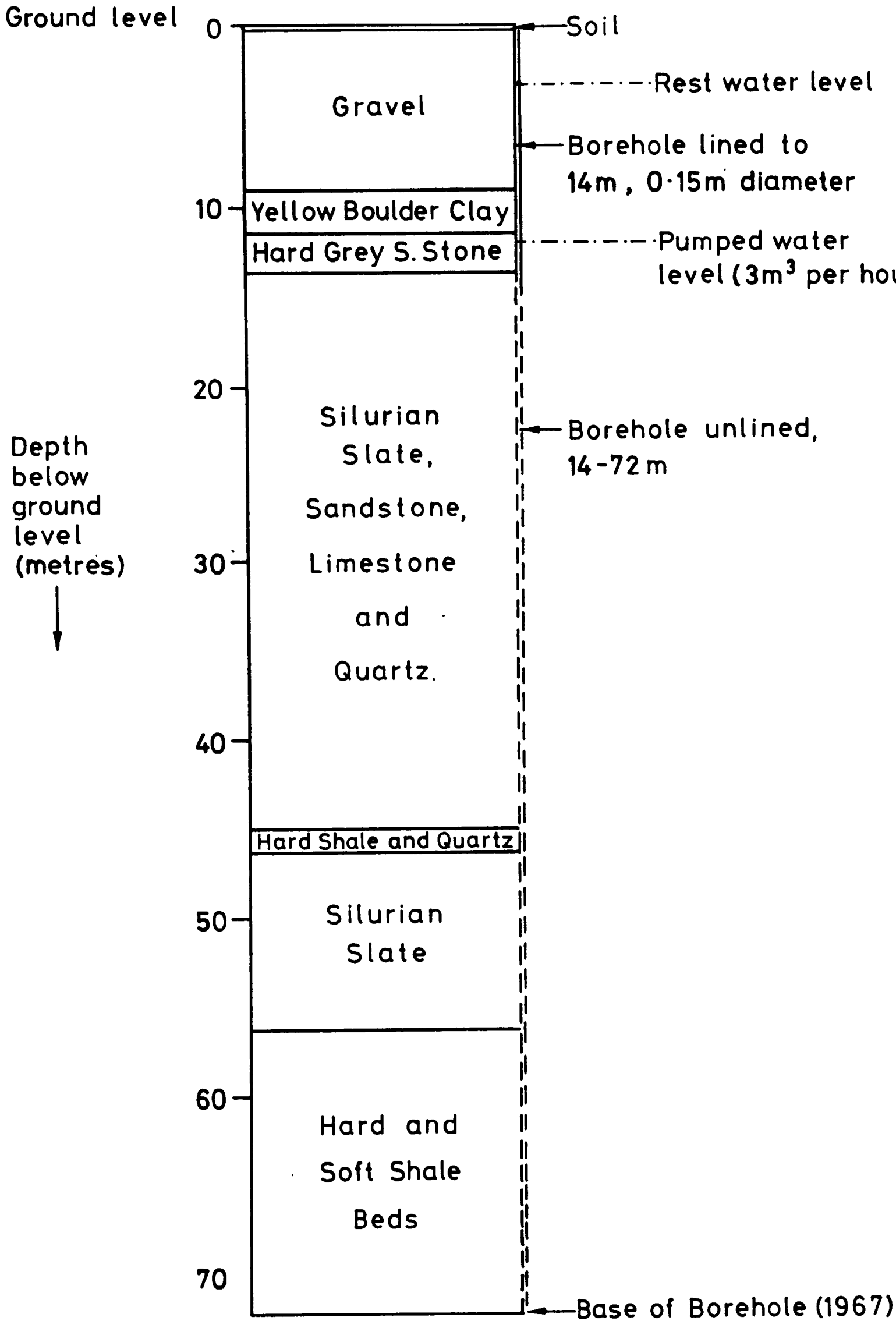
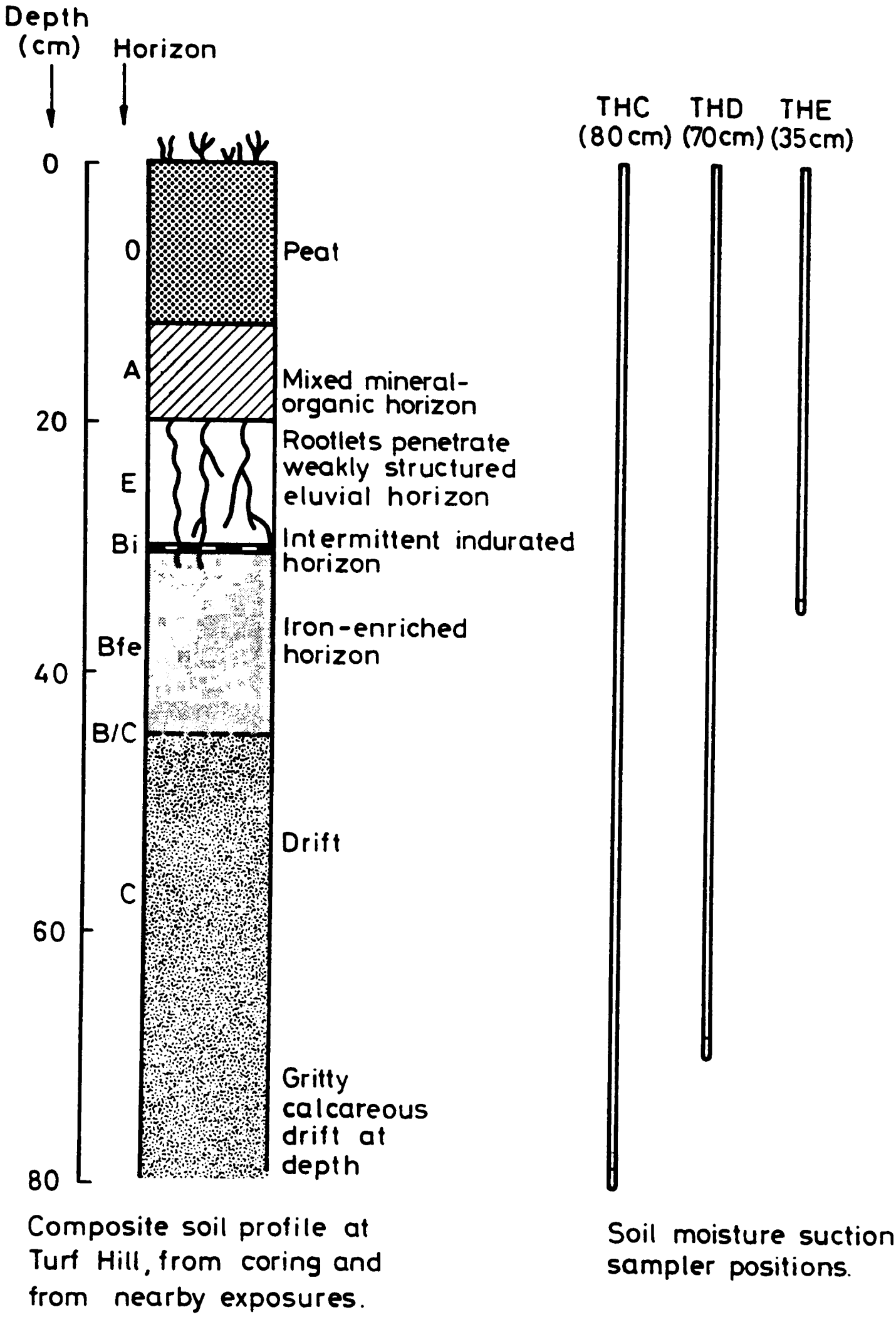


Fig. 3.6 Stratigraphical log from the borehole at Higher Tren House, Malham area



Composite soil profile at Turf Hill, from coring and from nearby exposures.

Soil moisture suction sampler positions.

Fig. 3.7 Soil profile and soil moisture suction sampler depths on Turf Hill, Malham area

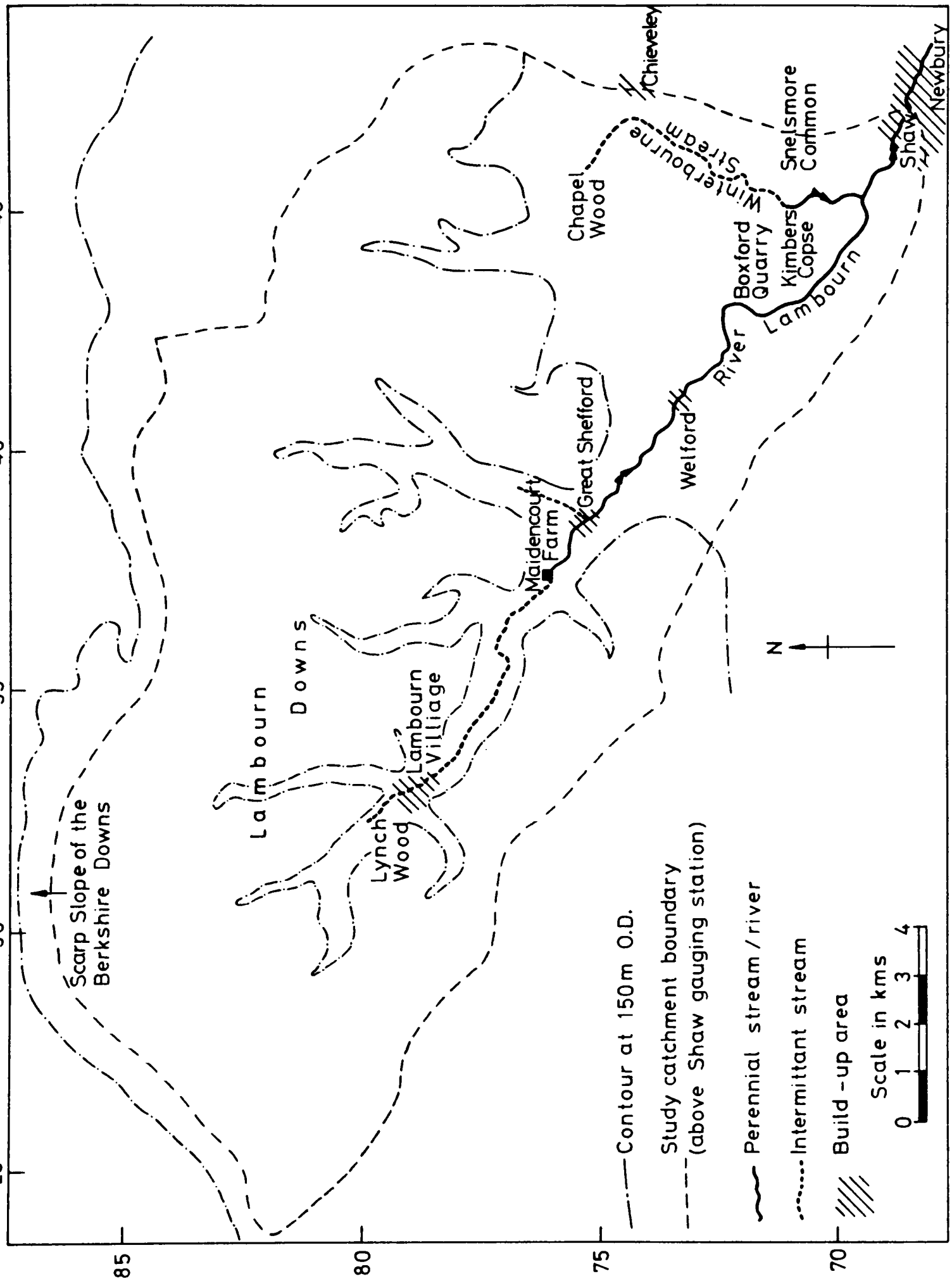


Fig. 3.8 Drainage and relief of the Lambourn area

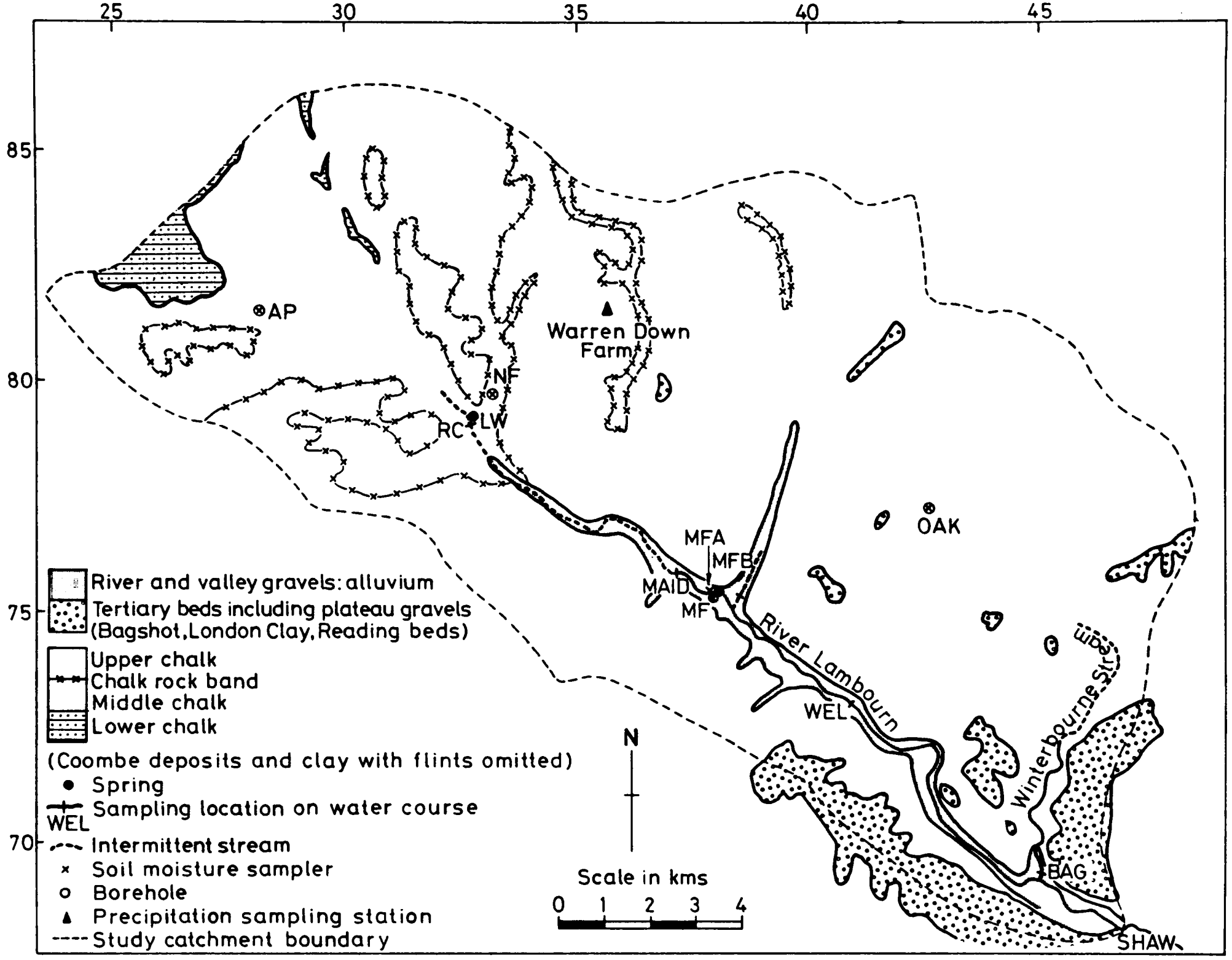


Fig. 3.9 Geology and sampling locations in the Lambourn area; for site abbreviations, see section 3.2.2(e)

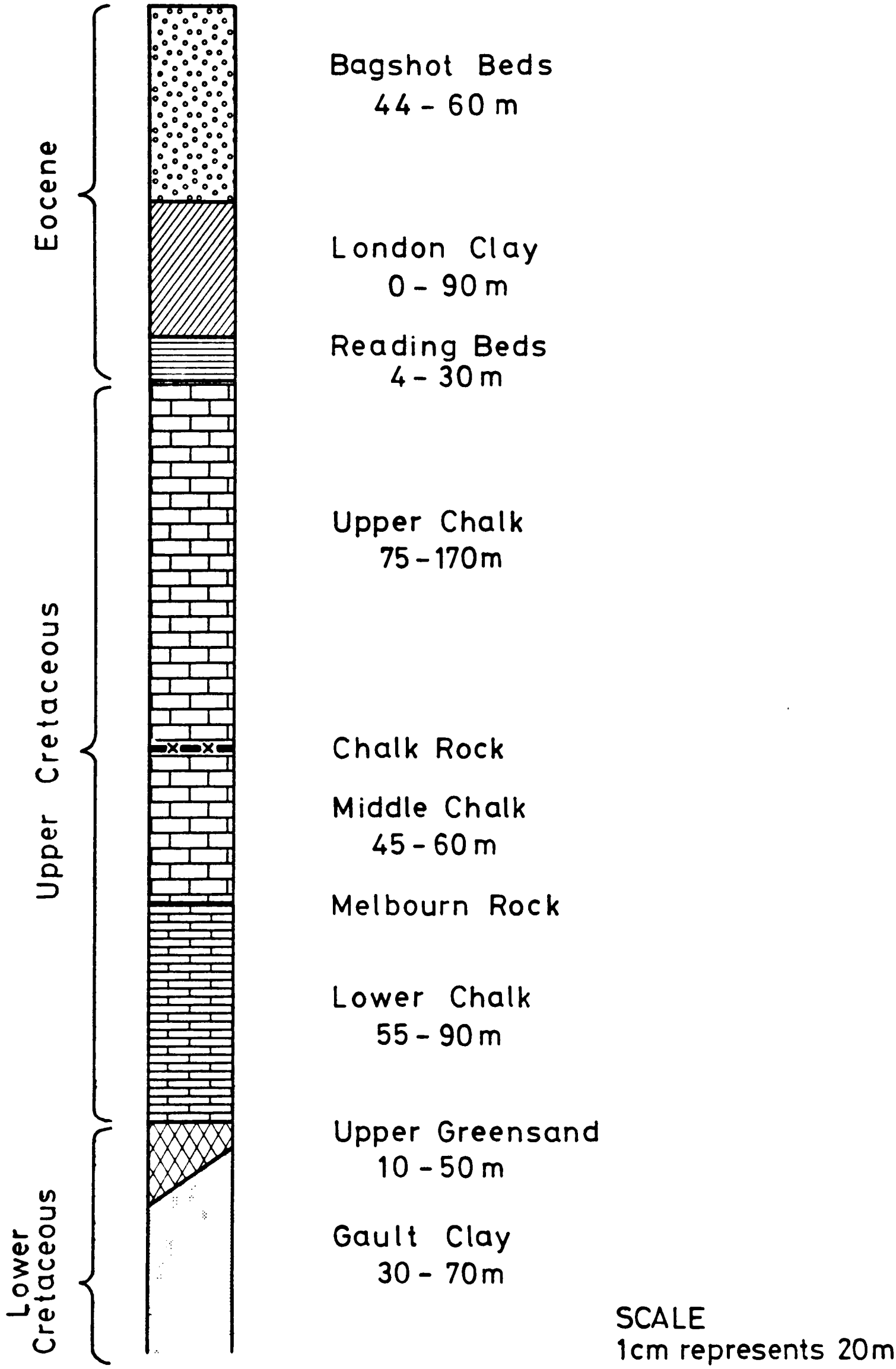


Fig. 3.10 Generalised vertical geological section in the Lambourn area (Source: INSTITUTE OF GEOLOGICAL SCIENCES & THAMES WATER AUTHORITY, 1978)

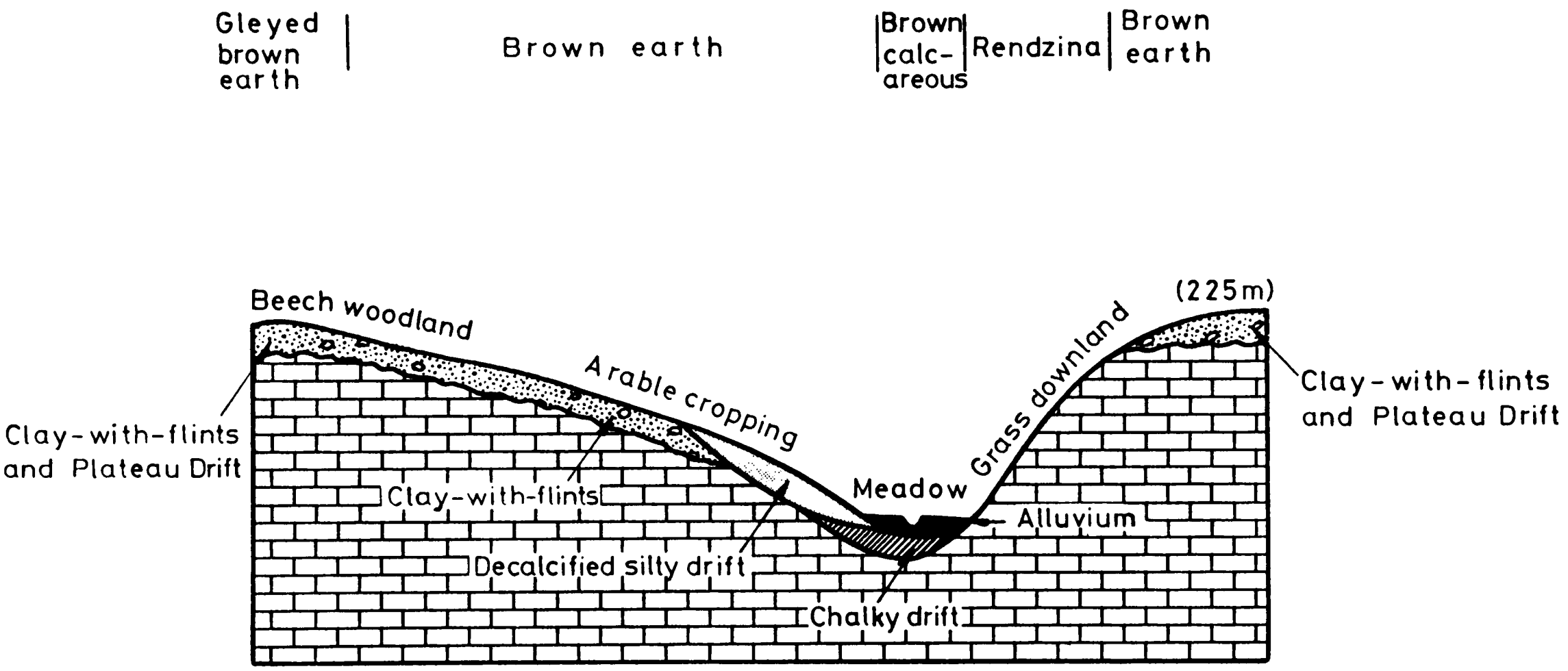
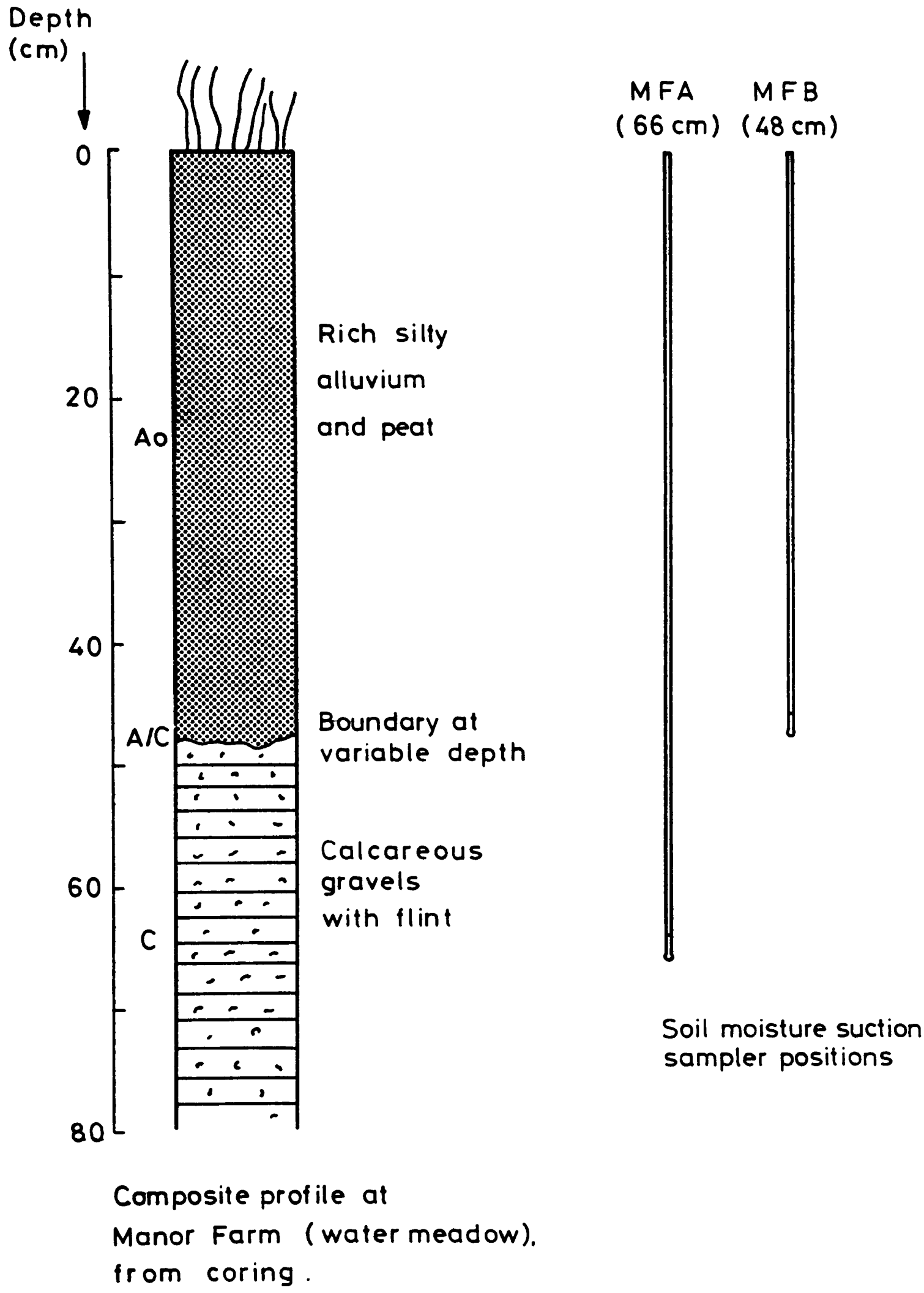


Fig. 3.11 Cross section of a typical Chalk river valley in the Lambourn area, showing soil types and land use (Sources: JARVIS, 1973; CURTIS et al., 1976)



Composite profile at
Manor Farm (water meadow),
from coring.

Fig. 3.12 Soil profile and soil moisture suction sampler depths at Manor Farm, Lambourn area

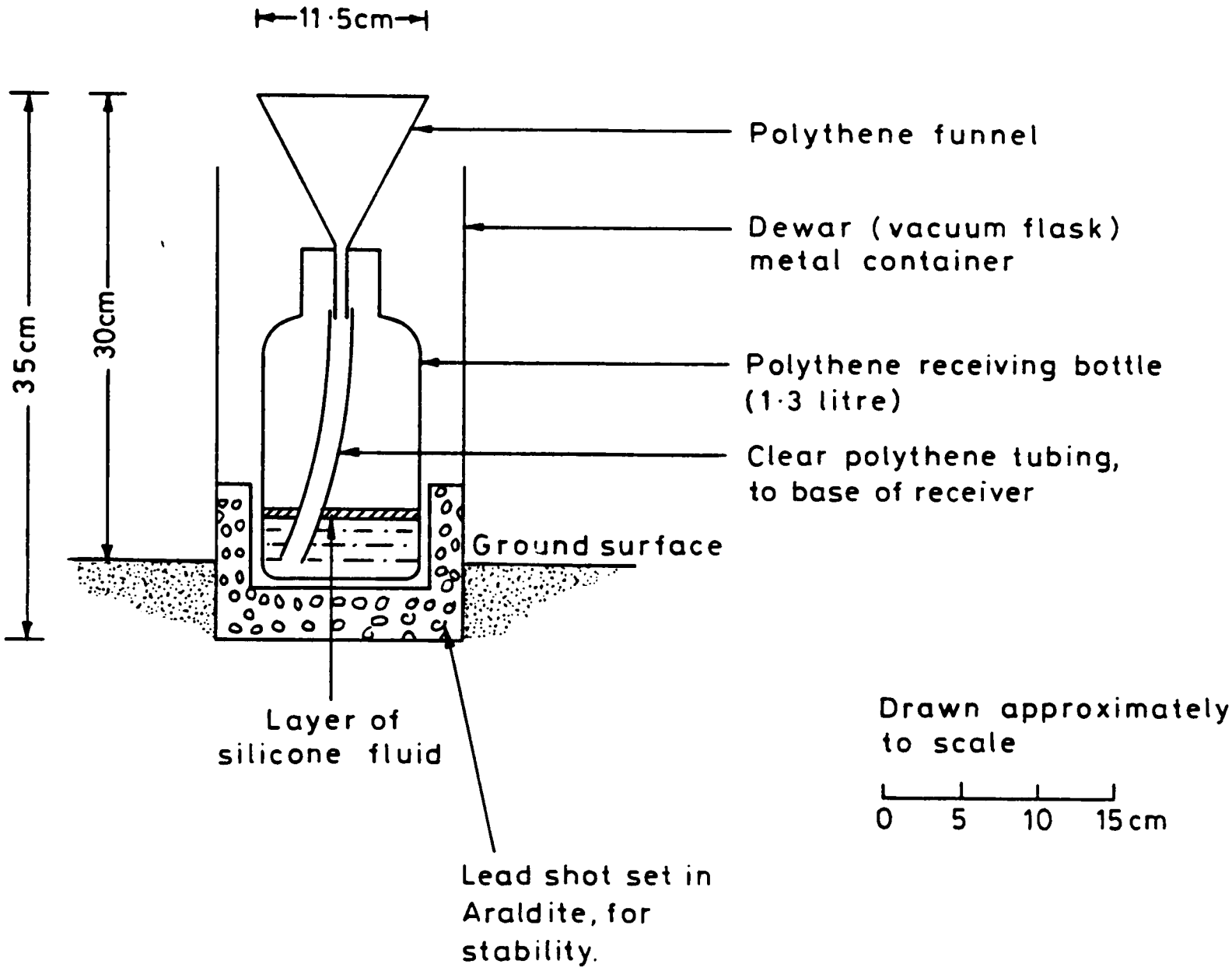


Fig. 3.13 The 'Harwell' style collector for stable isotopes in precipitation

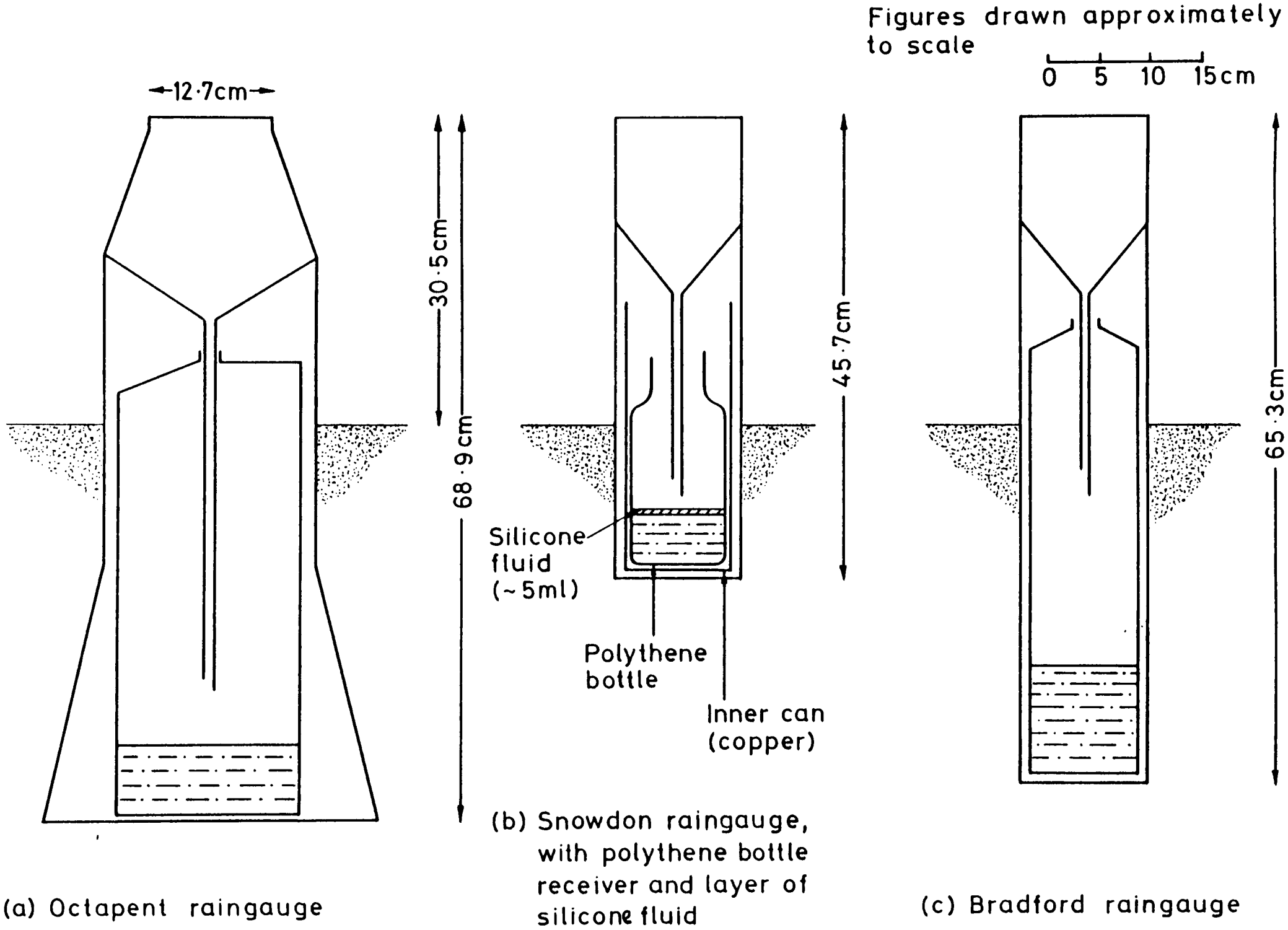


Fig. 3.14 Standard raingauges used as collectors for stable isotopes in precipitation: (a) Octapent raingauge, (b) modified Snowdon raingauge and (c) Bradford raingauge (Source: METEOROLOGICAL OFFICE, 1981)

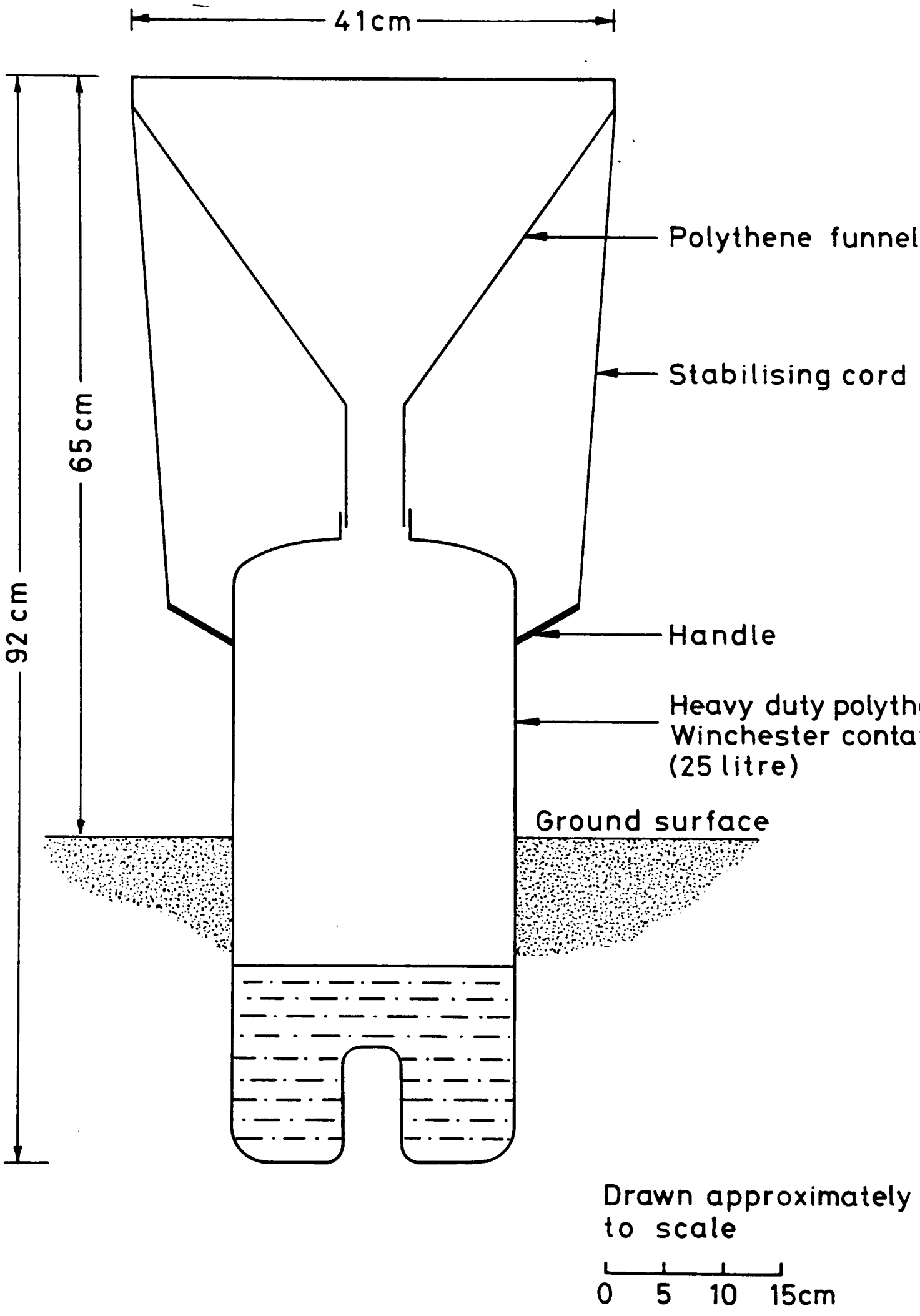


Fig. 3.15 The collector for tritium in precipitation, installed at Malham Tarn Field Centre

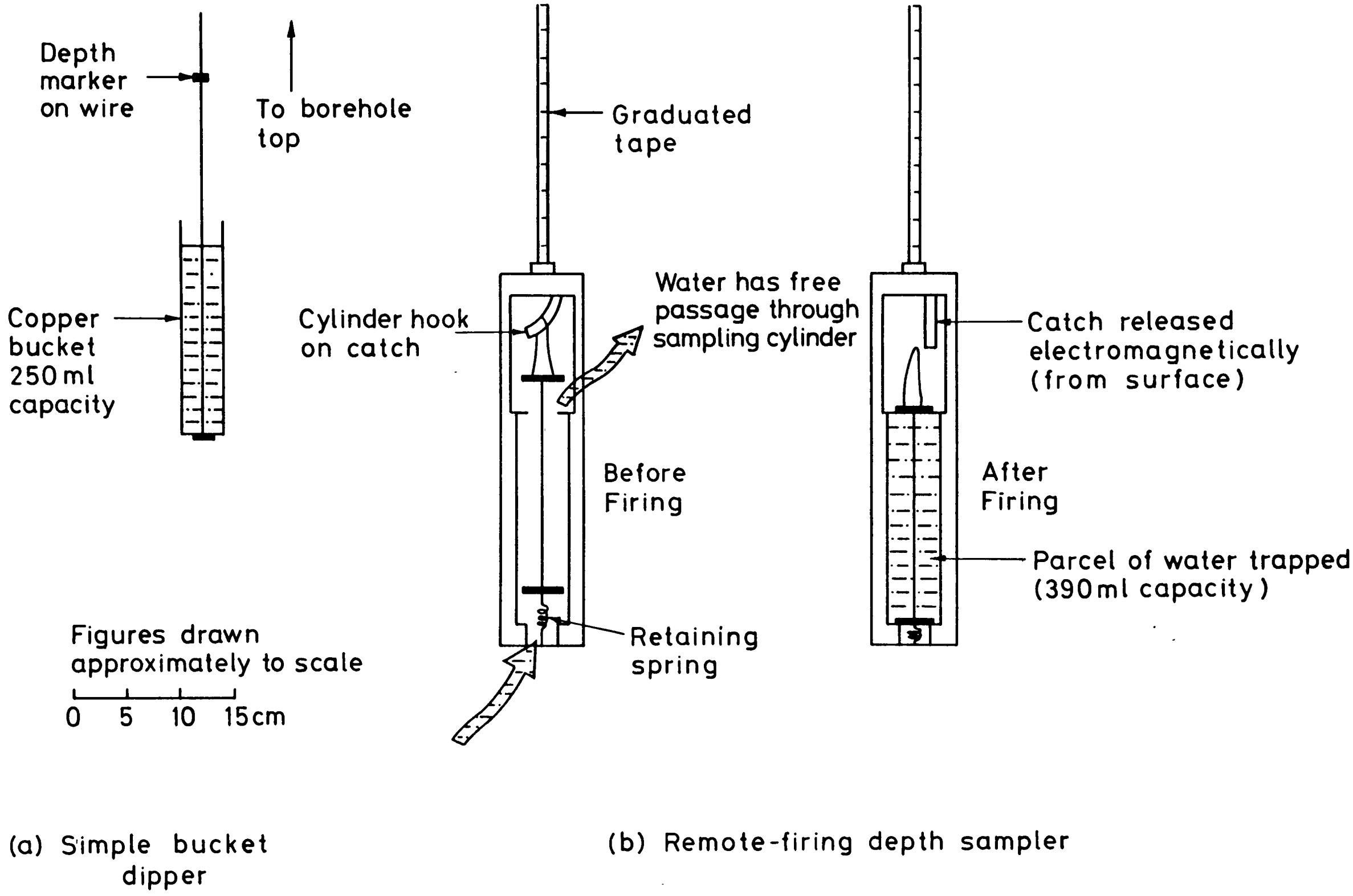
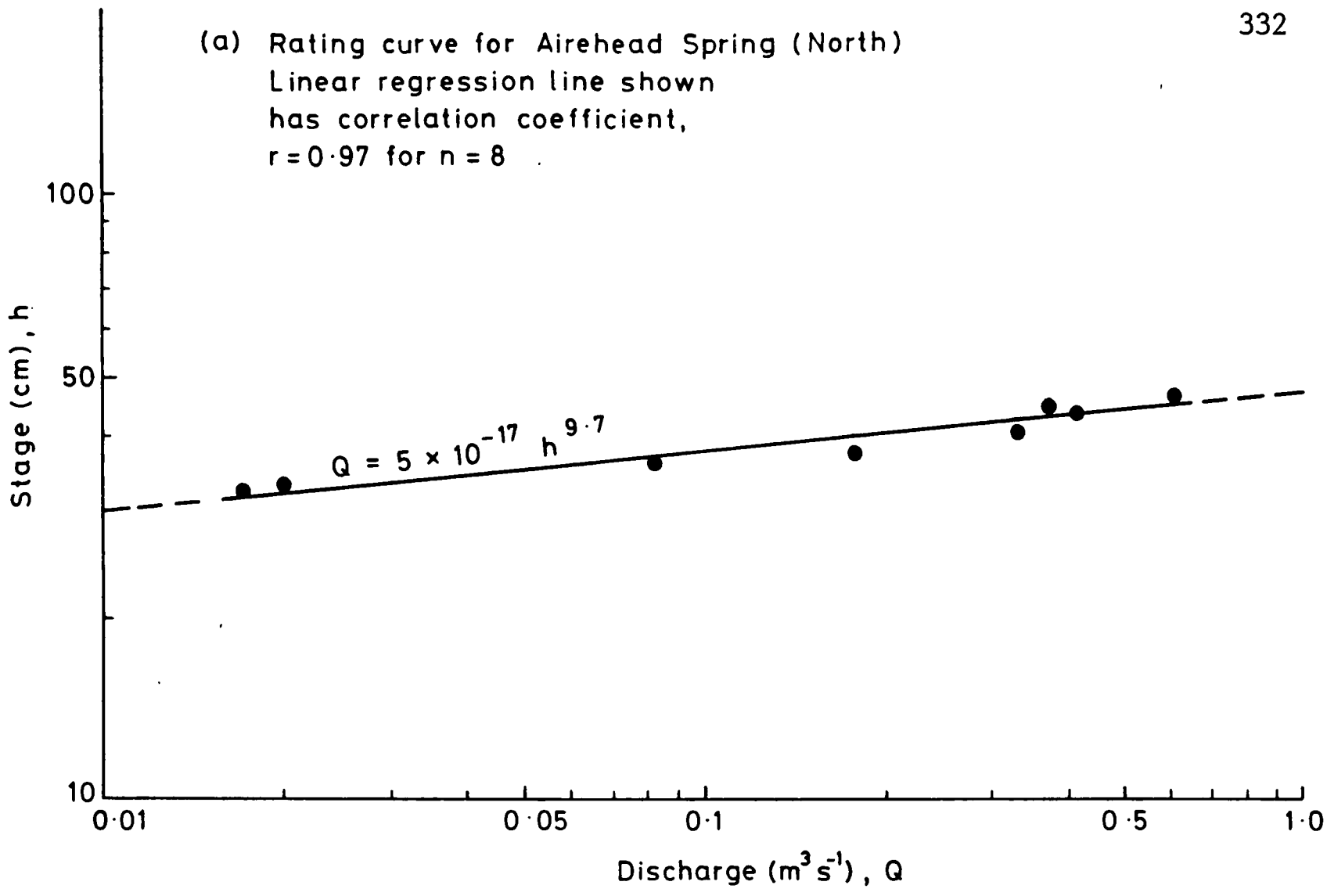


Fig. 3.16 Borehole water samplers: (a) simple bucket dipper, (b) remote-firing depth sampler



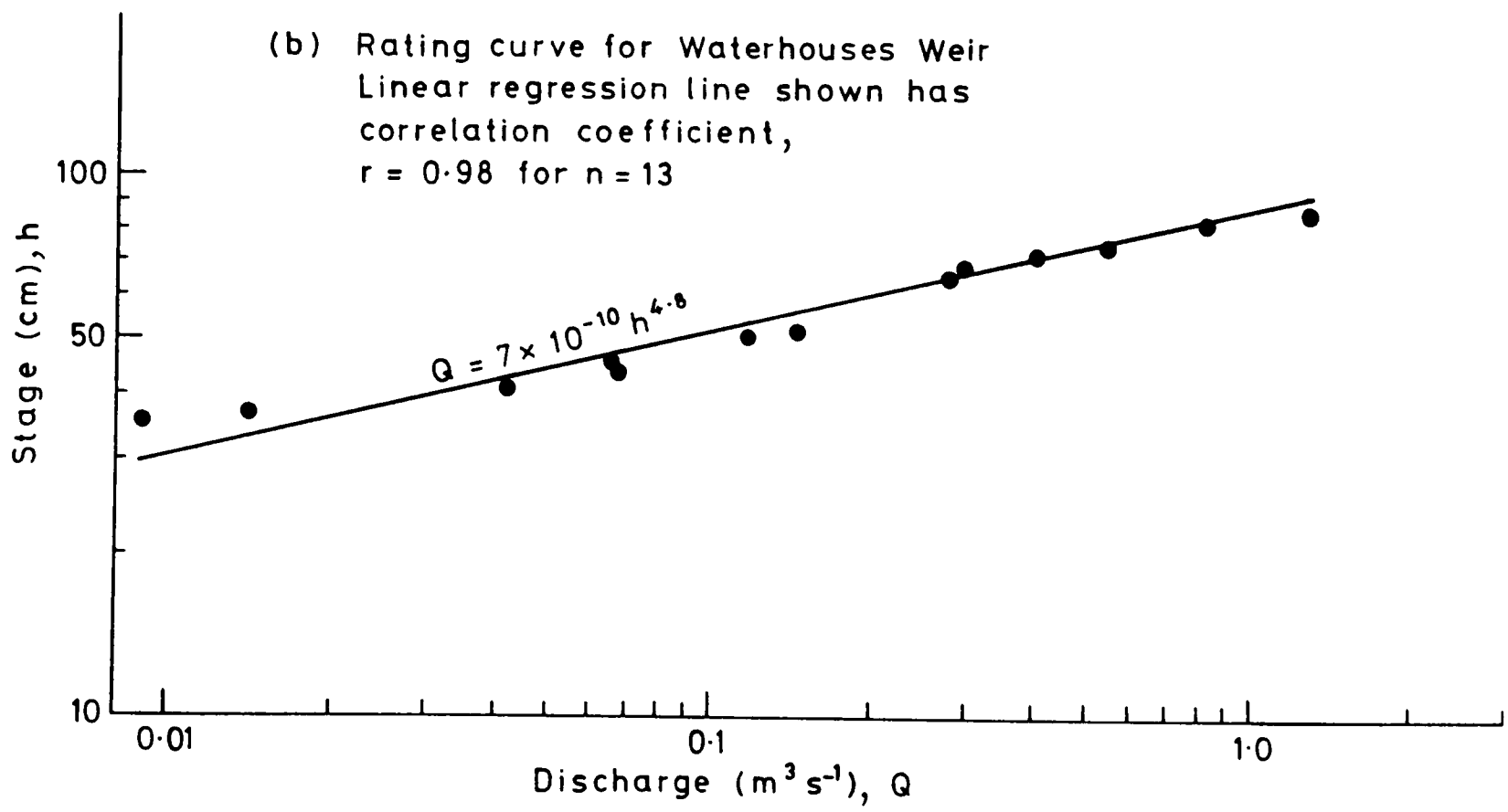


Fig. 3.17 Stage/discharge rating curves at the stage boards of (a) Airehead Spring (North) and (b) Waterhouses weir

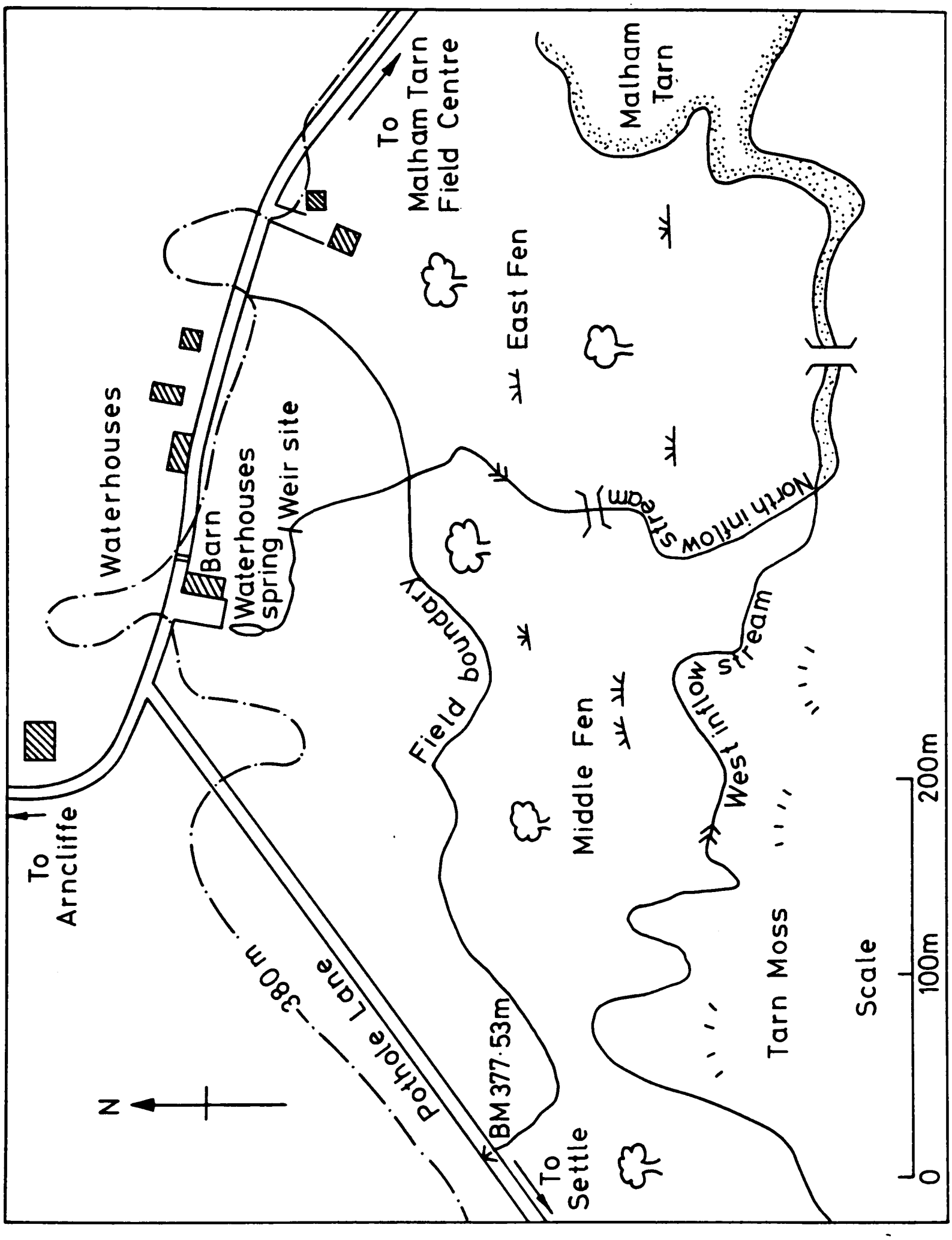


Fig. 3.18 The siting of the weir at Waterhouses

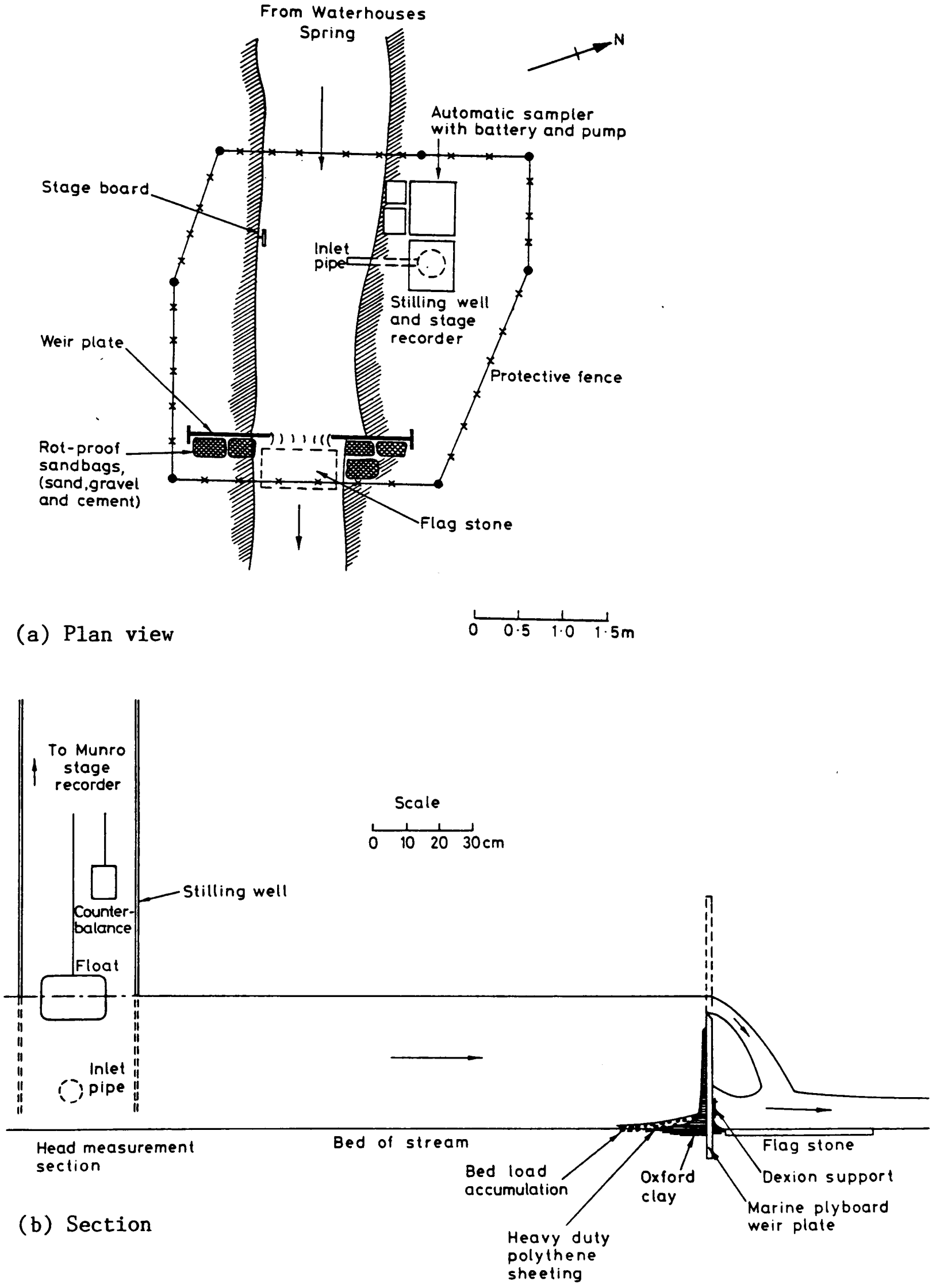


Fig. 3.19 The weir installation at Waterhouses: (a) plan view, (b) section

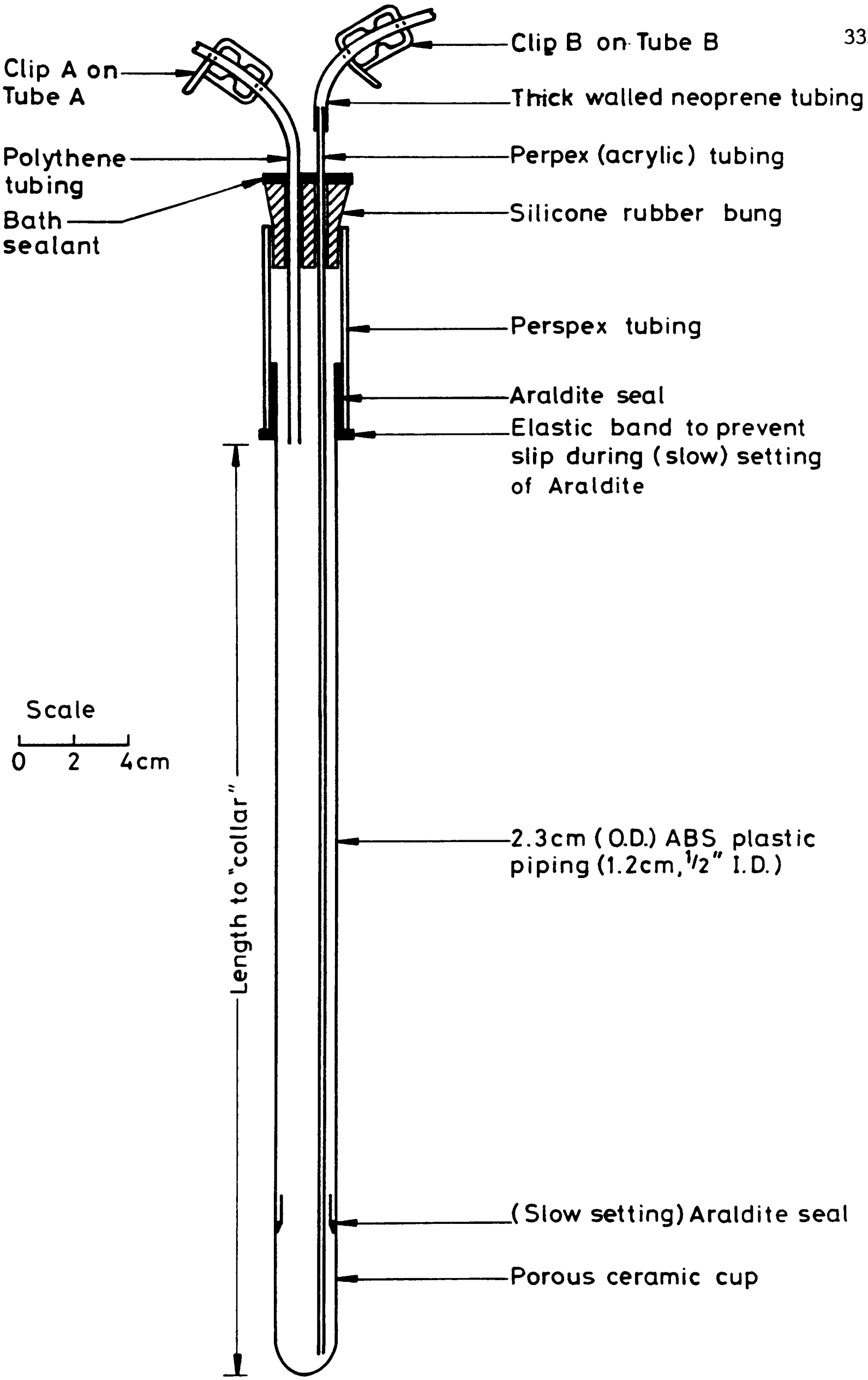
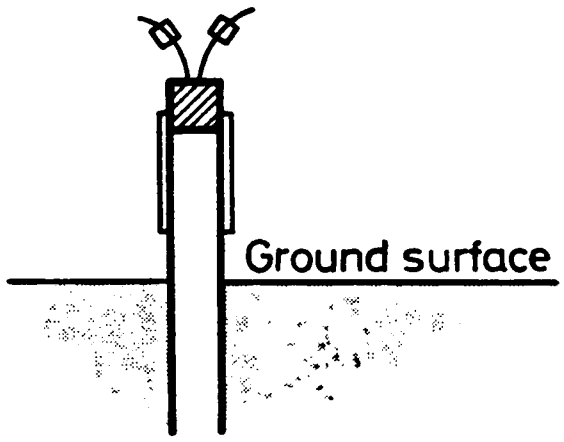
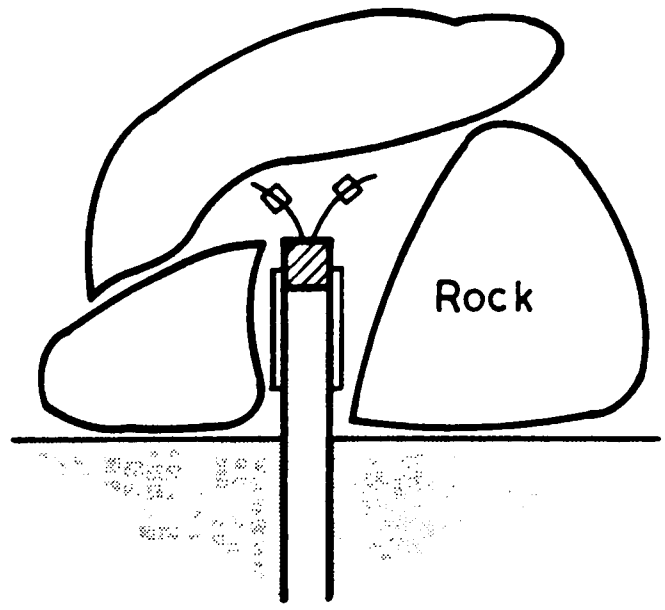


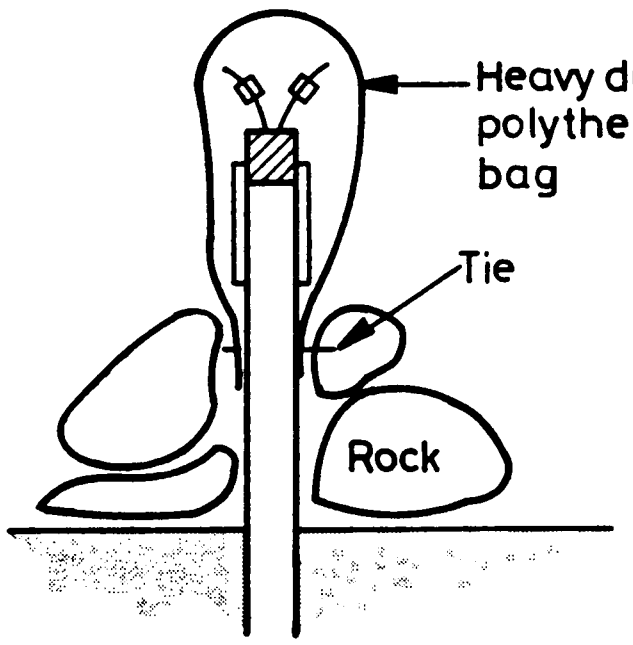
Fig. 3.20 A soil moisture suction sampler



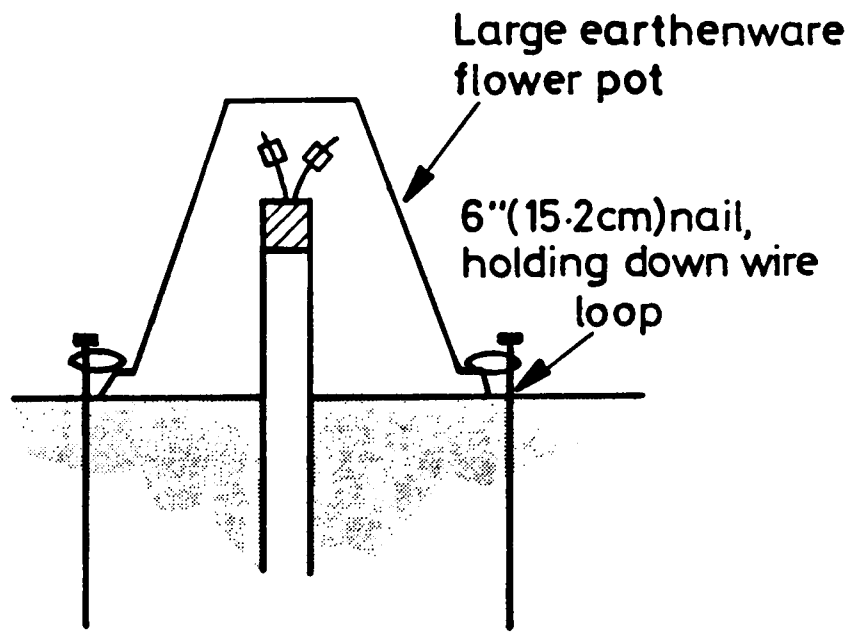
(a) No protection



(b) Cairn protection



(c) Bag and Cairn
(prominent sampler)



(d) Flower pot

Fig. 3.21 Protection of soil moisture suction samplers in the field

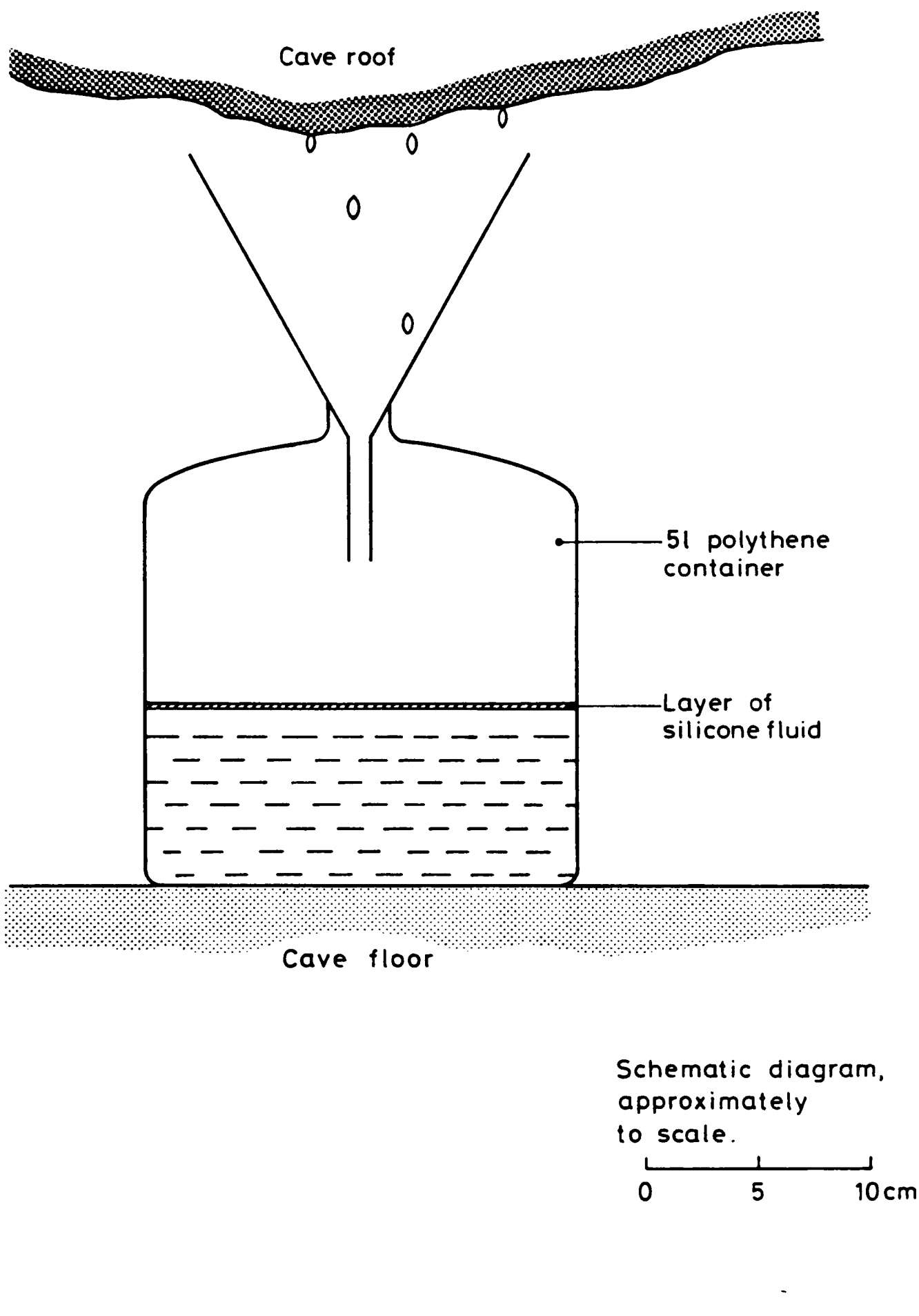
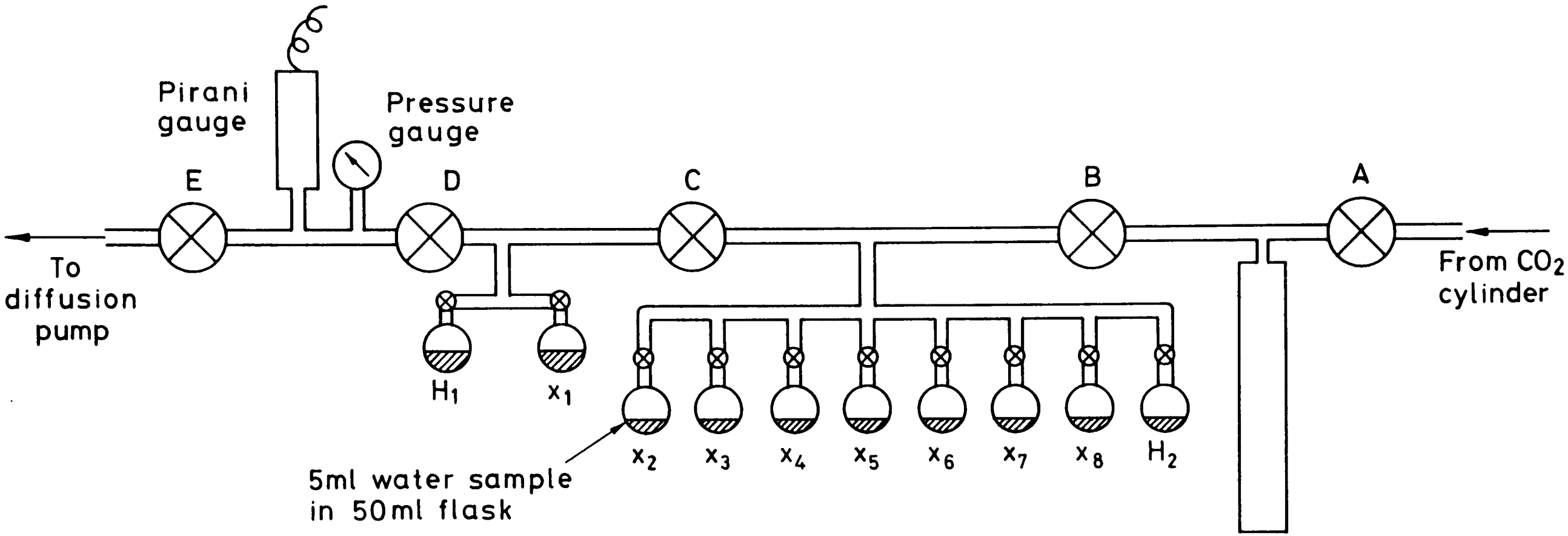


Fig. 3.22 Collection of cave drips for stable isotope analysis; Chapel Cave, Malham area



Water samples

H_1, H_2 Internal standards (East Hendred borehole water)

$x_1 - x_8$ Samples of unknown $\delta^{18}O$ values

Fig. 3.23 The preparation line for oxygen isotope equilibration between water sample and $CO_{2(g)}$

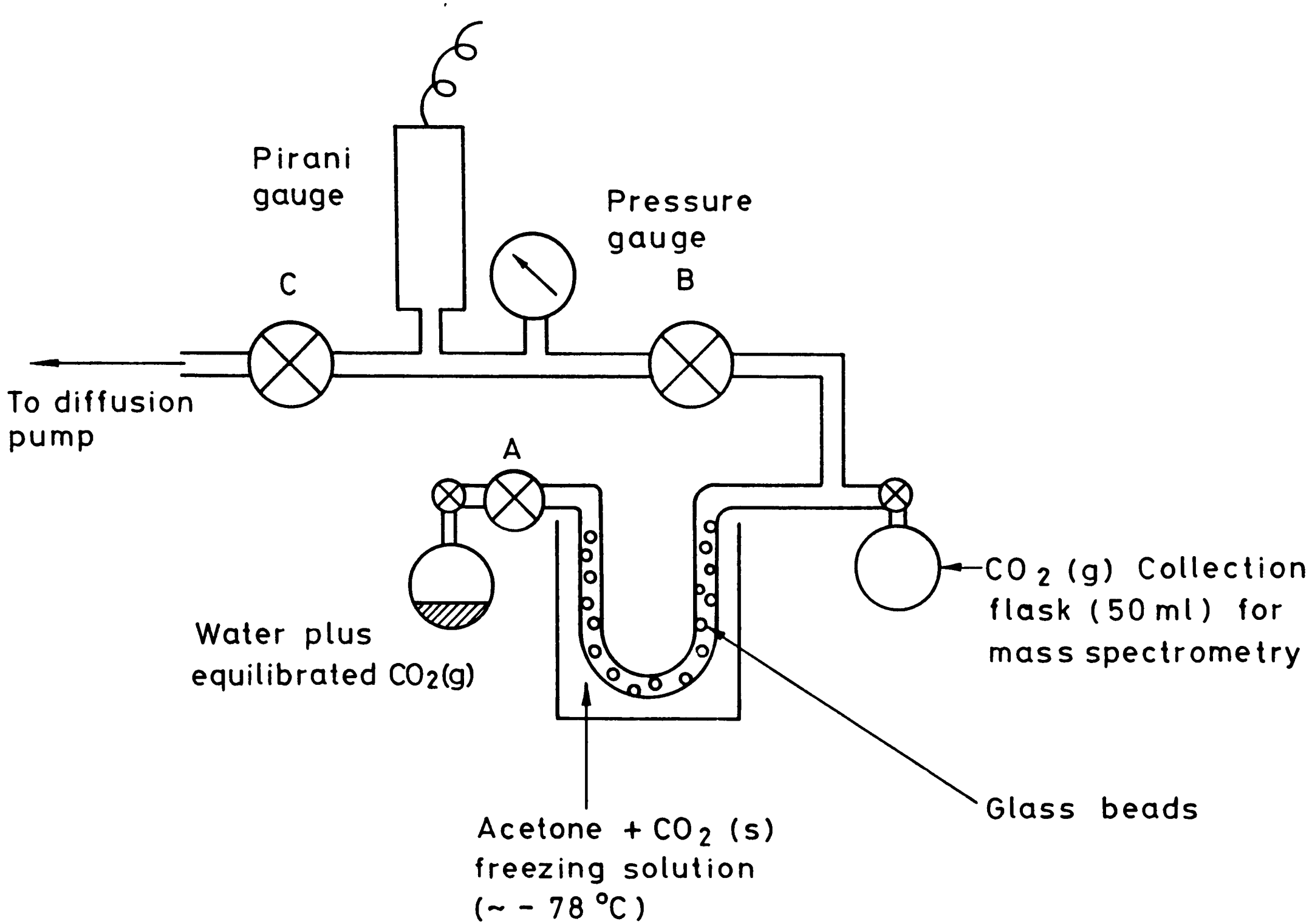


Fig. 3.24 The transfer and drying of equilibrated $CO_{2(g)}$ prior to oxygen isotope ($^{18}O/^{16}O$) analysis

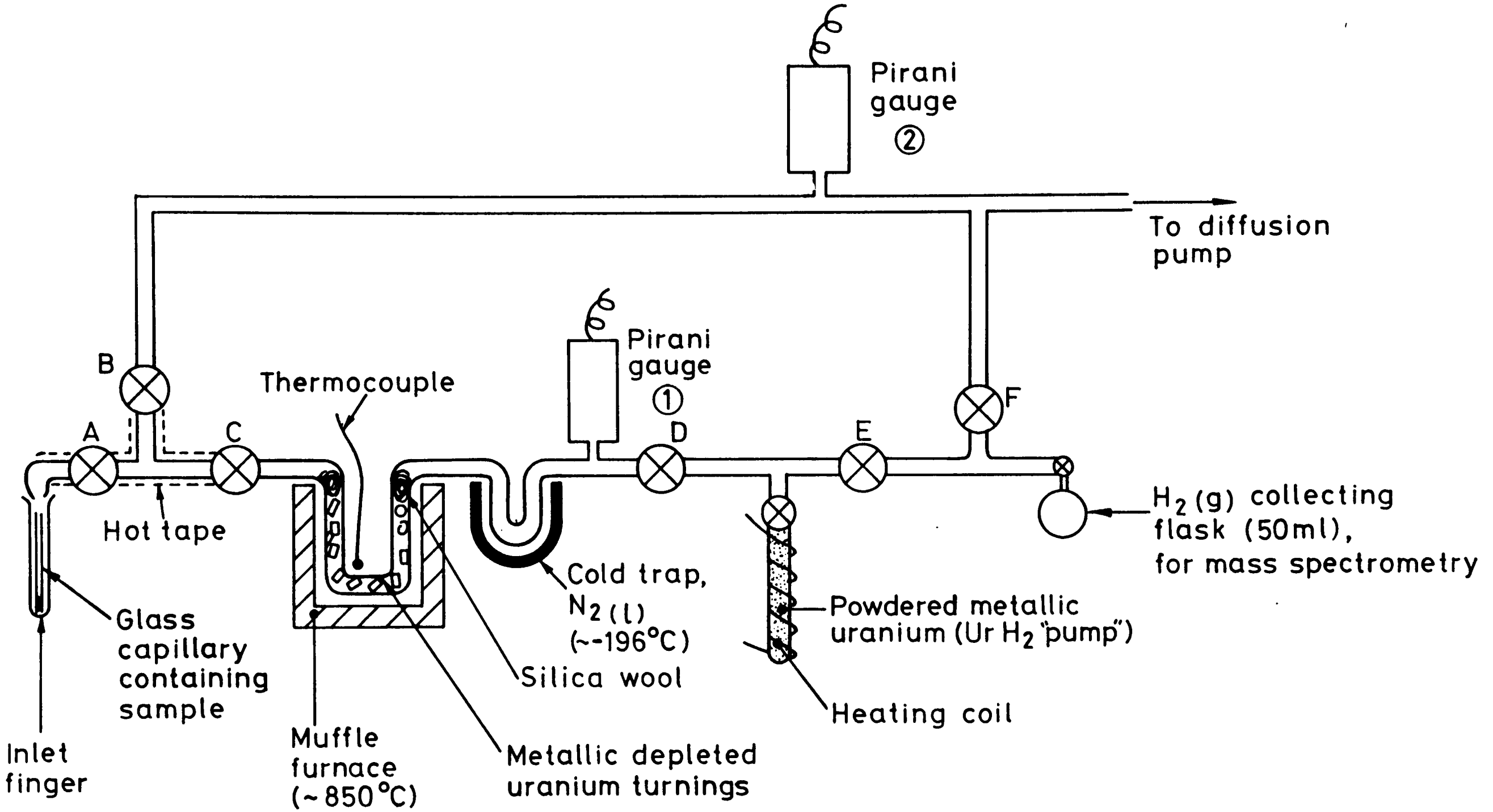


Fig. 3.25 The preparation line for the production of hydrogen gas from water samples, for hydrogen isotope (D/H) analysis

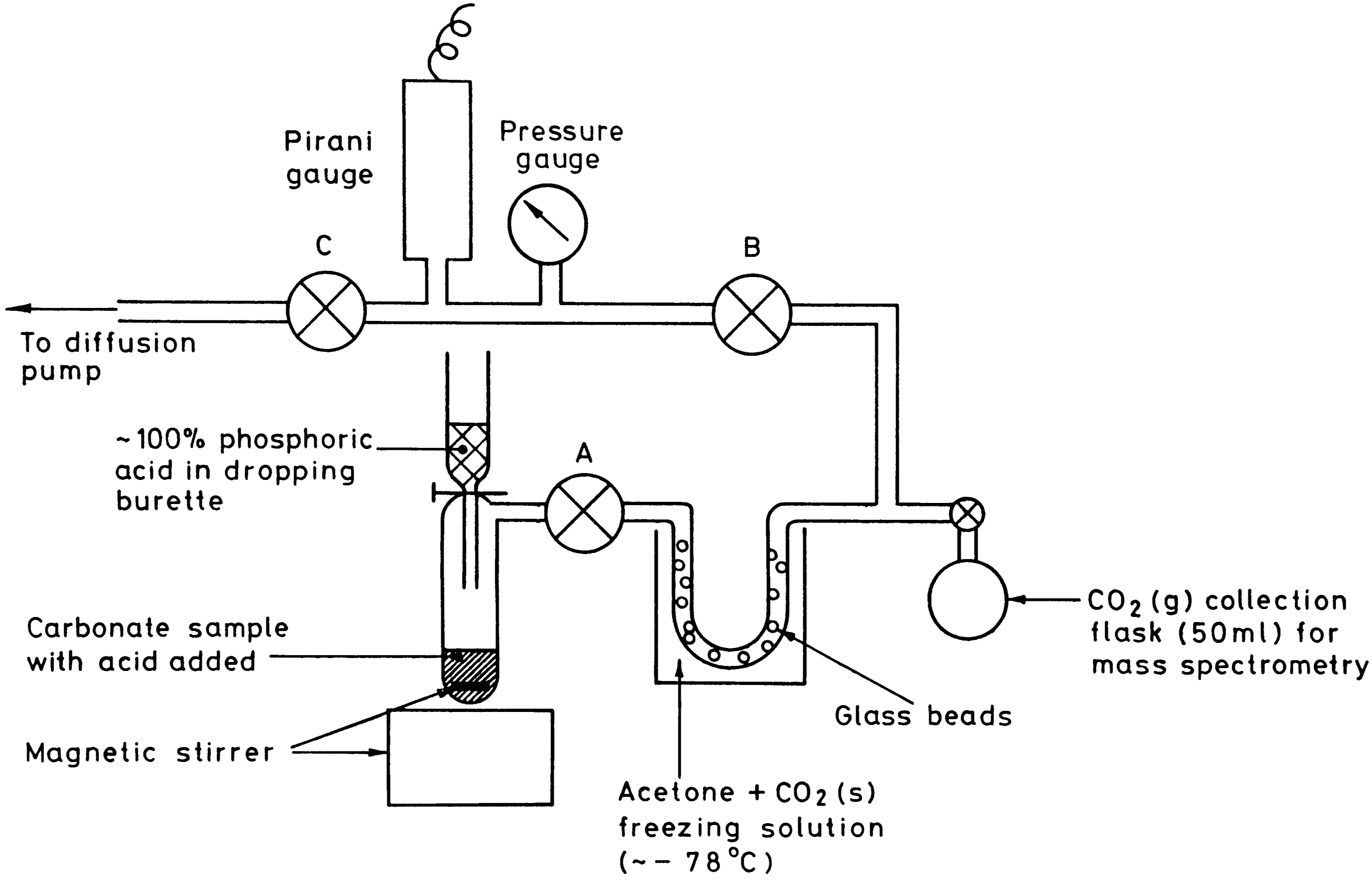


Fig. 3.26 The acidification of carbonate precipitate samples, for stable carbon isotope ($^{13}C/^{12}C$) analysis

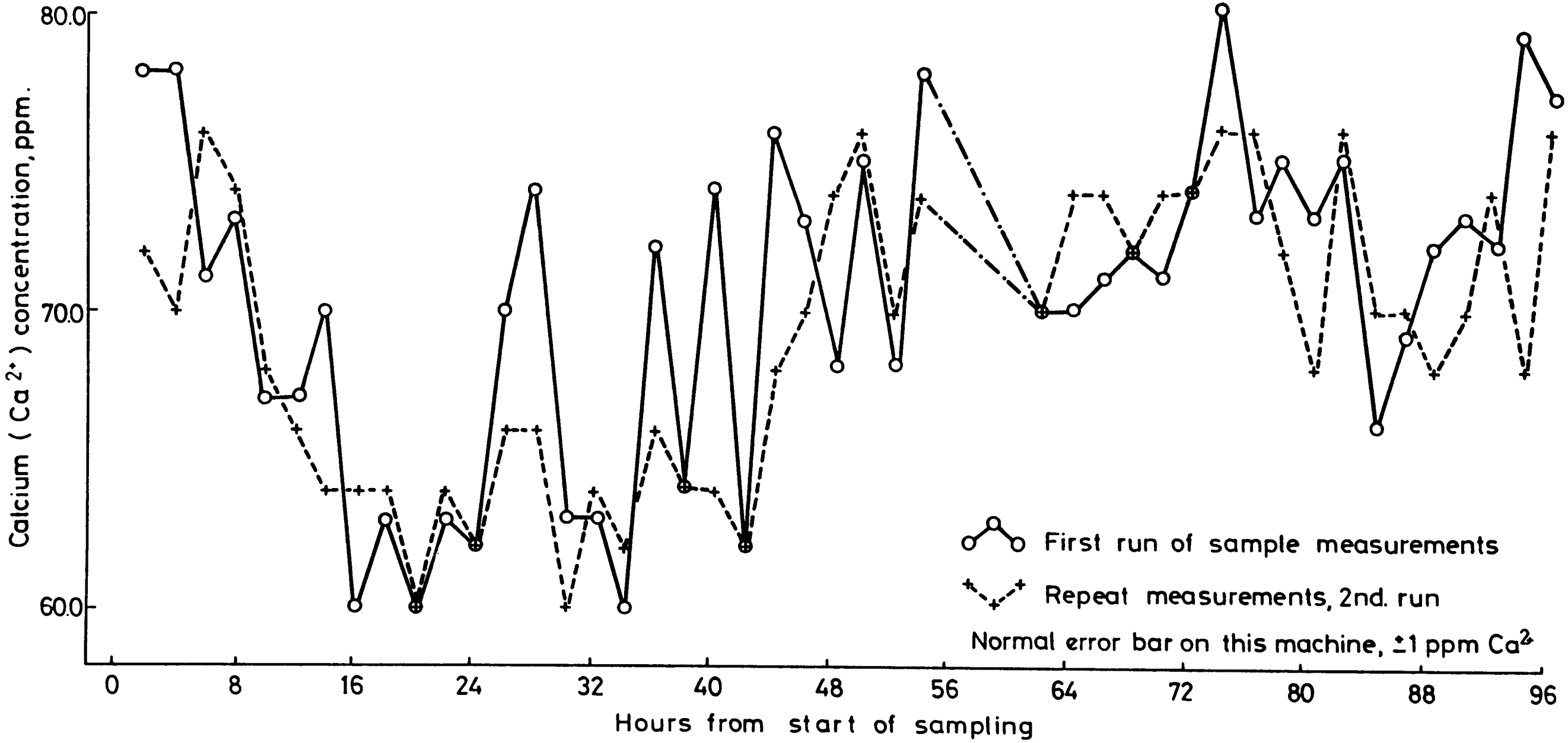


Fig. 3.27 Problems with reproducibility of calcium determinations, using a Pye Unicam Atomic Absorption Spectrophotometer (model SP191); samples from hydrograph studies, October 1982

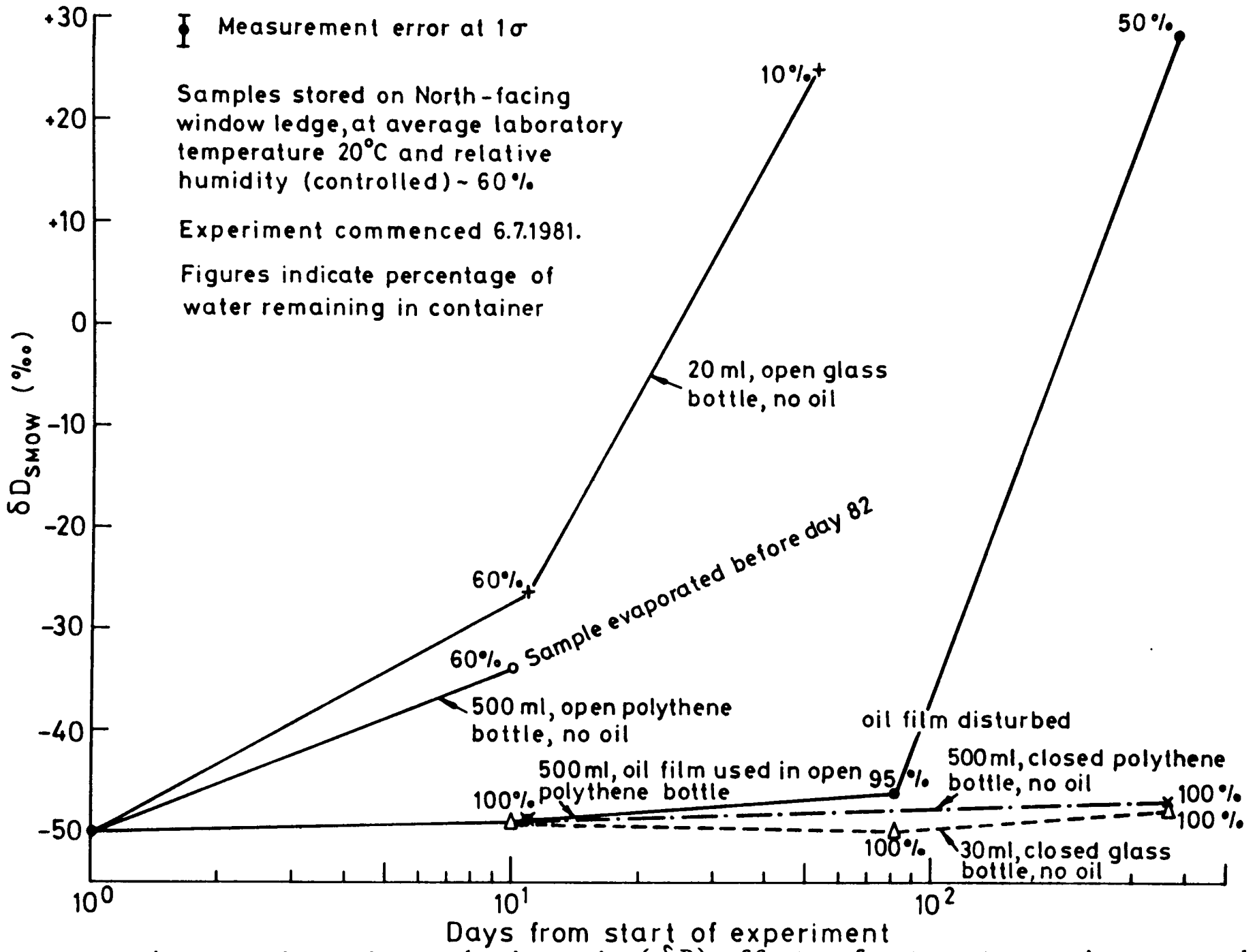


Fig. 3.28 Laboratory experiment to investigate the isotopic (δD) effects of water storage in an open bottle, with and without the use of an oil film, and in different closed bottle types

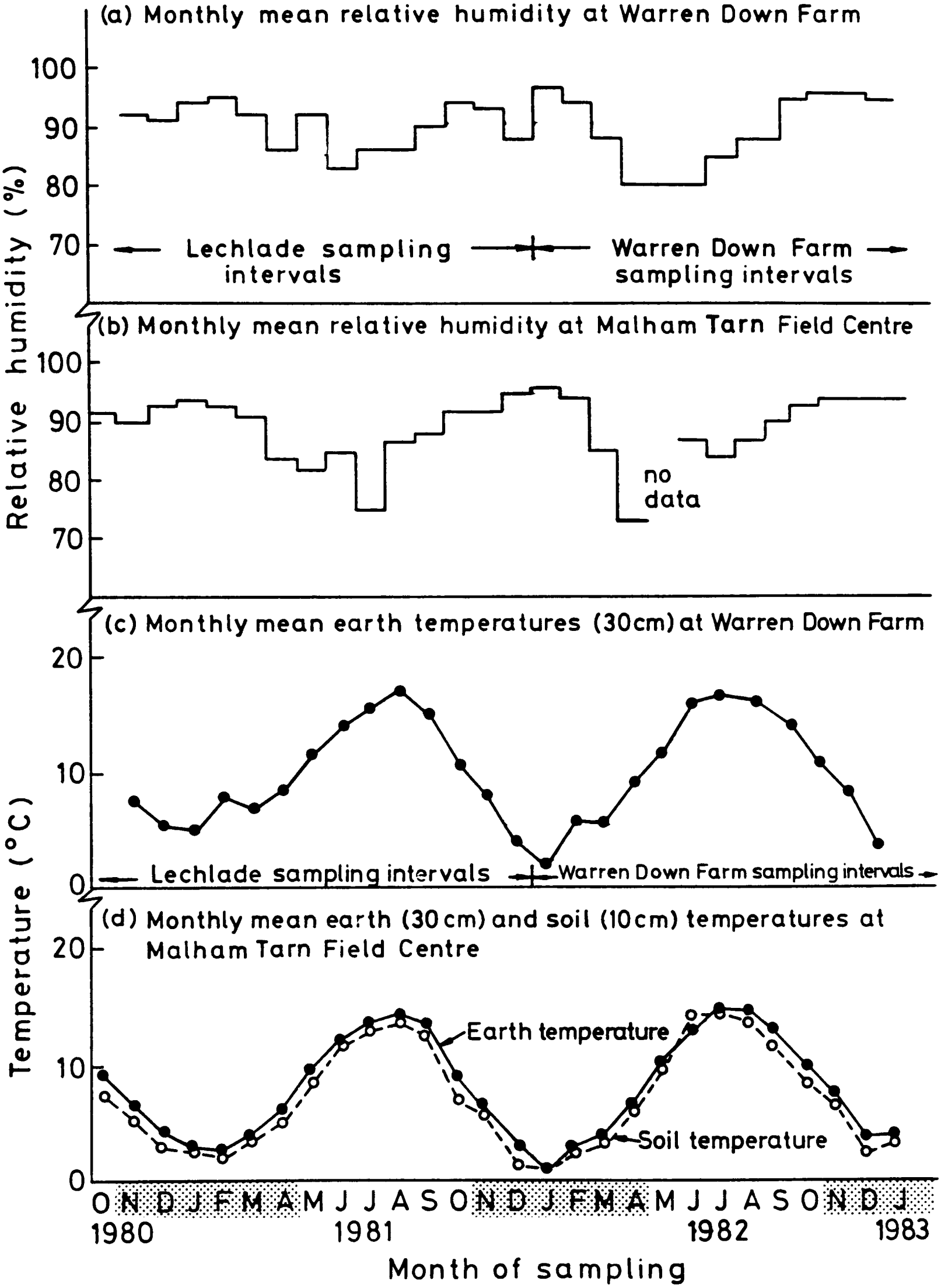


Fig. 3.29 Relative humidity and earth/soil temperatures at (a) and (c), Warren Down Farm, and (b) and (d), Malham Tarn Field Centre

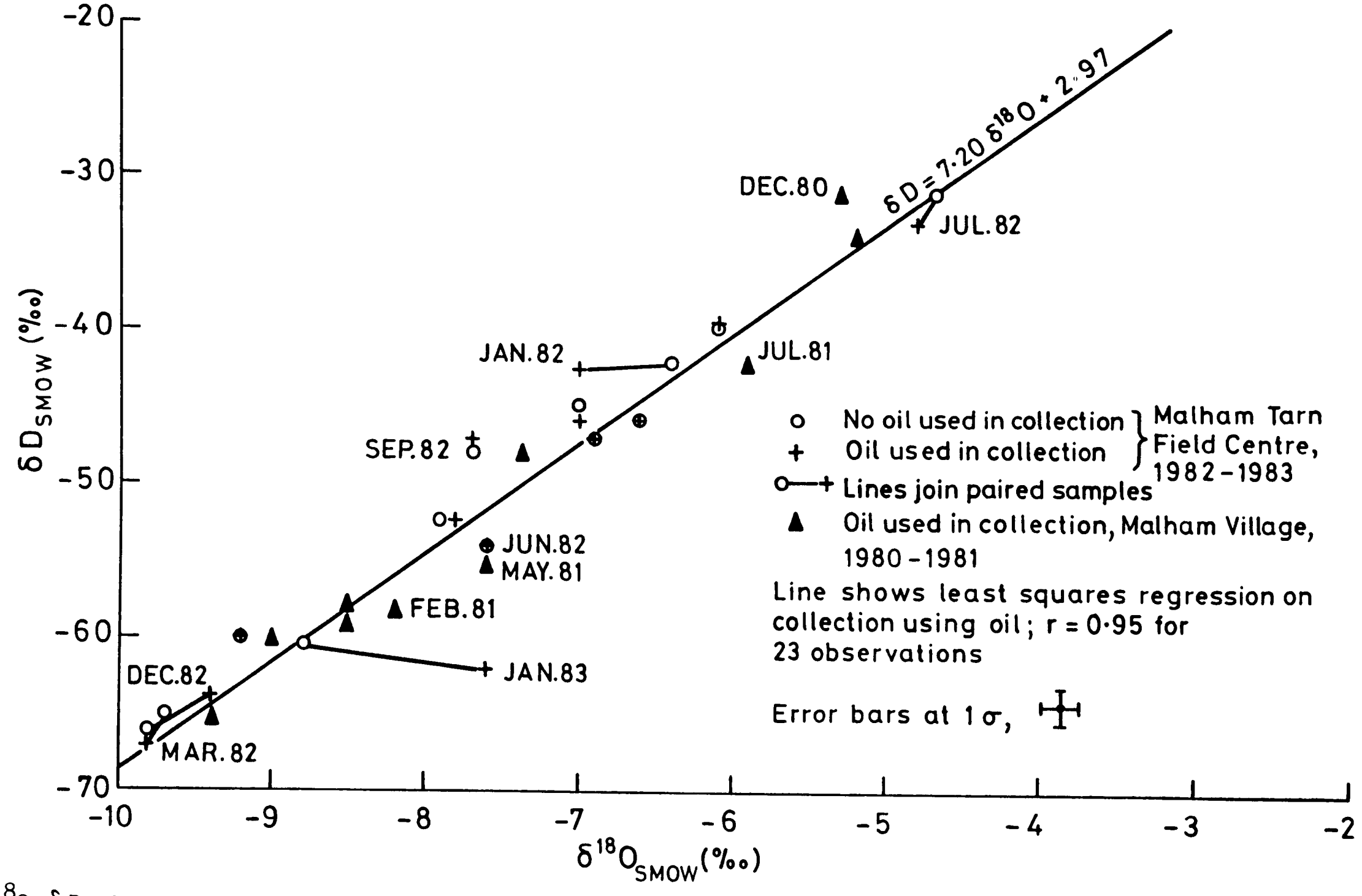
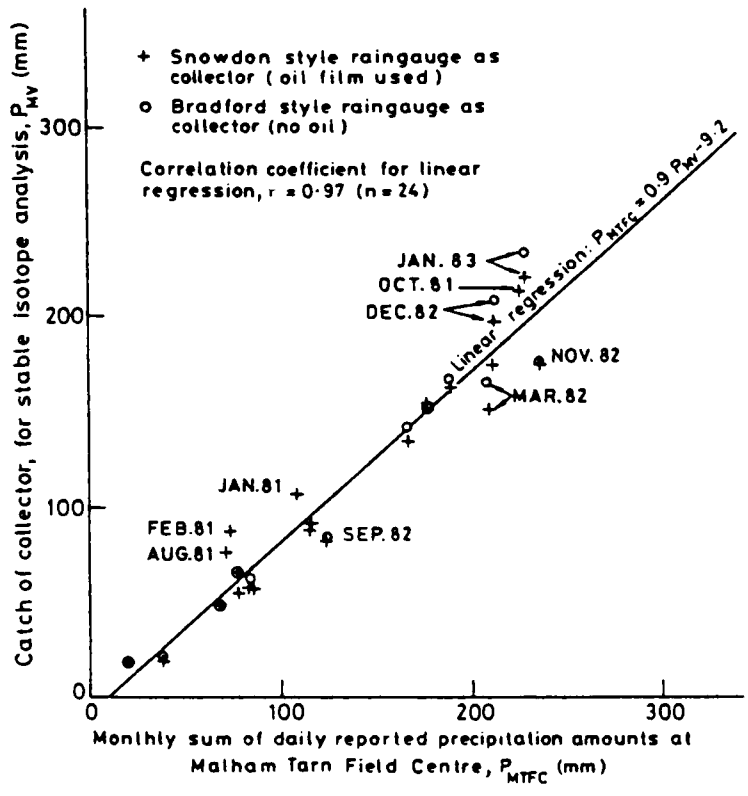
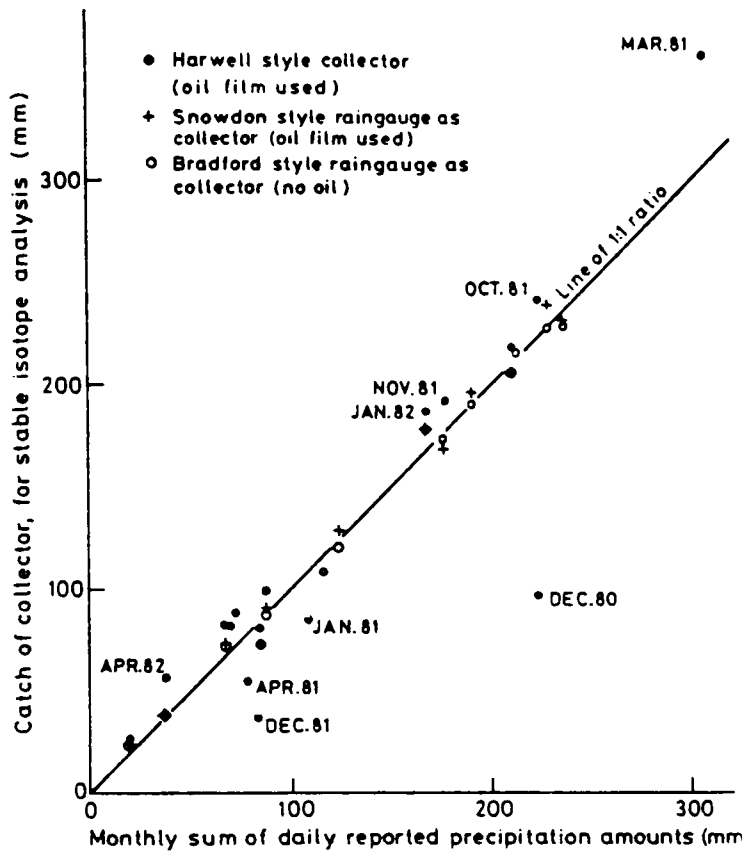


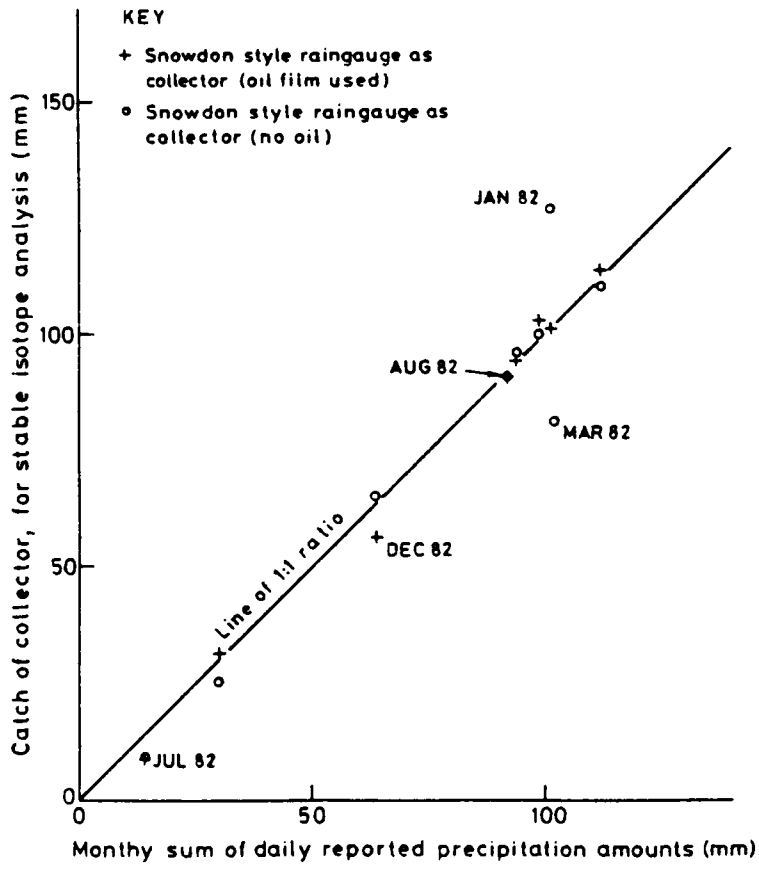
Fig. 3.30 $\delta^{18}O$–δD plot for monthly precipitation collections with and without the use of oil, at Malham Tarn Field Centre and Malham Village



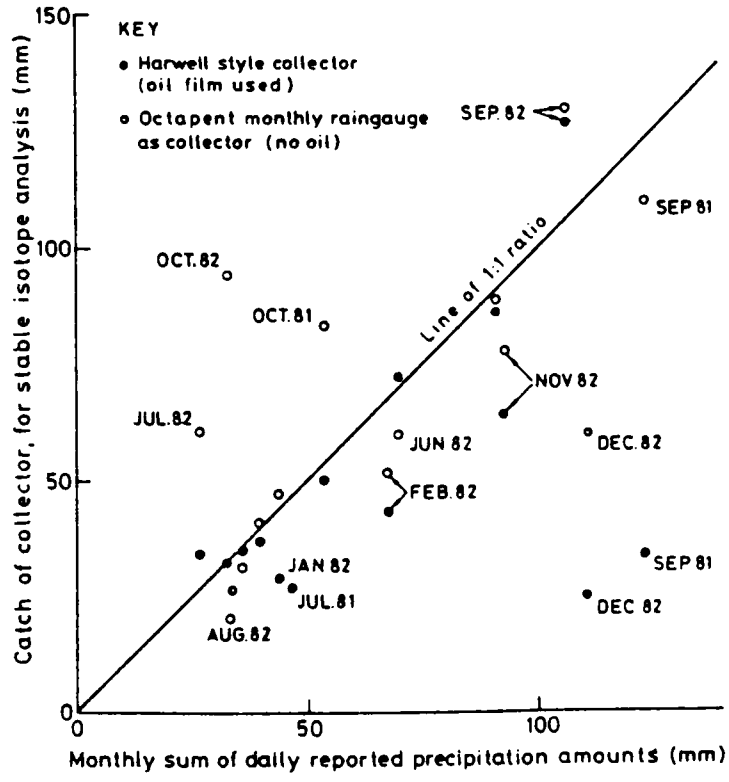
(a) Malham Village



(b) Malham Tarn Field Centre



(c) Warren Down Farm



(d) Lechlade

Fig. 3.31 Monthly precipitation catches using different stable isotope collectors, in comparison with monthly sums of daily reported precipitation amounts, at (a) Malham Village, (b) Malham Tarn Field Centre, (c) Warren Down Farm and (d) Lechlade

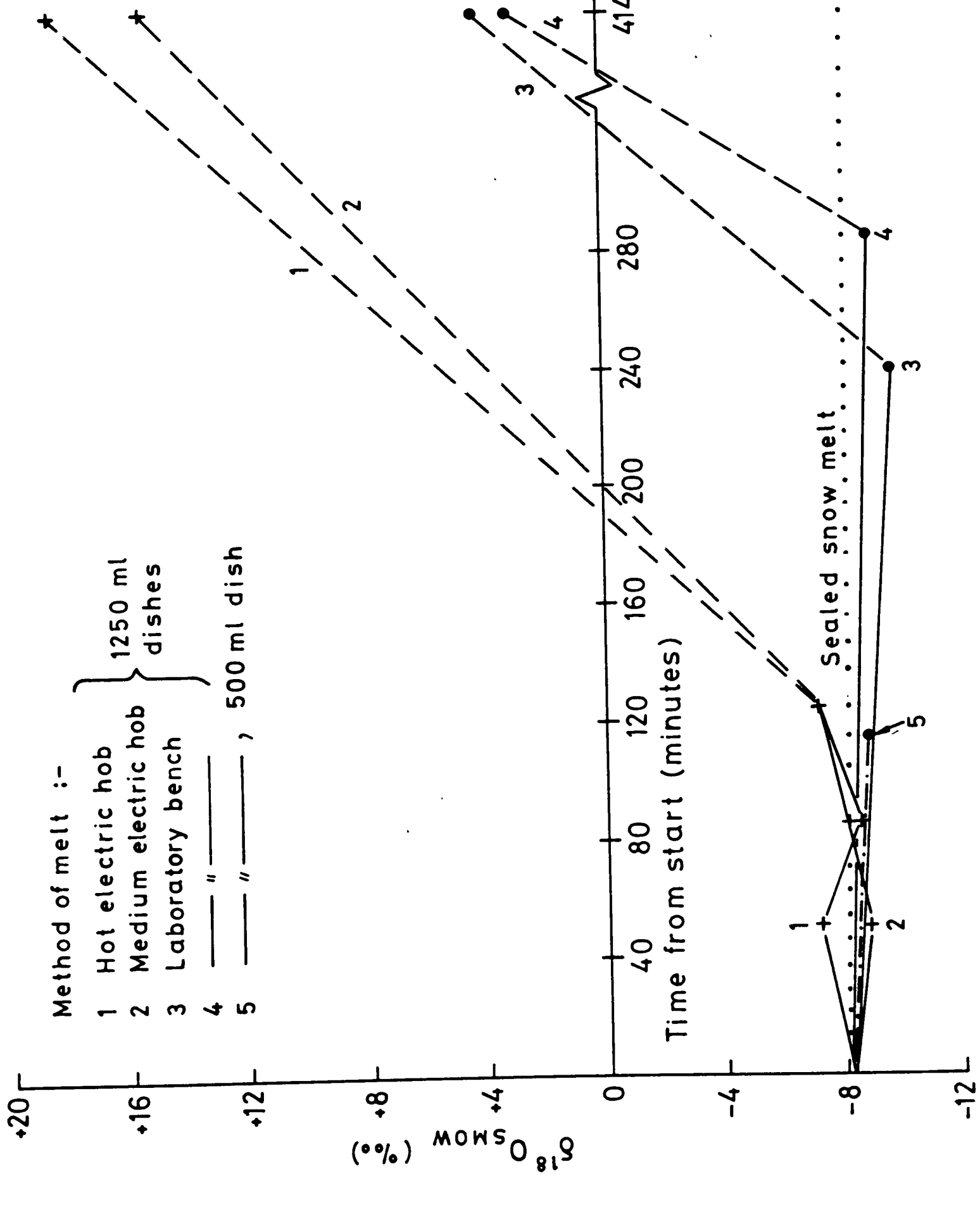


Fig. 3.32 Snow sample melt experiment: changing $\delta^{18}O$ composition of samples, through time

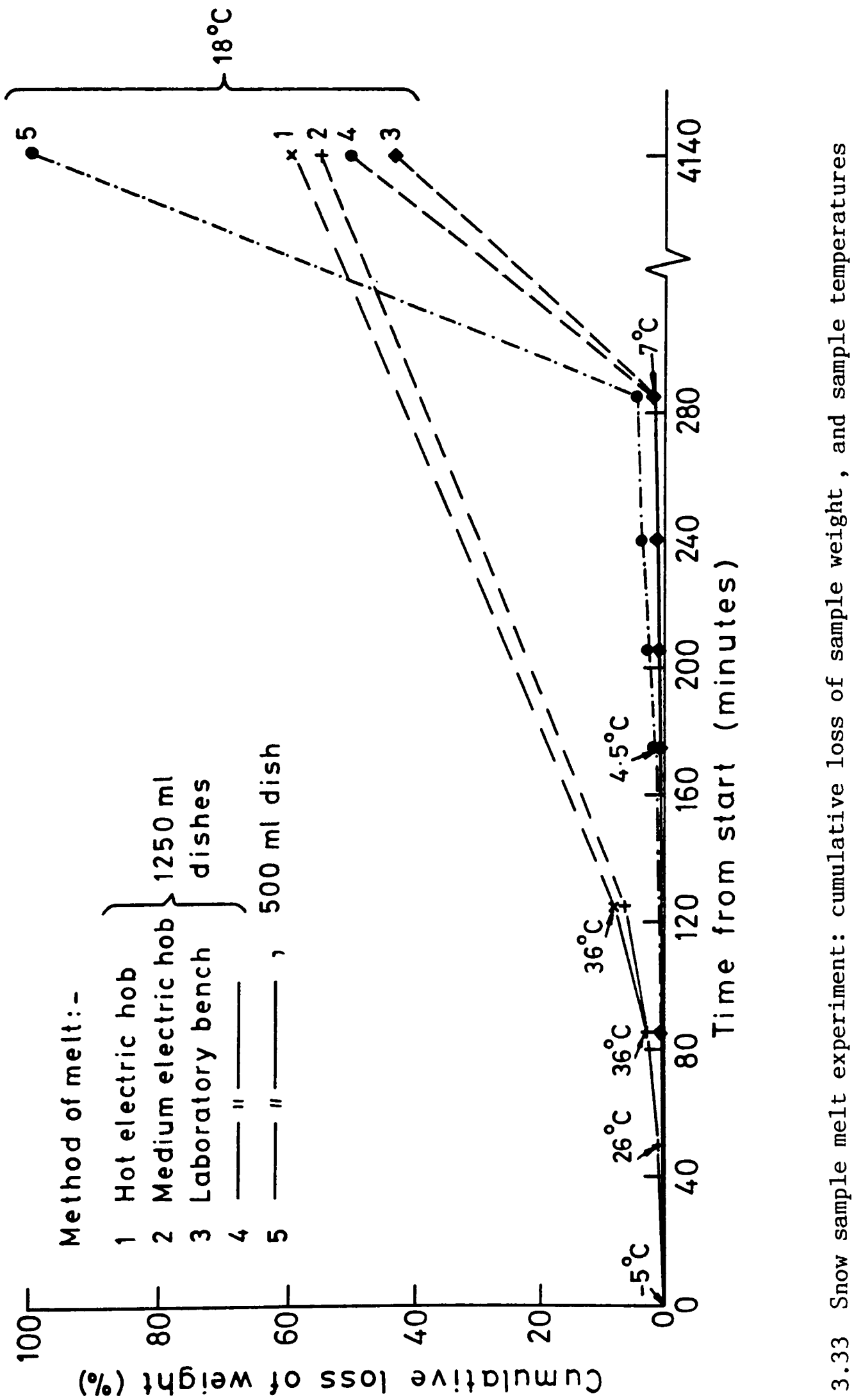


Fig. 3.33 Snow sample melt experiment: cumulative loss of sample weight, and sample temperatures

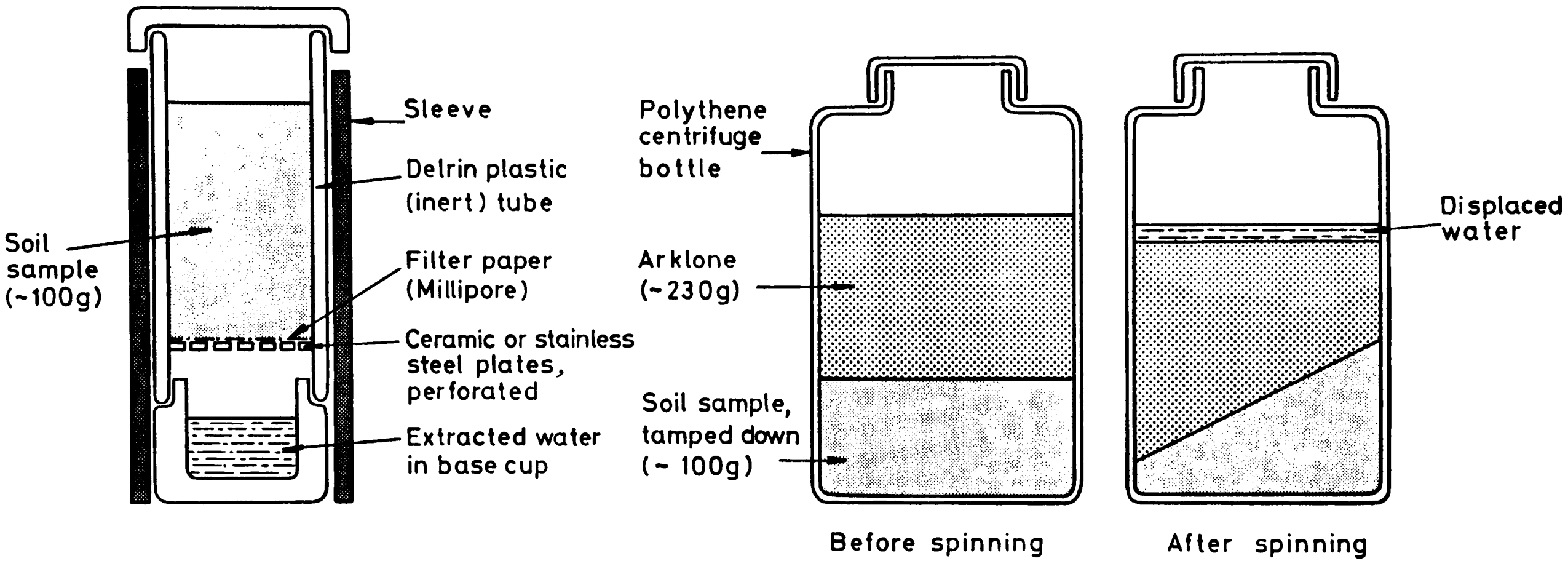


Fig. 3.34 Centrifuge extraction of soil moisture; (a) by drainage, (b) by displacement

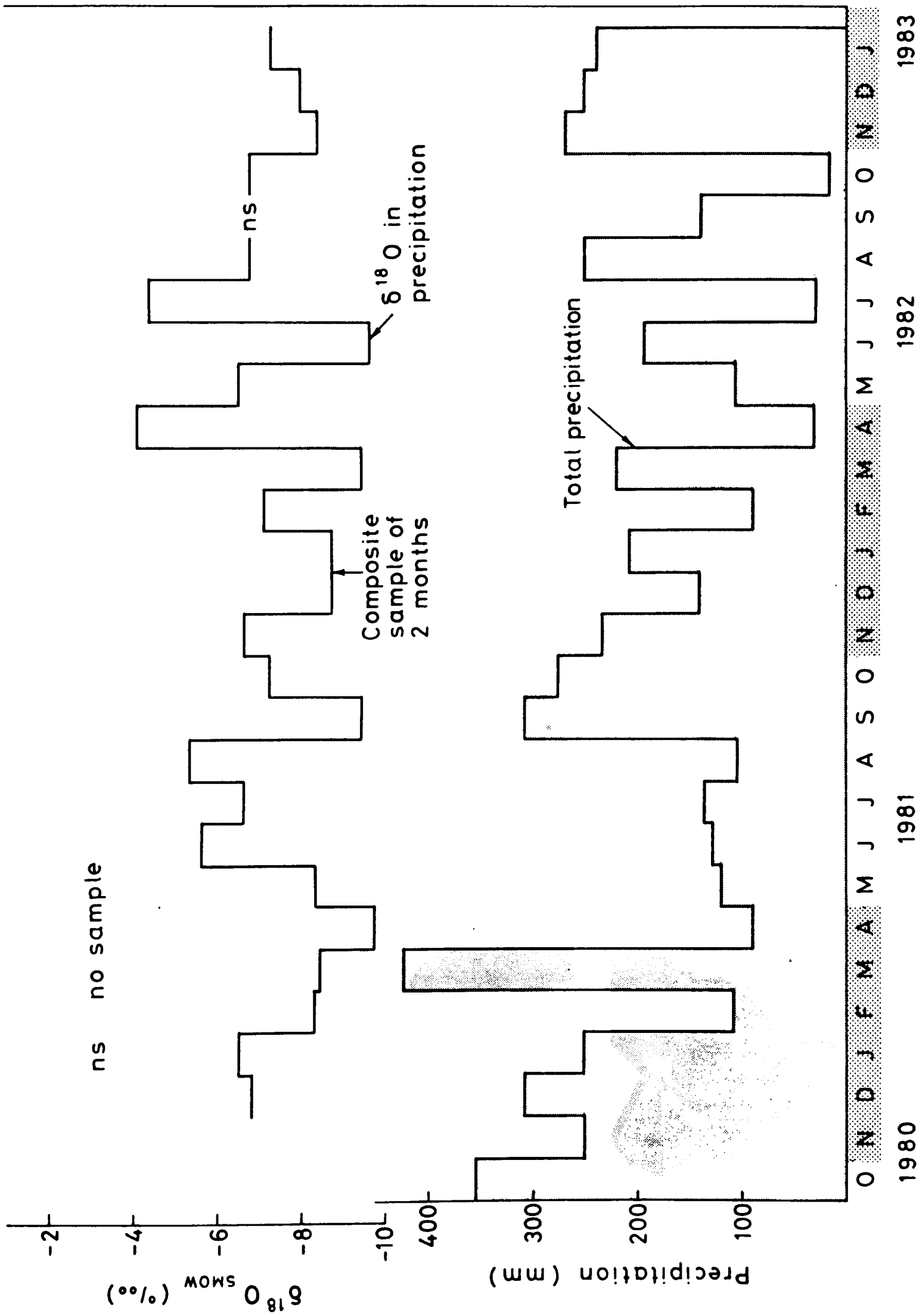


Fig. 4.1 Fountains Fell monthly $\delta^{18}O$ in precipitation and total precipitation amounts, October 1980– January 1983

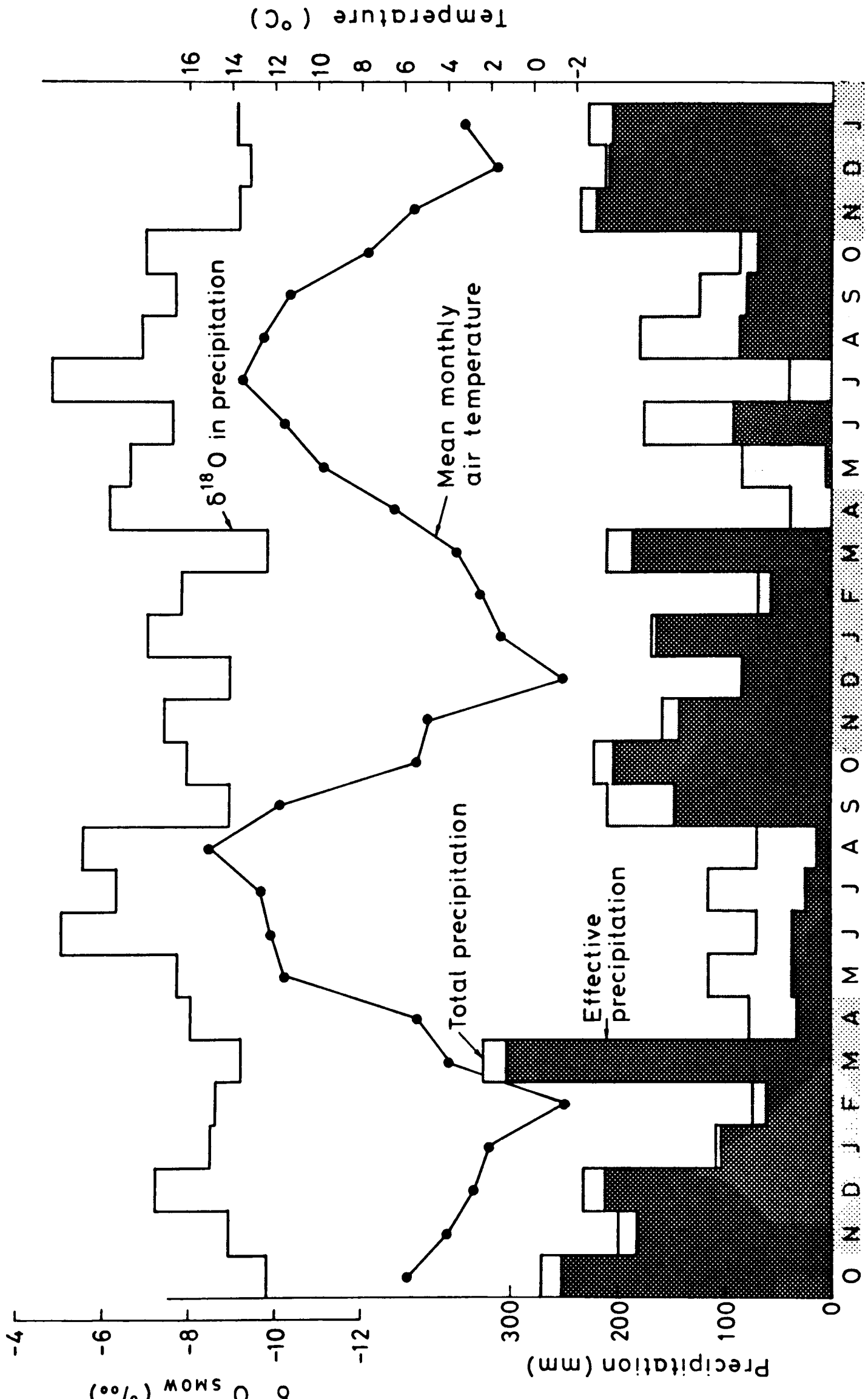


Fig. 4.2 Malham Tarn Field Centre monthly $\delta^{18}O$ in precipitation, total and effective precipitation amounts, and mean monthly temperature, October 1980– January 1983

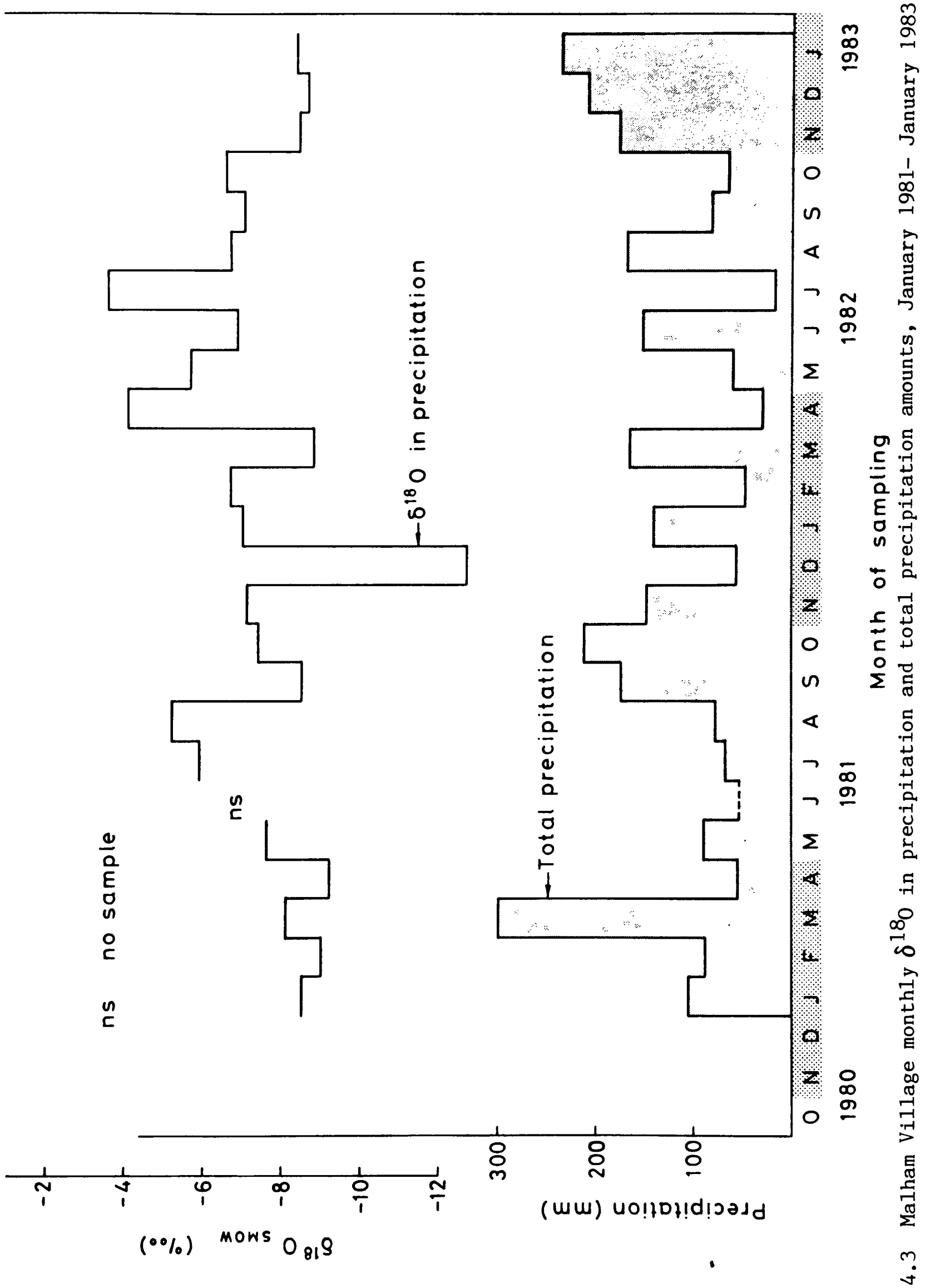


Fig. 4.3 Malham Village monthly $\delta^{18}O$ in precipitation and total precipitation amounts, January 1981- January 1983

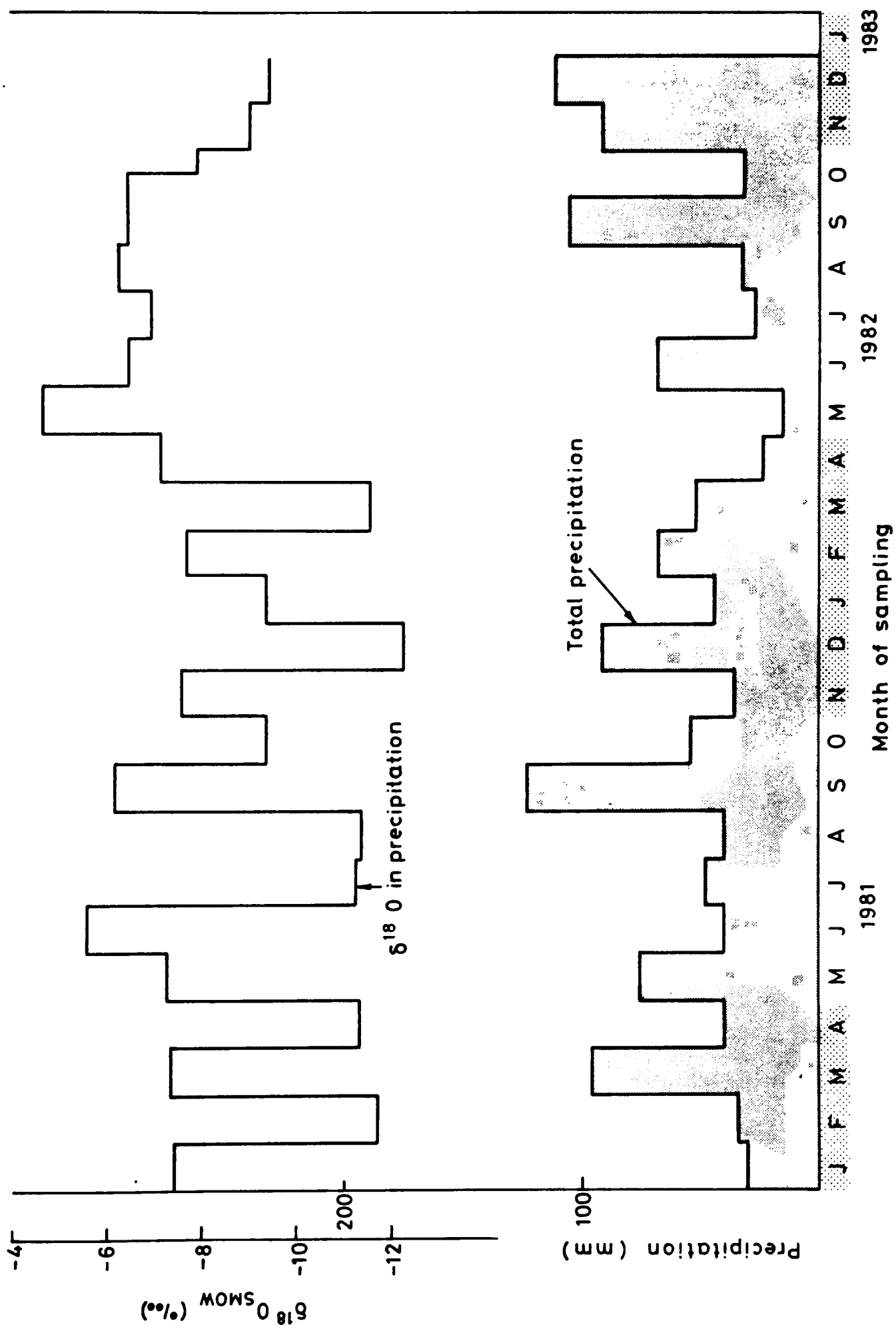


Fig. 4.4 Lechlade monthly $\delta^{18}O$ in precipitation and total precipitation amounts, January 1981- January 1983

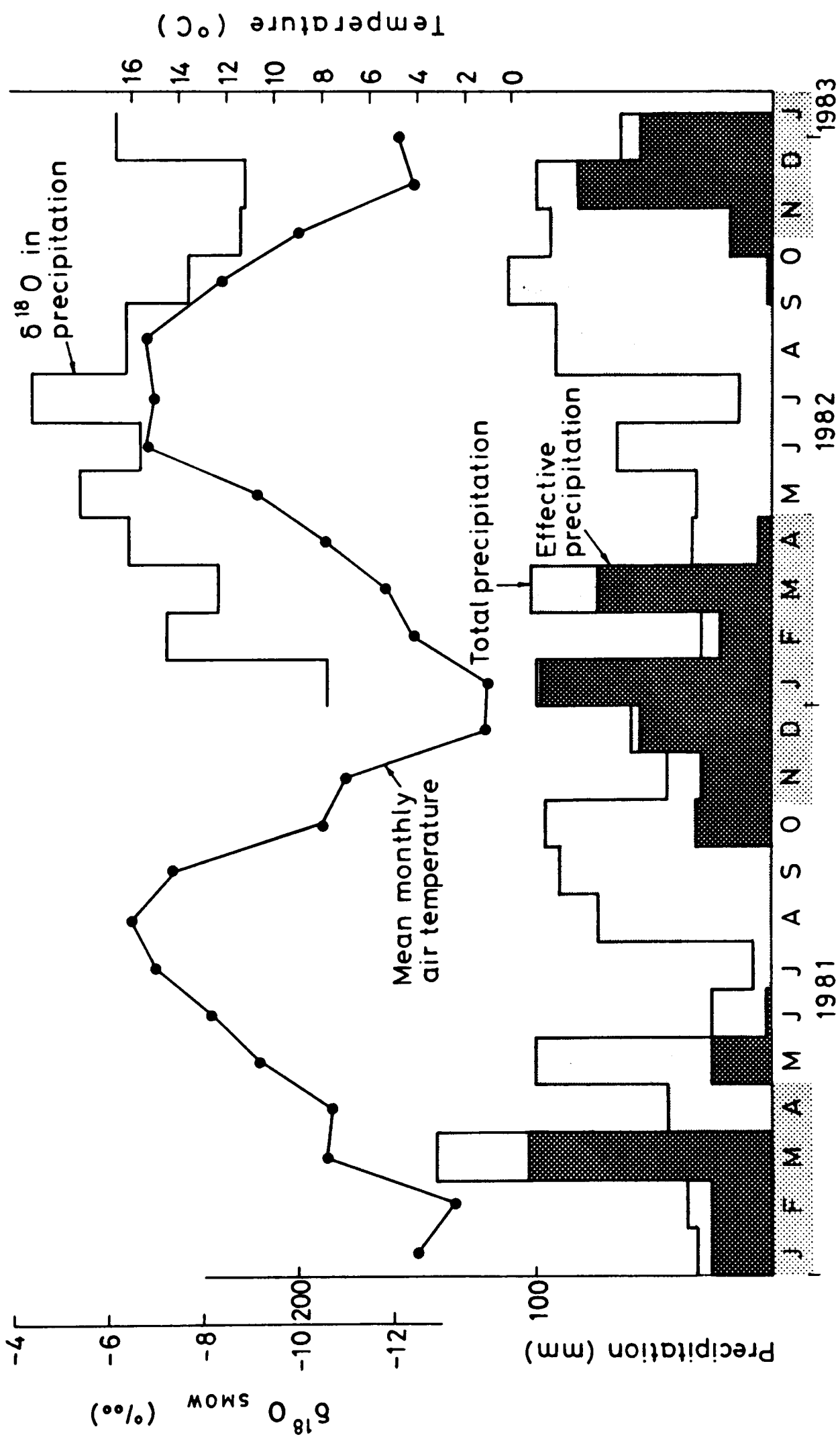


Fig. 4.5 Warren Down Farm monthly $\delta^{18}O$ in precipitation, total and effective precipitation amounts, and mean monthly temperature, January 1981- January 1983

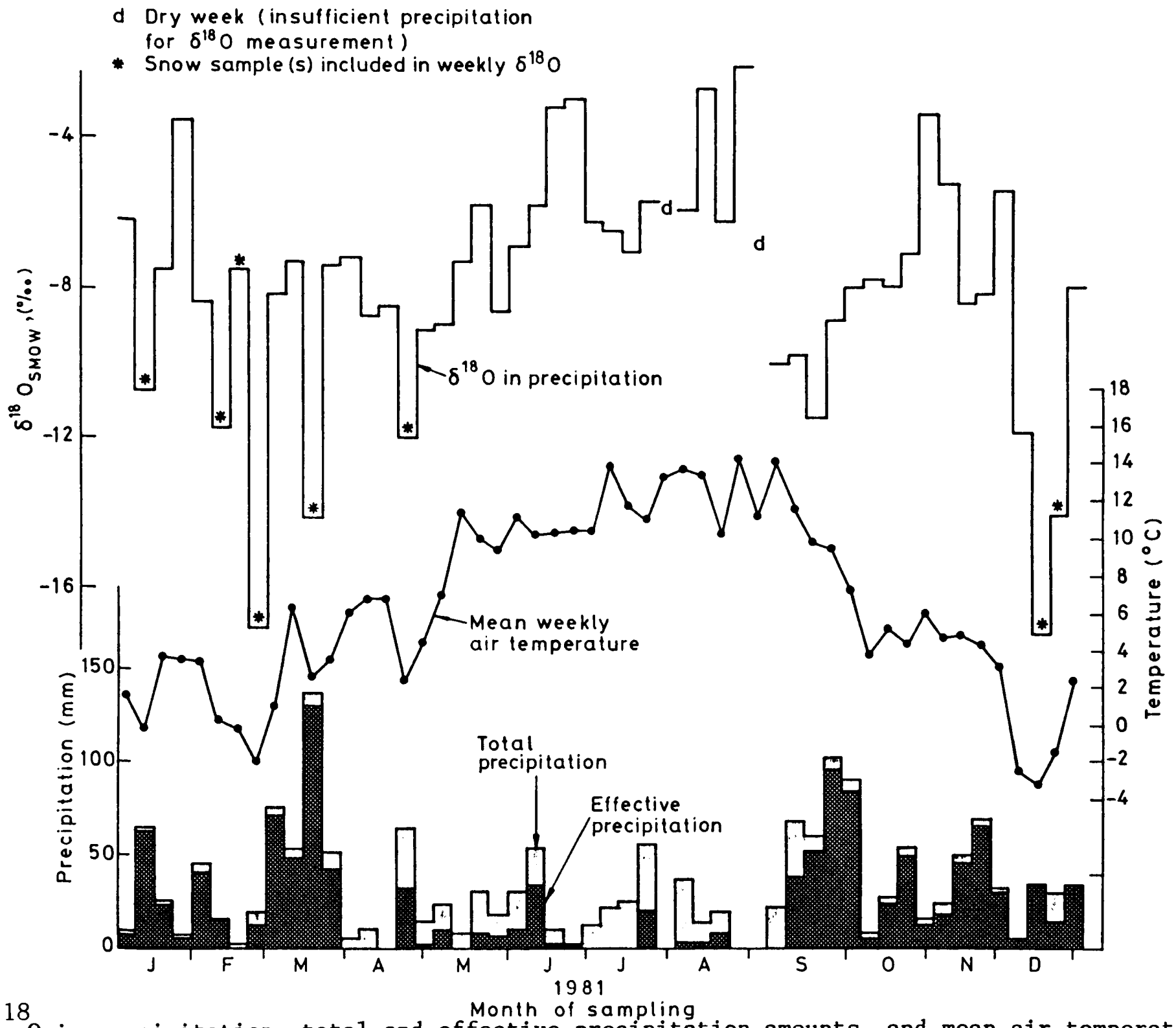


Fig. 4.6 Weekly $\delta^{18}O$ in precipitation, total and effective precipitation amounts, and mean air temperature, at Malham Tarn Field Centre; 1981

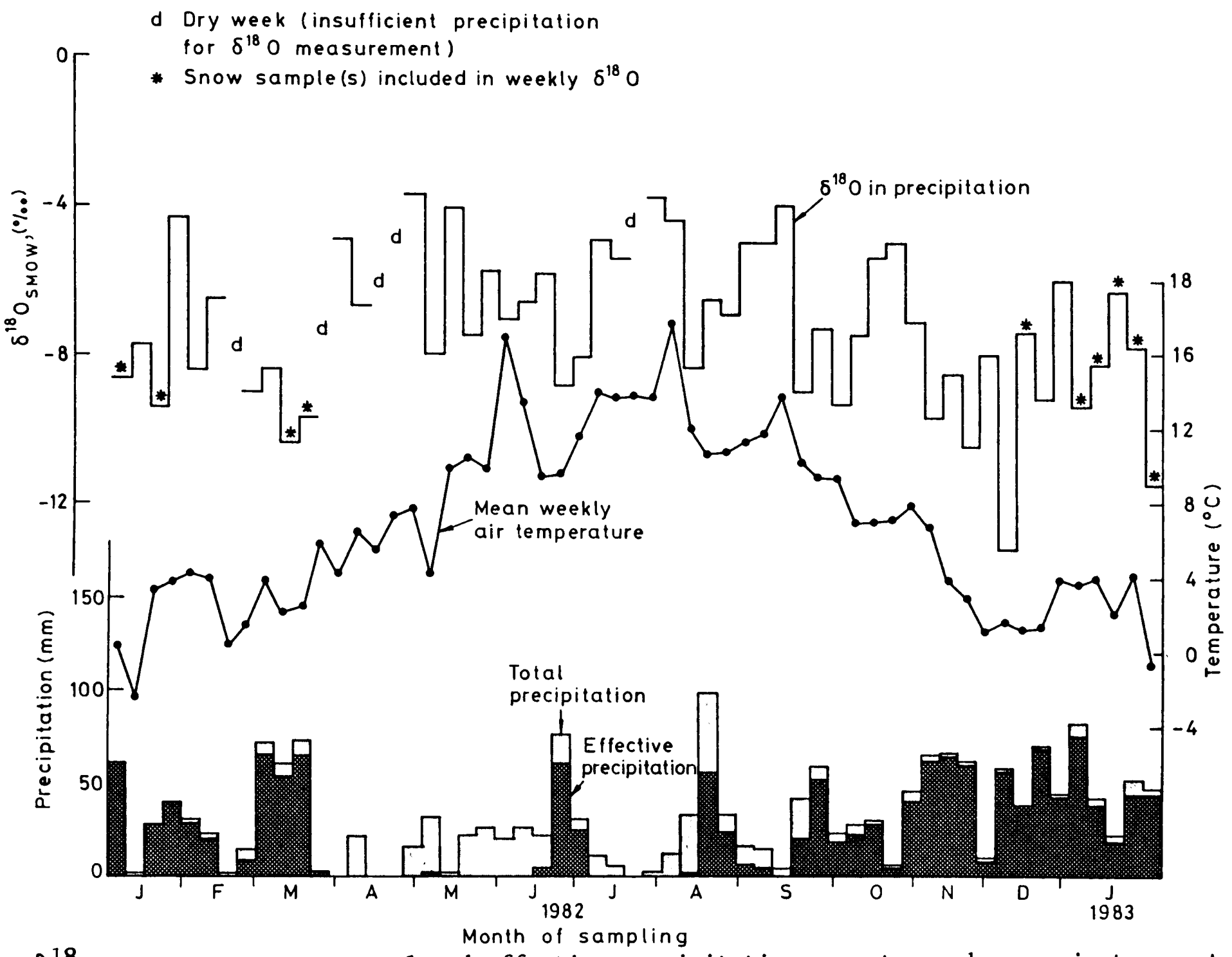


Fig. 4.7 Weekly $\delta^{18}O$ in precipitation, total and effective precipitation amounts, and mean air temperature, at Malham Tarn Field Centre; 1982

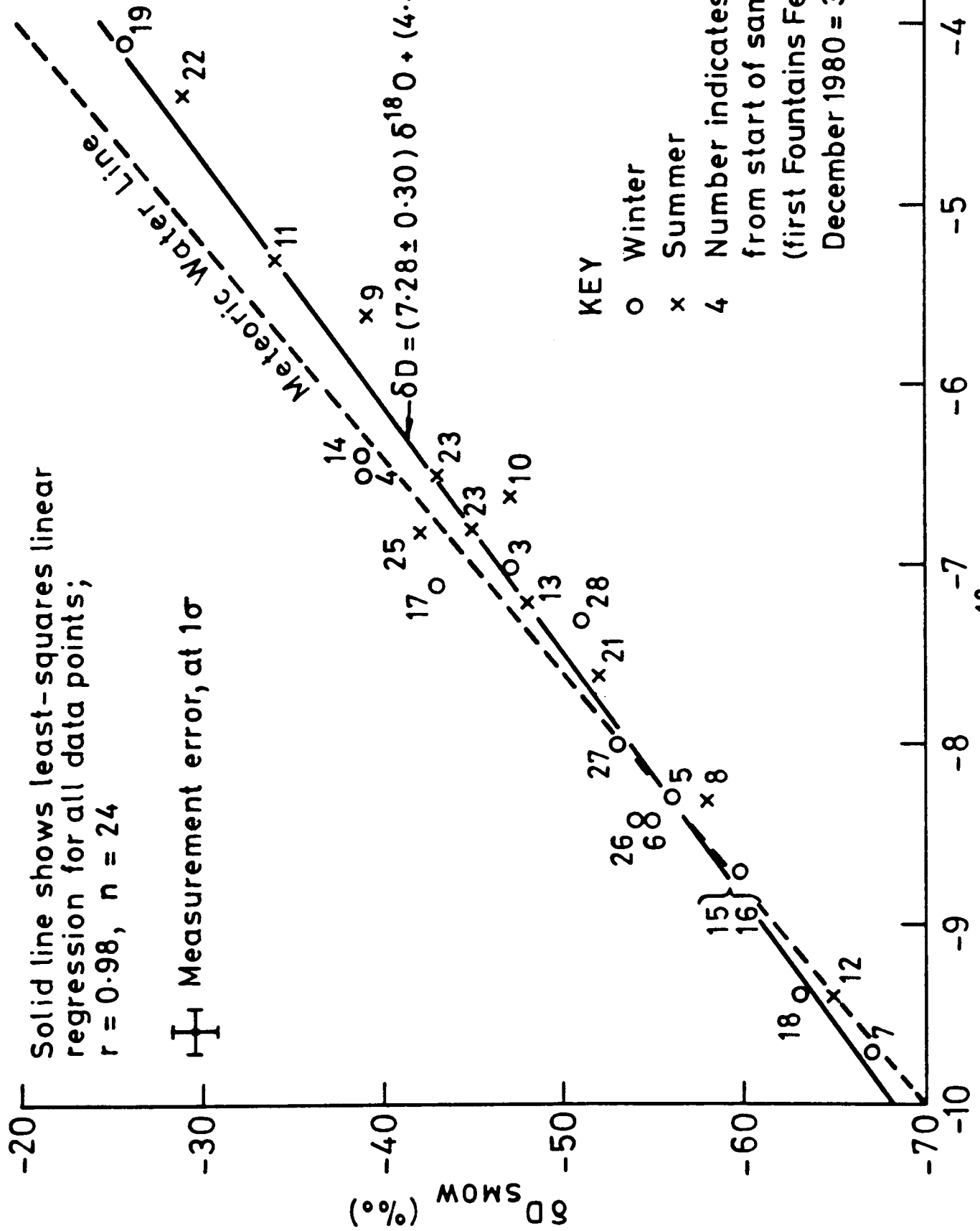


Fig. 4.8 $\delta^{18}O$–δD plot for monthly precipitation collections at Fountains Fell, Malham area

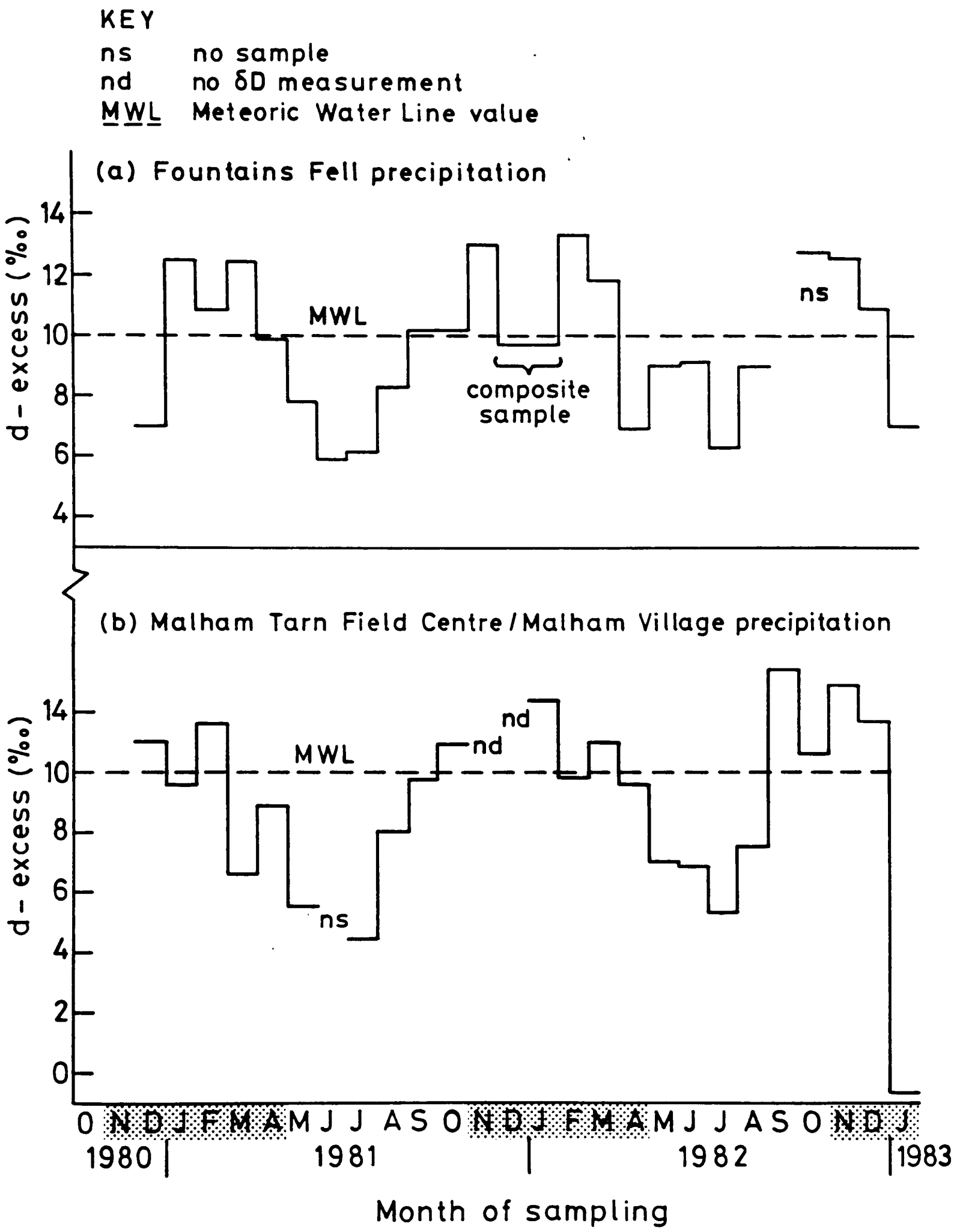


Fig. 4.9 d-excess values in monthly precipitation at (a) Fountains Fell and (b) Malham Tarn Field Centre/Malham Village

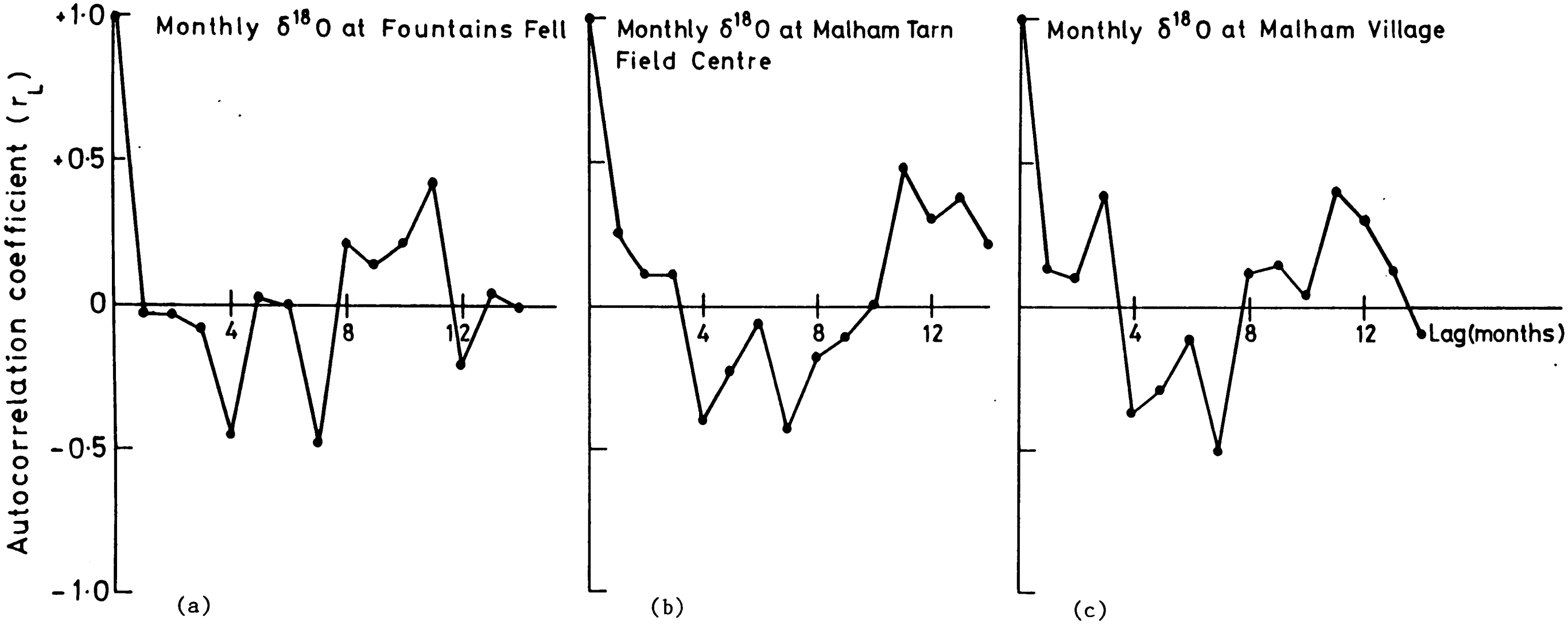


Fig. 4.10 Correlograms of monthly $\delta^{18}O$ in precipitation at (a) Fountains Fell, (b) Malham Tarn Field Centre and (c) Malham Village

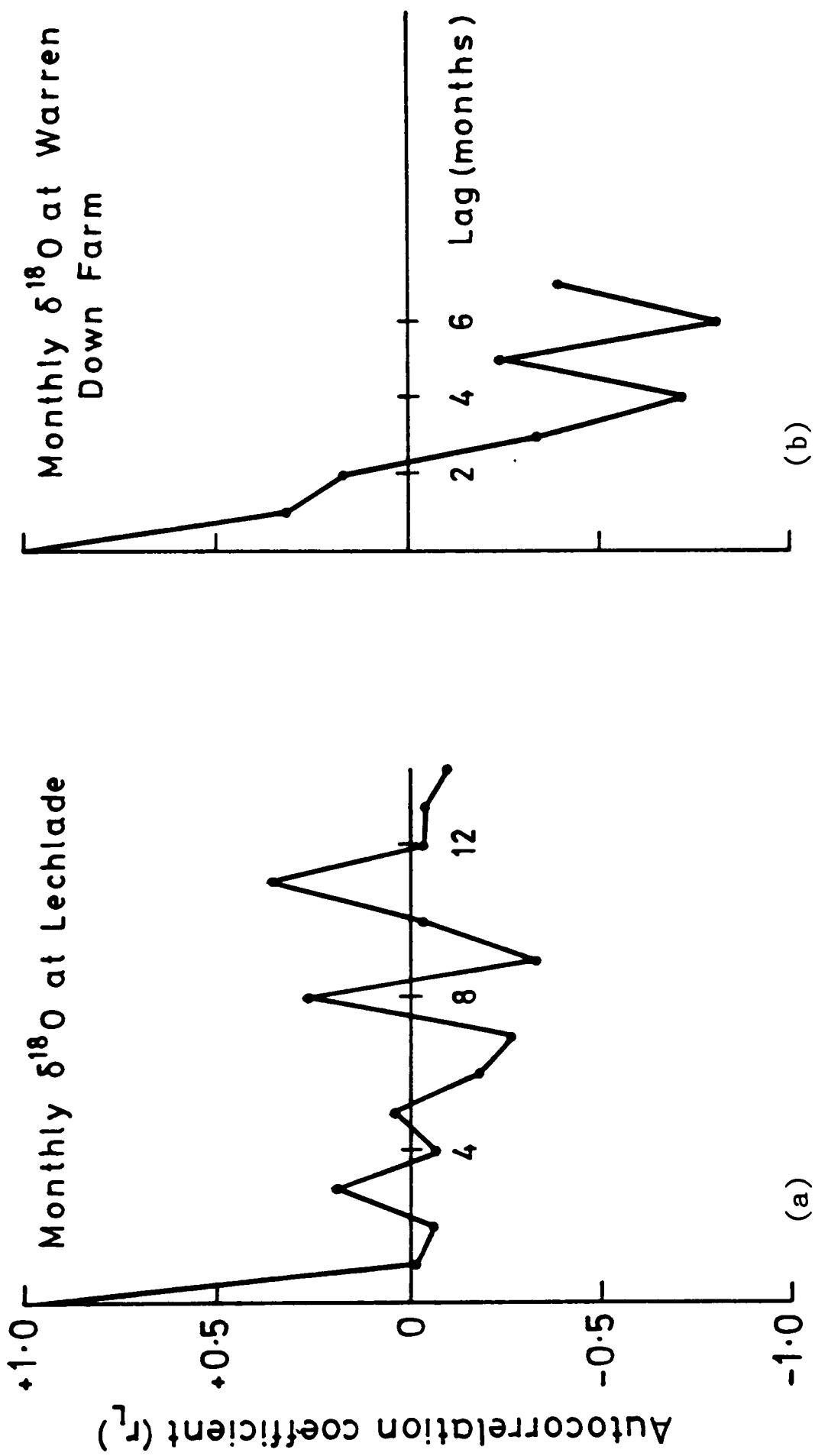


Fig. 4.11 Correlograms of monthly $\delta^{18}O$ in precipitation at (a) Lechlade and (b) Warren Down Farm

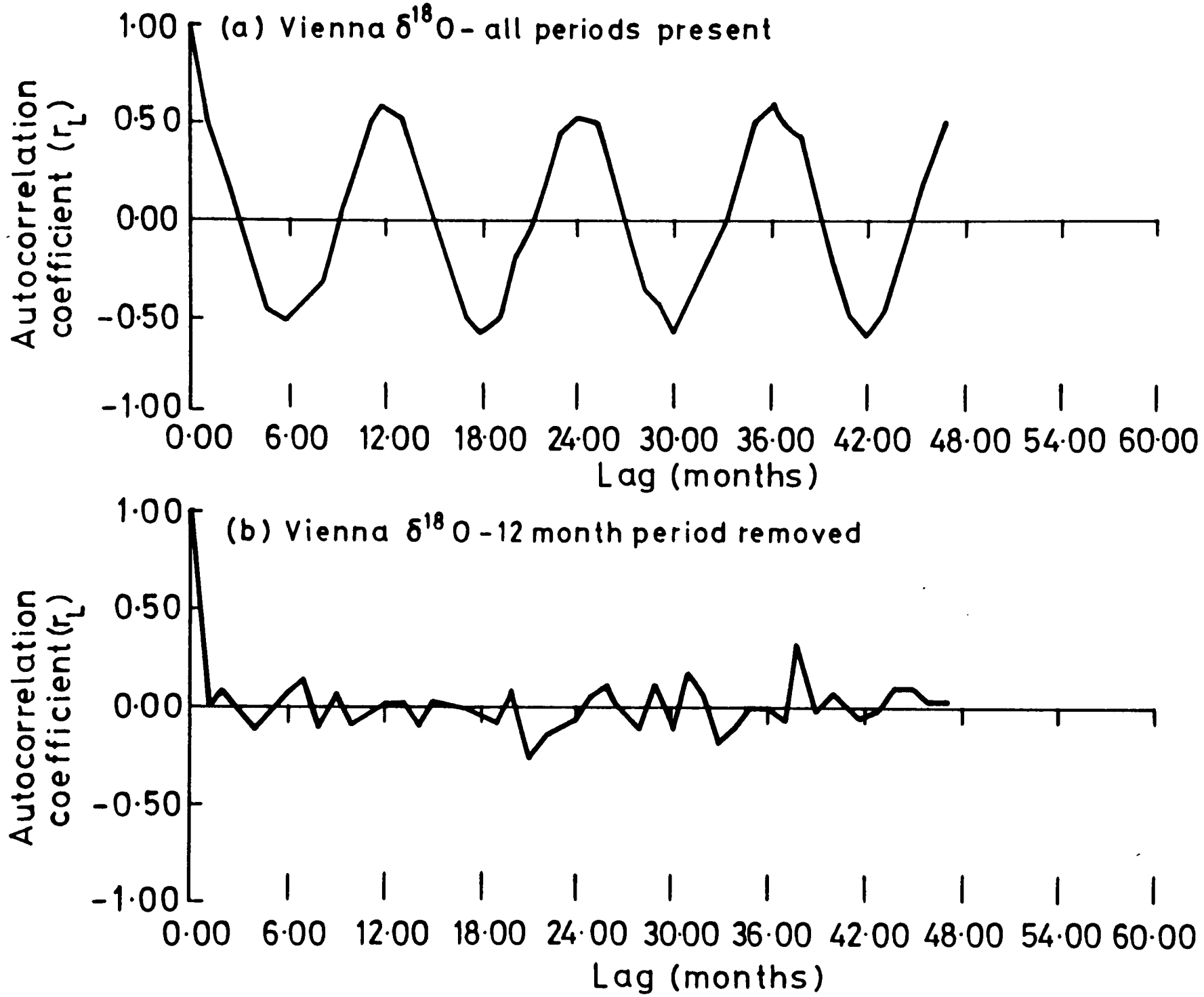


Fig. 4.12 Correlograms of monthly $\delta^{18}O$ in precipitation at Vienna; (a) original data, (b) 12-month periodic component removed (Source: YURTSEVER & GAT, 1981)

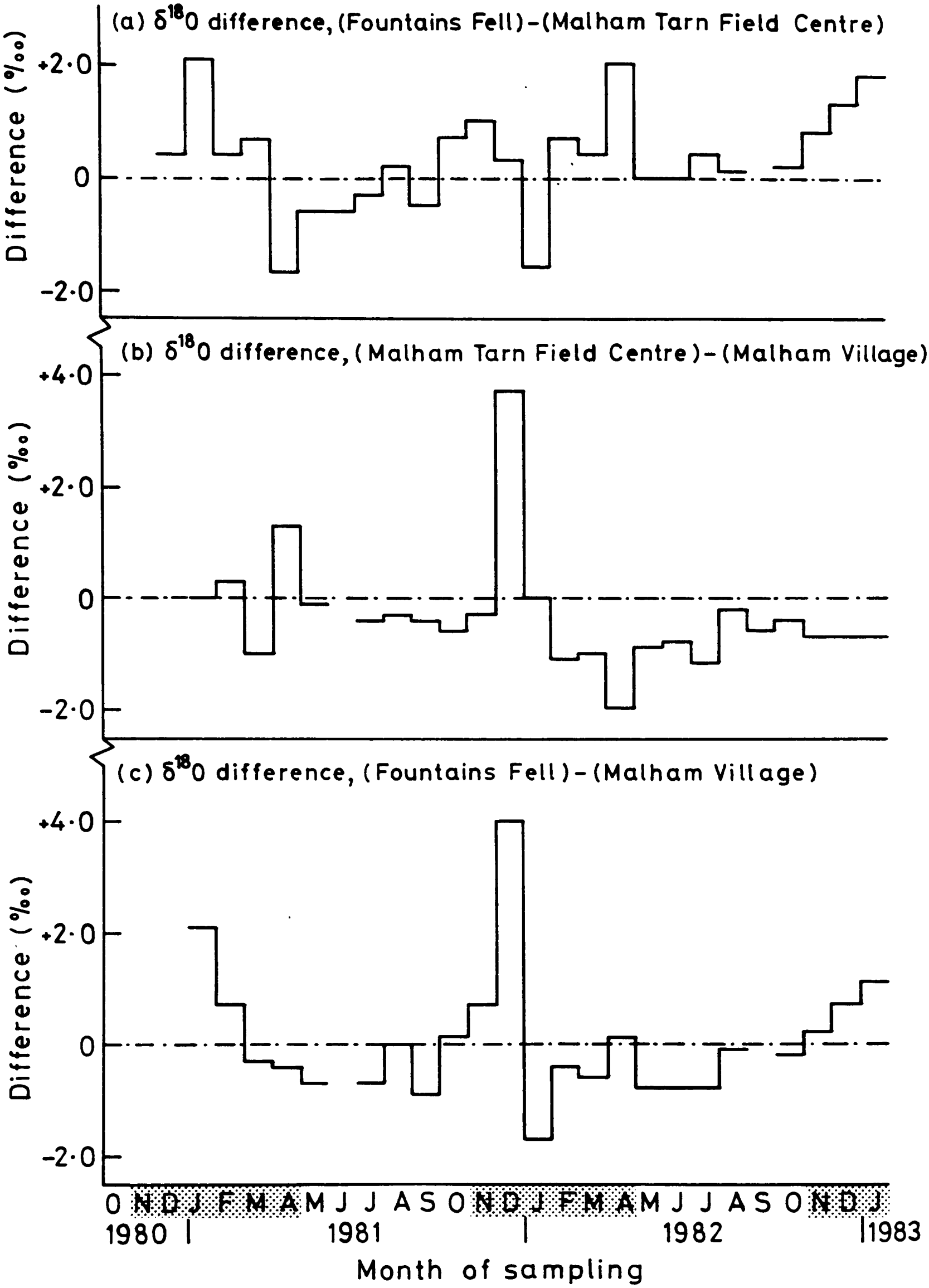


Fig. 4.13 $\delta^{18}O$ differences in monthly precipitation collected at 3 altitudes in the Malham area: Fountains Fell (657 m), Malham Tarn Field Centre (395 m), Malham Village (185 m)

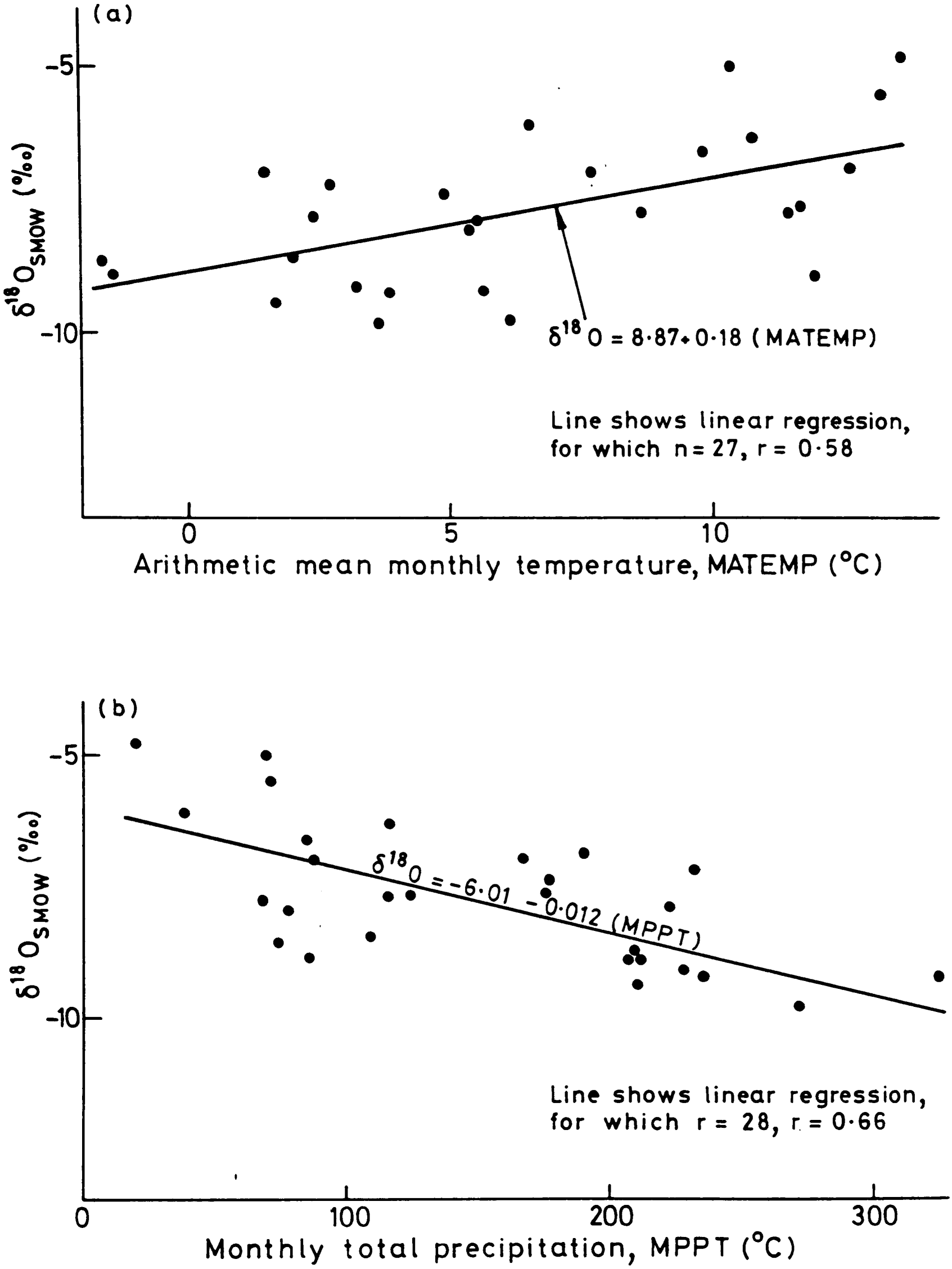


Fig. 4.14 Monthly $\delta^{18}O$ in precipitation at Malham Tarn Field Centre plotted against meteorological parameters; (a) mean monthly temperature, (b) monthly total precipitation

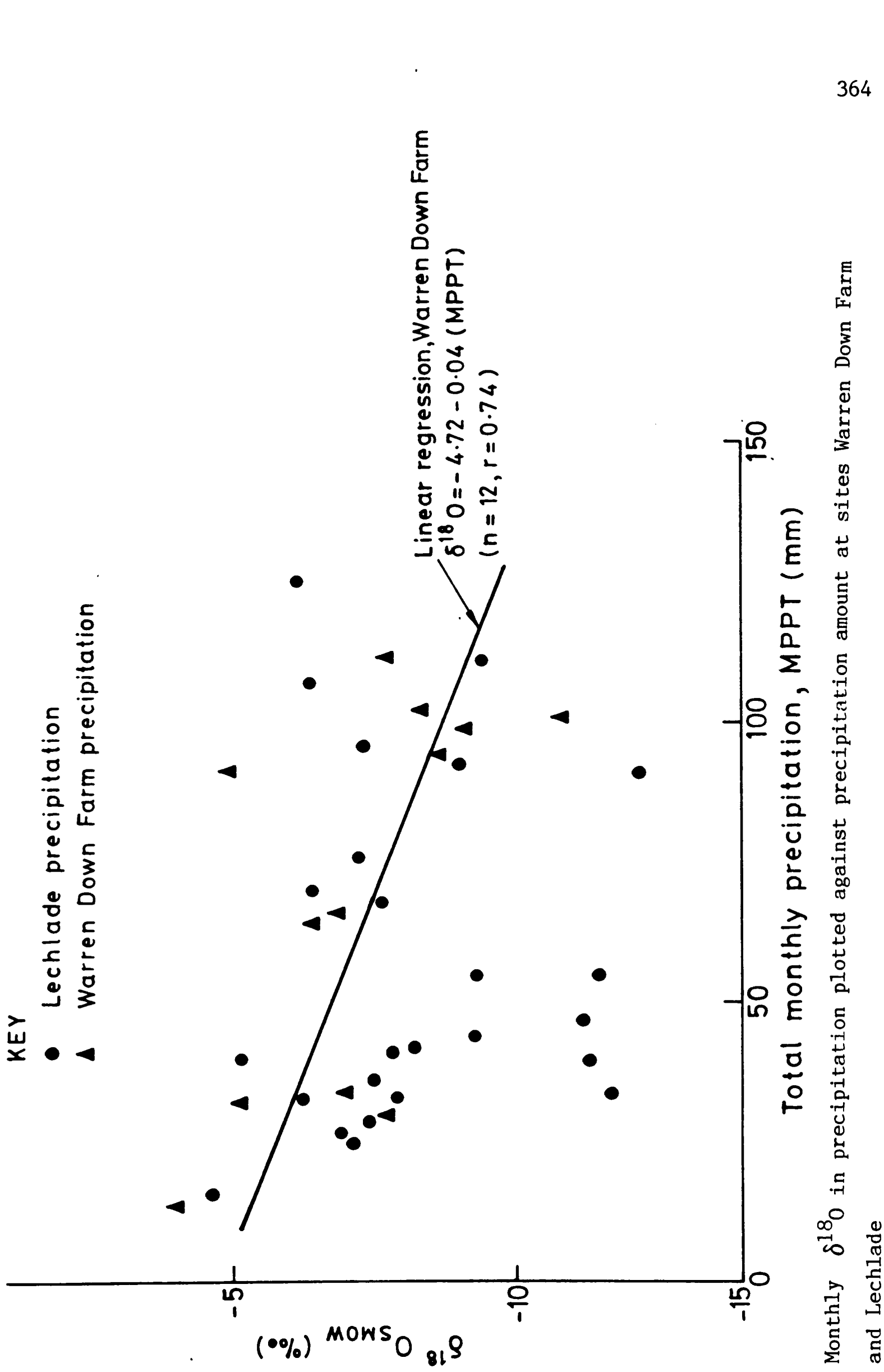


Fig. 4.15 Monthly $\delta^{18}O$ in precipitation plotted against precipitation amount at sites Warren Down Farm and Lechlade

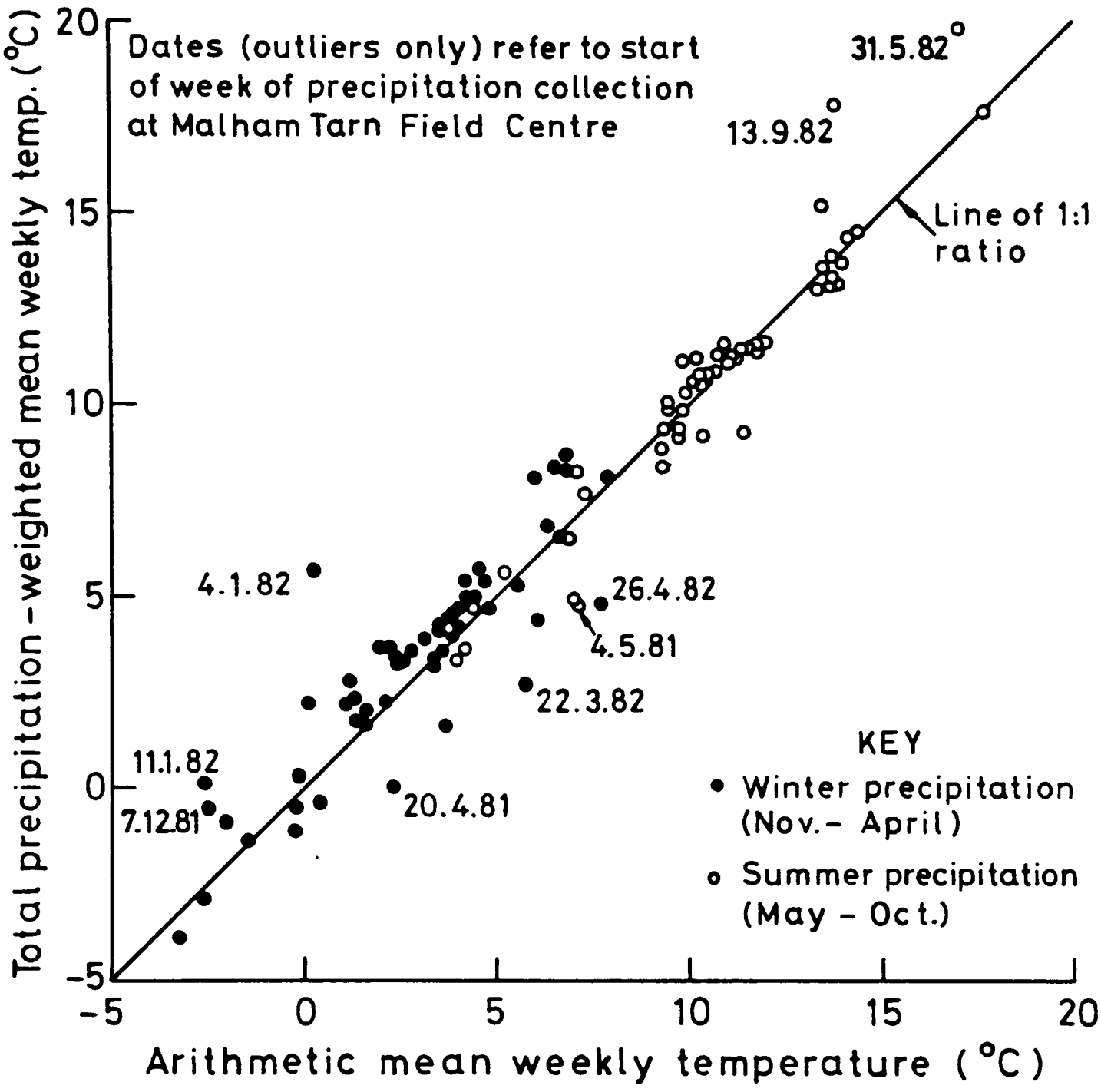


Fig. 4.16 Comparison of precipitation-weighted temperatures and arithmetic mean temperatures, for weekly data from Malham Tarn Field Centre

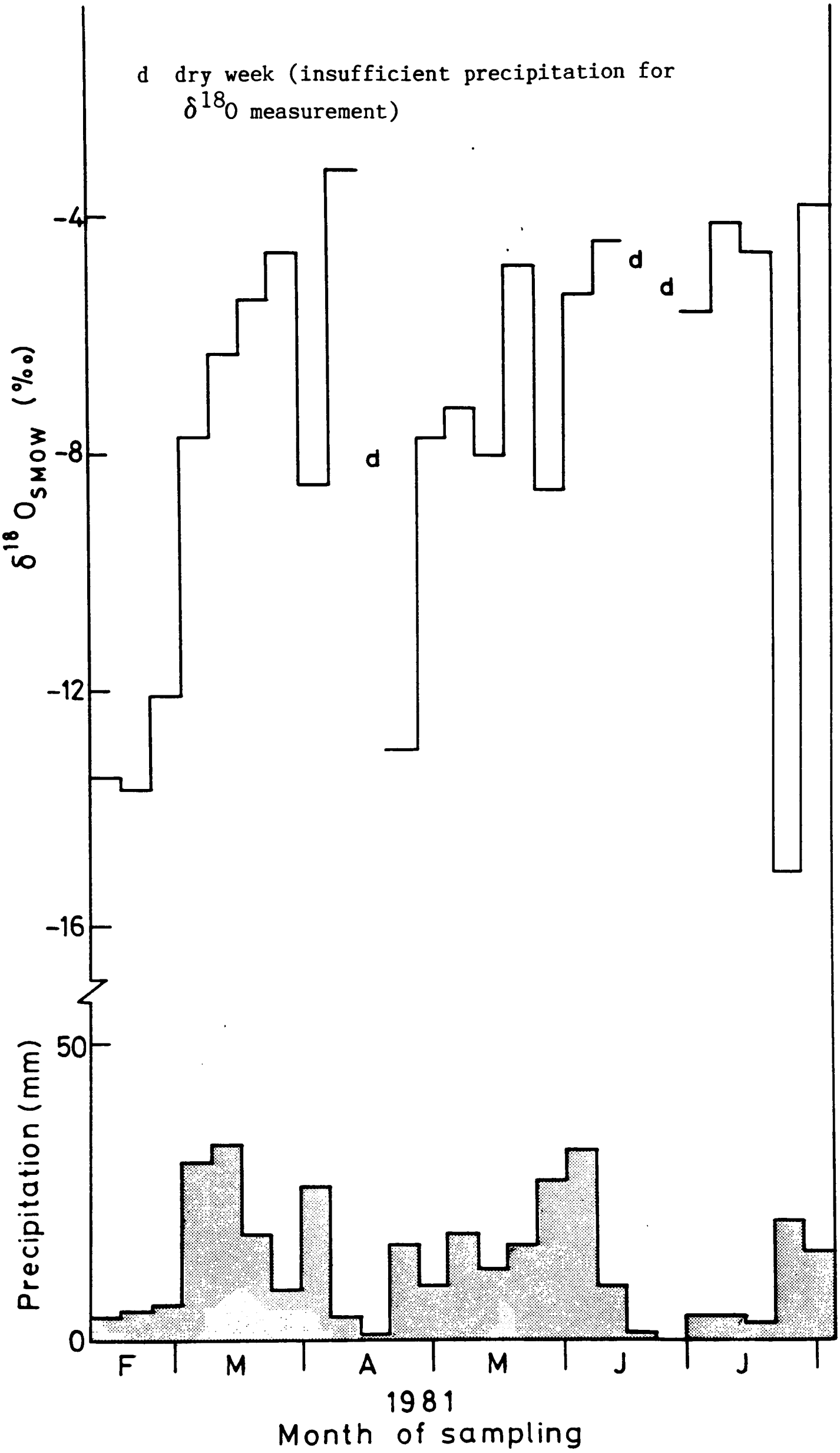


Fig. 4.17 Weekly $\delta^{18}O$ in precipitation and total precipitation amounts at Lechlade, February 1981- July 1981

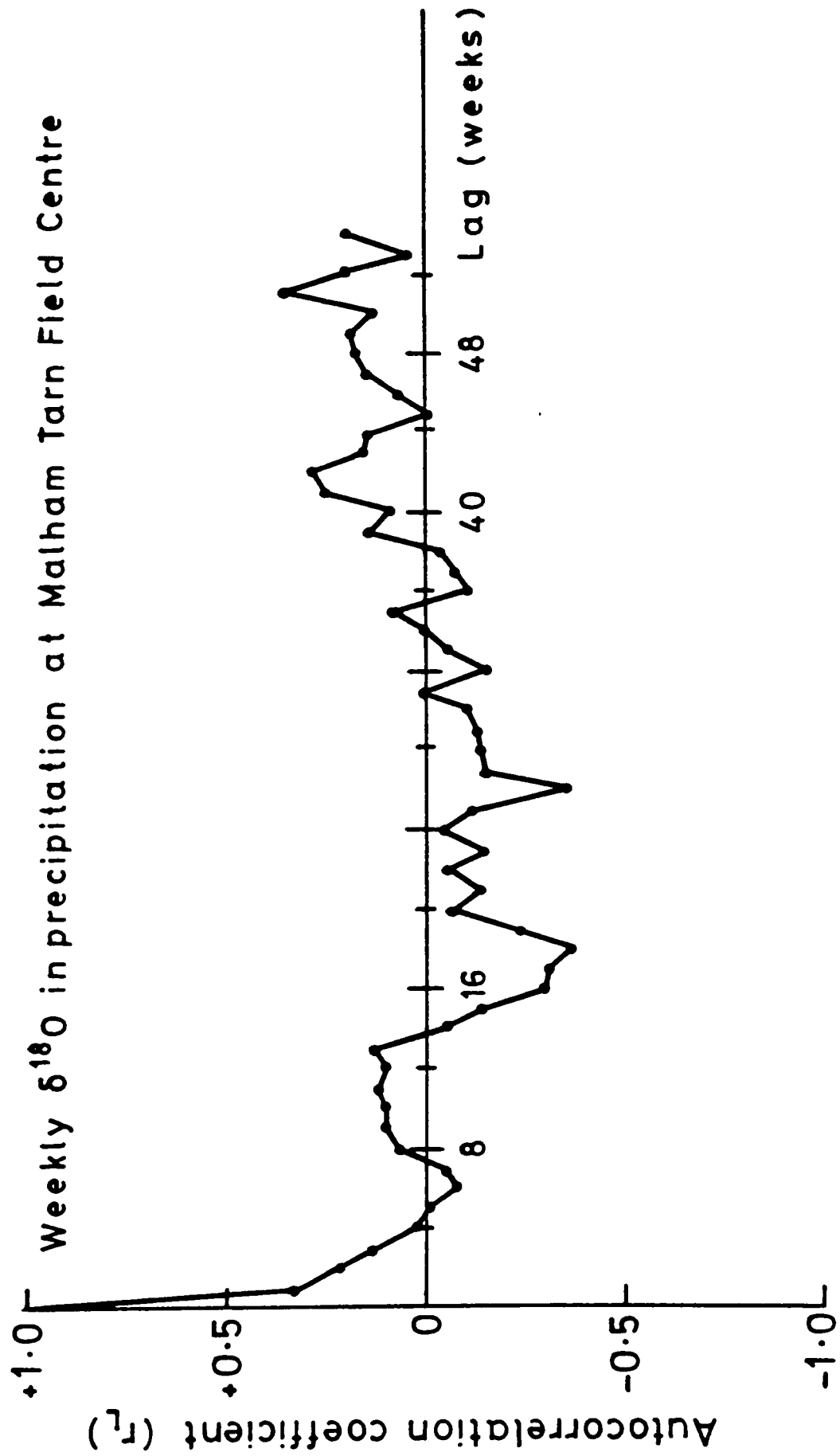


Fig. 4.18 Correlogram of weekly $\delta^{18}O$ in precipitation at Malham Tarn Field Centre

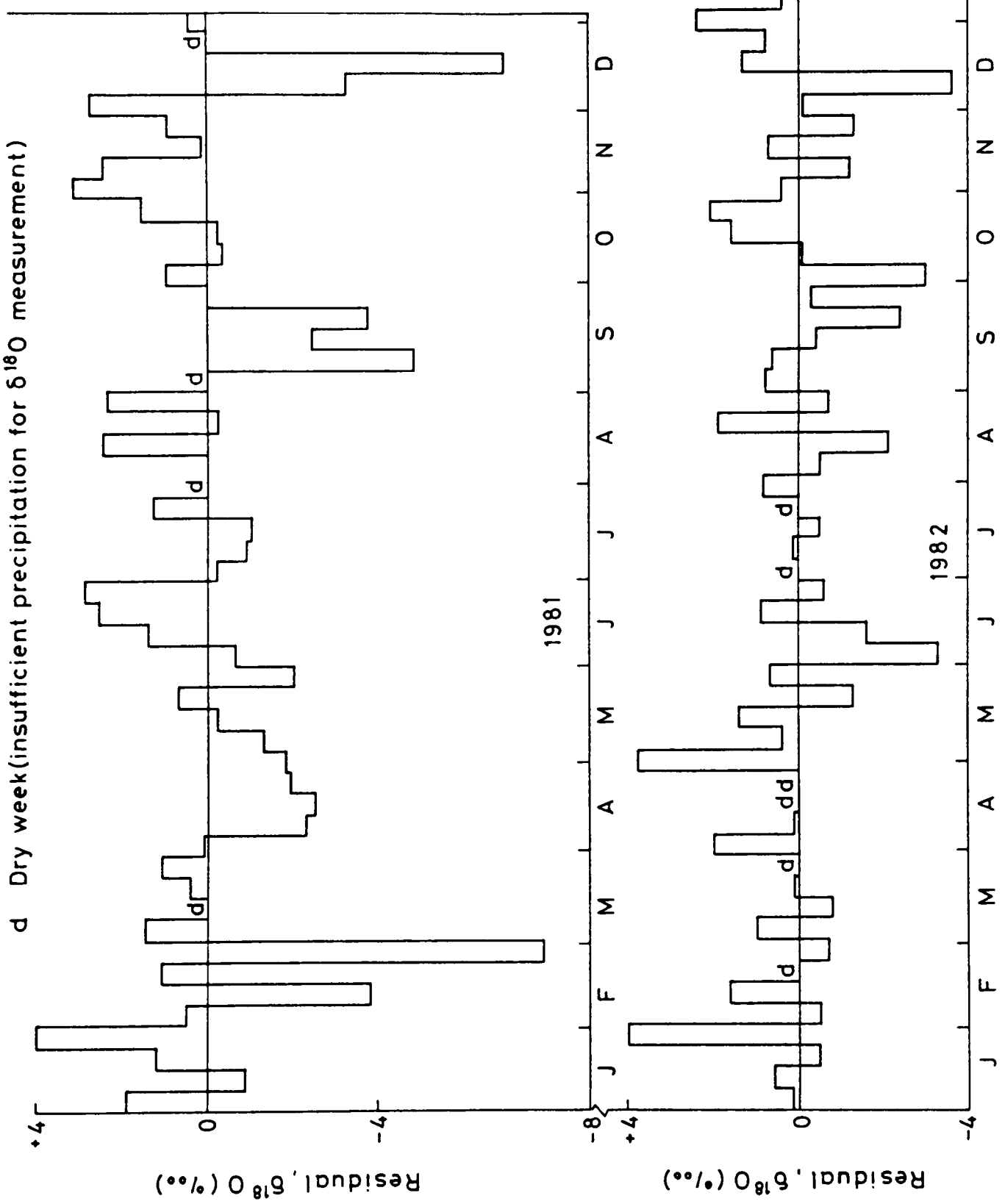


Fig. 4.19 Residual $\delta^{18}O$ values after linear regression of weekly $\delta^{18}O$ in precipitation against temperature and precipitation amount; data from Malham Tarn Field Centre, January 1981- January 1983

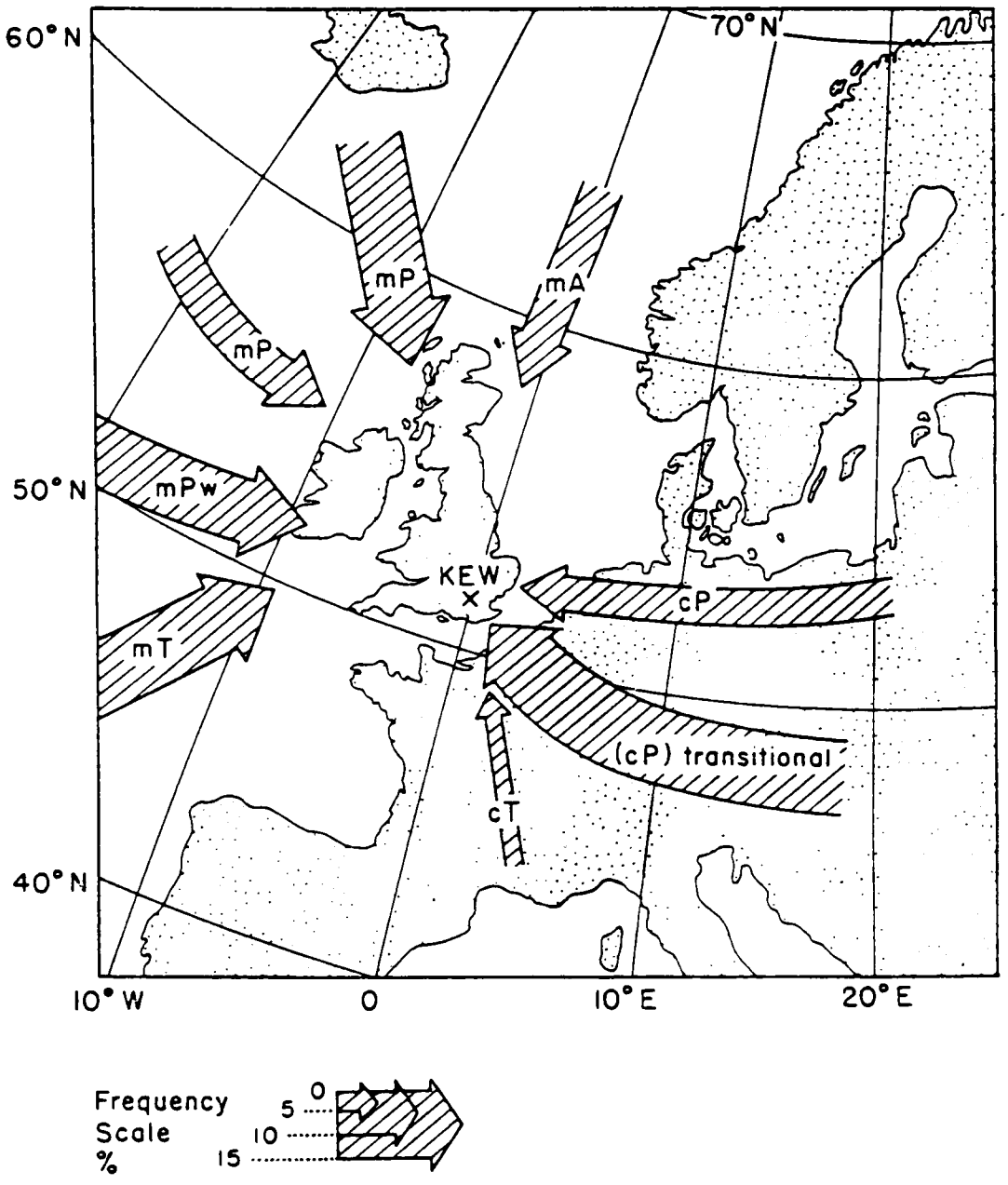


Fig. 4.20 Average air mass frequencies for Kew (London) in January (from BARRY & CHORLEY, 1976, p.234)

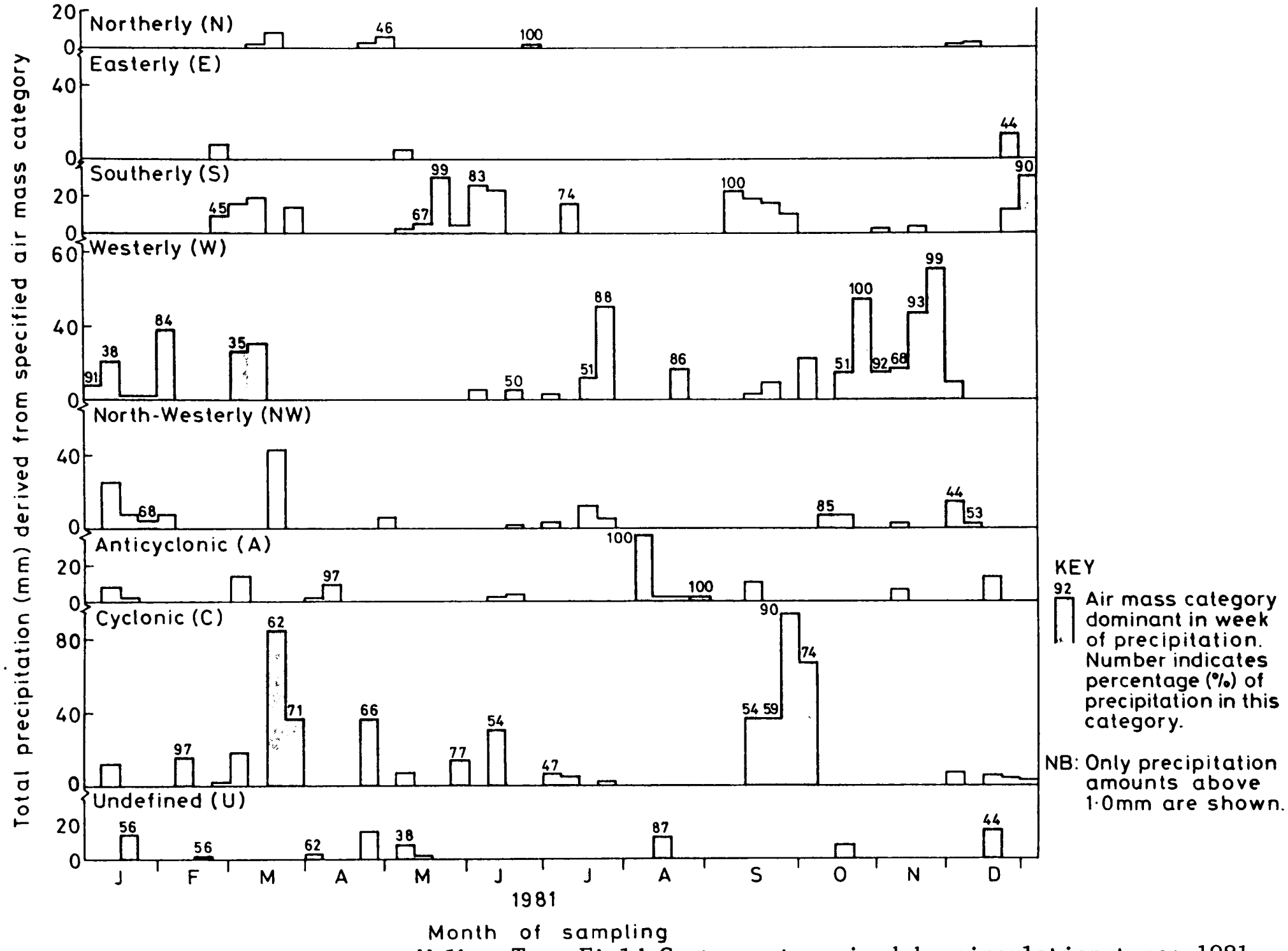


Fig. 4.21 Weekly precipitation amounts at Malham Tarn Field Centre categorised by circulation type; 1981

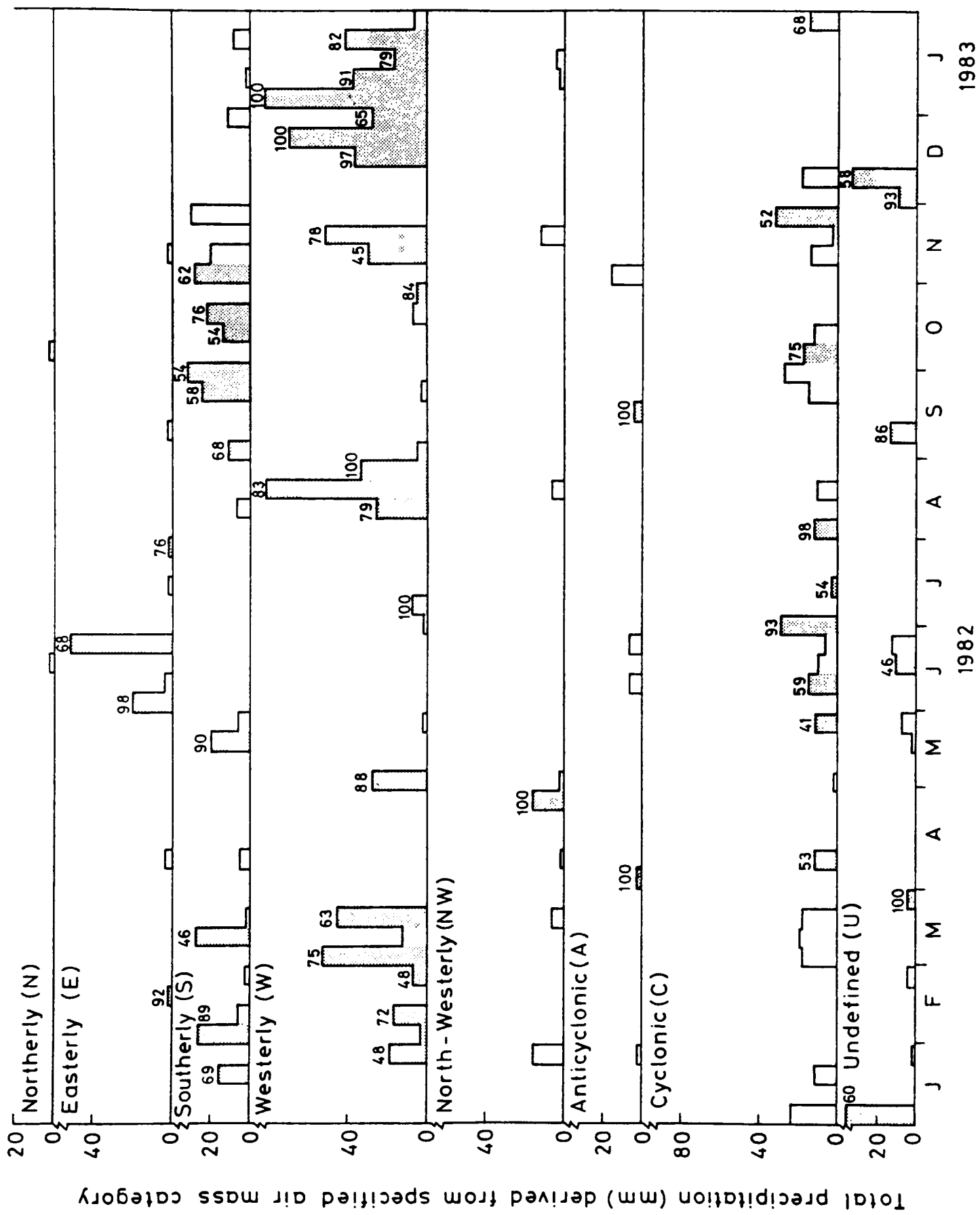


Fig. 4.22 Weekly precipitation amounts at Malham Tarn Field Centre categorised by circulation type; 1982 and January 1983 (For key see fig. 4.21)

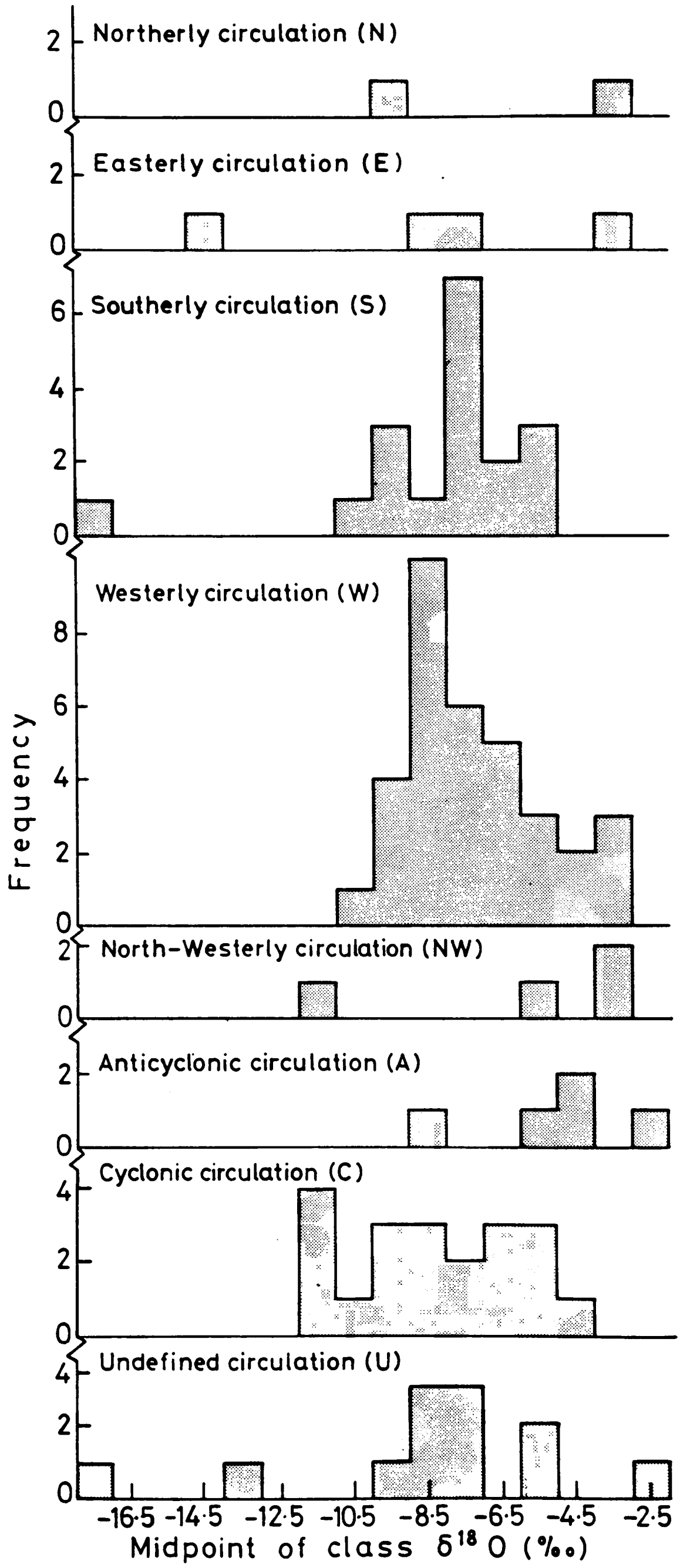


Fig. 4.23 Histograms of weekly $\delta^{18}O$ in precipitation, categorised by circulation type; data from Malham Tarn Field Centre

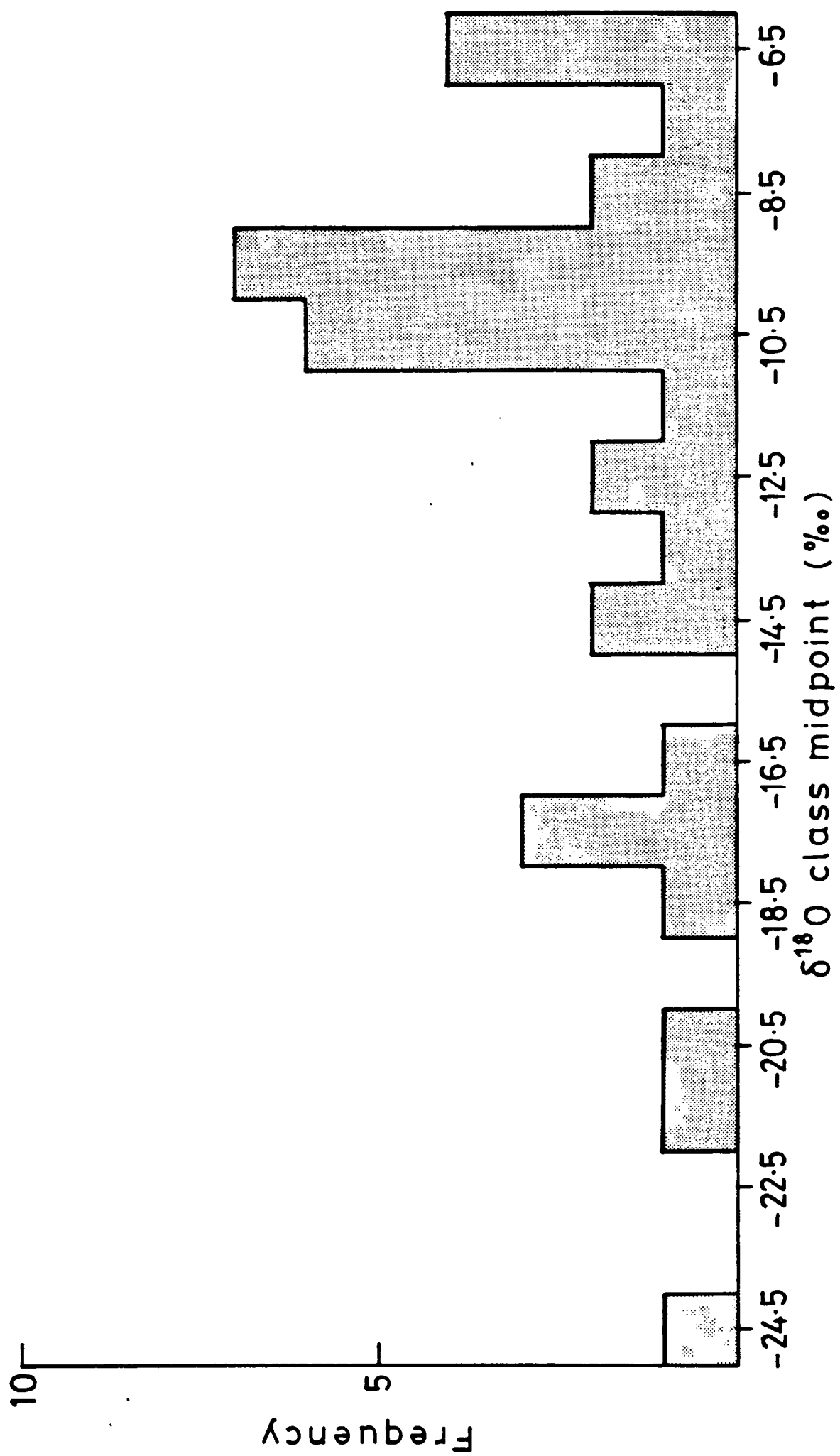


Fig. 4.24 Frequency histogram showing $\delta^{18}O$ values of all s

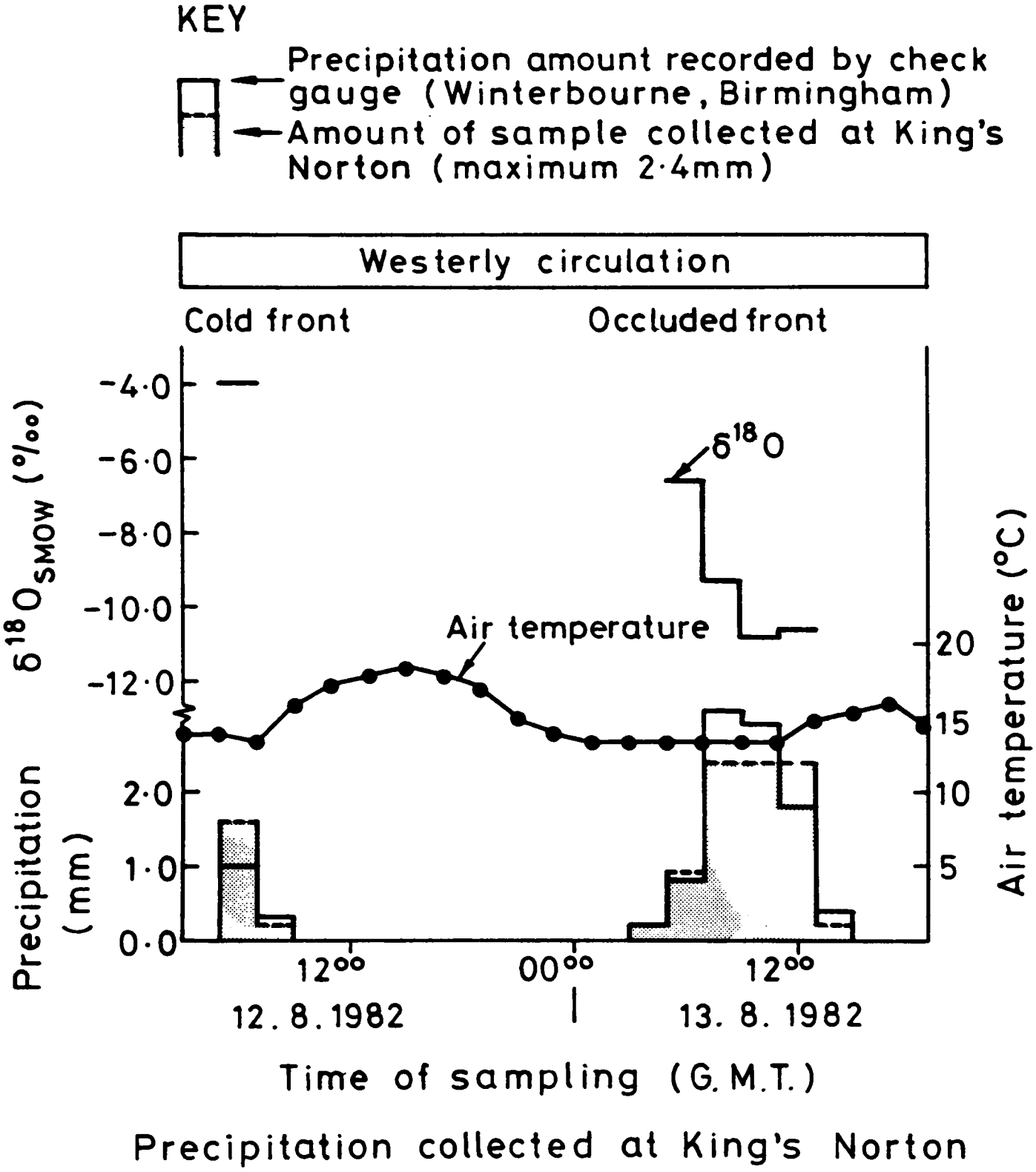


Fig. 4.25 Within-storm sampling of precipitation: King's Norton, 12.8 - 13.8.1982

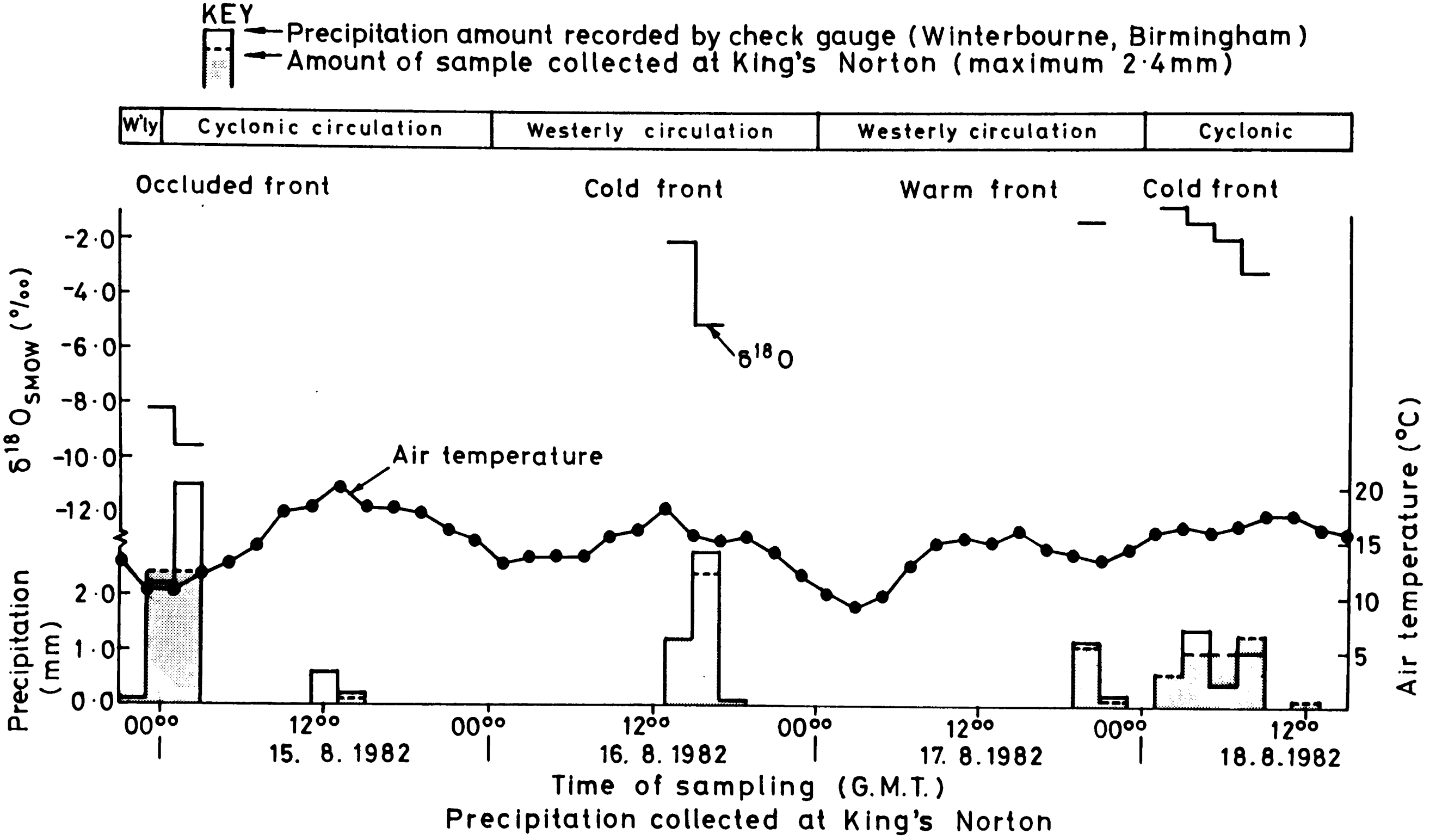


Fig. 4.26 Within-storm sampling of precipitation: King's Norton, 14.8 - 18.8. 1982

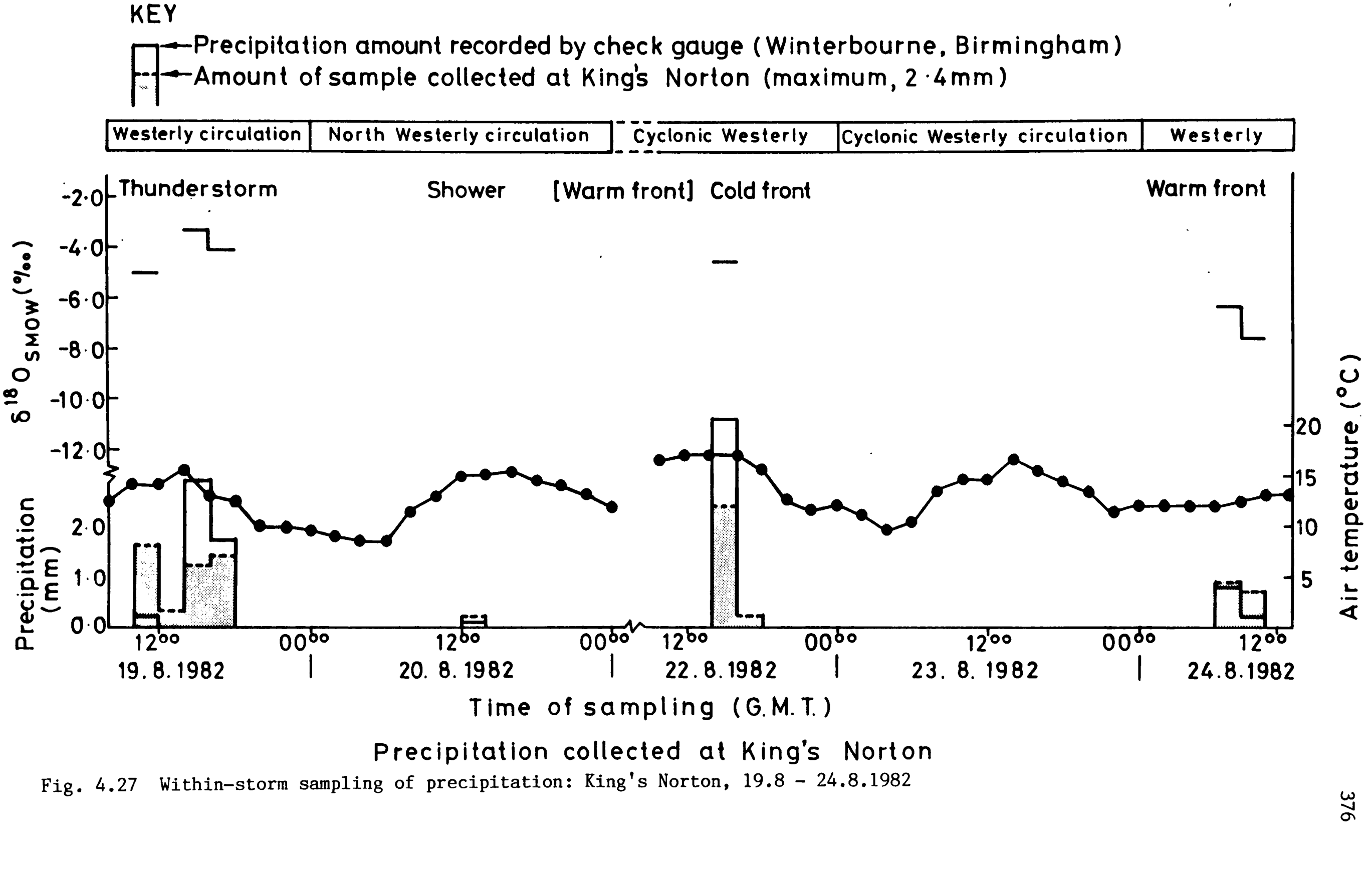


Fig. 4.27 Within-storm sampling of precipitation: King's Norton, 19.8 - 24.8.1982

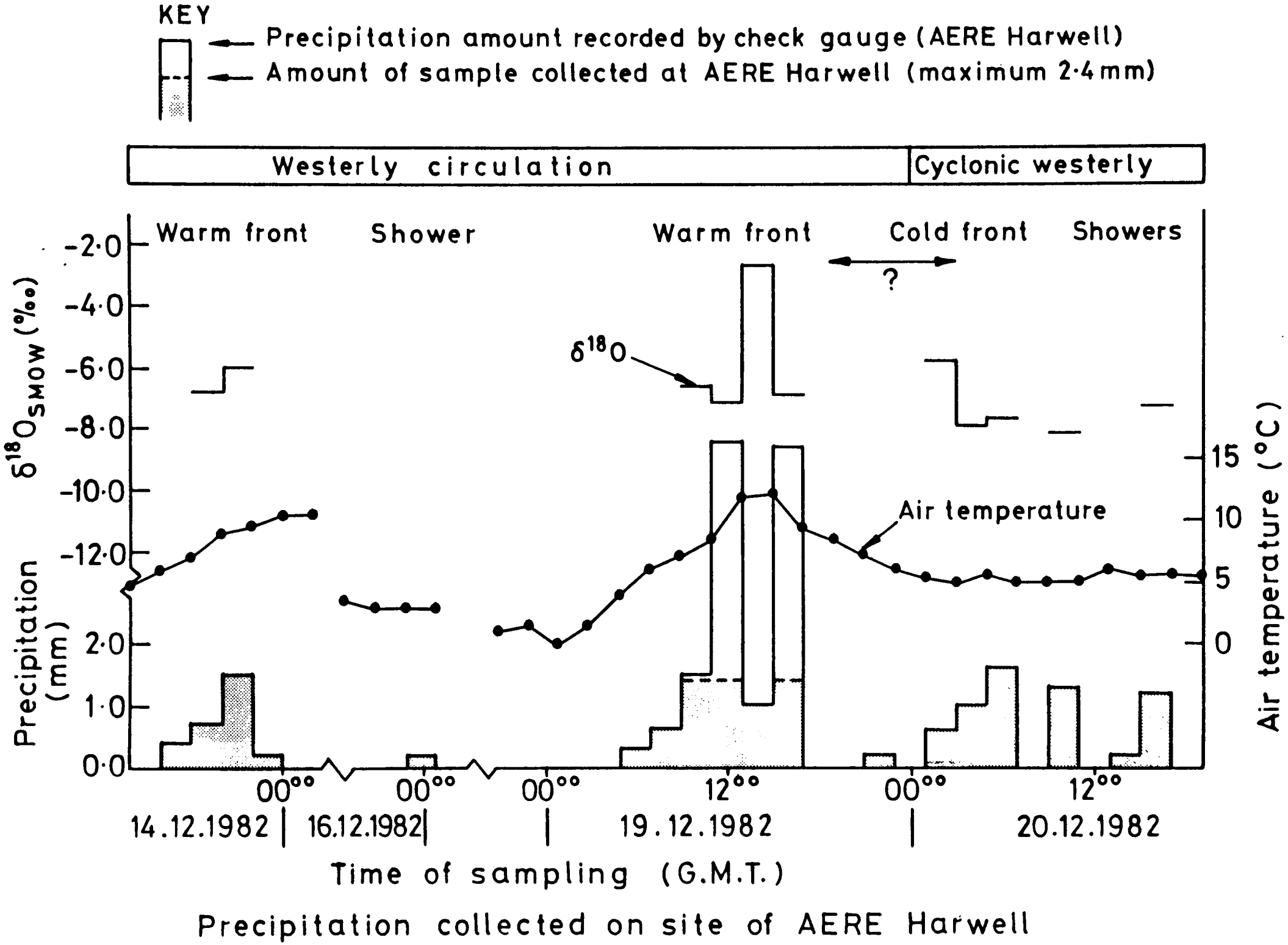


Fig. 4.28 Within-storm sampling of precipitation: AERE Harwell, 14.12 - 20.12.1982

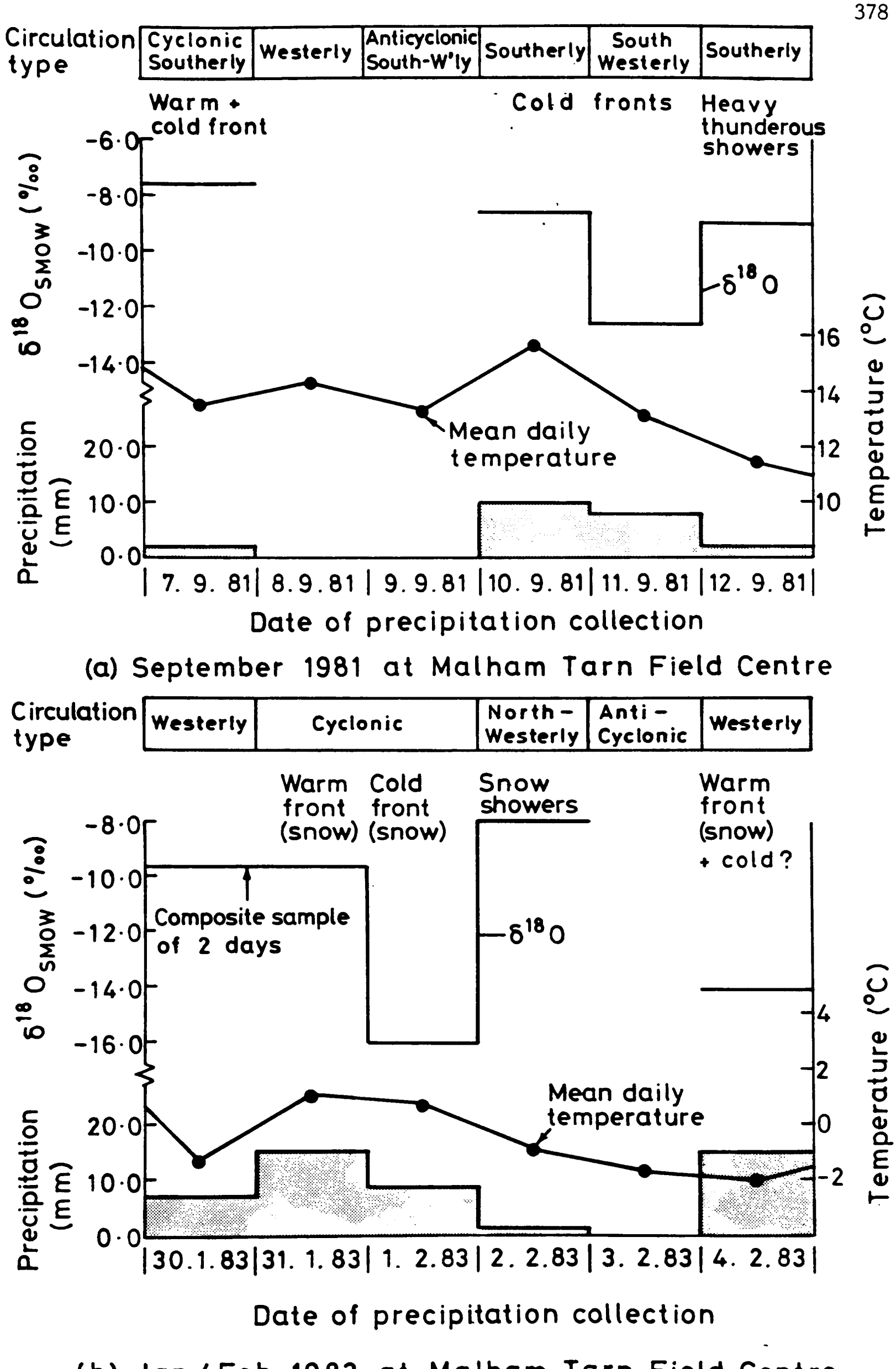
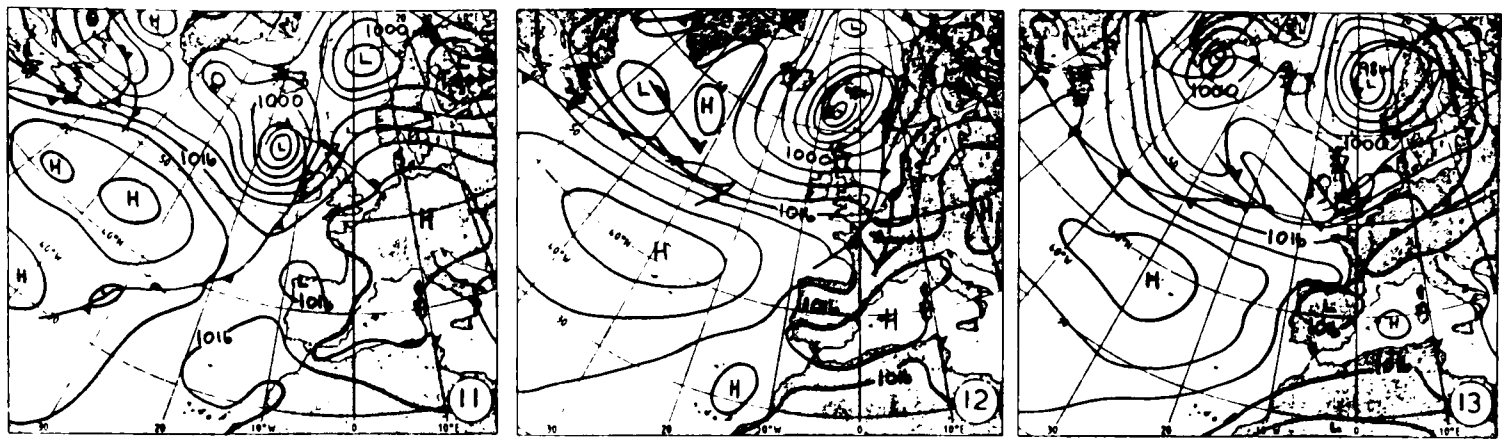
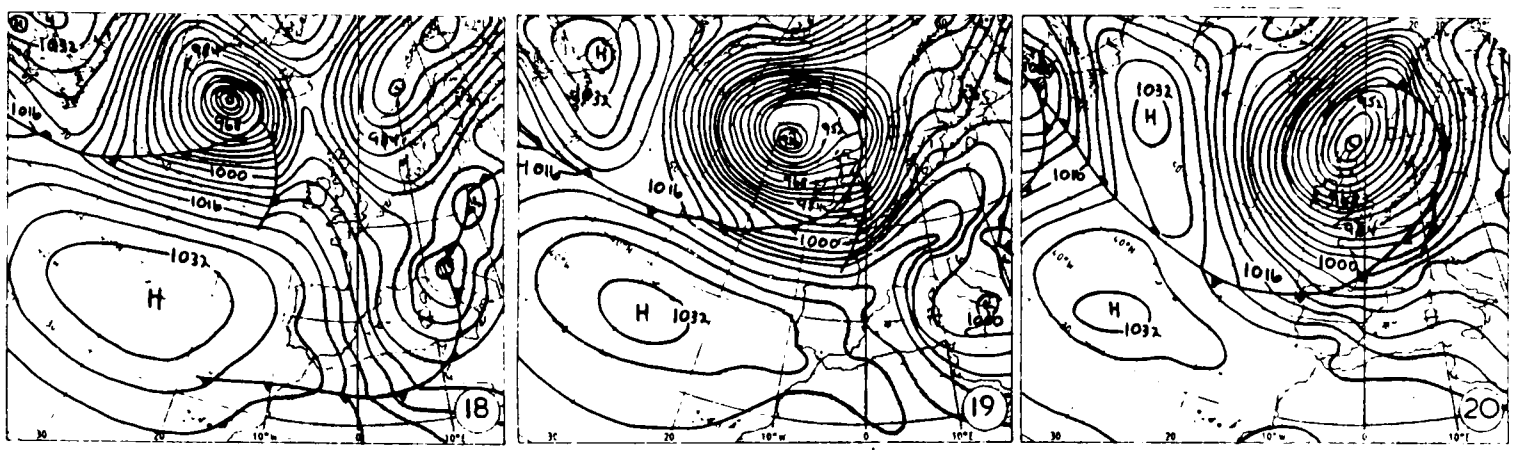


Fig. 4.29 Daily sampling of precipitation at Malham Tarn Field Centre: (a) 7.9. – 12.9.1981, (b) 30.1 - 4.2.1983



(a) 11-13th August, 1982



(b) 18-20th December, 1982



(c) 30th January- 4th February, 1983

Fig. 4.30 Synoptic charts for NW Europe, at 12^{00} G.M.T.: (a) 11.8 - 13.8.1982, (b) 18.12 - 20.12.1982, (c) 30.1 - 4.2.1982
(Source: Weather Logs, published by the Royal Meteorological Society)

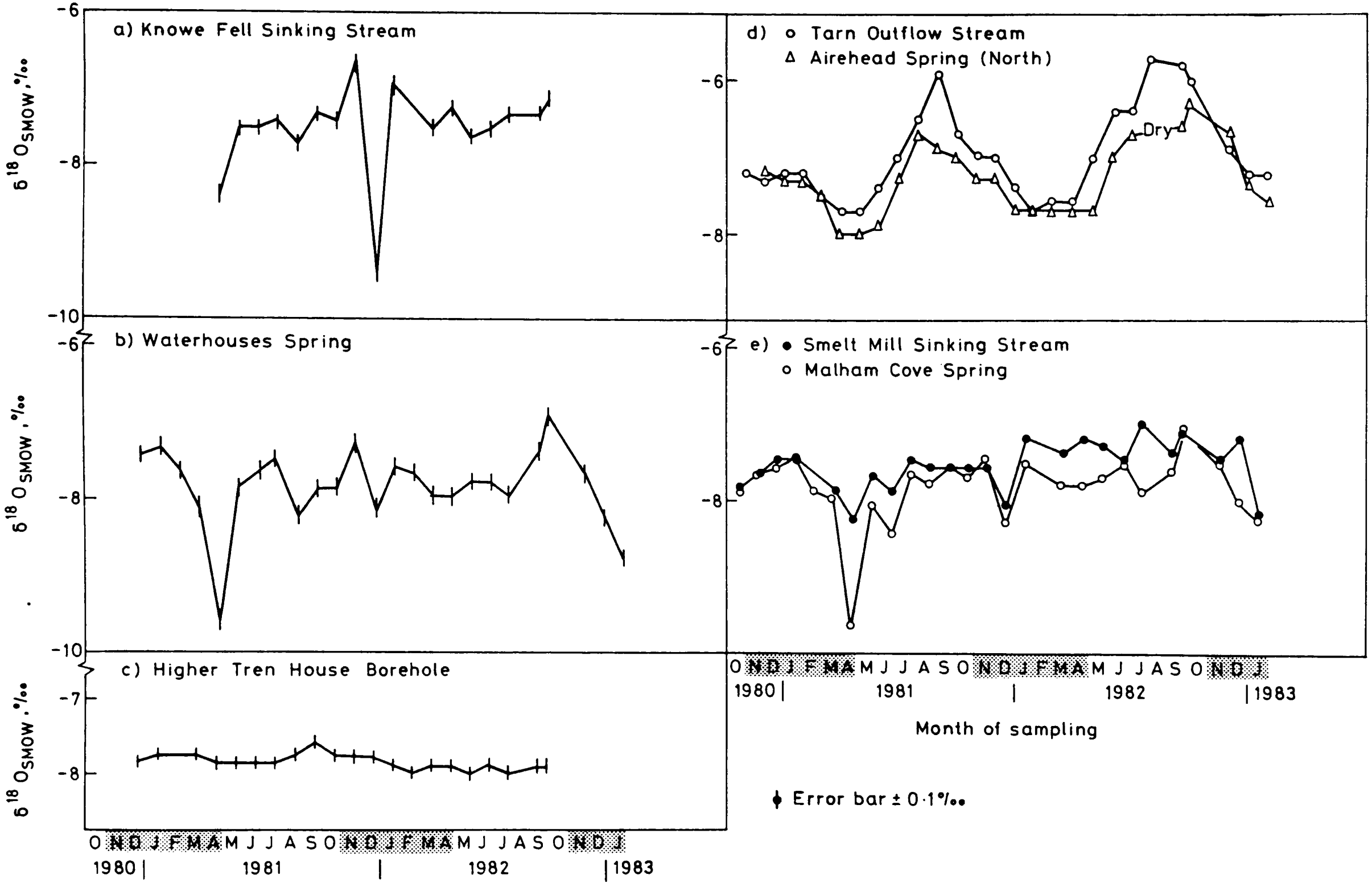


Fig. 4.31 Malham area $\delta^{18}O$ results from monthly sampling of surface and groundwaters: major sites (October 1980- January 1983)

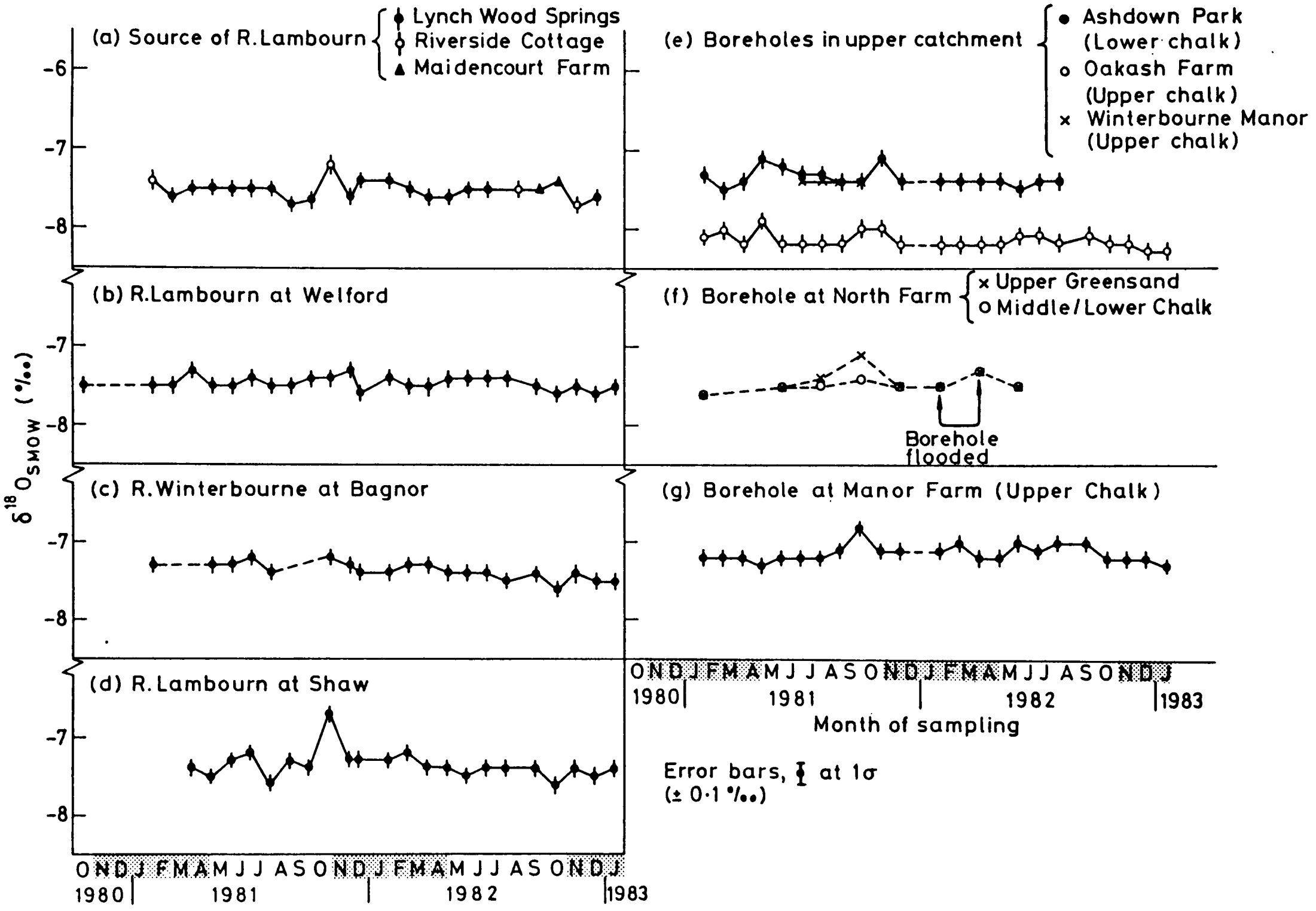


Fig. 4.32 Lambourn area $\delta^{18}O$ results from monthly sampling of surface and groundwaters (October 1980– January 1983)

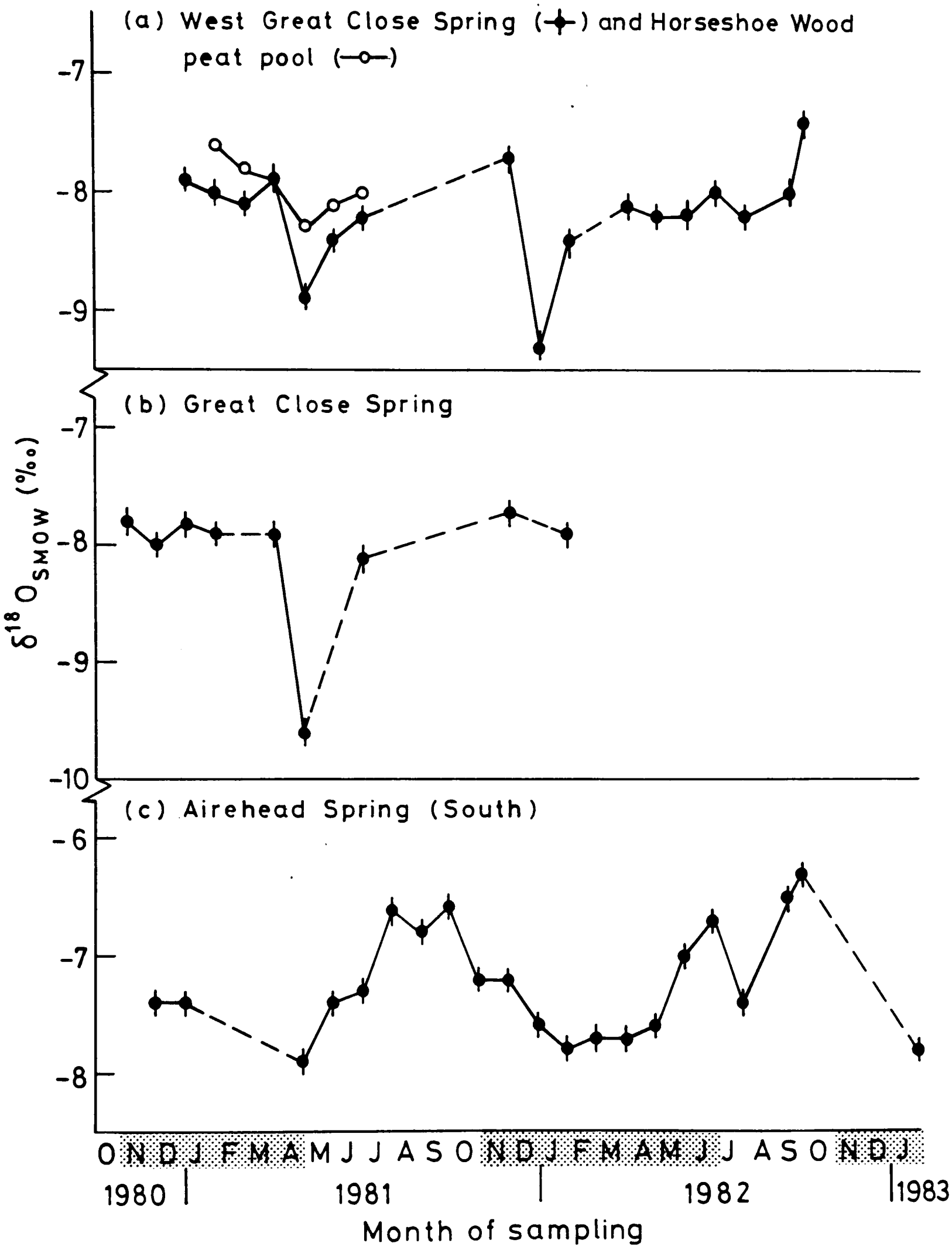


Fig. 4.33 Malham area $\delta^{18}O$ results from monthly sampling of surface waters: minor sites (October 1980- January 1983)

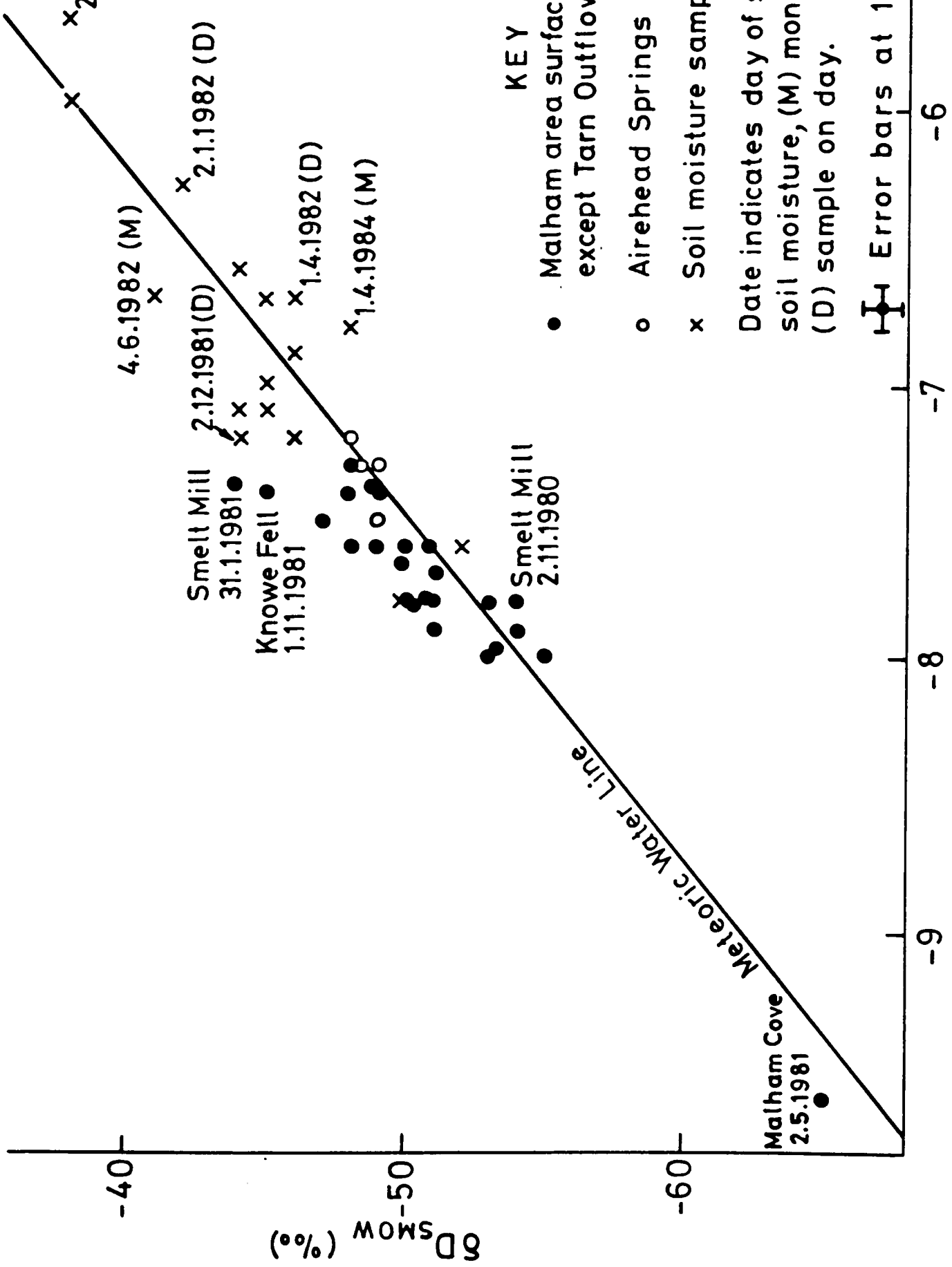


Fig. 4.34 $\delta^{18}O$–δD plot of Malham area surface, groundwater and soil moisture samples

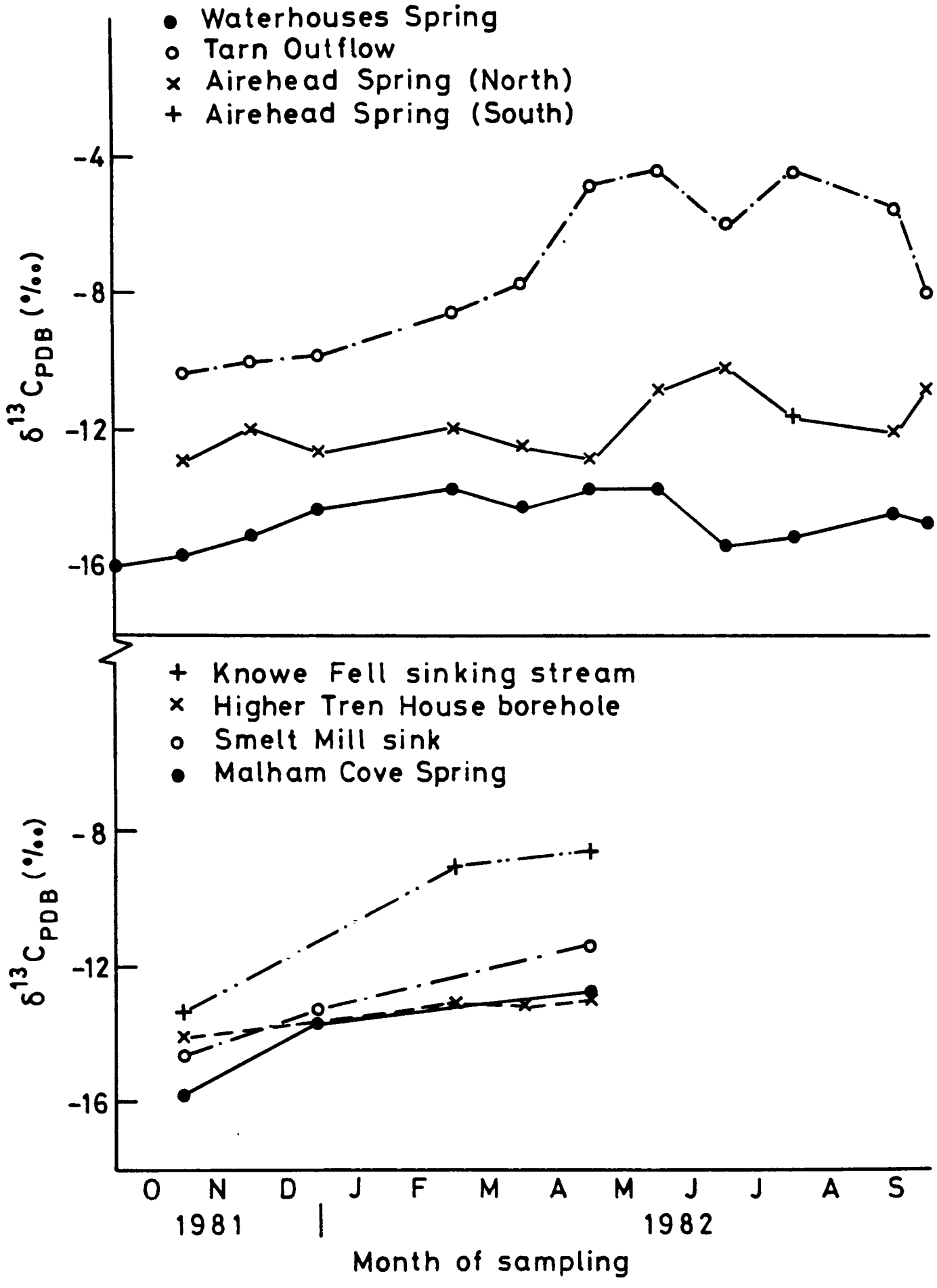


Fig. 4.35 Malham area $\delta^{13}C$ results from monthly sampling of surface waters

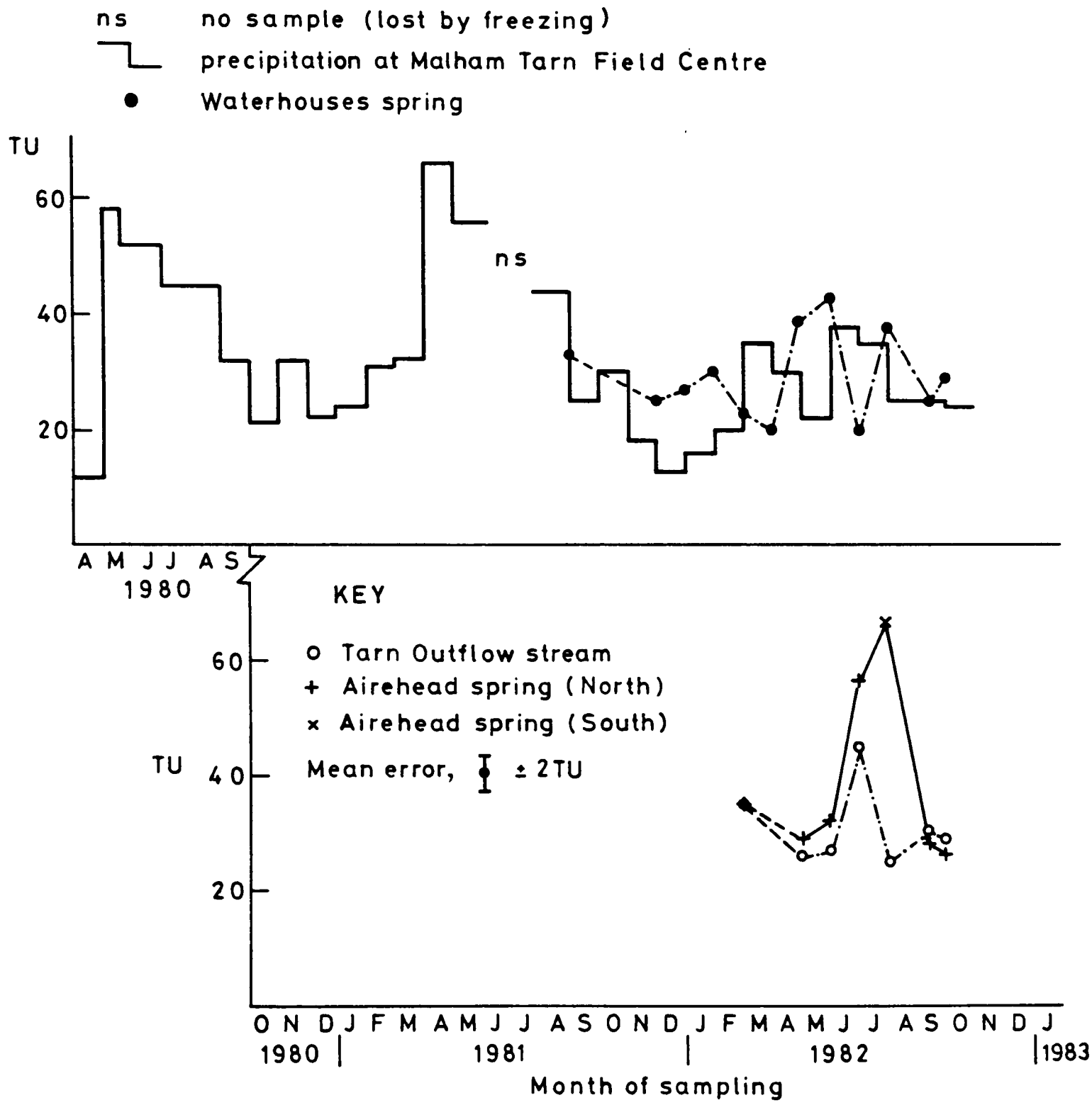


Fig. 4.36 Tritium results (TU) from monthly accumulations of precipitation at Malham Tarn Field Centre and from discrete sampling of surface waters in the Malham area (early precipitation data from THORPE, 1981)

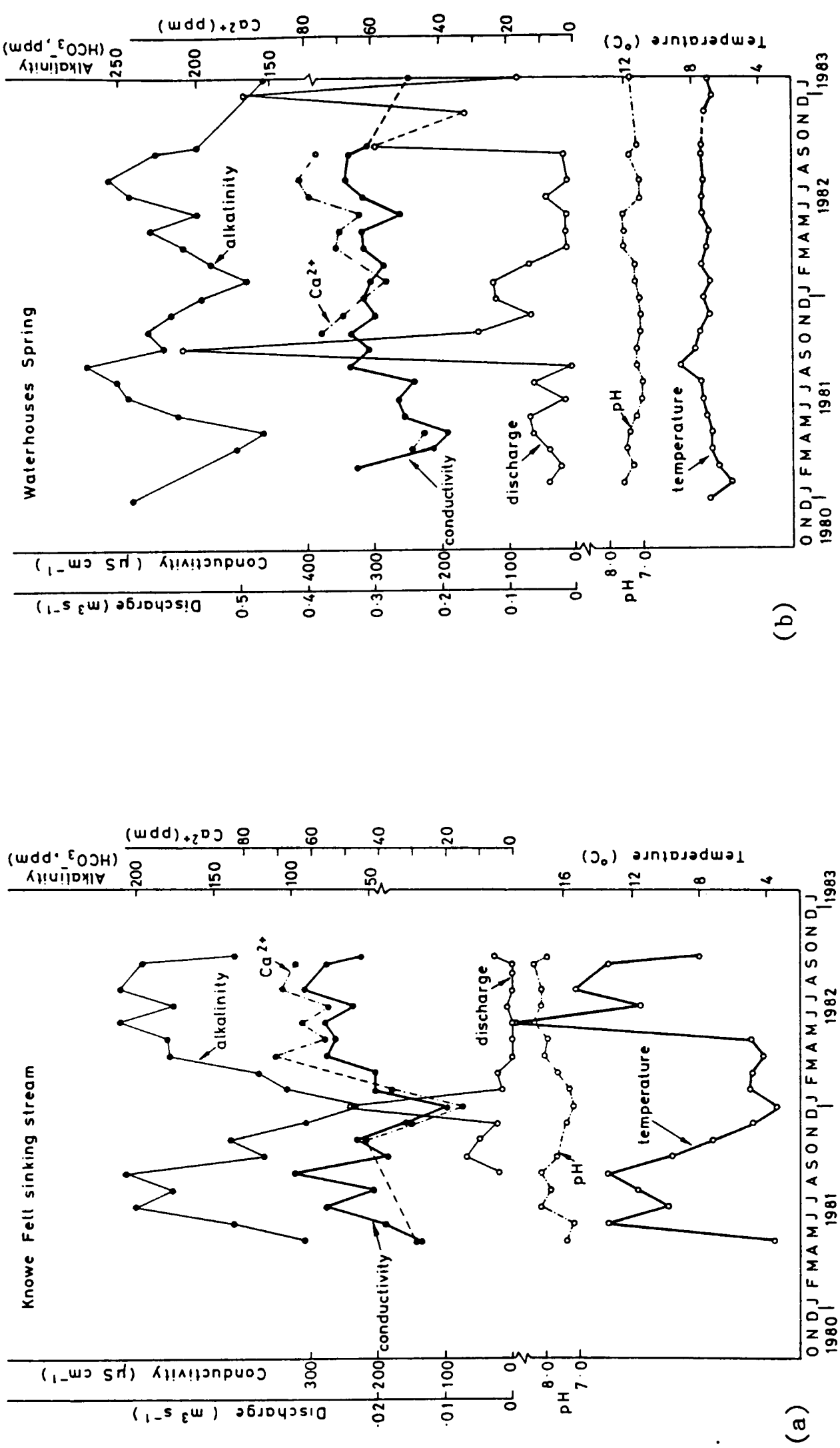


Fig. 4.37 Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Malham area: (a) Knowe Fell sinking stream, (b) Waterhouses Spring

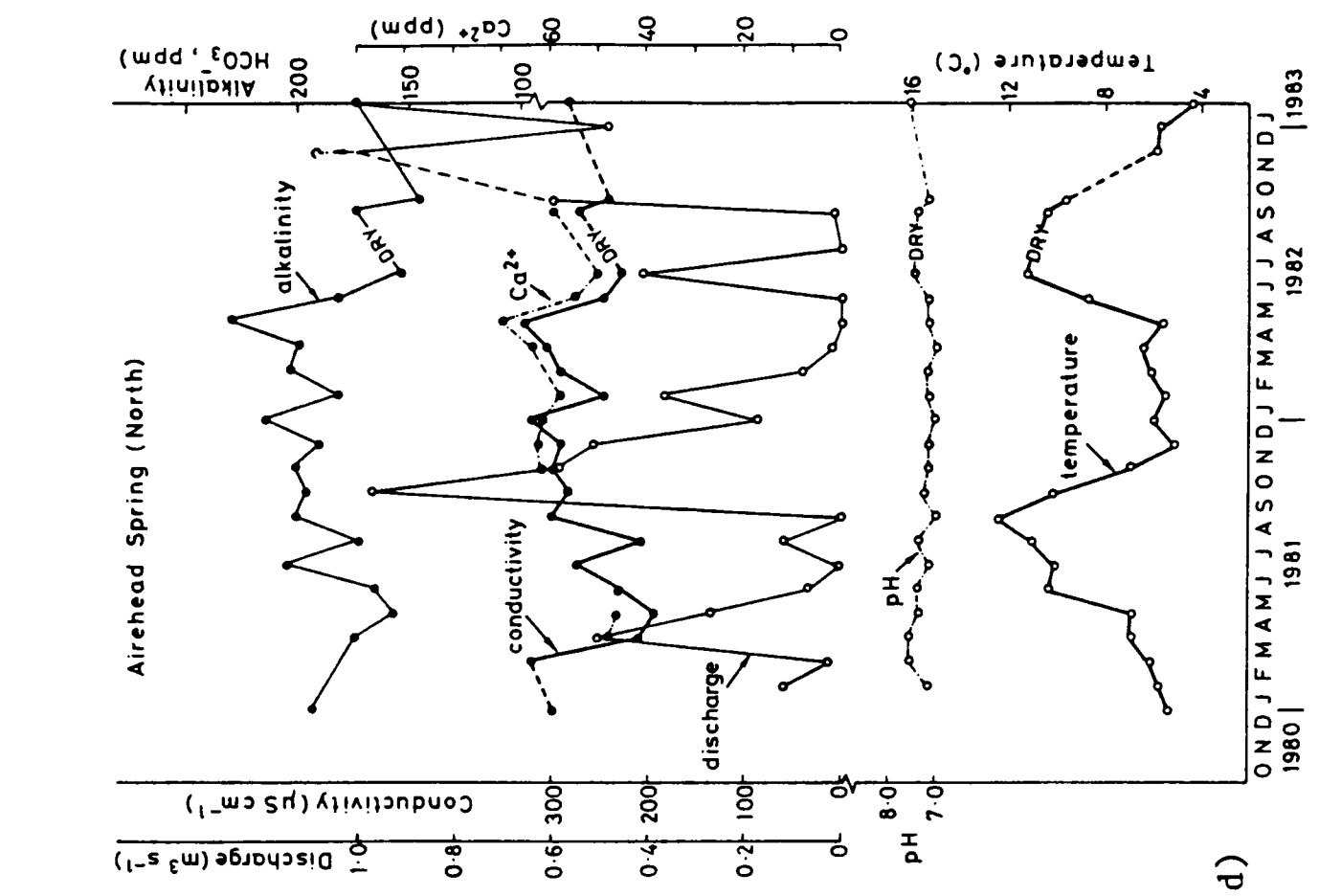
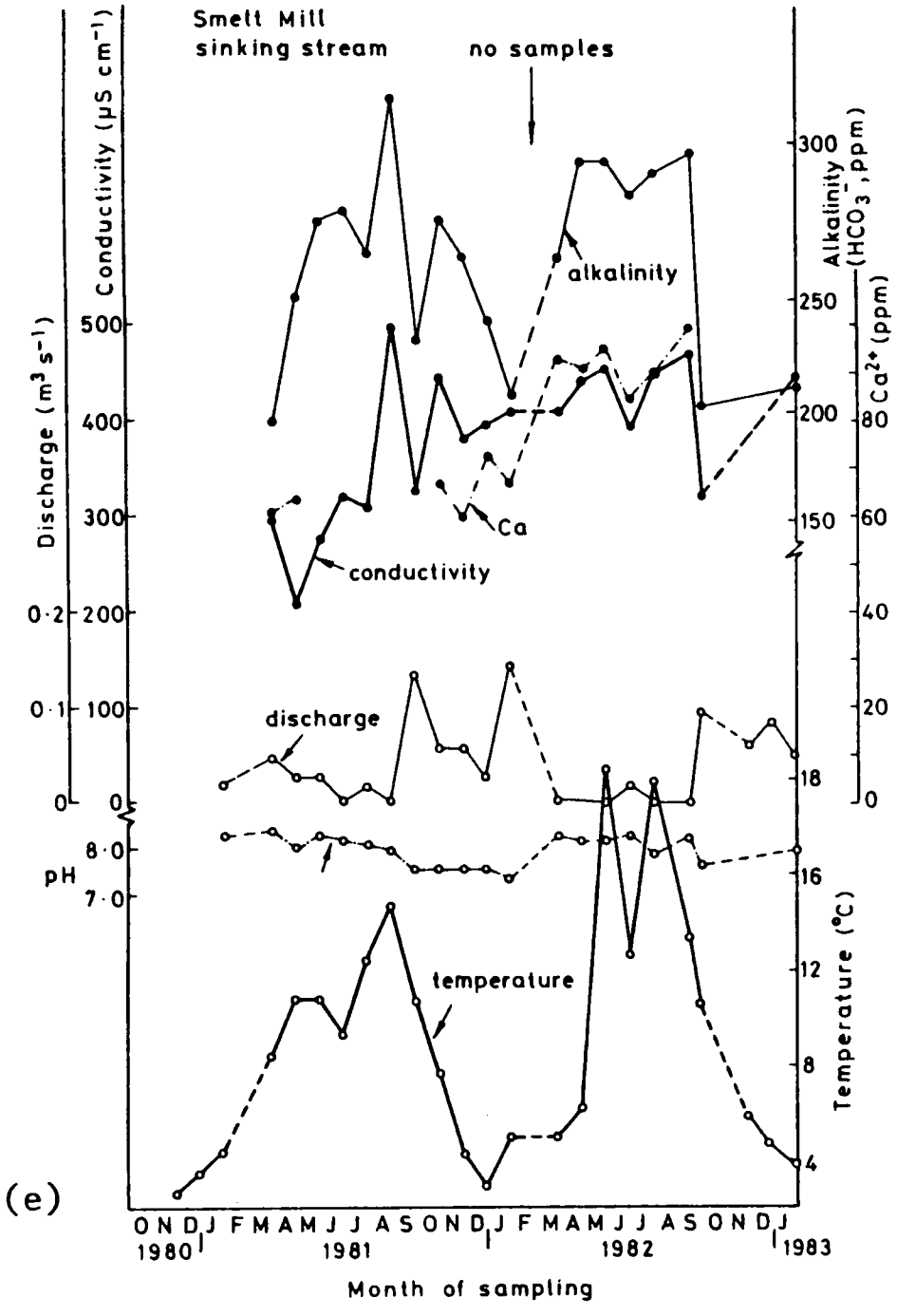


Fig. 4.37 (cont.) Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Malham area: (c) Tarn Outflow stream, (d) Airehead Spring (North).



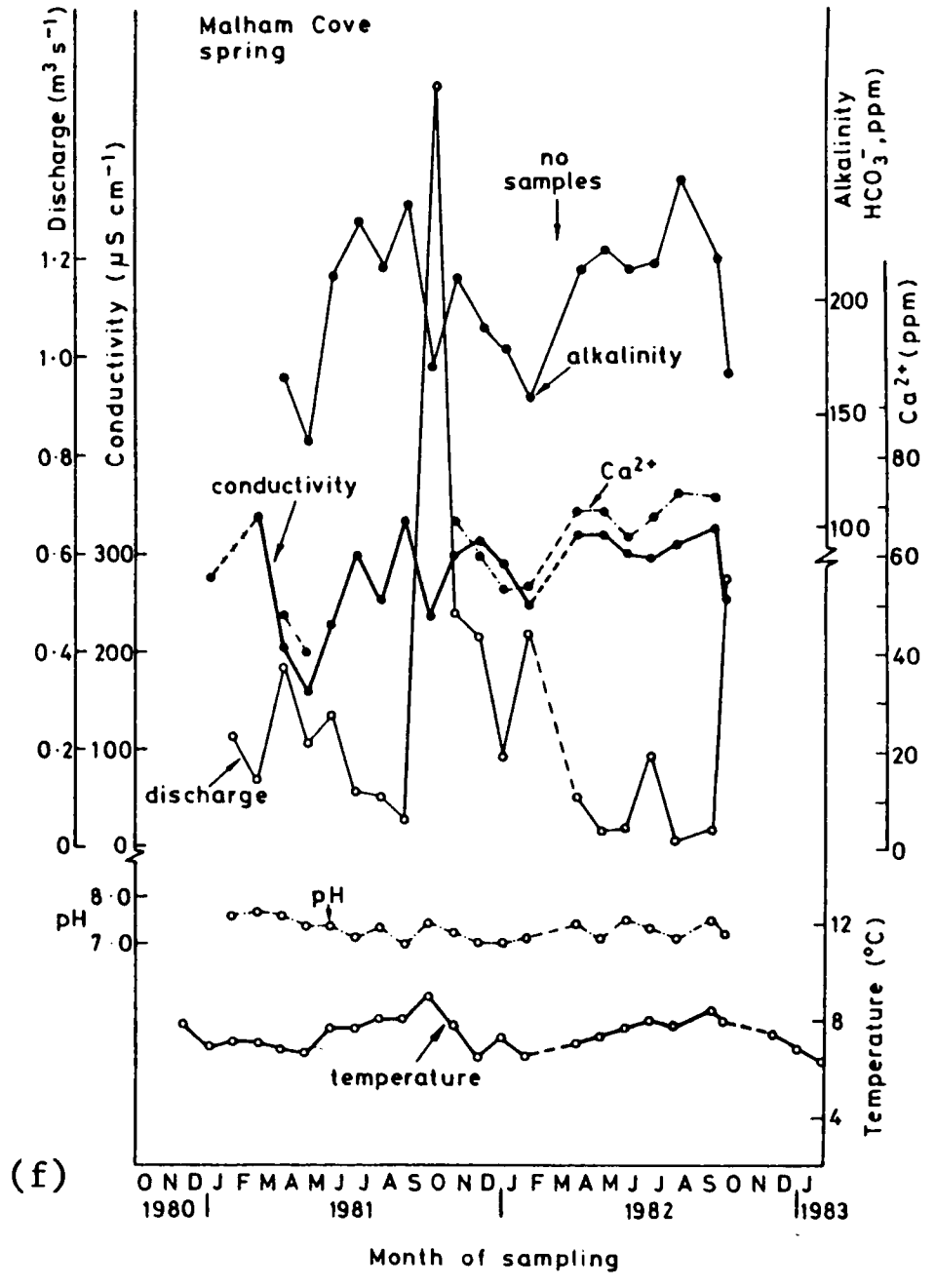


Fig. 4.37 (cont.) Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Malham area: (e) Smelt Mill sinking stream, (f) Malham Cove Spring

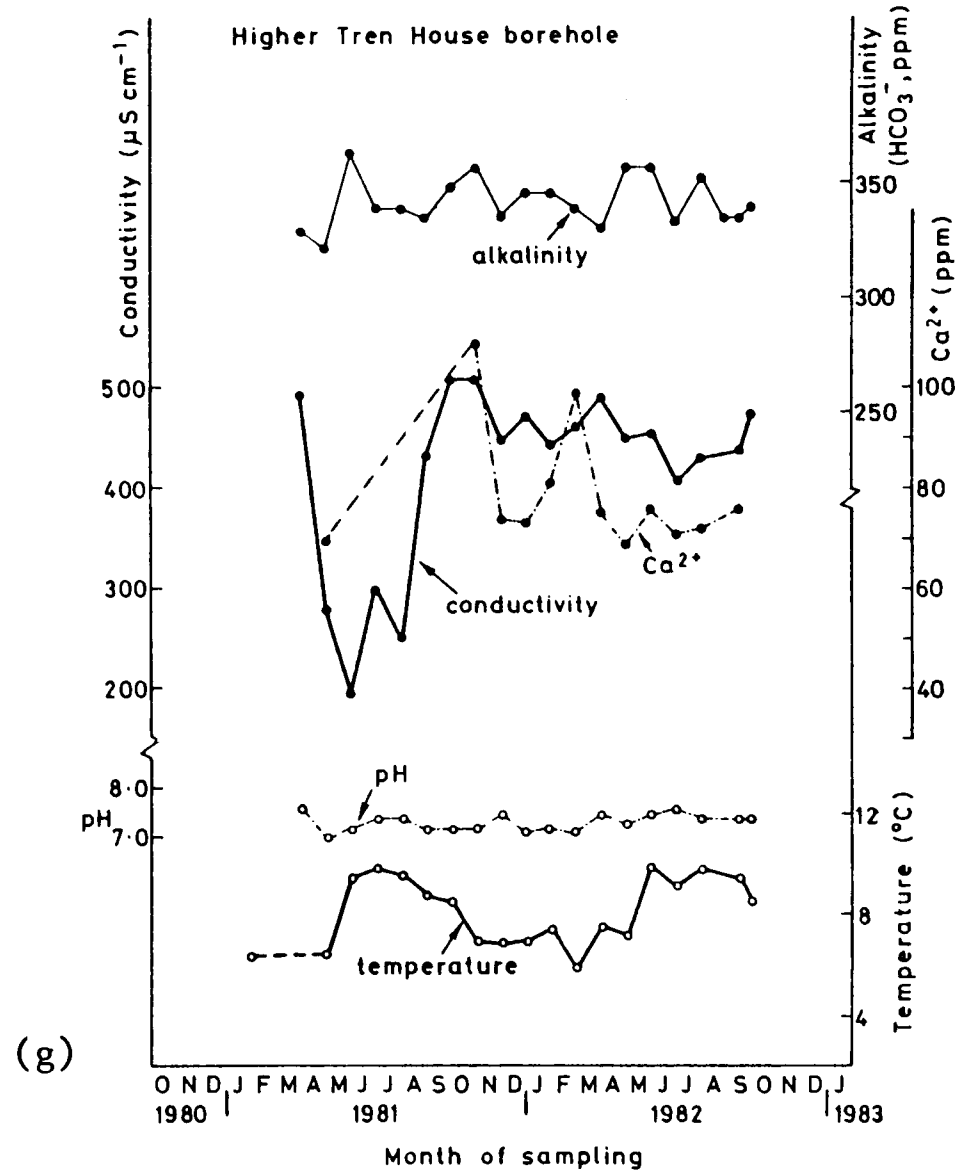


Fig. 4.37 (cont.) Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Malham area: (g) Higher Tren House borehole

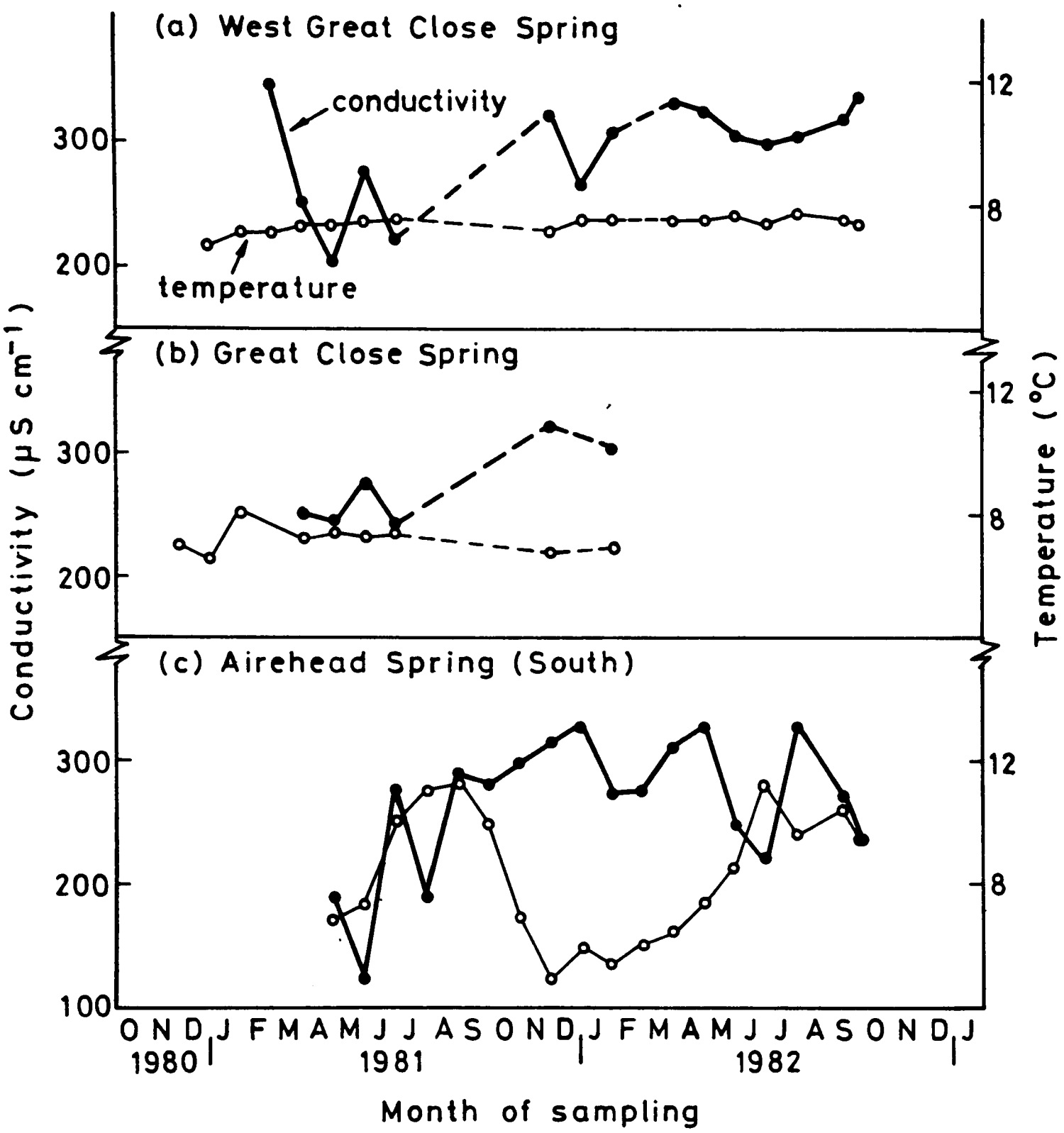
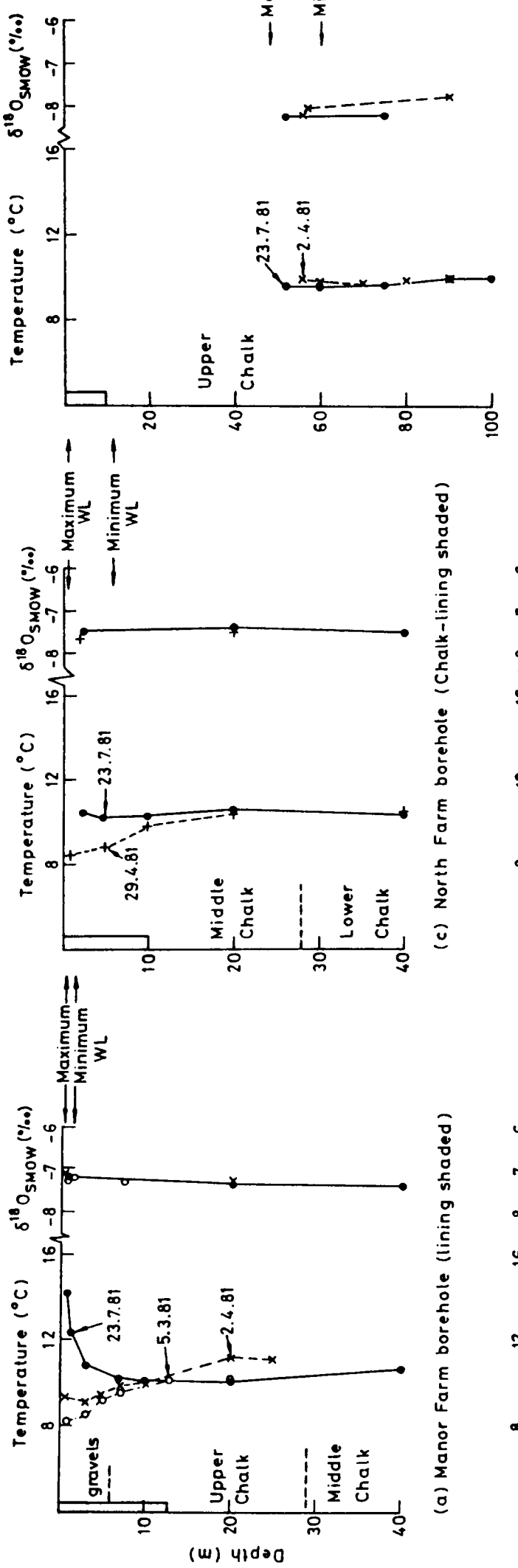


Fig. 4.38 Monthly conductivity and temperature at Malham area minor sites: (a) West Great Close Spring, (b) Great Close Spring, (c) Airehead Spring (South)



(e) Oakash borehole (lining shaded)

(c) North Farm borehole (Chalk-lining shaded)

(a) Manor Farm borehole (lining shaded)

(d) North Farm borehole (Upper Greensand)

(b) Ashdown Park borehole

Fig. 4.39 Lambourn borehole depth sampling: temperature and $\delta^{18}O$ results

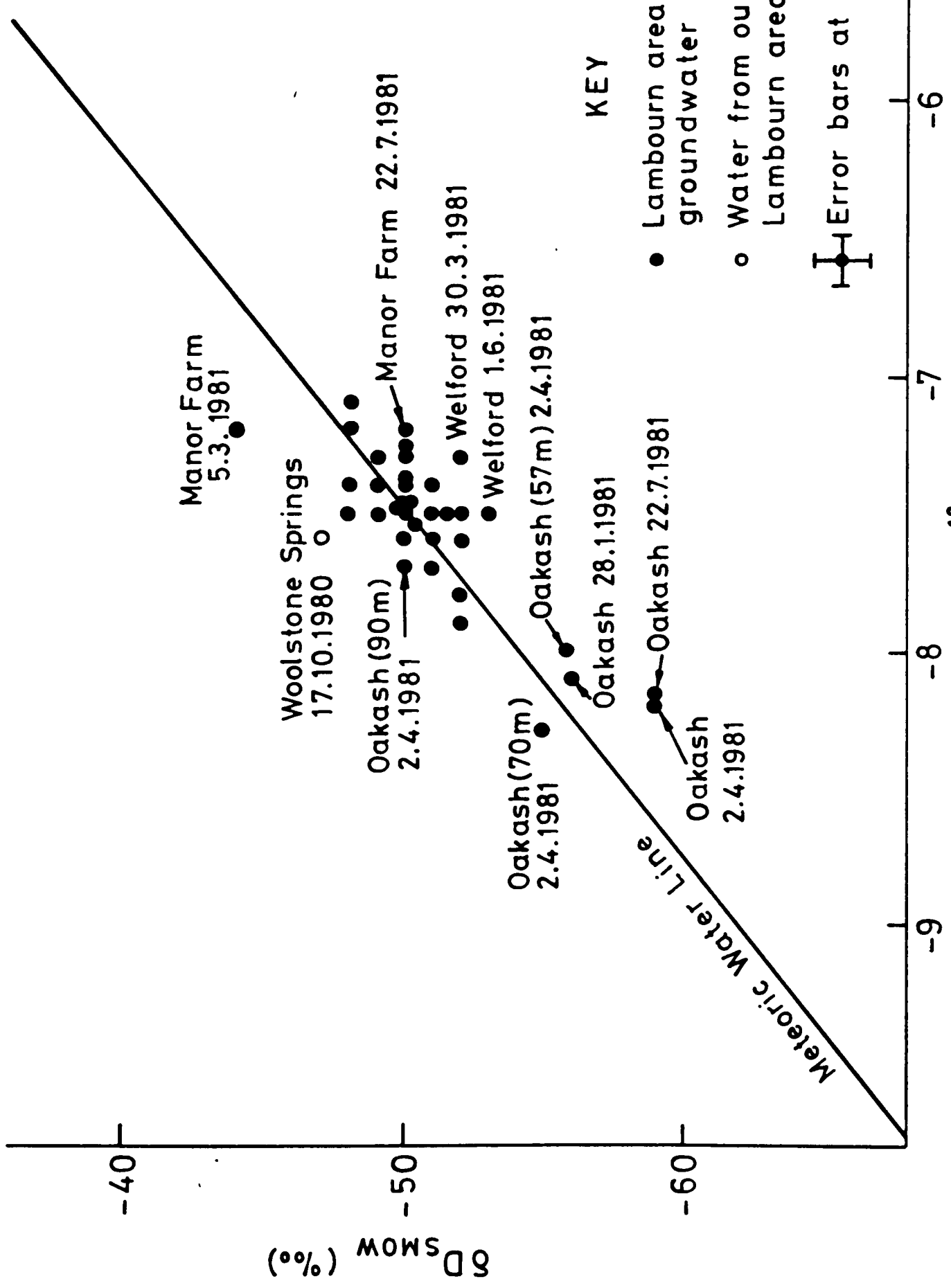


Fig. 4.40 $\delta^{18}O - \delta D$ plot of Lambourn area surface and groundwater samples

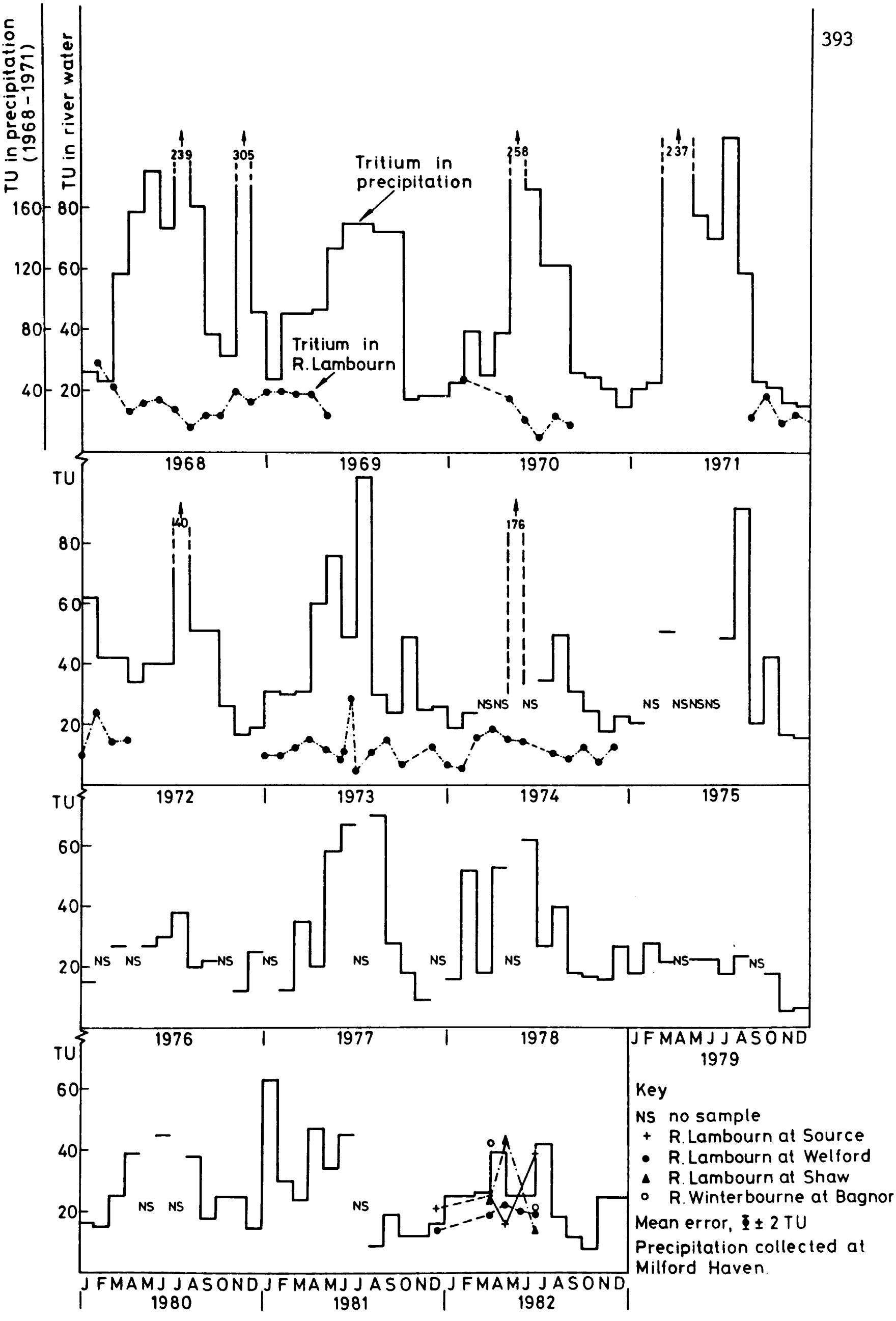
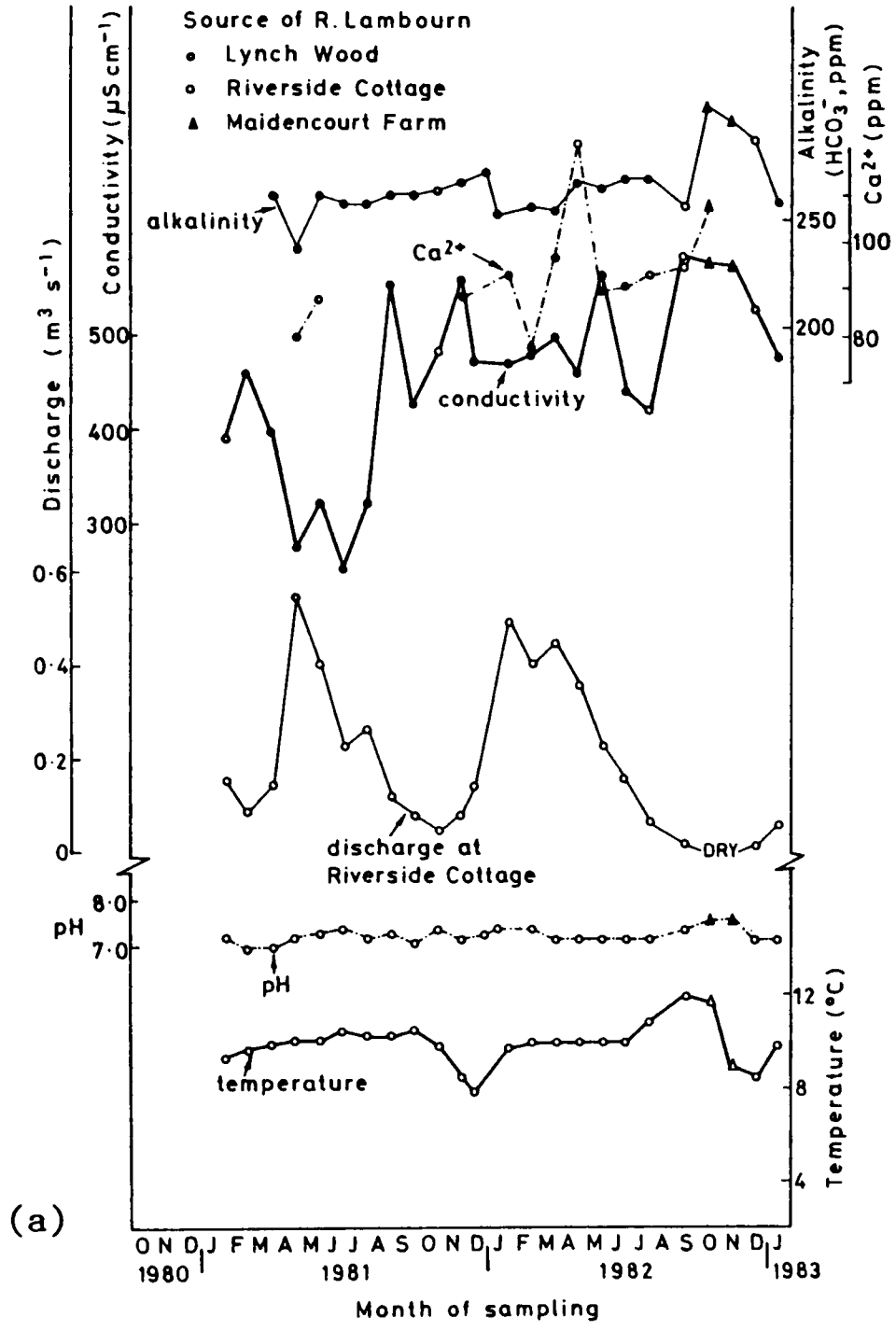


Fig. 4.41 Tritium in monthly precipitation at Milford Haven (Source: CAMBRAY et al., 1968- 1982) and in Lambourn area surface waters (1968- 1982)



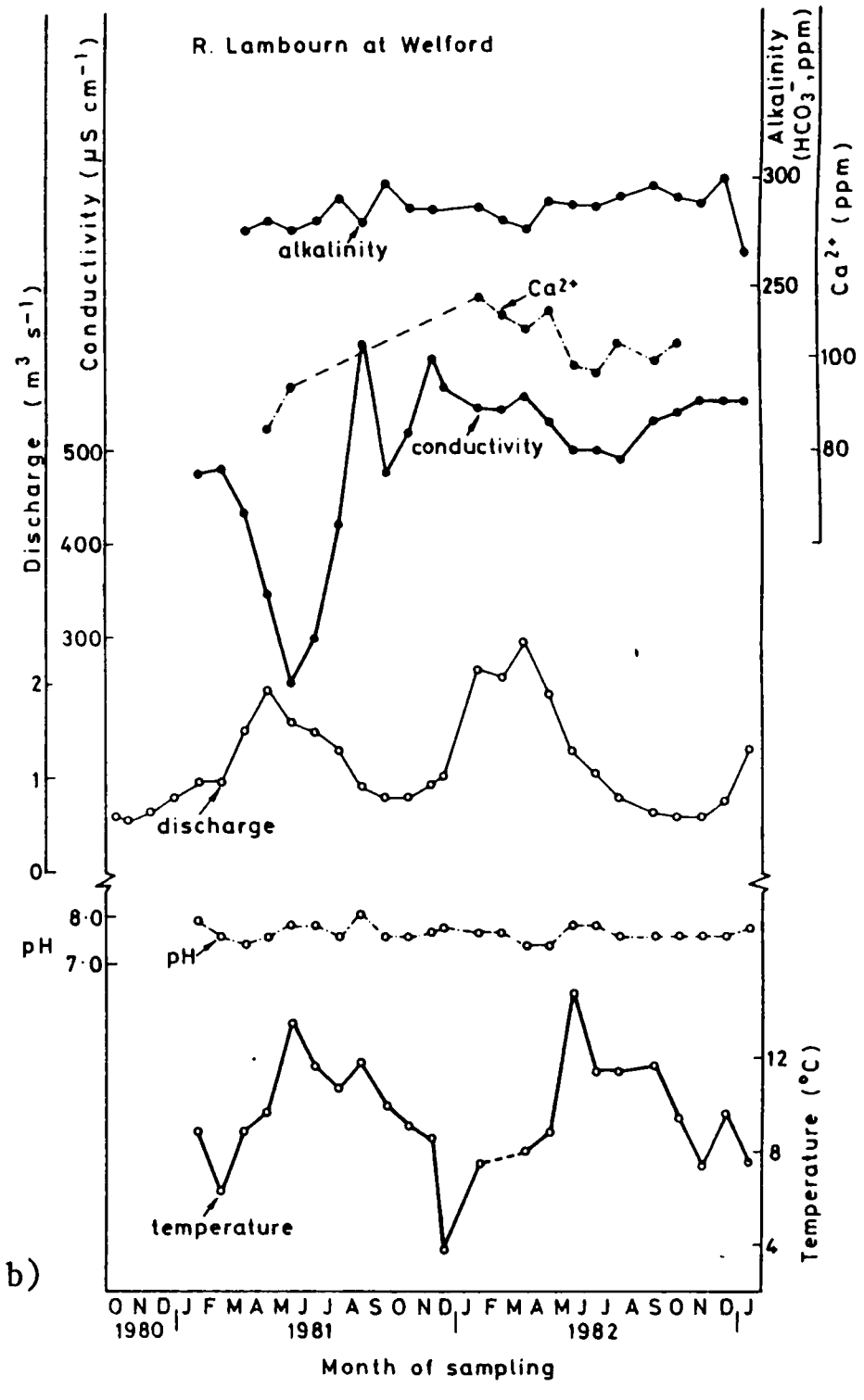
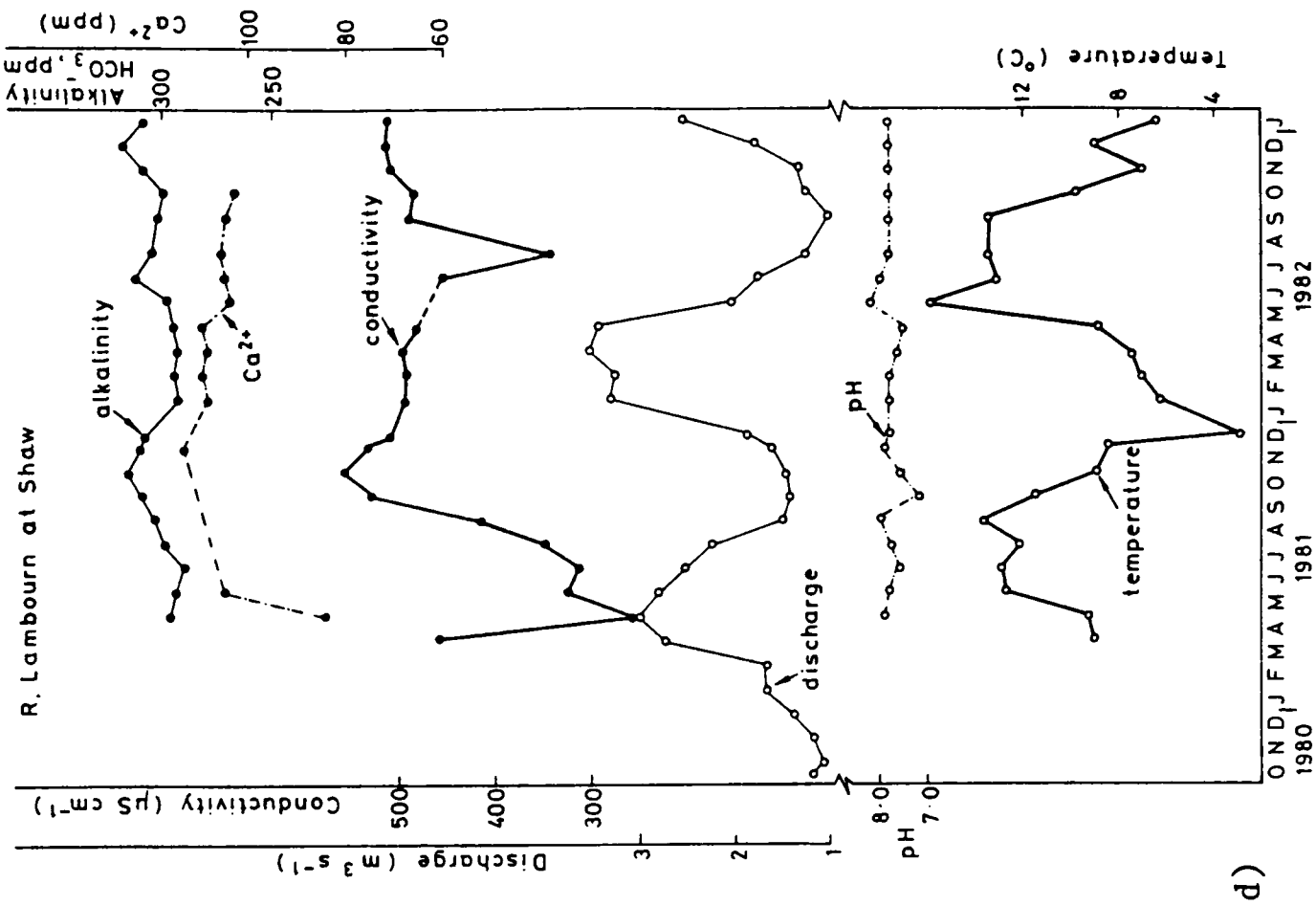


Fig. 4.42 Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Lambourn area: (a) Source of R. Lambourn, (b) R. Lambourn at Welford



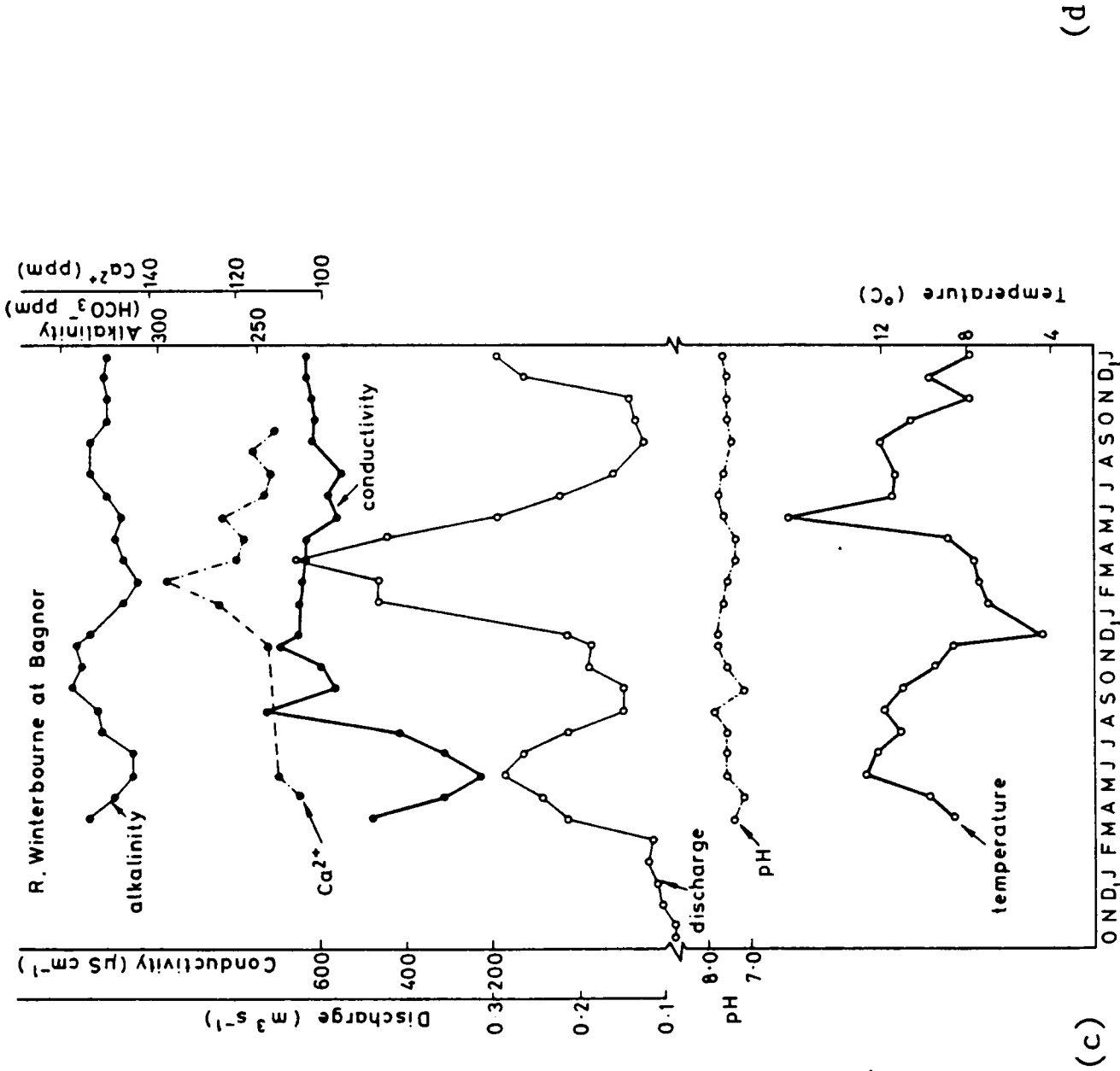


Fig. 4.42 (cont.) Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Lambourn area: (c) R. Winterbourne at Bagnor, (d) R. Lambourn at Shaw

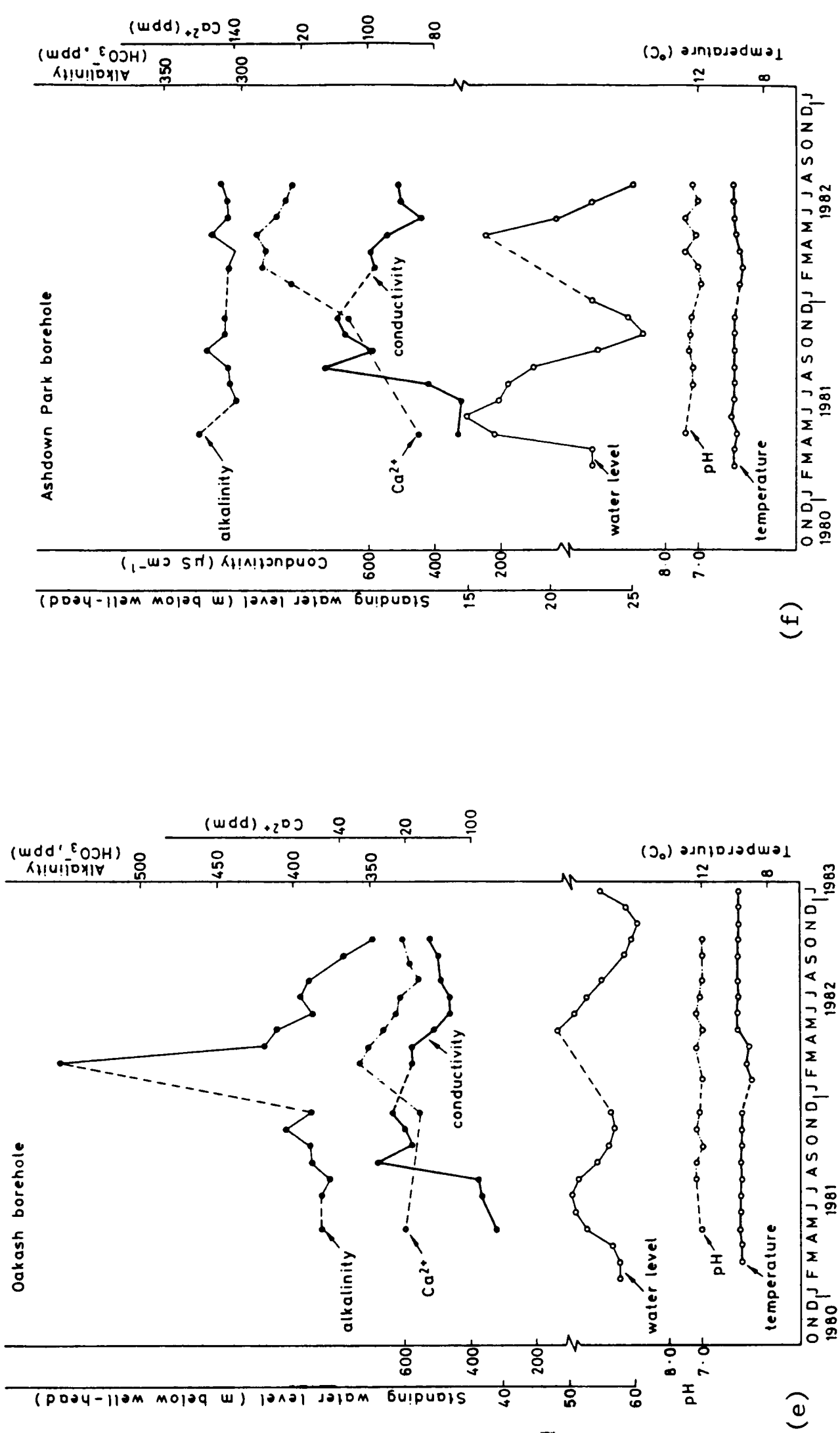
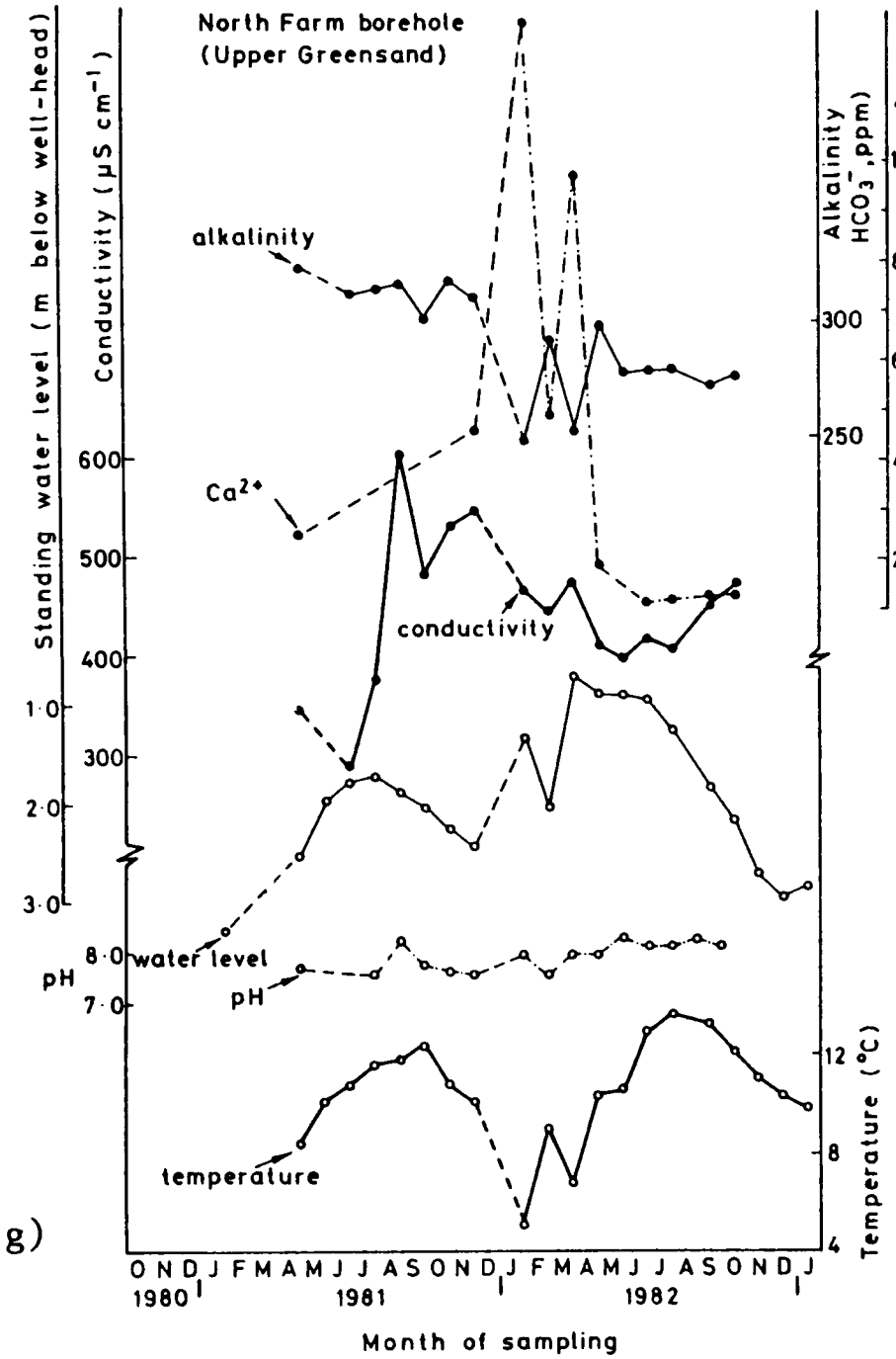
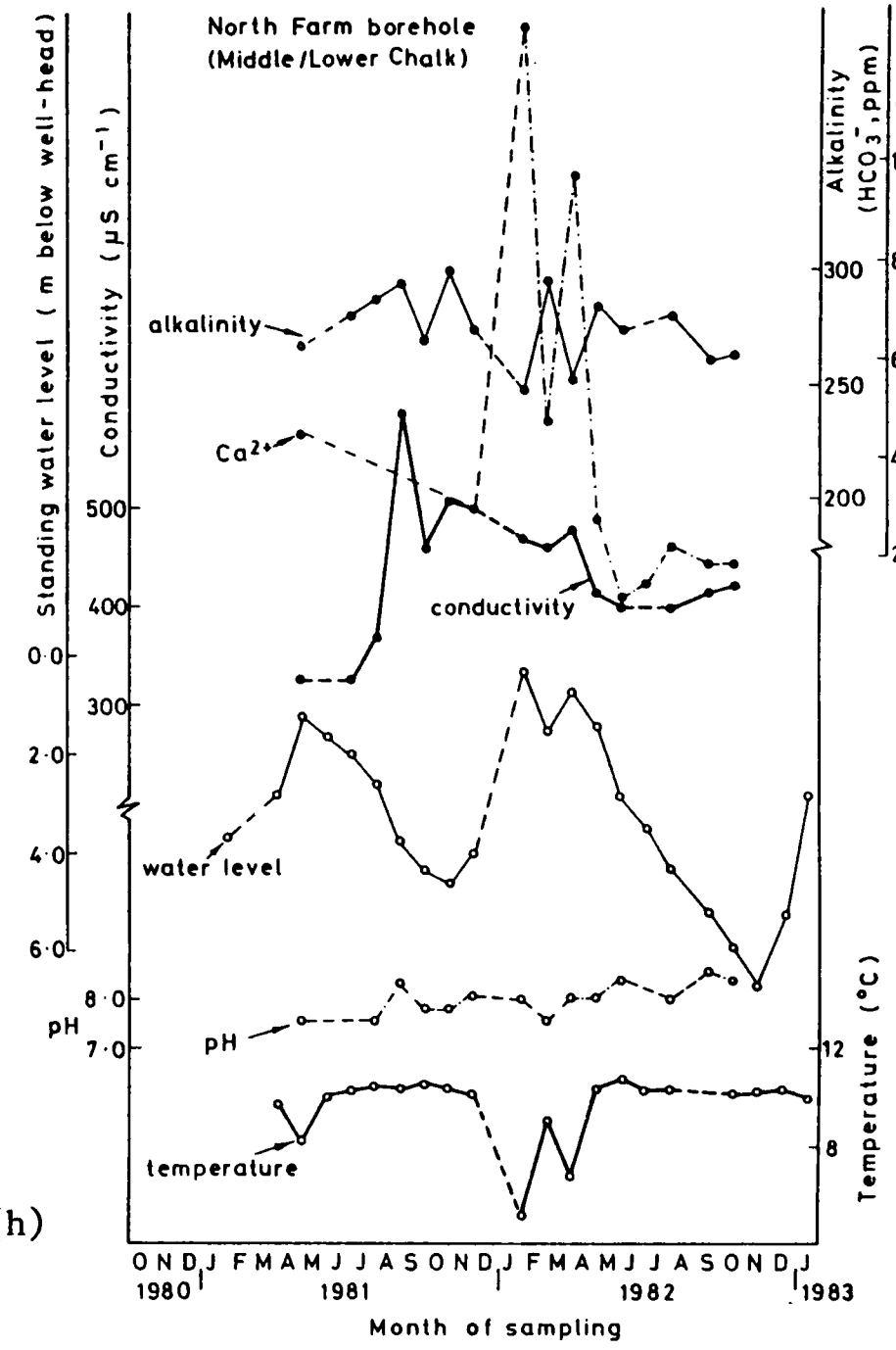


Fig. 4.42 (cont.) Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Lambourn area: (e) Oakash borehole, (f) Ashdown Park borehole



(g)



(h)

Fig. 4.42 (cont.) Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Lambourn area: (g) North Farm borehole (Upper Greensand), (h) North Farm borehole (Chalk)

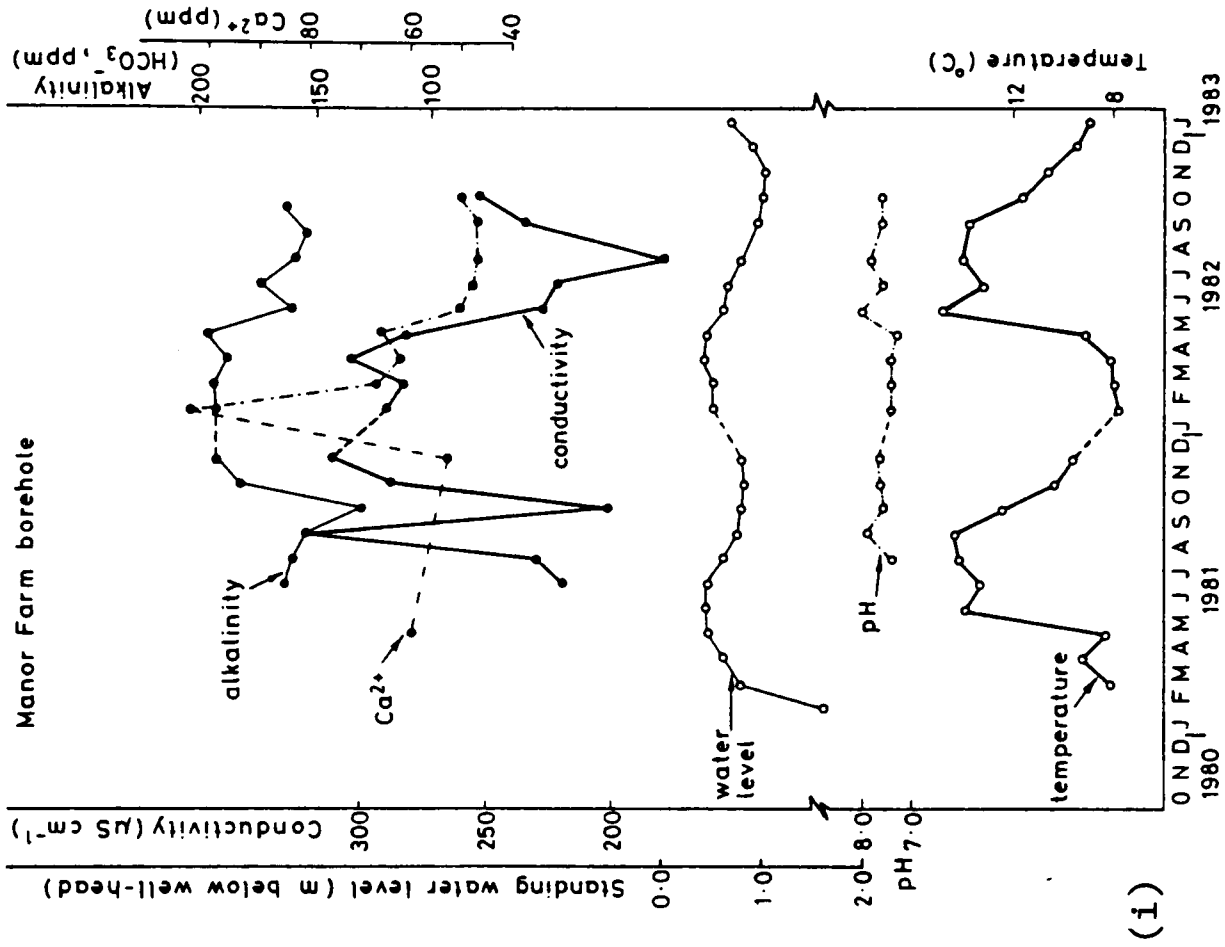


Fig. 4.42 (cont.) Conventional hydrological measurements and chemical analyses of surface and groundwaters in the Lambourn area: (i) Manor Farm borehole

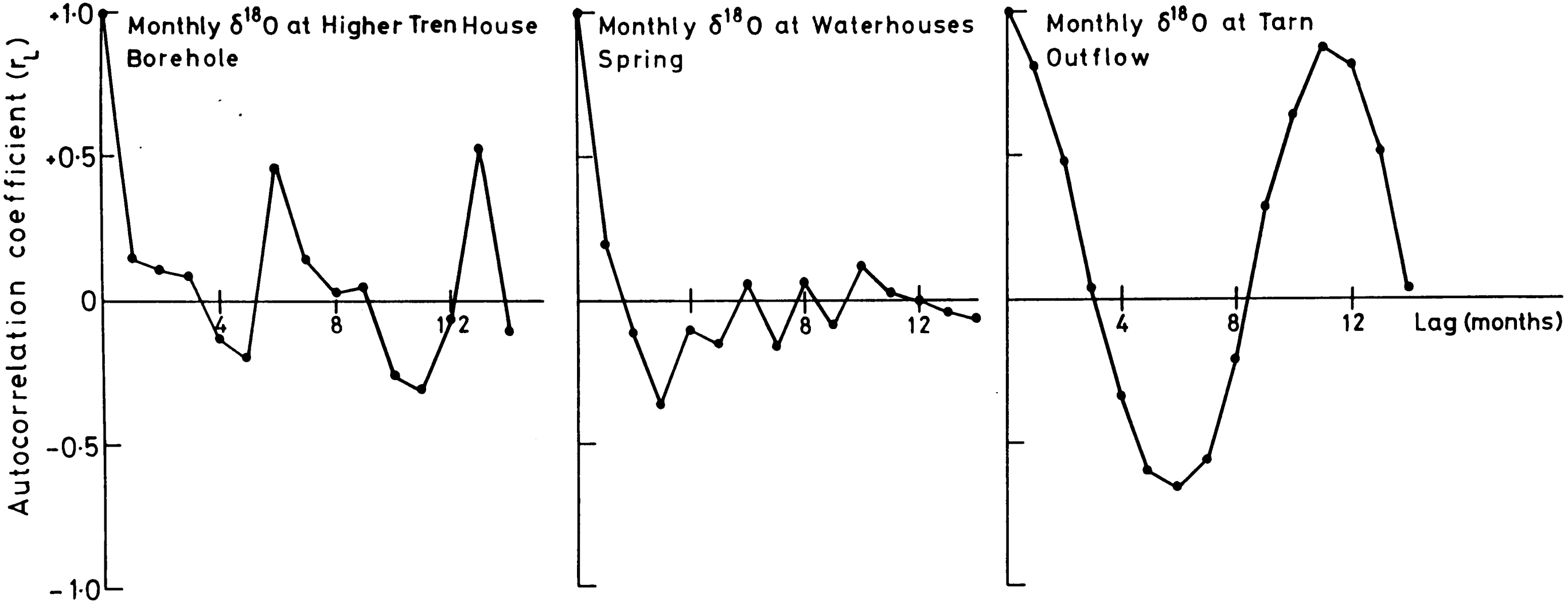


Fig. 4.43 Correlograms of Malham area monthly $\delta^{18}O$ series for (a) Higher Tren House, (b) Waterhouses Spring and (c) Tarn Outflow

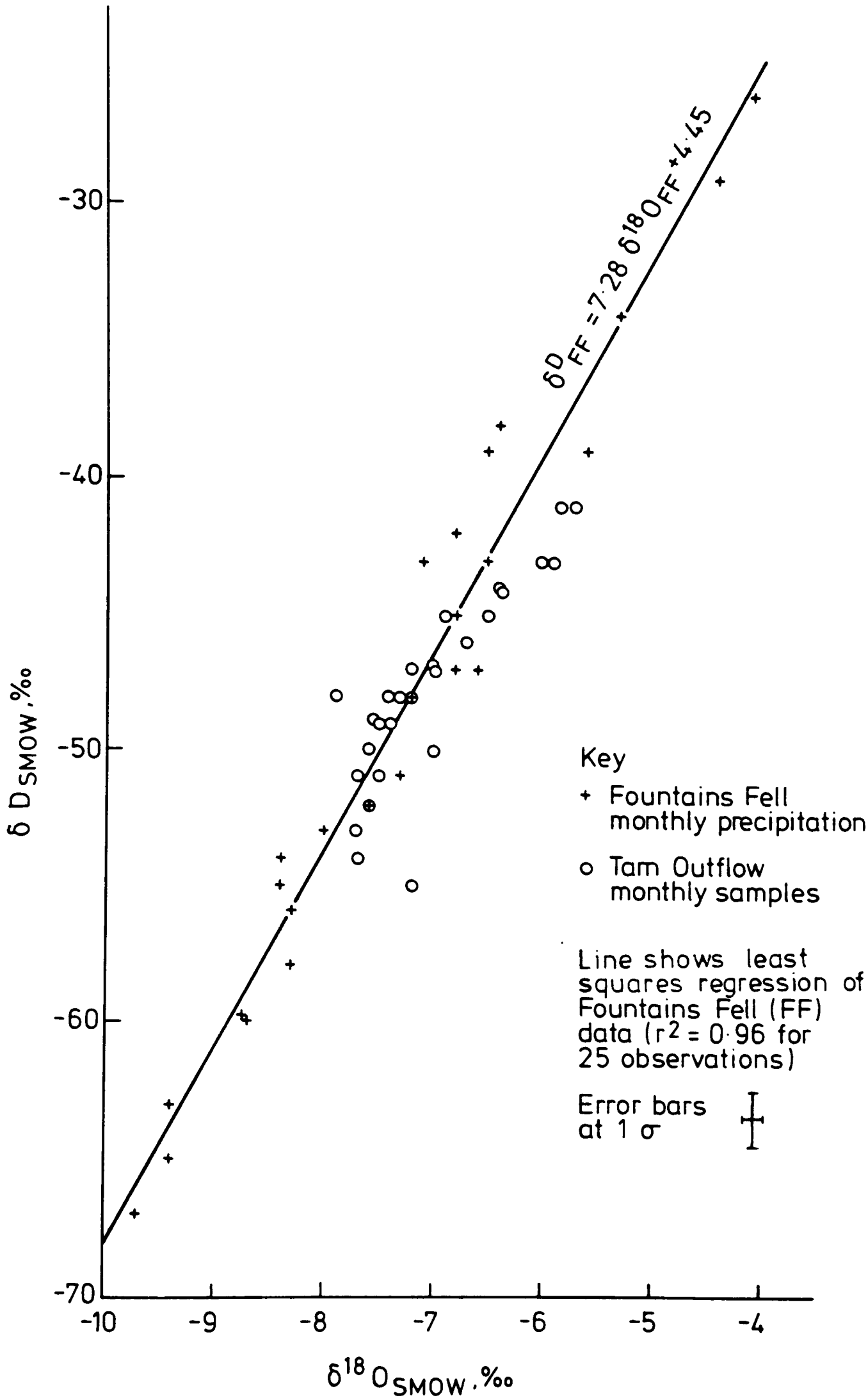


Fig. 4.44 $\delta^{18}O$–δD plot of Tarn Outflow stream and Fountains Fell precipitation samples, Malham area

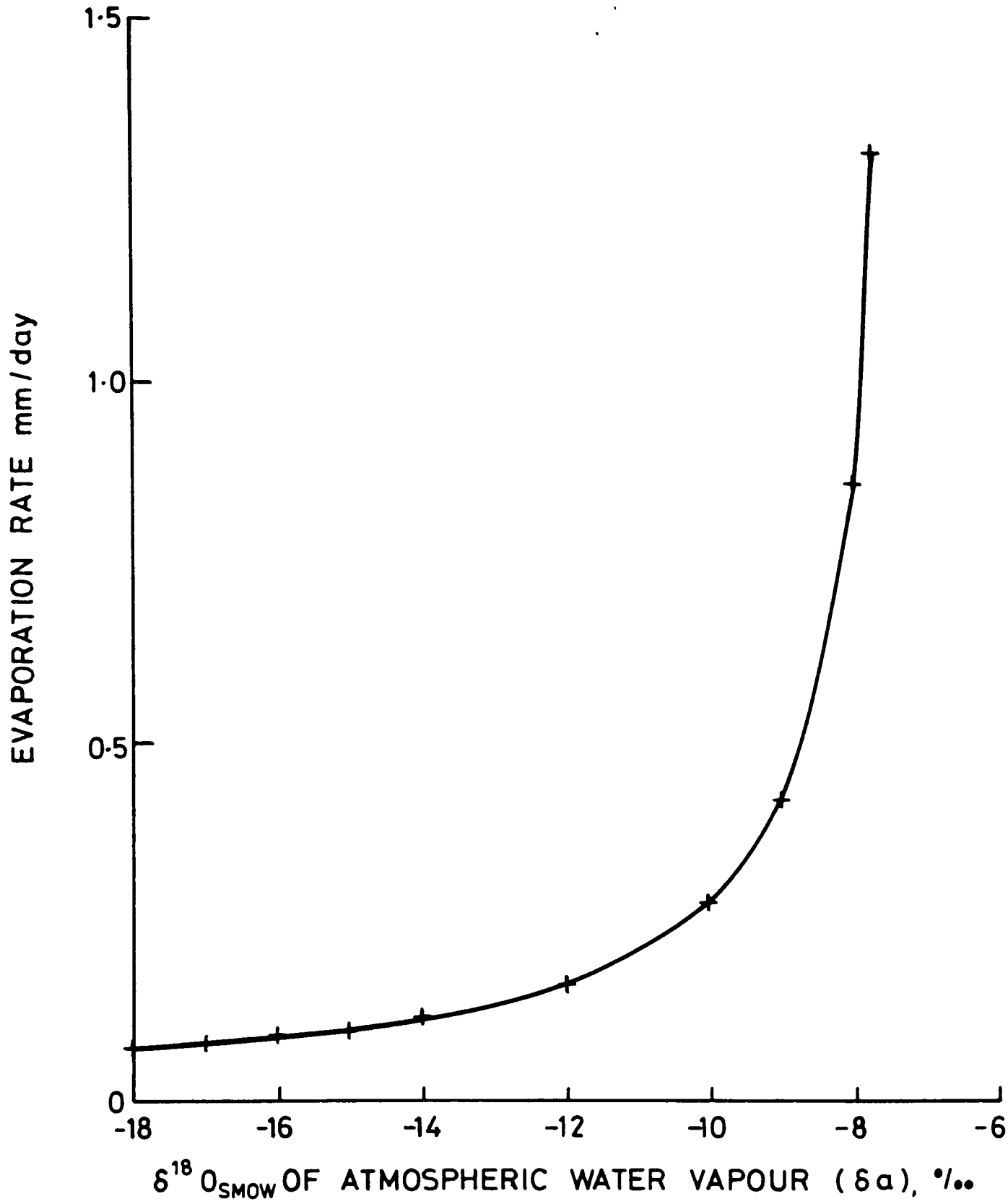


Fig. 4.45 The dependence of calculated evaporation from a lake upon the assumed value of δ_a: data for Malham Tarn, July 1981

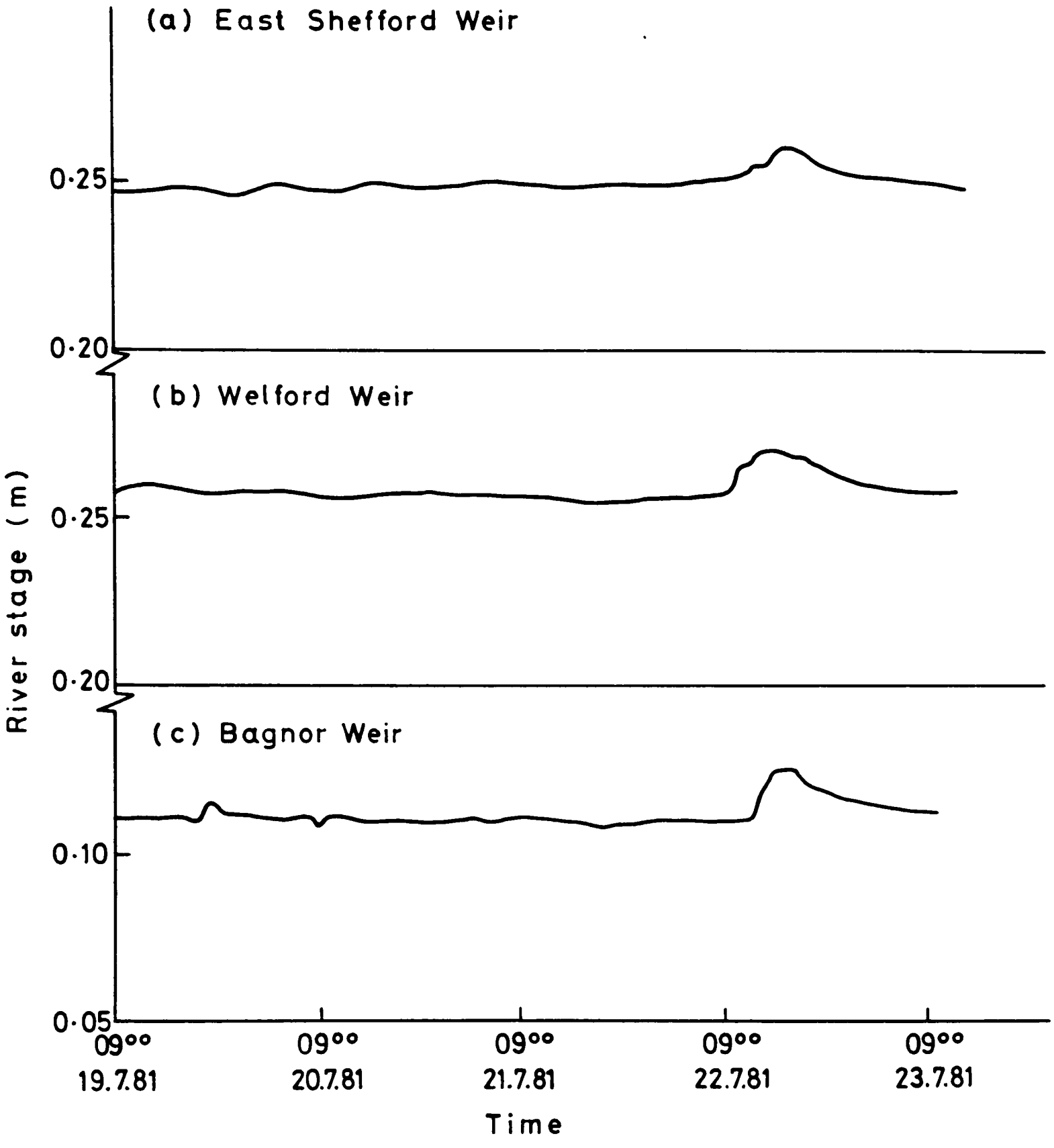


Fig. 4.46 Autographic river stage records at (a) East Shefford, (b) Welford and (c) Bagnor over an event of discharge 'flashiness'
(Equivalent rise in discharge at Welford on 22.7.81 is from 1.303 to 1.398 $m^3 s^{-1}$)

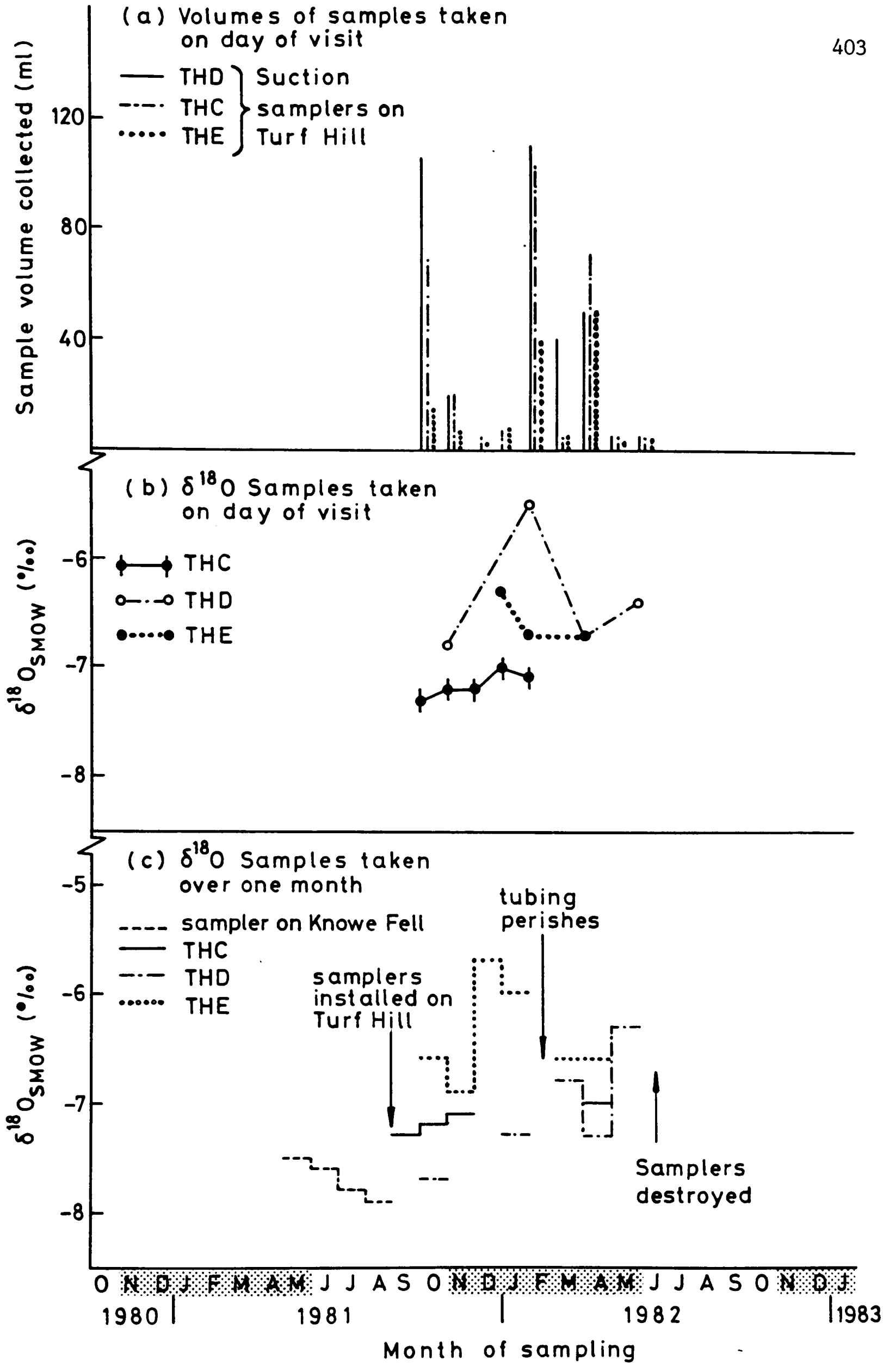


Fig. 4.47 Soil moisture obtained using the suction cup method in the Malham area: (a) amounts extracted, (b) $\delta^{18}O$ on day of sampling, (c) $\delta^{18}O$ of moisture collected over one month

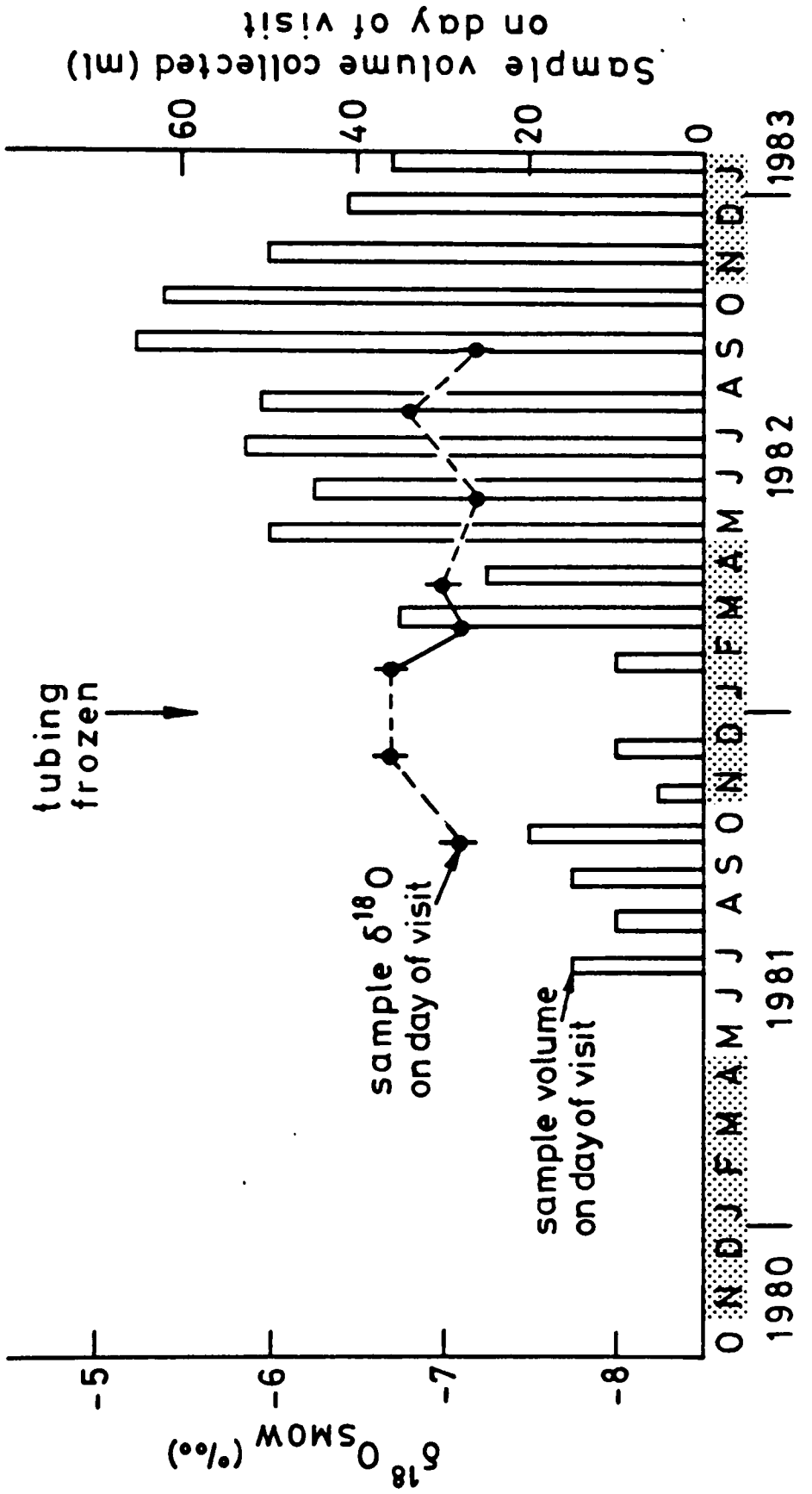


Fig. 4.48 Soil moisture obtained using the suction cup method in the Lambourn area (Manor Farm): amounts extracted and $\delta^{18}O$ of moisture on day of sampling

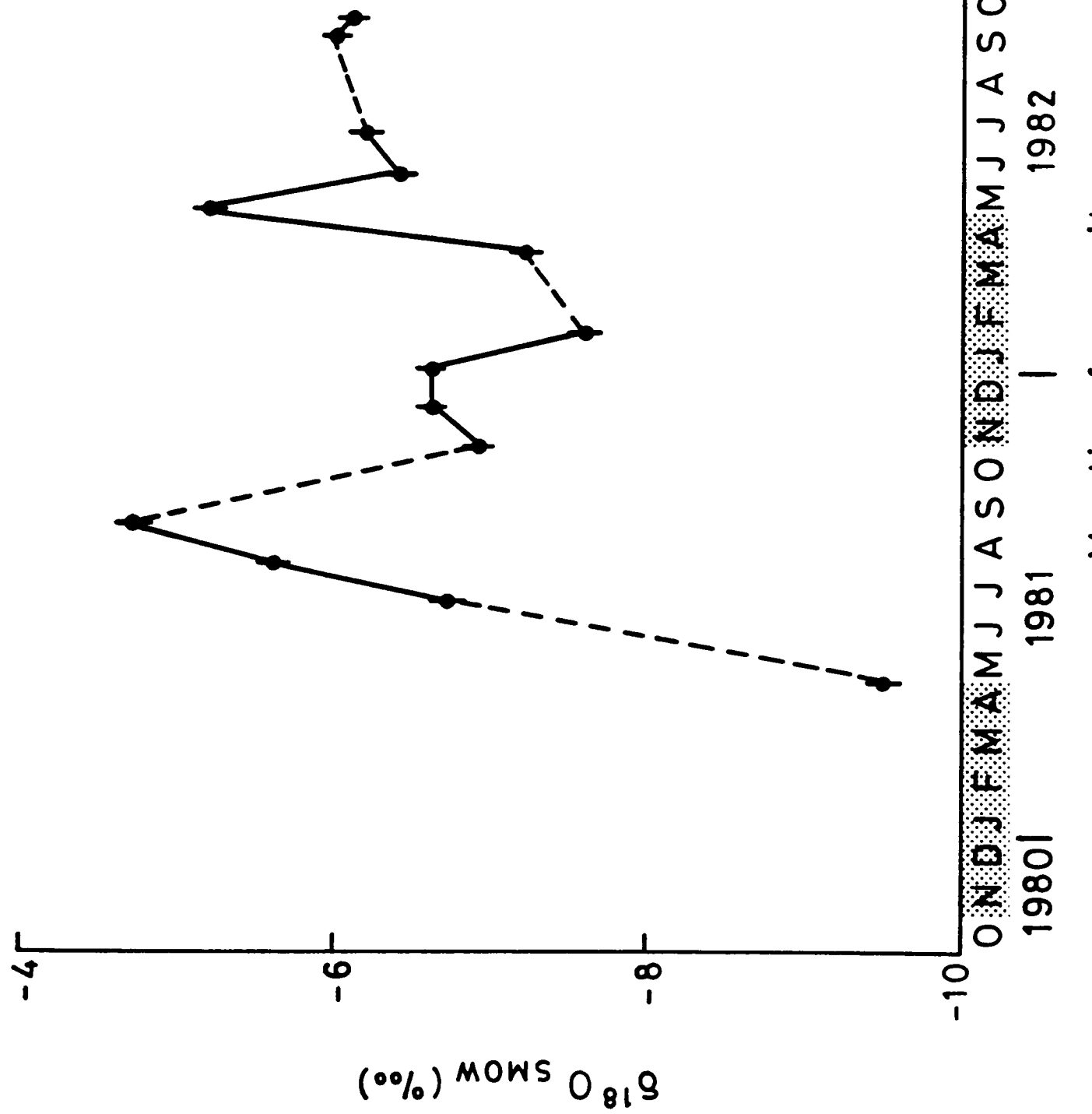


Fig. 4.49 $\delta^{18}O$ in monthly accumulations of cave drips in Chapel Cave, Malham area

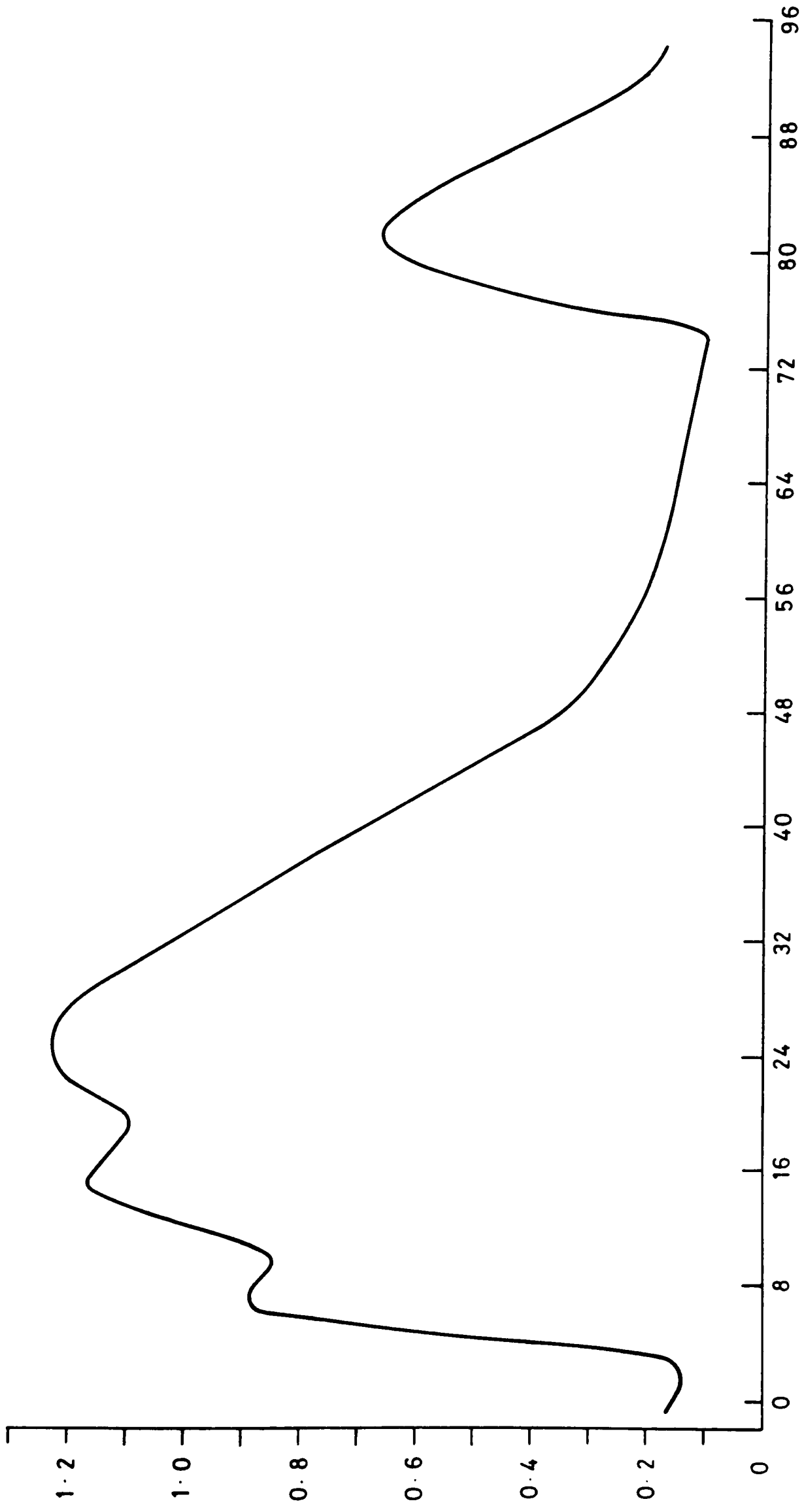


Fig. 4.50 Storm sampling at Waterhouses, October 1981: discharge at weir

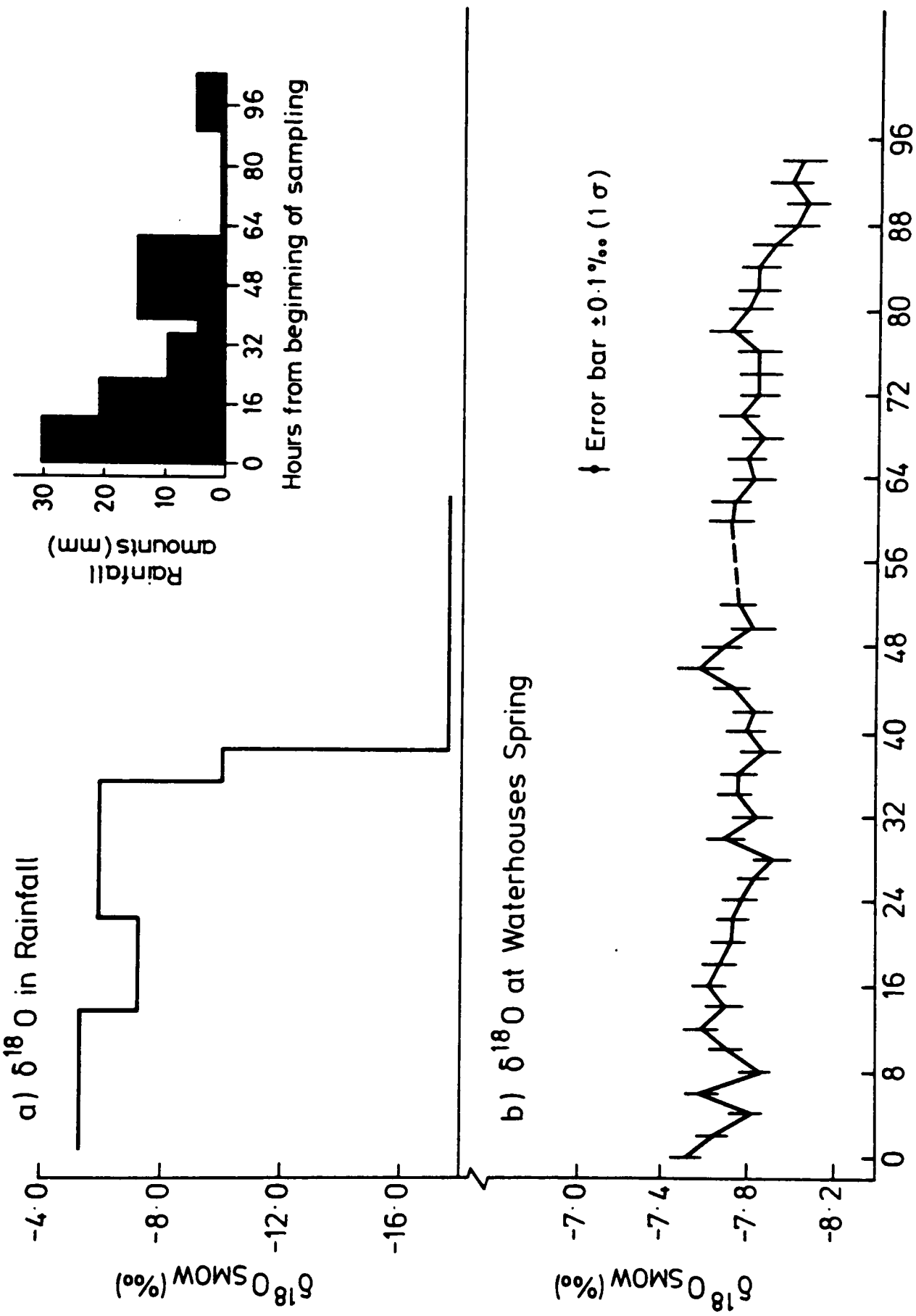


Fig. 4.51 Storm sampling at Waterhouses, October 1981: (a) $\delta^{18}O$ in rainfall, (b) $\delta^{18}O$ at Waterhouses Spring

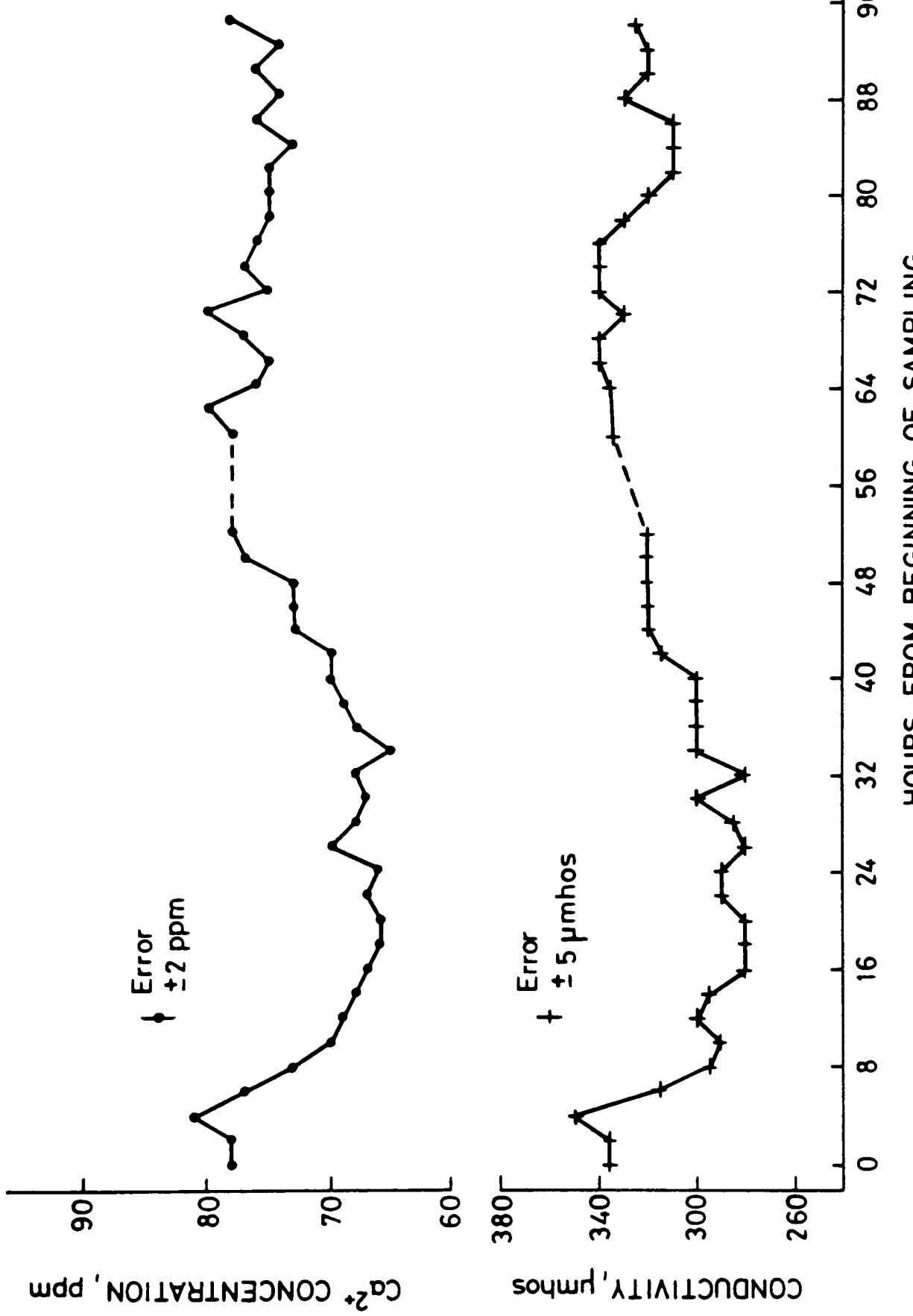


Fig. 4.52 Storm sampling at Waterhouses, October 1981 : Ca^{2+} concentration and conductivity

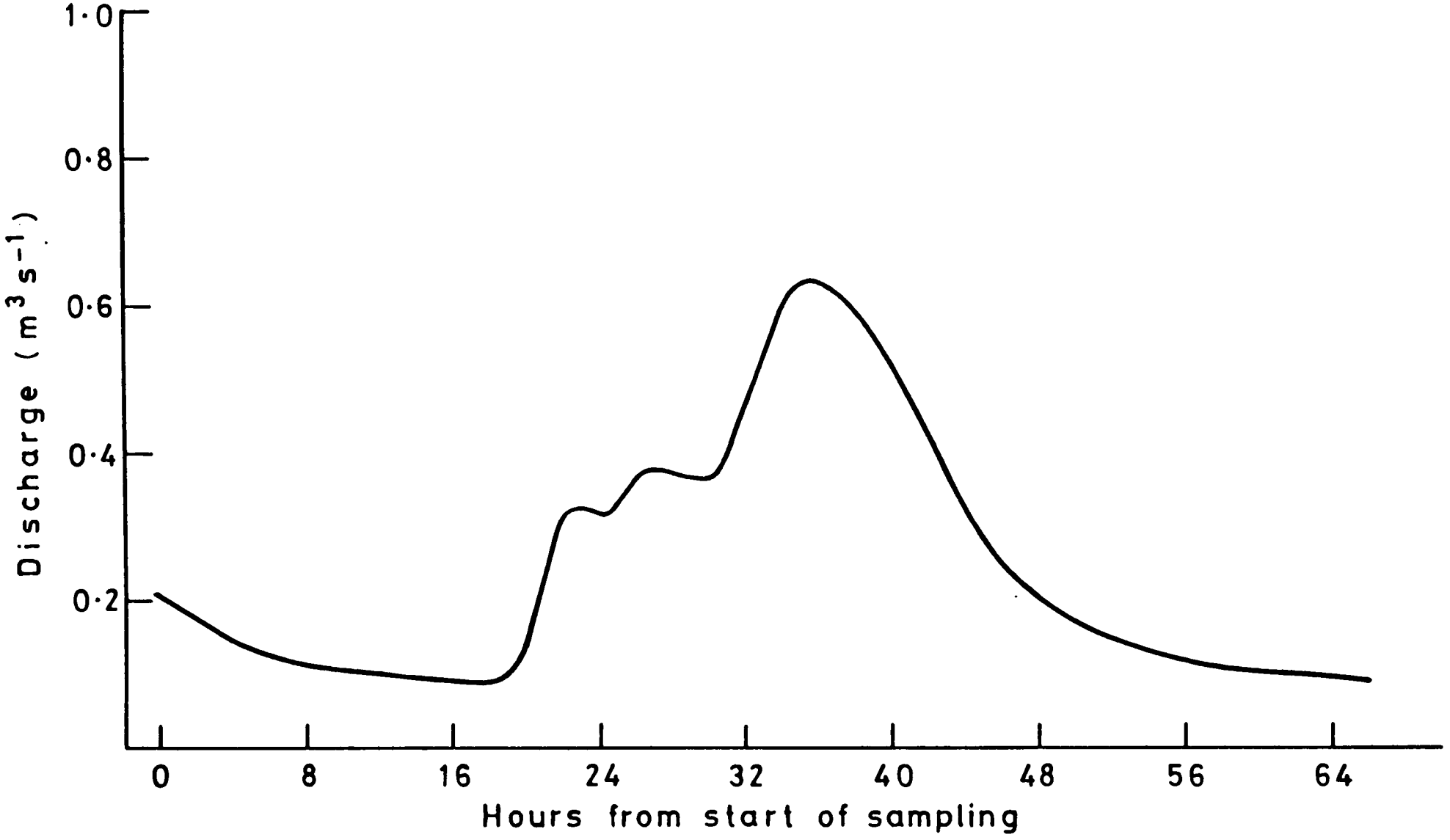


Fig. 4.53 Storm sampling at Waterhouses, November 1981: discharge at weir

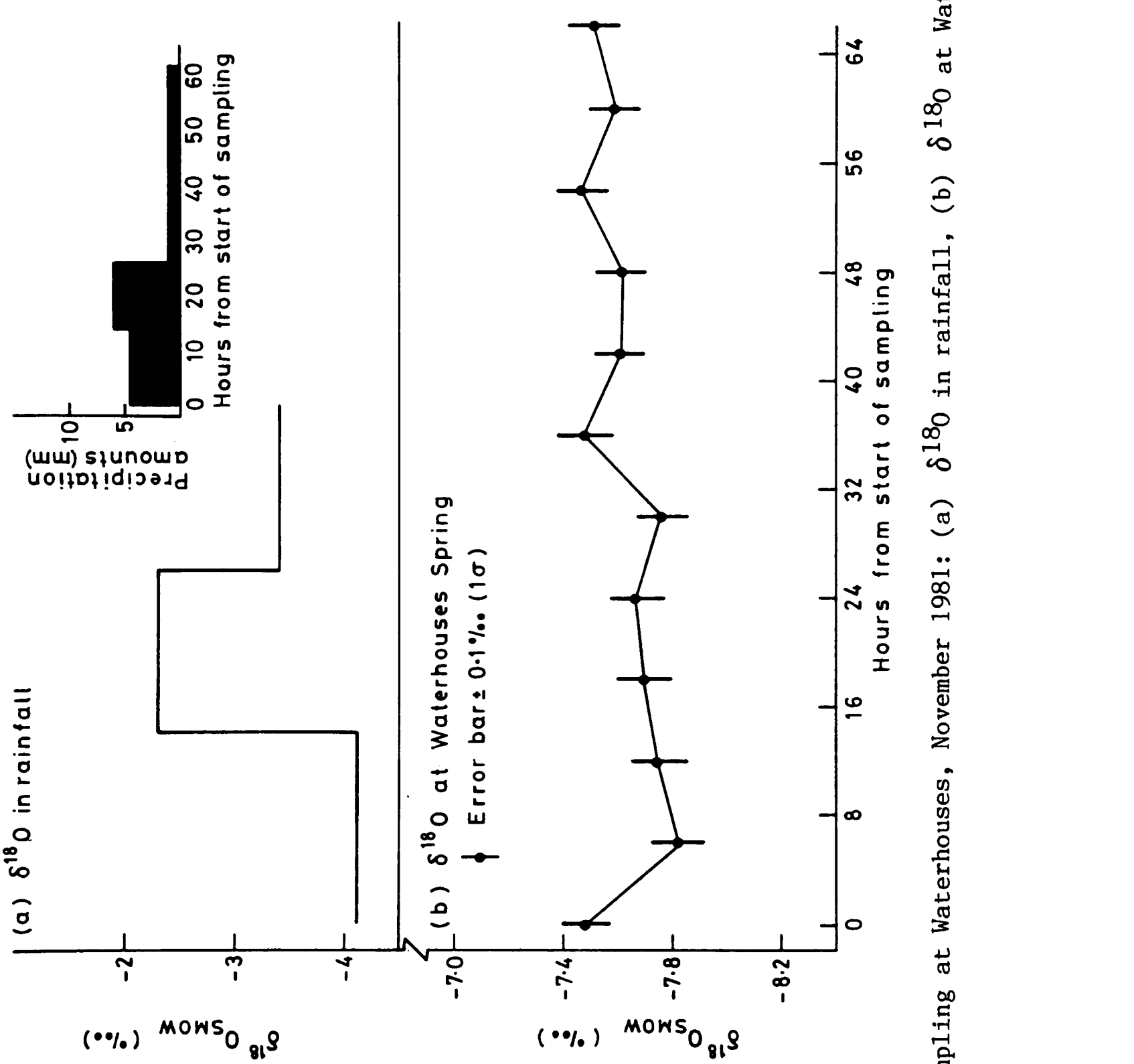


Fig. 4.54 Storm sampling at Waterhouses, November 1981: (a) $\delta^{18}O$ in rainfall, (b) $\delta^{18}O$ at Waterhouses Spring

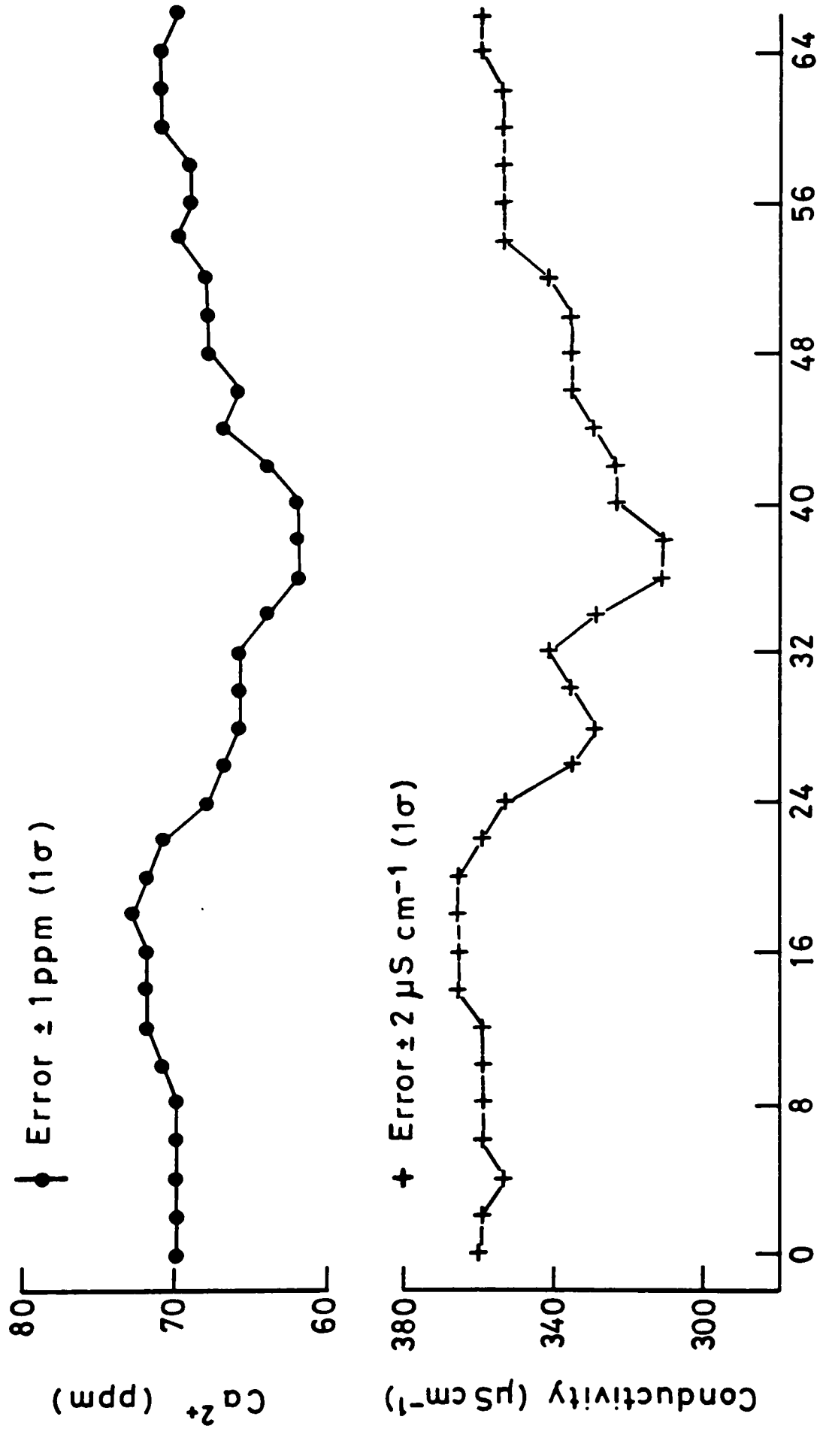


Fig. 4.55 Storm sampling at Waterhouses, November 1981: Ca^{2+} concentration and conductivity

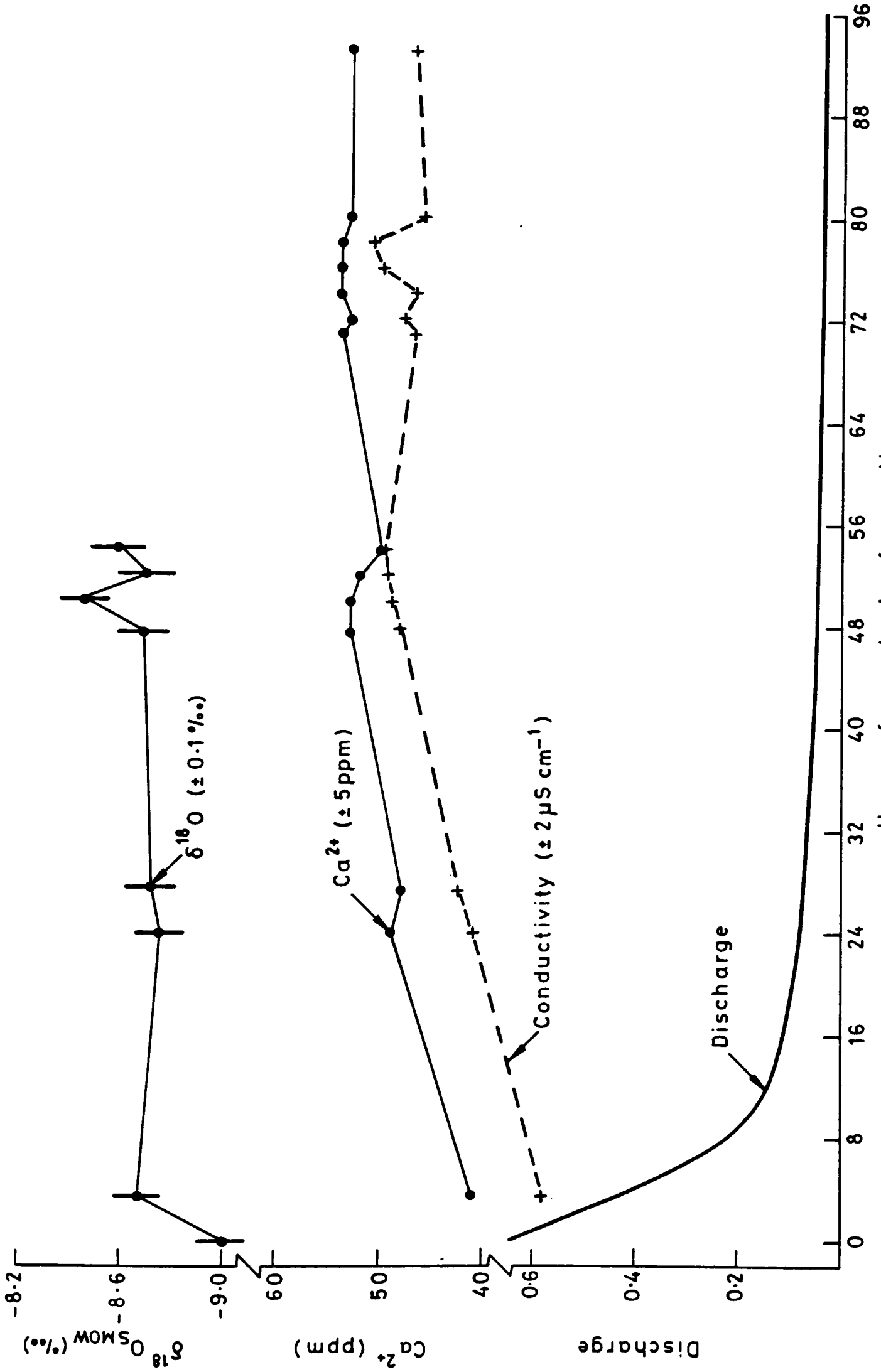


Fig. 4.56 Storm sampling at Waterhouses, February 1983: $\delta^{18}O$, Ca^{2+} concentration, conductivity and discharge at Waterhouses Spring

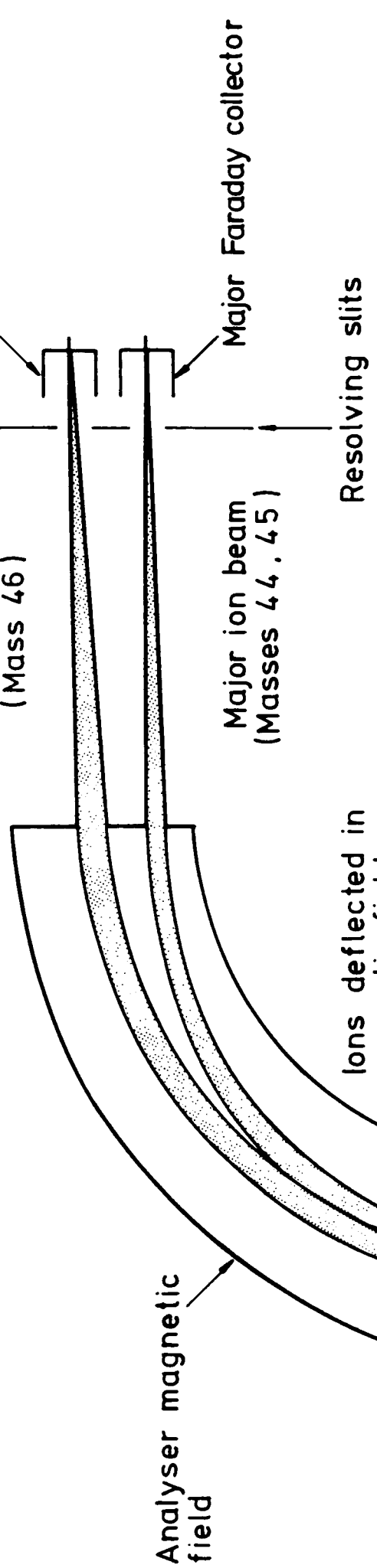


Fig. 6.1 Mass spectrometer ion optics, exemplified for the measurement of $^{18}O/^{16}O$



Plate I Malham Cove



Plate II Peaty podsol on Turf Hill



Plate III Malham Tarn and Tarn Outflow, with Malham Tarn Field Centre in the background; June 1982



Plate IV Airehead Spring (North) in low flow; May 1982



Plate V Waterhouses weir in low flow; June 1982



Plate VI Waterhouses weir storm event; November 1981



Plate VII Malham Tarn Field Centre meteorological station (White tritium collector prominent in near left-hand corner)



Plate VIII Lambourn area: view across the dry valley north of Great Shefford, November 1982



Plate IX River Lambourn at Shaw: the Crump weir in low flow, November 1982



Plate X Water meadow and River Lambourn at Manor Farm, November 1982



Plate XI Snowdon raingauge assembly, modified for the collection of precipitation under silicone oil



(a)



(b)

Plate XII Automatic rainfall sampler: (a) outer box and funnel, (b) inner distributing system



Plate XIII Soil moisture suction sampler and hand pump: Manor Farm, Lambourn area



Plate XIV Cave drip collection in Chapel Cave, Malham area

Property	Isotopic water molecules			
	H_2O [a,b]	$H_2{}^{18}O$ [a]	D_2O [b]	HDO [b]
Density (g cm^{-3}) at 20°C	0.9982		1.1050	
Density (g cm^{-3}) at 30°C		1.1078	1.1032	1.1049
Temperature (°C) at maximum density	4.0	4.3	11.2	
Boiling point (°C) at $101.3x10^3$ Pa	100.00	100.14	101.42	100.74
Melting point (°C) at $101.3x10^3$ Pa	0.00	0.28	3.81	
Ionic product at 25°C	$1x10^{-14}$		$0.16x10^{-14}$	

Vapour pressure ratios	H_2O [a,b]/$H_2{}^{18}O$ [a]	H_2O [a,b]/D_2O [b]
at 20°C	1.0094	1.1529
at 100°C	1.0050	1.0326

Key to superscripts:-

[a] Deuterium at natural abundance

[b] Oxygen at natural abundance

Table 2.1 : A comparison of physical properties and vapour pressure ratios of isotopic species of water (Sources : GAT, 1981b, HOEFS, 1973)

δ_a	δ_b	$(\delta_a-\delta_b)$	$10^3 \ln\alpha_{a-b}$	α
1.00	0	1.00	1.00	1.00000
5.00	0	5.00	4.99	1.00500
10.00	0	10.00	9.95	1.01000
15.00	0	15.00	* 14.89	1.01500
20.00	0	20.00	* 19.80	1.02000
10.00	5.00	5.00	4.96	1.00498
20.00	15.00	5.00	* 4.91	1.00493
30.00	25.00	5.00	* 4.87	1.00488
30.00	20.00	10.00	* 9.76	1.00980
30.00	15.00	15.00	* 14.76	1.01478
30.00	10.00	20.00	* 19.61	1.01980

* Denotes that a divergence is noticeable in the approximation

$$10^3 \ln\alpha \simeq \delta_a - \delta_b$$

NOTE: For explanation of notation, see text.

Table 2.2 : Comparison between values of $(\delta_a - \delta_b)$, α and $10^3 \ln\alpha$, to assess the acceptability of approximations.
(Source: FRIEDMAN & O'NEIL, 1977)

Materials between which fractionation taking place	Fractionation factors α_{18_O}	α_D	References
Water solid(ice)-vapour			
at 0°C	1.0152	1.132	MAJOUBE(1971a)
at -10°C	1.0166	1.151	MAJOUBE(1971a)
Water liquid-vapour			
at 20°C	1.0098	1.084	MAJOUBE(1971b)
at 0°C	1.0035	1.111	MAJOUBE(1971b), ARNASON(1969)
Water solid(ice)-liquid			
at 0°C	1.0035	1.0208	MAJOUBE(1971a), ARNASON(1969)

NOTE: The accuracy of experimental determinations (at 1σ) of α_{18_O} and α_D are estimated to be approximately 0.0005 and 0.005 respectively (FERRONSKY & POLYAKOV, 1982)

Table 2.3 : Examples of equilibrium stable isotope fractionation factors between different phases of water (Source: GAT, 1981b)

Dew point t_0, °C	After cooling to temperature $t=t_0-20$			After cooling to temperature $t=t_0-40$			Cooling mechanism
	Fraction remaining vapour, f	Isotopic composition of condensation, °/₀₀ δD_c	$\delta^{18}O_c$	Fraction remaining vapour, f	Isotopic composition of condensation, °/₀₀ δD_c	$\delta^{18}O_c$	
0	0.20	-150	-17.1				Isobaric cooling
20	0.26	-95	-11.7	0.05	-223	-28.2	
40	0.30	-63	-8.2	0.08	-153	-19.8	
0	0.29	-107	-12.9				Moist adiabatic cooling (at 1000 mb)
20	0.43	-52	-6.6	0.13	-144	-18.3	

NOTE: δ_c values express the isotopic compositions of new (instantaneously formed) condensate, after rainout due to the cooling of the vapour to the specified temperature (20°C or 40°C) below dew point (t_0) of the vapour. δ_c values are given with respect to the initial total vapour δ value of 0°/₀₀.

Table 2.4 : Calculations of δ values in precipitation, using the Rayleigh model of condensation (Source: DANSGAARD, 1964)

Dew point t_0, °C	After cooling to temperature $t=t_0-20$			After cooling to temperature $t=t_0-40$			Cooling mechanism
	Fraction remaining vapour, f	Isotopic composition of condensation, °/₀₀ δD_c	$\delta^{18}O_c$	Fraction remaining vapour, f	Isotopic composition of condensation, °/₀₀ δD_c	$\delta^{18}O_c$	
0	0.20	-150	-17.1				Isobaric cooling
20	0.26	-95	-11.7	0.05	-223	-28.2	
40	0.30	-63	-8.2	0.08	-153	-19.8	
0	0.29	-107	-12.9				Moist adiabatic cooling (at 1000 mb)
20	0.43	-52	-6.6	0.13	-144	-18.3	

NOTE: δ_c values express the isotopic compositions of new (instantaneously formed) condensate, after rainout due to the cooling of the vapour to the specified temperature (20°C or 40°C) below dew point (t_0) of the vapour. δ_c values are given with respect to the initial total vapour δ value of 0°/₀₀.

Table 2.4 : Calculations of δ values in precipitation, using the Rayleigh model of condensation (Source: DANSGAARD, 1964)

AUTHORS	DATE	LOCATION	ALTITUDE (m) Maximum	Minimum	Range	PRECIPITATION COLLECTION	ISOTOPIC ALTITUDE EFFECT (°/oo/100m) δD	δ18O	NOTES
FONTES et al.	1967	Alps, France (Evian basin)	870	320	550	Monthly at low altitudes only (385m, 395m)		0.42	Inferred from regional lapse rate (0.6°C/100m) and DANSGAARD coefficient (0.7°/oo/°C)
DINÇER et al.	1970	N. Czechoslovakia (Modry Dul basin)	1410	1030	380	Monthly at 2 stations (1030m, 1410m)		0.28 (±0.04)	Deviations from average effect caused by (1) difficulties of snow catch at high altitude; (2) evaporation from light rains
MOSER & STICHLER	1970	Mont Blanc, Alps.	4810	2200	2610	Fresh snow collected during 2-day ascent (17 sampling points)	4±1		Other sampling runs on Alps in fair agreement
ARNASON	1970	Iceland	620	100	520	Monthly at 3 stations (100m, 120m, 620m)	5.2		Annual average (5.4 in winter, 4.9 in summer)
SIEGENTHALER et al.	1970	Alps, Switzerland	1200	550	650	Fortnightly at 8 stations		0.2 to 0.37	Results from paired stations in nearby locations at different altitudes: variations in effect according to local climates. Scatter of points greater in winter than summer, and noticeable due to short sampling period.
PAYNE & YURTSEVER	1974	Cordillera de Marrabios Nicaragua	1745	0	1745	Monthly sampling at 5 stations		0.26	Weighted average for rainy season only
STAHL et al.	1974	Sperkhios Valley, Greece	2050	200	1850	None	1.2	0.16	Values obtained by inference from (known) recharge altitudes of spring waters

Table 2.5 The isotope altitude effect: a summary of published values, 1967 - 1984 (sources given)
(continued on next page)

AUTHORS	DATE	LOCATION	ALTITUDE (m) Maximum	Minimum	Range	PRECIPITATION COLLECTION	ISOTOPIC ALTITUDE EFFECT (°/oo/100m) δD	$\delta^{18}O$	NOTES
ZUPPI et al.	1974	Apennines, Italy	1452	4	1448	Monthly for 1 year at 15 stations		0.34 0.28	- West-facing slope - East-facing slope Effect more pronounced in Winter (eg.0.54 of 0.17 in Summer for the west-facing slope)
RAUERT & STICHLER	1974	Alps, Austria	3000	1750	1250	None	3		Inferred from seepage in mountain tunnel and depth of overburden
FONTES	1976	Kilimanjaro, Tanzania	6300	4600	1700	Single event, collection of fresh snow		0.3	Study by Tongiori } Reported by FONTES (1976)
		Mt. Cameroon, Cameroon	4070	0	4070	Not given		0.16	Study by Fontes & Olivry } Reported by FONTES (1976)
BARTOLOMI et al.	1979	Maritime Alps, Italy	2000	400	1600	Monthly at 7 stations (Oct. & April only)	2.5 (±0.1)	0.31 (±0.01)	Averages of 2 'representative' months only.
TENU & DAVIDESCU	1984	Transylvanian Alps, Romania	1250	136	1114	Monthly at 7 stations	1.7	0.21	Mean annual weighted values
LEONTIADIS et al.	1984	Kato Nevrokapi, Greece	2172	540	1632	None		0.44	Inferred from well-defined recharge altitudes of spring waters
This study	1984	Pennines, U.K. (Malham area)	657	185	472	Monthly at 3 stations (185m,395m,657m)		0.11	Average value of summer months only.

Table 2.5 (cont.) The isotope altitude effect: a summary of published values, 1967 - 1984 (sources given)

Isotopic grouping of precipitation	Features of $\delta^{18}O$ - δD relationship and δ variability	Features of stations in group	Example stations			
			Location	Variance(σ^2) $\delta^{18}O$	δD	Mean weighted d-excess, ‰
I	All samples plot relatively close together. No distinct $\delta^{18}O$- δD correlation	Island/ship stations with no dry season and little temperature variation.	Ascension Island, Atlantic Ocean	1.0	58.2	9.3
II	Wider δ-range than group I, caused by seasonal amount or temperature effect. Distinct linear $\delta^{18}O$- δD correlation, slope ~8	Typically coastal stations	Valentia, Ireland	2.4	119.5	7.4
III	Slope ~8 for low δ values. Slope<8 for δ's in relatively dry and/or warm season(s)	Continental climates	Vienna, Austria	18.2	832.9	6.7
IV	Slope <8	Generally dry or periodically dry climates; some island stations where net evaporation very high	Alice Springs, Australia	19.8	876.9	12.2
V	Slope > 8	Locations where light rains exchange with evaporated water. Certain high latitude stations.	Entebbe, Uganda	4.8	332.0	12.8

NOTE: Isotopic groupings are adapted by the author from DANSGAARD(1964). Isotopic data for the example stations are from YURTSEVER & GAT(1981).

Table 2.6 : Isotopic grouping of stations monitoring stable isotopes in precipitation (after DANSGAARD, 1964)

Climatic Type	Isotopic grouping of precipitation	IAEA/WMO network station example	Mean weighted value, °/oo (variance, σ^2) $\delta^{18}O$	δD	d-excess	Mean temperature, °C (σ^2)	Mean annual precipitation, mm.
1	I	Djakarta, Indonesia	-5.6 (3.5)	-35.1 (209.8)	10.2	27.0 (0.5)	1823
2	II	Manila, Philippines	-6.7 (7.2)	-41.9 (361.3)	11.8	27.1 (1.6)	1938
3	IV	Alexandria, Egypt	-4.5 (4.6)	-21.4 (220.1)	15.9	17.1 (10.9)	194
4	IV	Windhoek, S. Africa	-4.2 (19.4)	-22.5 (884.2)	12.2	21.1 (8.0)	379
5	V	Rio de Janeiro, Brazil	-4.8 (3.7)	-29.8 (296.1)	12.0	23.8 (4.8)	1241
6	II	Waco, USA	-4.0 (7.9)	-23.6 (302.5)	8.8	19.6 (66.9)	797
7	II	Valentia, Ireland	-5.8 (2.4)	-38.4 (119.5)	7.4	10.3 (9.0)	1345
8	II	Gibraltar, U.K.	-4.4 (4.4)	-25.3 (171.1)	9.8	16.7 (10.1)	971
9	III	Ankara, Turkey	-8.2 (14.8)	-55.8 (805.8)	9.8	12.4 (59.0)	428
10	III	Vienna, Austria	-9.4 (18.2)	-67.1 (832.9)	6.7	10.3 (59.2)	616
11	III	Edmonton, Canada	-17.4 (45.3)	-133.3 (2452.9)	6.6	4.4 (135.4)	425
12	II	Bethel, Alaska	-12.0 (15.3)	-94.4 (564.9)	1.2	-2.8 (114.9)	331
13	IV	Groennedal, Greenland	-11.5 (9.0)	-89.7 (380.1)	2.1	1.3 (21.9)	1091
14	IV	Argentine Bay, Antarctica	-10.6 (7.9)	-88.6 (388.6)	0.9	-3.9 (15.0)	389

NOTES : [a]After STRAHLER (1969)

[b]After DANSGAARD (1964). For explanation see table 2.6

Table 2.7 Comparison of STRAHLER's (1969) climatic type with isotopic grouping of precipitation; examples from the IAEA/WMO precipitation network

Water type	Frequency of sampling	Parameters measured in addition to stable isotopes	Sampling locations: Malham area	Sampling locations: Lambourn area
Precipitation	Monthly	Amount Tritium (at MTFC) Basic meteorological parameters (at MTFC and Warren Down Farm)	Malham Village Malham Tarn Field Centre (MTFC) Fountains Fell	Lechlade Warren Down Farm (Tritium extrapolated from Milford Haven)
	Weekly	Amount (and basic met. parameters at MTFC)	MTFC	Lechlade
	Between and within storms	Amount	MTFC	(AERE Harwell)
Surface waters	Monthly	Discharge Water chemistry $\delta^{13}C$ and tritium, at selected locations	Knowe Fell sinking stream Waterhouses spring West Great Close spring Smelt Mill sink Tarn Outflow Malham Cove springs Airehead springs (North and South)	Source of R. Lambourn R. Lambourn at Welford R. Lambourn at Shaw R. Winterbourne at Bagnor
	2-hourly (storm hydrograph)	Discharge Water chemistry	Waterhouses	-
Groundwaters	Monthly	Water level (not Higher Tren House) Water chemistry $\delta^{13}C$ (not at Lambourn boreholes)	Higher Tren House	Oakash Ashdown Park North Farm Manor Farm
Cave drips	Monthly	Amount	Chapel Cave	
Soil water	Monthly	Amount	Turf Hill	Manor Farm

Table 3.1 : Sampling programme for the Malham and Lambourn areas

Land use	Area (km^2)	%
Rough grazing	12.7	82
Grassland	1.9	12
Open water	0.6	4
Riparian area	0.3	2
TOTAL	15.5	100

Table 3.2 : Land use in the Malham area

Source	Methods	Sinks tested	Effects at springs	
			Malham Cove	Airehead
TATE, 1879	Water pulse	WS	No effect	Increased discharge
"	Water pulse	WS	Increased discharge after 2 h 10 min	Increased discharge after 1 h 25 min
THOMPSON, 1891	Fluorescein (c. 500 g)	WS	No effect after 3 h	No effect after 3 h
HOWARTH et al. 1900	Water pulse June 1899	WS	No effect	Increased discharge after c. 2 h
"	Water pulse Aug 1899(x2)	WS	Increased discharge	Increased discharge
"	Fluorescein (c. 100 g) May 1899	WS	No effect after 6 h	No effect after 6 h
"	Ammonium sulphate (650 kg) June 1899	WS	Trace detected after 11 days	Strongly positive after 11 days
"	Fluorescein (c. 1,500 g) June 1899	SM	Green colouration after 10 days	No effect
"	Sodium chloride (3,000 kg)July 1899	SM	Chloride detected after 11 days	No effect
SMITH & ATKINSON, 1977	Water pulse April 1972	WS	No effect	Increased discharge after 1 h 30 min
"	Lycopodium (4 kg) 1972	WS	Positive after 24-28.5 h	Positive after 13.5-24 h
"	Rhodamine WT (300 g) 1972	WS	Trace detected	Positive after 25.5 h
"	Lycopodium (4 kg) 1972	SM	Positive after 2-6.5 h	Positive after 6.5-10 h
"	Water pulse July 1973	WS	Discharge increased slightly after 4 h 15 min	Increased discharge after 1 h 30 min
"	Rhodamine WT (300 g) 1973	WS	Positive after 20 h	Positive after 43 h
"	Pyranine (100 g) 1973	SM	Positive after 22 h	Positive after 22 h

NOTE: WS= Water Sinks, SM= Smelt Mill

Table 3.3 : Summary of connections established by water tracing in the Malham area (Source: SMITH & ATKINSON, 1977)

Land use	Area (km^2)	%
Cereals	117	50
Grass	70	30
Root crops	24	10
Woodland	19	8
Rough grazing	2	1
Riparian area	2	1
TOTAL	234	100

Table 3.4 : Land use in the Lambourn area
(source:BRETTELL, 1971)

Site	Reference	NGR (SU)	Strata sampled	Observation borehole ?	Well top level (m O.D.)	Drilled depth below Datum (m)	Depth of lining (m)
Oakash	OAK	427 774	U. Ch.	yes	170.3	95	10
Ashdown Park	AP	281 816	U. Ch.	yes	162.1	34.4	no lining
North Farm:							
Chalk	NFCh	332 797	M. Ch. L. Ch	no	127.8	107	10
U. Greensand	NFUG	332 797	U.G.	no	127.8	130	100
Manor Farm	MF	331 754	U. Ch. M. Ch. L. Ch.	yes	106.8	101	12.8

NOTE: U.Ch.= Upper Chalk, M. Ch.= Middle Chalk, L. Ch.= Lower Chalk, U.G.= Upper Greensand

Table 3.5 : Boreholes routinely sampled in the Lambourn area

Site	Met. Office approved style ?	Description	Silicone fluid used ?	Sample collecting period (inclusive) From	To
MV	No	Harwell style collector, 11.5 cm diam. funnel	Yes	30.12.80	31.1.81
MV	Yes	Snowdon style, with polythene bottle receiver	Yes	31.1.81	1.2.83
MV	Yes	Bradford style	No	1.12.81	1.2.83
MTFC	No	Harwell style collector, 11.5 or 6.5 cm diam. funnel	Yes	30.12.80	1.2.83
MTFC	No	Measuring cylinder of THORPE (1981)	Yes	23.9.78	6.1.81
MTFC	Yes	Snowdon style, with polythene bottle receiver	Yes	4.1.82	1.2.83
MTFC	Yes	Bradford style	No	4.1.82	1.2.83
MTFC	No	Tritium collector	No	23.9.78	1.2.83 (continuing)
FF	Yes	Octapent style	No	1.12.80	1.2.83 (continuing)
LECH	No	Harwell style, 11.5 cm diam. funnel	Yes	1.1.74	3.2.83 (continuing)
LECH	Yes	Octapent style	No	8.5.81	6.1.83
WF	Yes	Snowdon style, with polythene bottle receiver	No	19.12.81	14.1.83
WF	Yes	Snowdon style, with polythene bottle receiver	Yes	19.12.81	14.1.83

NOTE: For site abbreviations, see sections 3.2.1(e) and 3.2.2(e)

Table 3.6 Precipitation collectors, for stable isotopes and tritium, used in the Malham and Lambourn study areas

Design	No. samples in cycle	Portability	Cycle running time*	Flexibility in sampling period ?	Pre-set delay before firing possible ?	Power	Relative cost (1 is highest)	Comments
Converted thermo-hydrograph	52	Good	$4\frac{1}{3}$ days	None	No	Clockwork	1	Funnel tracks across sample bottles; risk of sample loss between bottle positions. Much design and field test work needed. Rugged basic mechanism
Converted Packard belt (from liquid scintillation counter)	200	Poor	$16\frac{1}{2}$ days	Possible	Possible	Battery/ mains	2	Electronics to be designed. Belt mechanism not proven in field conditions
Rock & Taylor quartz timer + rotary arm distribution	48	Good	4 days	Yes 5 mins- 99 h	Yes 0 mins- 99 h	Battery	3	Mechanism proven in field conditions. Corresponds to mechanism of automatic stream water sampler

* Time taken for a complete cycle of samples, using a 2 h sampling period, to match that normally used for automatic stream sampling over storm events

Table 3.7 Comparison of specifications for three possible automatic rainfall sampler designs

Sampler ref.	Length to collar, cm	Sampler volume, cm^3	Uptake experiments* Vacuum set, 10^5 x Pa	Time elapsed in hours	Vacuum remaining	Volume of sample, ml	Location installed	Depth of cup, cm	Protection	Date sampled From	To
MFA	50	89					Manor Farm	50	None	2.7.81	14.1.83
MFB	70	114					Manor Farm	66	None	2.7.81	14.1.83
THC	75	125	8.0	0.42	-	85	Turf Hill	80	Cairn	3.10.81	4.6.82
			-	0.75	-	5					
THD	66	103	8.0	0.42	-	88	Turf Hill	70	Initially none; cairn from 31.1.82	3.10.81	4.6.82
			-	0.75	-	5					
THE	57	98	8.0	1.13	-	50	Turf Hill	33	Bag + cairn	3.10.81	4.6.82
			-	0.75	-	5					

* Uptake experiments were carried out prior to sampler installation, placing samplers in 11 cm depth of water. A vacuum could not be held when the ceramic pot was completely dry, but 8.0×10^5 Pa suction was held when moist (with no free water supply), for at least 2 hours

Table 3.8 Soil moisture suction sampler specifications and details of installation

Month of precipitation	Difference[a] (‰), $\delta^{18}O_{\text{no oil}} - \delta^{18}O_{\text{oil}}$				Difference[b] (‰)
	LECH[c]	WF	MV	MTFC	MTFC
Mar 1981	+0.8				
Apr 1981	+1.5				
May 1981	+0.1				
Jun 1981	0.0				
Jul 1981	+2.2				
Aug 1981	+5.8				
Sep 1981					
Nov 1981					
Dec 1981			+0.3		
Jan 1982		-0.2	+0.2	+0.6	0.0
Feb 1982		-0.3	+0.1	-0.1	+0.1
Mar 1982	+0.7	-0.1	-0.1	0.0	+0.1
Apr 1982		-0.6	-0.8	0.0	-0.1
May 1982		+0.3	-0.3	0.0	-0.5
Jun 1982		-0.1	0.0	0.0	-0.2
Jul 1982		+0.4	-0.8	+0.1	-0.2
Aug 1982		+1.4	0.0	0.0	0.0
Sep 1982		0.0	0.0	0.0	+0.2
Oct 1982		+0.2	-0.2	0.0	0.0
Nov 1982		-0.2	0.0	0.0	+0.3
Dec 1982		-0.2	-0.1	-0.4	+0.2
Jan 1982			0.0	+0.4	+0.1

NOTES: [a] The isotopic difference is calculated for pairs of standard style precipitation collectors (see table 3.6), except for LECH where comparison is between a non-standard Harwell collector and an Octapent collector.

[b] The difference calculated is $\delta^{18}O_{\text{Harwell collector}} - \delta^{18}O_{\text{Snowdon collector}}$ both collectors using oil.

[c] For site abbreviations, see sections 3.2.1(e) and 3.2.2(e)

Table 3.9 $\delta^{18}O$ differences in monthly precipitation measured between paired collectors, with and without the use of oil

Precipitation station at which $\delta^{18}O$ measured	Monthly mean meteorological parameters with which $\delta^{18}O$ difference correlated								
	Relative humidity			Earth temperature			Precipitation amount		
	n	r	significance level of r	n	r	significance level of r	n	r	significance level of r
Lechlade	6	-0.20	-	6	0.10	-	6	-0.29	-
Warren Down Farm	12	-0.13	-	12	0.59	**	12	0.20	-
Malham Tarn Field Centre	12	0.12	-	13	-0.15	-	13	0.04	-
Malham Village	13	0.79	***	13	-0.44	+	14	0.49	**

NOTE : For explanation of symbols denoting significance levels, see Appendix B.

Table 3.10 Correlation of $\delta^{18}O$ differences ('no oil' - 'oil') in monthly precipitation collection with monthly mean meteorological parameters.

Location and soil type	Sampling date	Method of soil moisture extraction								% yield of total moisture content (at 105°C)[a]
		Suction cup		Centrifuge				Vac. distillation		
				Drainage		Displacement				
		δ D	δ^{18}O	δ D	δ^{18}O	δ D	δ^{18}O	δ D	δ^{18}O	
Knowe Fell, peaty podsol, A horizon (0-15 cm)	7.6.81			-42						42.9%
				-39						27.6%
Knowe Fell, peaty podsol, B_s horizon (15-45 cm)	7.6.81	-50	-7.5			-39				45.2%
						-41				48.6%
Above Chapel Cave, rendzina (0-10 cm)	7.6.81			-41						35.4%
				-44						30.8%
Knowe Fell, peaty podsol, A horizon (0-15 cm)	28.6.81			-28[b]						4.4%
Knowe Fell, peaty podsol, B_s horizon (15-45 cm)	28.6.81	-52	-7.6			-24[b]				24.3%
Manor Farm water meadow, peat (10-40 cm)	2.7.81	-43		-40[b]						22.3%
Knowe Fell, peaty podsol, A horizon (0-25 cm)	4.9.81				-4.6[b]					10.1%
Knowe Fell, peaty podsol, B_s horizon (25-45 cm)	4.9.81		-7.9				-4.6[b]		-4.8	9.9%
										99.9%

NOTES: [a] Refers to methods requiring destructive sampling, ie. not suction cup extraction method

[b] Refers to extractions made using a slower speed centrifuge (4600 rpm, compared with 13000 rpm for other samples)

Table 3.11 Isotopic measurements of soil moisture extracted by four different methods

Sampling dates[a] From	To	$\delta^{18}O_{SMOW}$, ‰ FF	MTFC	MV	δD_{SMOW}, ‰ FF	MTFC[b]	^{3}H, TU MTFC	Precipitation, mm FF	MTFC	MV	EFF[c]	Temperature,[d] °C MA-TEMP	MP-TEMP	MEP-TEMP	SOIL	RH, %
30.10.80	2.11.80	x	-9.8	x	x	-61	20.7	353.2	272.5	x	252.6	6.1	7.5	7.6	7.3	92
2.11.80	29.11.80	x	-8.9	x	x	-54	31.5	250.0	200.8	x	183.3	x	x	x	5.2	90
29.11.80	7.1.81	-6.8	-7.2	x	-47	-42	25.3	307.0	233.3	x	212.6	2.7	3.4	3.5	3.1	93
7.1.81	31.1.81	-6.5	-8.5	-8.5	-39	-59	24.3	252.0	109.0	106.4	103.0	2.0	0.5	0.4	2.4	94
31.1.81	28.2.81	-8.3	-8.6	-9.0	-56	-60	31.0	109.0	74.4	87.0	60.6	-1.6	2.5	3.1	2.0	93
28.2.81	28.3.81	-8.4	-9.2	-8.2	-55	-59	32.4	423.0	326.4	300.0	303.3	3.9	4.1	4.1	3.5	91
28.3.81	2.5.81	-9.7	-8.0	-9.2	-67	-65	65.7	90.0	78.2	53.7	32.7	5.4	1.9	-0.3	5.1	84
2.5.81	6.6.81	-8.3	-7.7	-7.6	-58	-55	54.6	121.0	116.0	90.8	36.6	9.7	8.9	7.7	8.4	82
6.6.81	28.6.81	-5.6	-5.0	x	-39	x	x	128.0	69.2	x	37.1	10.3	10.6	10.9	11.6	85
28.6.81	26.7.81	-6.6	-6.3	-5.9	-47	-43	x	135.3	115.7	67.9	22.1	10.8	11.5	11.7	12.8	75
26.7.81	3.9.81	-5.3	-5.5	-5.2	-34	-34	44.5	103.9	70.7	77.1	12.7	13.2	12.7	11.5	13.6	87
3.9.81	2.10.81	-9.4	-8.9	-8.5	-65	-58	25.2	309.0	210.8	173.1	146.1	11.9	10.8	10.2	12.3	88
2.10.81	1.11.81	-7.2	-7.9	-7.4	-48	-48	29.7	276.0	222.6	213.1	203.5	5.5	7.0	7.1	6.8	92
1.11.81	2.12.81	-6.4	-7.4	-7.1	-38	x	17.6	234.0	177.1	150.5	162.3	4.9	5.2	5.1	5.4	92
2.12.81	2.1.82	-8.7	-8.9	-12.7	-60	x	13.1	141.6	83.0	57.2	83.0	-1.4	-2.0	-1.4	1.2	95
2.1.82	31.1.82	-8.7	-7.0	-7.0	-60	-43	15.8	208.4	167.4	133.8	163.6	1.5	4.5	4.6	1.0	96
31.1.82	28.2.82	-7.1	-7.8	-6.7	-43	-52	19.7	90.0	67.6	47.8	58.0	2.4	3.6	3.8	2.3	94
28.2.82	1.4.82	-9.4	-9.8	-8.8	-63	-67	35.2	220.0	209.4	151.1	185,5	3.6	3.3	3.3	2.9	85
1.4.82	2.5.82	-4.1	-6.1	-4.1	-26	-39	30.3	31.0	38.0	28.0	1.5	6.5	6.8	6.8	5.8	73
2.5.82	4.6.82	-6.5	-6.6	-5.7	-43	-46	21.5	107.0	84.0	57.6	3.2	9.8	7.8	7.2	9.6	x
4.6.82	1.7.82	-7.6	-7.6	-6.9	-52	-54	38.2	193.0	175.6	153.4	91.6	11.6	11.7	10.0	14.0	87
1.7.82	1.8.82	-4.4	-4.8	-3.6	-29	-33	34.5	29.5	19.6	17.8	0.1	13.6	13.4	11.2	14.1	84
1.8.82	1.9.82	-6.8	-6.9	-6.7	-45	-47	24.8	251.0	190.0	163.0	85.9	12.6	10.0	11.4	13.4	87
1.9.82	2.10.82	x	-7.7	-7.1	x	-47	25.0	139.0	123.8	80.7	78.7	11.4	10.6	9.8	11.5	90
2.10.82	31.10.82	-6.8	-7.0	-6.6	-42	-46	23.9	17.0	86.8	64.7	71.0	7.7	7.8	7.8	8.1	93
31.10.82	26.11.82	-8.4	-9.2	-8.5	-54	-60	x	269.0	235.7	173.5	221.8	5.6	5.5	5.5	6.4	94
26.11.82	1.1.83	-8.0	-9.4	-8.7	-53	-64	x	251.0	211.4	197.2	210.0	1.7	2.3	2.3	2.3	94
1.1.83	2.2.83	-7.3	-9.1	-8.4	-51	-62	x	238.0	228.3	220.5	206.6	3.2	3.9	4.6	3.2	94

NOTES: [a] Sampling dates for FF are on the first of each corresponding calendar month
[b] δ D for combined series MTFC/MV
[c] Effective precipitation at MTFC
[d] Monthly temperatures at MTFC (see section 4.2.1(e))

RH = relative humidity
For site abbreviations, see section 3.2.1(e)
x = data not available

Table 4.1 Malham area isotopes in monthly precipitation, and associated meteorological parameters

Sampling dates		$\delta^{18}O_{SMOW}$	Precipitation	Temperature, °C	
From	To	°/oo	amount, mm	MATEMP	MPTEMP
5.11.80	3.12.80	-8.2	42.4	5.5	8.8
3.12.80	8.1.81	-7.8	41.4	4.7	4.8
8.1.81	3.2.81	-7.4	29.1	4.0	3.5
3.2.81	4.3.81	-11.7	33.9	2.3	4.9
4.3.81	1.4.81	-7.3	95.9	7.7	8.4
1.4.81	8.5.81	-11.3	39.9	7.1	4.6
8.5.81	1.6.81	-7.2	76.2	11.3	10.3
1.6.81	1.7.81	-5.0	40.4	12.7	13.2
1.8.81	3.8.81	-11.2	47.4	15.1	14.6
3.8.81	1.9.81	-11.3	40.2	16.4	16.2
1.9.81	5.10.81	-6.1	124.7	13.7	12.5
5.10.81	2.11.81	-9.3	54.1	7.3	7.6
2.11.81	2.12.81	-7.5	35.7	6.5	7.4
2.12.81	5.1.82	-12.2	91.1	1.0	1.7
5.1.82	5.2.82	-9.3	44.2	1.9	0.4
5.2.82	8.3.82	-7.6	68.3	4.2	5.3
8.3.82	2.4.82	-11.5	55.4	5.5	5.2
2.4.82	5.5.82	-7.1	24.7	7.9	9.2
5.5.82	3.6.82	-4.6	16.3	12.4	10.5
3.6.82	8.7.82	-6.4	70.5	15.2	14.6
8.7.82	2.8.82	-6.9	26.8	16.3	17.2
2.8.82	2.9.82	-6.2	32.9	15.2	16.2
2.9.82	13.10.82	-6.4	106.7	12.8	11.7
13.10.82	1.11.82	-7.9	32.6	9.0	9.3
1.11.82	7.12.82	-9.0	92.9	6.5	8.1
7.12.82	6.1.83	-9.4	111.2	4.3	5.0

NOTE: Temperature data for the relevant periods are taken from Warren Down Farm (For abbreviations used, see section 4.2.1(e))

Table 4.2 Lechlade $\delta^{18}O$ in monthly precipitation, and associated meteorological parameters

Sampling dates		$\delta^{18}O_{SMOW}$	Precipitation, mm		Temperature, °C				Relative humidity, %
From	To	°/oo	Total	Effective	MATEMP	MPTEMP	MEPTEMP	Earth	
19.12.81	27.1.82	-10.6	101.0	98.6	1.1	2.0	2.0	1.8	97
27.1.82	25.2.82	-7.4	29.5	21.1	4.2	5.3	5.8	5.7	94
25.2.82	30.3.82	-8.3	101.5	74.2	5.3	5.3	5.5	5.2	88
30.3.82	30.4.82	-6.4	33.6	5.7	7.8	9.7	10.4	9.1	80
30.4.82	28.5.82	-5.4	32.5	0.1	10.8	9.0	6.9	11.4	80
28.5.82	29.6.82	-6.7	66.5	0.4	15.4	14.6	12.8	15.9	80
29.6.82	29.7.82	-4.4	13.6	0.0	15.1	14.6	-	16.5	85
29.7.82	12.9.82	-6.4	91.4	0.6	15.4	16.3	16.9	16.1	88
12.9.82	13.10.82	-7.7	112.4	1.2	12.2	11.4	10.8	13.8	95
13.10.82	17.11.82	-8.8	93.6	17.1	9.0	9.2	8.9	10.7	96
17.11.82	15.12.82	-8.9	99.4	82.4	4.2	5.9	5.8	8.3	96
15.12.82	14.1.82	-6.2	64.1	56.8	4.8	5.3	5.2	3.8	97

NOTE: For mean temperature abbreviations, see section 4.2.1(e)

Table 4.3 Warren Down Farm $\delta^{18}O$ in monthly precipitation, and associated meteorological parameters

Data set	n	model r	Parameter	Parameter Estimate	Standard Error	Parameter Ho value	Student's t for Ho	Significance of difference between parameter estimate and Ho value
Fountains Fell monthly precipitation (1.12.1980 - 3.2.1983)	25	0.98	Slope	7.28	0.30	0 8	24.54 -2.43	*** **
			Intercept	4.45	2.20	0 10	2.02 -2.52	* **
Malham Tarn Field Centre/ Malham Village monthly precipitation (30.12.1980 - 1.2.1983)	23	0.95	Slope	7.22	0.51	0 8 7.28±0.30	14.26 -1.53 0.10	*** + -
			Intercept	3.10	3.85	0 10 4.45±2.20	0.80 -1.79 -0.30	- * -
Fountains Fell : summer months only	11	0.98	Slope	7.28	0.43	0 8 7.28±0.30	16.86 -1.66 0.00	*** + -
			Intercept	3.73	2.98	0 10 4.45±2.20	1.25 -2.10 -0.19	** * -
Fountains Fell ; winter months only	14	0.98	Slope	7.54	0.43	0 8 7.28±0.43 7.28±0.30	17.54 -1.08 0.42 0.49	*** - - -
			Intercept	6.96	3.36	0 10 3.73±2.98 4.45±2.20	2.07 -0.90 0.72 0.62	* - - -

NOTE: Least - squares linear regression performed : δD = (Slope ± s.e.)δ^{18} + (Intercept ± s.e.)

NOTE: Ho is the null hypothesis parameter value. A two-tailed Student's t test for (n-2) degrees of freedom determines the probability of the parameter being significantly different from its Ho value.
Significance levels of this difference are expressed as symbols (*** etc.) which are explained in Appendix B.

Table 4.4 $\delta^{18}O$- δD linear regression for Malham area monthly precipitation data

Data set (full annual cycles)	n	Arithmetic means °/oo (σ^2)			Means weighted for total precipitation, °/oo			Means weighted for effective precipitation °/oo			Mean Monthly precipitation mm (σ^2)	Mean annual precipitation mm, in study period	Mean monthly temperature °C ($\sigma^{2\circ}C$)
		$\delta^{18}O$	δD	d-excess	$\delta^{18}O$	δD	d-excess	$\delta^{18}O$	δD	d-excess			
Fountains Fell (1.1.1981 - 1.1.1983)	24	-7.3 (2.3)	-48 (124.5)	10.1 (5.9)	-7.7	-51	10.6	-7.9	-52	11.3	172.0 (9877.4)	2064.4	-
Malham Tarn Field Centre (7.1.1981 - 1.1.1983)	24	-7.6 (1.9)	-	-	-8.0	-	-	-8.3	-	-	135.9 (5688.5)	1631.2	6.8 (21.7)
Malham Village (7.1.1981 - 1.1.1983)	24	-7.3 (3.6)	-	-	-7.6	-	-	-7.9	-	-	112.8 (4679.4)	1353.2	-
Malham Tarn Field Centre/Malham Village (7.1.1981 - 1.1.1983)	24	-7.5 (2.0)	-51 (102.7)	9.4 (8.1)	-7.9	-53	9.7	-8.1	-55	10.3	-	-	-
Lechlade (8.1.1981 - 6.1.1983)	24	-8.3 (4.8)	-	-	-8.4	-	-	-9.3	-	-	58.0 (968.8)	695.6	9.0 (24.0)
Warren Down Farm (19.12.1981 - 14.1.1983)	12	-7.3 (2.9)	-	-	-7.8	-	-	-8.7	-	-	69.9 (1202.7)	839.1	8.8 (25.0)

NOTES : All collections under oil, except for Fountains Fell data.

[a]Correlations of isotopic data applied to fill data gaps in September 1982 (at Fountain Fell) and June 1981 (at Malham Village)

Table 4.5 Stable isotopes in monthly precipitation, and monthly meteorological parameters : summary statistics for full annual cycles

Data set (all observations with some data gaps)	n	Arithmetic means, °/oo (σ^2) $\delta^{18}O$	δD	d-excess	Means weighted for total precipitation, °/oo $\delta^{18}O$	δD	d-excess	Means weighted for effective precipitation °/oo $\delta^{18}O$	δD	d-excess	n for meteor-ological data	mean monthly precipit-ation mm (σ^2)	Mean monthly temperature °C (σ^2)
Fountains Fell (1.12.1980 - 3.2.1983)	25	-7.3 (2.2)	-49 (118.8)	9.7 (5.3)	-7.6	-51	10.0	-7.8	-52	10.6	28	188.5 (10404.0)	-
Malham Field Centre (3.10.1980 - 1.2.1983)	28	-7.8 (1.9)	-	-	-8.2	-	-	-8.4	-	-	28	149.9 (6157.1)	6.5 (20.2)
Malham Village (7.1.1981 - 1.2.1983)	24	-7.4 (3.5)	-	-	-7.8	-	-	-8.0	-	-	24	119.4 (5021.1)	-
Malham Tarn Field Centre/ Malham Village (7.1.1981 - 1.2.1983)	25/23[a]	-7.5 (1.9)	-51 (111.5)	9.0 (111.5)	-7.8	-53	9.0	-7.9	-54	9.4	28	-	-
Lechlade (5.11.1980 - 6.1.1983)	26	-8.3 (4.6)	-	-	-8.3	-	-	-9.1	-	-	26	56.7 (910.4)	8.7 (23.2)

NOTES: Warren Down Farm results for the complete set of results are identical to those given in table 4.5

[a] 25 observations for $\delta^{18}O$ data; 23 observations for δD and d-excess data.

Table 4.6 Stable isotopes in monthly precipitation, and monthly meteorological parameters: summary statistics for original data sets

	$\delta^{18}O$ FF	$\delta^{18}O$ MTFC	$\delta^{18}O$ MV	PPT FF	PPT MTFC	PPT MV
$\delta^{18}O$ FF	-	0.78 *** 25	0.79 *** 23	-0.43 ** 25	-0.49 ** 25	-0.42 ** 23
$\delta^{18}O$ MTFC		-	0.83 *** 24	-0.62 *** 28	-0.66 *** 28	-0.61 *** 24
$\delta^{18}O$ MV			-	-0.35 * 24	-0.41 * 24	-0.32 * 24
PPT FF				-	0.99 *** 28	0.92 *** 24
PPT MTFC					-	0.97 *** 24
PPT MV						-

NOTES : Values given (1) correlation coefficient (r)
(2) level of significances of r (see Appendix B for symbol notation) and
(3) number of data pairs in correlation

$\delta^{18}O$ refers to $\delta^{18}O$ ($^{o}/oo$) in precipitation ; PPT is the amount (mm) of precipitation.

For site abbreviations, see section 3.2.1 (e)

Table 4.7 : Correlation matrix of monthly $\delta^{18}O$ in precipitation and precipitation amounts for three collection stations in the Malham area.

Lapse rate		$\delta^{18}O$ gradient with cooling (SIEGENTHALER & MATHER, 1983)		Calculated gradient	
Description	$^{o}C/100m$	Isobaric cooling $^{o}/oo/^{o}C$	Moist adiabatic cooling $^{o}/oo/^{o}C$	Resultant rate $^{o}/oo/100m$	Resultant difference $^{o}/oo/472m$
Met Office standard for U.K. (TAYLOR, 1976)	0.6	-0.62		-0.37	-1.7
			-0.38	-0.23	-1.1
Median U.K. saturated adiabatic lapse rate (TAYLOR, 1976)	0.5	-0.62		-0.31	-1.5
			-0.38	-0.19	-0.9
Northern Pennines (MANLEY, 1943)	0.69	-0.62		-0.43	-2.0
			-0.38	-0.26	-1.2

Table 4.8 Theoretical temperature lapse rates, isotopic cooling effects, and resultant $\delta^{18}O$ gradients with altitude.

	Stations between which $\delta^{18}O$ difference calculated	Division	n	Arithmetic Mean ‰	σ ‰	Mean weighted for precipitation ‰
(a)	FF - MTFC	All data	25	0.33	0.94	0.40
	"	Summer	11	-0.02	0.41	-0.02
	"	Winter	14	0.61	1.15	0.66
(b)	MTFC - MV	All data	24	-0.34	1.06	-0.43
	"	Summer	11	-0.54	0.33	-0.48
	"	Winter	13	-0.16	1.42	-0.39
(c)	FF - MV	All data	23	0.05	1.18	0.00
	"	Summer	10	-0.50	0.39	-0.46
	"	Winter	13	0.46	1.41	0.30

NOTE: FF = Fountains Fell (657m O.D.)
MTFC = Malham Tarn Field Centre (395m O.D.)
MV = Malham Village (185m O.D.)
"Summer" = May - October inclusive
"Winter" = November - April inclusive

Table 4.9 : Altitudinal differences in $\delta^{18}O$ in monthly precipitation; summary statistics for Malham area collection stations.

Data set[a]	n	Independent variable[b]	Intercept value	Intercept standard error	Slope value	Slope standard error	r	Significance level of r	% variance explained by model (r^2 x 100)
Malham Tarn Field Centre	27	MATEMP	-8.87	0.39	0.18	0.05	0.58	***	34
"	27	MPTEMP	-9.08	0.42	0.21	0.05	0.61	***	37
"	27	MEPTEMP	-9.05	0.43	0.21	0.06	0.58	***	34
"	28	MPPT	-6.01	0.44	-0.012	0.003	-0.66	***	44
"	28	MEPPT	-6.40	0.32	-0.011	0.002	-0.71	***	50
"	27	MATEMP	-7.20	0.48	0.15	0.04	0.80	***	64
		MPPT			-0.010	0.002			
"	27	MPTEMP	-7.40	0.46	0.18	0.04	0.82	***	67
		MPPT			-0.010	0.002			
Fountains Fell	25	MATEMP[c]	-8.13	0.47	0.13	0.06	0.42	**	18
"	25	MPPT	-6.14	0.56	-0.006	0.003	-0.43	**	18
Malham Village	24	MATEMP[c]	-9.09	0.51	0.26	0.06	0.65	***	42
"	24	MPPT	-6.40	0.73	-0.008	0.005	-0.32	+	10
Warren Down Farm	12	MATEMP	-9.25	0.81	0.22	0.08	0.66	**	44
"	12	MPTEMP	-9.46	0.92	0.24	0.09	0.64	**	41
"	12	MEPTEMP	-9.05	0.95	0.18	0.10	0.51	+	26
"	12	MPPT	-4.72	0.80	-0.036	0.010	-0.74	***	55
'	12	MEPPT	-6.29	0.46	-0.032	0.010	-0.72	***	52
"	12	MATEMP	-6.68	0.76	0.18	0.05	0.91	***	83
		MPPT			-0.031	0.007			
"	12	MPTEMP	-6.82	0.84	0.19	0.06	0.90	***	81
		MPPT			-0.031	0.007			
Lechlade	26	MATEMP[d]	-10.00	0.81	0.19	0.08	0.43	**	18
"	26	MPPT	-8.19	0.93	-0.002	0.014	-0.03	-	0

NOTES : For explanation of symbols denoting significance levels, see Appendix B

[a] Full data sets are used

[b] For explanation of independent variable names, see section 4.2.1(e)

[c] Temperature data used from Malham Tarn Field Centre for relevant sampling periods

[d] Temperature data used from Warren Down Farm for relevant sampling periods

Table 4.10 Linear regression of monthly $\delta^{18}O$ in precipitation against meteorological variables

Ref.	'In' date	$\delta^{18}O_{SMOW}$ ‰	Precipitation, mm		Temperature, °C			No. days with snow
			Total	Eff.	WATEMP	WPTEMP	WEPTEMP	
1	2.2.81	-8.3	45.5	41.7	3.4	3.4	3.4	1
2	9.2.82	-11.7	15.9	14.6	0.2	3.3	3.5	3
3	16.2.81	-7.5	2.3	0.0	-0.2	-1.1	-	4
4	23.2.81	-17.1	19.6	12.4	2.0	-0.9	-0.5	4
5	2.3.81	-8.2	75.8	70.9	2.1	3.6	3.7	1
6	9.3.81	-7.3	53.5	47.6	6.4	6.6	6.6	0
7	16.3.81	-11.4	137.0	130.0	2.6	3.2	3.2	2
8	23.3.81	-7.4	51.2	42.4	5.6	5.3	5.7	1
9	30.3.81	-7.2	4.8	0.1	6.1	4.4	3.5	0
10	6.4.81	-8.7	9.8	0.3	6.8	8.3	9.3	1
11	13.4.81	-8.5	0.7	0.0	6.8	8.7	-	0
12	20.4.81	-12.0	55.1	32.2	2.4	0.0	-0.6	4
13	27.4.81	-9.1	14.6	1.1	4.5	5.7	6.0	0
14	4.5.81	-9.0	22.9	10.3	7.0	4.9	3.1	2
15	11.5.81	-7.3	7.9	0.2	11.5	9.3	8.8	0
16	18.5.81	-5.8	30.2	8.2	10.0	10.4	10.1	0
17	15.5.81	-8.6	18.5	6.8	9.4	8.4	8.2	0
18	1.6.81	-6.9	30.7	11.0	11.2	11.3	11.0	0
19	8.6.81	-5.8	54.8	34.4	10.2	10.6	10.8	0
20	15.6.81	-3.2	10.7	2.7	10.3	10.8	12.0	0
21	22.6.81	-3.0	2.7	0.0	10.4	9.2	-	0
22	29.6.81	-6.2	12.6	0.1	10.4	10.5	10.7	0
23	6.7.81	-6.4	22.1	0.9	14.0	13.2	12.8	0
24	13.7.81	-7.0	25.2	0.9	11.8	11.6	11.5	0
25	20.7.81	-5.7	55.8	20.1	11.0	11.6	11.7	0
26	27.7.81	x	0.2	0.0	13.4	13.0	-	0
27	3.8.81	-5.9	36.9	2.6	13.8	13.2	12.6	0
28	10.8.81	-2.7	13.9	2.7	13.5	13.6	13.7	0
29	17.8.81	-6.2	19.0	7.4	11.2	11.1	10.9	0
30	24.8.81	-2.1	0.7	0.0	14.4	14.5	-	0
31	31.8.81	x	0.0	0.0	13.2	-	-	0
32	7.9.81	-10.0	21.8	0.9	14.2	14.4	14.5	0
33	14.9.81	-9.8	68.1	38.1	11.6	11.6	11.1	0
34	21.9.81	-11.4	60.5	51.3	9.8	9.4	9.3	0
35	28.9.81	-8.9	102.8	95.5	9.5	10.0	10.1	0
36	5.10.81	-8.0	89.6	84.0	7.3	7.8	7.8	0
37	12.10.81	-7.8	8.5	5.3	3.8	4.1	4.1	2
38	19.10.81	-7.9	28.5	23.6	5.2	5.6	5.7	0
39	26.10.81	-7.1	53.6	50.9	4.4	4.7	4.7	1
40	2.11.81	-3.4	15.8	13.2	6.0	8.1	8.1	0
41	9.11.81	-5.2	24.5	18.5	4.7	5.4	5.7	0
42	16.11.81	-8.4	49.9	46.5	4.8	4.7	4.7	0
43	23.11.81	-8.2	70.3	68.2	4.3	5.0	5.0	5
44	30.11.81	-5.4	31.2	30.4	3.2	3.9	3.9	1
45	7.12.81	-11.8	4.9	4.9	-2.5	-0.5	-0.5	3
46	14.12.81	-17.3	34.1	34.1	-3.2	-3.9	-3.9	3
47	21.12.81	-14.1	29.4	x	x	x	x	7

NOTE: 'In' date refers to start of week of precipitation sampling
x = data not available
Abbreviations for weekly temperature means are comparable with those denoting monthly means (see section 4.2.1(e))

Table 4.11 Malham Tarn Field Centre weekly $\delta^{18}O$ values in precipitation and weekly meteorological parameters (1981)

(continued on next page)

Ref.	'In' date	$\delta^{18}O_{SMOW}$ ‰	Precipitation, mm		Temperature, °C			No. days with snow
			Total	Eff.	WATEMP	WPTEMP	WEPTEMP	
48	1.1.82	-8.0	33.9	33.7	2.4	3.4	3.5	0
49	4.1.82	-8.6	60.8	60.1	0.3	5.7	5.8	4
50	11.1.82	-7.7	1.0	0.3	-2.5	0.1	0.1	0
51	18.1.82	-9.4	28.4	27.7	3.4	3.3	3.3	1
52	25.1.82	-4.3	40.0	38.9	3.8	4.4	4.4	2
53	1.2.82	-8.4	30.8	28.4	4.3	5.3	5.1	0
54	8.2.82	-6.5	23.4	20.5	4.0	3.3	3.2	0
55	15.2.82	x	0.0	0.0	1.3	=	=	3
56	22.2.82	-9.0	15.4	9.1	1.4	1.8	1.8	1
57	1.3.82	-8.4	71.4	65.2	3.9	4.0	4.1	0
58	8.3.82	-10.4	59.9	52.9	2.1	2.3	2.3	4
59	15.3.82	-9.7	72.7	64.4	2.4	3.2	3.3	6
60	22.3.82	x	4.4	3.1	5.8	2.7	2.7	0
61	29.3.82	-4.9	1.0	0.0	4.2	5.4	-	2
62	5.4.82	-6.7	21.7	0.8	6.5	8.4	8.7	2
63	12.4.82	x	0.0	0.0	5.5	-	-	0
64	19.4.82	x	0.0	0.0	7.4	-	-	0
65	26.4.82	-3.7	16.3	0.7	7.8	4.8	4.5	1
66	3.5.82	-8.0	32.2	1.5	4.2	3.6	3.6	3
67	10.5.82	-4.1	2.9	0.0	9.9	11.1	-	0
68	17.5.82	-7.5	22.4	0.8	10.5	10.8	10.9	0
69	24.5.82	-5.8	26.1	0.9	9.9	9.8	9.7	0
70	31.5.82	-7.1	20.7	1.1	17.0	19.8	19.8	0
71	7.6.82	-6.7	25.8	0.9	13.5	15.2	16.5	0
72	14.6.82	-5.9	22.3	4.5	9.5	8.5	8.0	0
73	21.6.82	-8.9	76.8	60.7	9.6	9.4	9.4	0
74	28.6.82	-7.7	31.3	x	x	x	x	0
75	5.7.82	-5.0	11.0	0.1	14.0	13.7	11.2	0
76	12.7.82	-5.5	5.6	0.0	13.7	13.1	-	0
77	19.7.82	x	0.0	0.0	13.9	-	-	0
78	26.7.82	-3.9	2.1	0.0	13.7	13.9	-	0
79	2.8.82	-4.5	11.8	0.4	17.7	17.6	17.6	0
80	9.8.82	-8.4	33.2	1.3	12.0	11.7	11.6	0
81	16.8.82	-6.6	98.2	55.7	10.7	10.9	10.7	0
82	23.8.82	-7.0	33.0	22.8	10.8	11.3	13.0	0
83	30.8.82	-5.1	16.3	6.0	11.3	11.3	11.3	0
84	6.9.82	-5.1	15.1	5.4	11.8	11.7	11.5	0
85	13.9.82	-4.1	3.8	0.1	13.8	17.8	17.8	0
86	20.9.82	-9.1	42.6	20.2	10.2	11.1	10.3	0
87	27.9.82	-7.4	59.3	52.9	9.4	9.4	9.4	0
88	4.10.82	-9.4	23.1	17.6	9.3	9.8	9.8	0
89	11.10.82	-7.6	27.3	22.0	6.9	6.5	6.4	0
90	18.10.82	-5.5	29.9	27.0	7.0	8.2	8.2	0
91	25.10.82	-5.1	6.4	4.5	7.1	4.9	4.7	0
92	1.11.82	-7.2	45.9	40.5	7.9	8.1	8.1	0
93	8.11.82	-9.8	65.4	61.2	6.7	6.6	6.6	1
94	15.11.82	-8.6	66.5	63.7	3.8	4.2	4.2	4
95	22.11.82	-10.6	61.9	59.8	2.9	3.6	3.6	0
96	29.11.82	-8.1	10.1	8.7	1.1	2.2	2.2	0
97	6.12.82	-13.3	57.6	56.5	1.6	1.7	1.7	2
98	13.12.82	-7.5	38.5	37.5	1.2	2.8	2.8	4
99	20.12.82	-9.3	69.9	68.9	1.3	1.3	1.3	3
100	27.12.82	-6.1	43.9	42.2	3.9	4.5	4.5	0
101	3.1.83	-9.4	82.7	75.1	3.7	4.2	4.3	3
102	10.1.83	-8.3	41.9	37.9	4.0	4.1	4.1	1
103	17.1.83	-3.2	21.8	15.8	2.0	3.7	4.1	1
104	24.1.83	-7.9	52.0	44.5	4.1	4.7	4.9	1

NOTE: 'In' date refers to start of week of precipitation sampling

x = data not available

Abbreviations for weekly temperature means are comparable with those denoting monthly means (see section 4.2.1(e))

Fig. 4.11 (cont.) Malham Tarn Field Centre weekly $\delta^{18}O$ values in precipitation, and weekly meteorological parameters (1982 and January 1983)

Ref.	'In' date	$\delta^{18}O_{SMOW}$ ‰	Precipitation total, mm
1	9.2.81	-13.5	4.0
2	16.2.81	-13.7	5.0
3	23.2.81	-12.1	6.0
4	2.3.81	-7.7	29.9
5	9.3.81	-6.3	32.8
6	16.3.81	-5.4	17.9
7	23.3.81	-4.6	8.6
8	30.3.81	-8.5	25.5
9	6.4.81	-3.2	3.5
10	13.4.81	x	0.9
11	20.4.81	-13.0	16.5
12	27.4.81	-7.7	9.3
13	4.5.81	-7.2	17.8
14	11.5.81	-8.0	12.5
15	18.5.81	-4.8	16.4
16	25.5.81	-8.6	26.8
17	1.6.81	-5.3	32.0
18	8.6.81	-4.4	8.8
19	15.6.81	x	1.0
20	22.6.81	x	0.0
21	29.6.81	-5.6	3.5
22	6.7.81	-4.1	3.7
23	13.7.81	-4.6	2.8
24	20.7.81	-15.1	19.8
25	27.7.81	-3.8	15.1

NOTE: 'In' date refers to start of week of precipitation sampling

x = data not available

Table 4.12 Lechlade $\delta^{18}O$ in weekly precipitation, and weekly precipitation amounts

Weekly precipitation at Malham Tarn Field Centre	n	$\delta^{18}O$ data			Mean weekly precipitation, mm (σ^2)	Mean monthly temperature, °C (σ^2)
		Arithmetic mean °/oo (σ^2)	Mean weighted for total precipitation °/oo	Mean weighted for effective precipitation °/oo		
All data 9.1.1981 - 5.2.1983	109[a]	-7.6 (7.29)	-8.3	-8.6	32.1 (727.05)	6.8 (22.02)
2 full annual cycles (reduced data set) 9.1.1981 - 2.1.1983	104[b]	-7.6 (7.37)	-8.3	-8.7	31.5 (730.38)	7.0 (22.12)

NOTES [a] If missing values are excluded, n = 102 for $\delta^{18}O$ data

[b] If missing values are excluded, n = 97 for $\delta^{18}O$ data

Table 4.13 Stable isotopes in weekly precipitation, and weekly meteorological parameters : summary statistics for Malham Tarn Field Centre

Data set[a]	n	Independent variable[b]	Intercept value	Intercept standard error	Slope value	Slope standard error	r	Significance level of r	% variance explained by model (r^2 x 100)
Malham Tarn Field Centre	100	WATEMP	-9.43	0.40	0.28	0.05	0.50	***	25
"	100	WPTEMP	-9.60	0.41	0.30	0.05	0.52	***	27
"	100	WEPTEMP	-9.64	0.42	0.28	0.05	0.50	***	25
"	100	WPPT	-6.17	0.40	-0.039	0.009	-0.39	***	16
"	100	WEPPT	-6.56	0.34	-0.038	0.009	-0.39	***	15
"	100	WATEMP WPPT	-8.14	0.51	0.25 -0.031	0.05 0.008	0.59	***	34
"	100	WPTEMP WPPT	-8.31	0.51	0.26 -0.031	0.05 0.008	0.61	***	37
Lechlade	22	WPPT	-7.52	1.42	-0.006	0.082	-0.02	-	2

NOTES : For explanation of symbols denoting significance levels, see Appendix B.

[a] Full data sets used

[b] Independent variable names of weekly values (prefix W) follow same pattern as those for monthly variables (prefix M); see section 4.2.1(e)

Table 4.14 Linear regression of weekly $\delta^{18}O$ in precipitation against meteorological parameters.

Circulation type	Features for recognition	Associated weather characteristics	Air mass type brought in
A	Anticyclone centred over U.K.	Mainly dry with light winds Warm with thunder in summer Cold in winter	cP
C	Depression stagnating or passing over U.K.	Mainly wet or disturbed weather Gales and thunderstorms possible	mP mPw mT
W	HP to south, LP to north of U.K.	Unsettled, with most rain in north and south of U.K.	mP mPw mT
NW	Anticyclone to west of U.K. (from Azores). Depressions deflected to Scandanavia	Unsettled, changeable weather, especially in north and east of U.K. Gale force winds Cooler than W type, milder than N type	mP mA
N	HP over Greenland LP over Scandanavia and North Sea	Cold and disturbed weather, especially in north and east, bringing late or early snow	mA
E	Anticyclone over Scandanavia and towards Iceland. Depressions over western North Atlantic and Azores	(Summer) Warm and thundery, dry in west (Winter) Cold in south, snow in east and north-east; fine in west and north-west	cA cP
S	HP over central and northern Europe blocks depressions, which track north or north-east	(Spring) Warm and thundery (Winter) Mild if oceanic air mass, cold if continental	mT cT (Summer) cP (Winter)

NOTE: Air mass types are after BELASCO (1952), circulation types after LAMB (1972)

HP = high pressure; LP = low pressure

Table 4.15 Circulation type recognition and associated weather and air masses (Sources: LAMB, 1972; PERRY, 1976; BARRY & CHORLEY, 1976)

Circulation Type	n[a]	$\delta^{18}O$, °/∞ mean	$\delta^{18}O$, °/∞ σ	Temperature, °C mean	Temperature, °C σ	Precipitation, mm mean	Precipitation, mm σ
Northerly	2	-6.1	4.3	7.4	4.2	8.6	8.4
Easterly	4	-8.5	4.3	10.2	7.2	25.2	35.5
Southerly	18	-8.1	2.7	7.5	4.7	29.4	15.3
Westerly	34	-7.2	1.9	5.7	3.9	42.3	24.7
North Westerly	5	-6.4	3.4	3.2	3.7	13.6	10.8
Anticyclone	5	-5.2	2.4	10.6	4.8	10.4	15.2
Cyclonic	20	-8.4	2.3	8.0	4.8	45.5	35.4
Undefined	12	-8.4	3.8	4.9	4.9	21.2	19.6

NOTE : [a] Number of observations taken as those for which $\delta^{18}O$ data available

Table 4.16 Summary statistics of weekly $\delta^{18}O$, temperature and precipitation by weekly dominant circulation type

Dependent variable	Step	Intercept	Circulation type regression coefficients								r	Significance of relationship	Percentage variance explained
			N	E	S	W	NW	A	C	U			
Weekly $\delta^{18}O$	1	-7.15							-0.051		0.31	***	9
(n= 101)	2	-7.00							-0.049	-0.091	0.36	***	13
	3	-6.71			-0.046				-0.044	-0.106	0.40	***	16
	4	-6.31			-0.057	-0.024			-0.046	-0.125	0.43	***	18
	5	-6.19		-0.068	-0.059	-0.026			-0.048	-0.118	0.45	***	20
	6	-6.03	-0.313	-0.073	-0.071	-0.030			-0.038	-0.124	0.47	***	22
	7	-5.94	-0.328	-0.071	-0.072	-0.031		-0.043	-0.039	-0.125	0.48	***	23
Residual $\delta^{18}O$	1	-0.32				0.026					0.24	**	6
(n= 99)	2	-0.43				0.025	0.058				0.29	**	8
	3	-0.36	-0.271			0.021	0.089				0.32	**	10
	4	-0.29	-0.279	-0.045		0.020	0.087				0.34	**	12
	5	-0.16	-0.226	-0.046		0.018	0.093		-0.016		0.36	**	13
	6	-0.08	-0.227	-0.042		0.017	0.091		-0.016	-0.031	0.37	**	14
	7	0.15	-0.264	-0.046	-0.028	0.014	0.081		-0.011	-0.043	0.38	**	15

NOTES: For explanation of significance symbols, see Appendix B

For explanation of $\delta^{18}O$ residuals see text, section 4.2.2(d)

Table 4.17: Forward stepwise linear regression of weekly $\delta^{18}O$ and residual $\delta^{18}O$ values against precipitation amounts, classified by circulation type at the time of precipitation

Date of sampling	Site of sampling, $\delta^{18}O_{SMOW}$ (‰)										
	AHN	AHS	MC	SM	TO	HTH	WH	WGC	GCS	KFS	CC
2.11.80	x	x	-7.8	-7,8	-7.2	x	x	x	-7.8	x	x
29.11.80	-7.2	-6.4	-7.6	-7.6	-7.3	x	x	x	-8.0	x	x
7.1.81	-7.3	-7.4	-7.5	-7.4	-7.2	-7.8	-7.4	-7.9	-7.8	x	x
31.1.81	-7.3	x	-7.4	-7.4	-7.2	-7.7	-7.3	-8.0	-7.9	x	x
28.2.81	-7.5	x	-7.8	x	-7.5	x	-7.6	-8.1	x	x	x
28.3.81	-8.0	x	-7.9	-7.8	-7.7	-7.5	-8.1	-7.9	-7.8	x	x
2.5.81	-8.0	-7.9	-9.6	-8.2	-7.7	-7.9	-9.6	-8.9	-9.6	-8.4	-9.5
6.6.81	-7.9	-7.4	-9.3	-7.6	-7.4	-7.8	-7.8	-8.4	x	-7.5	x
28.6.81	-7.3	-7.3	-8.6	-7.8	-7.0	-7.8	-7.6	-8.2	-8.1	-7.5	-6.7
26.7.81	-6.7	-6.6	-7.6	-7.4	-6.5	-7.8	-7.4	x	x	-7.4	-5.6
3.9.81	-6.9	-6.8	-7.7	-7.5	-5.9	-7,7	-8.2	x	x	-7.7	-4.7
2.10.81	-7.0	-6.6	-7.5	-7.5	-6.7	-7.5	-7.8	x	x	-7.3	x
1.11.81	-7.3	-7.2	-7.6	-7.5	-7.0	-7.7	-7.8	x	x	-7.4	-6.9
2.12.81	-7.3	-7.2	-7.4	-7.5	-7.0	-7.7	-7.2	-7.7	-7.7	-6.6	-6.6
2.1.82	-7.7	-7.6	-8.2	-8.0	-7.4	-7.7	-8.1	-9.3	x	-9.4	-6.6
31.1.82	-7.7	-7.8	-7.4	-7.1	-7.7	-7.8	-7.5	-8.4	-7.9	-6.9	-7.6
28.2.82	-7.7	-7.7	x	x	-7.6	-7.9	-7.6	x	x	-7.2	x
1.4.82	-7.7	-7.7	-7.7	-7.3	-7.6	-7.8	-7.9	-8.1	x	-7.5	-7.2
2.5.82	-7.7	-7.6	-7.7	-7.1	-7.0	-7.8	-7.9	-8.2	x	-7.2	-5.2
4.6.82	-7.0	-7.0	-7.6	-7.2	-6.4	-7.8	-7.7	-8.2	x	-7.6	-6.4
1.7.82	-6.7	-6.7	-7.4	-7.4	-6.4	-7.8	-7.7	-8.0	x	-7.5	-6.2
1.8.82	(dry)	-7.4	-7.8	-6.9	-5.7	-7.9	-7.9	-8.2	x	-7.3	x
14.9.82	-6.6	-6.5	-7.5	-7.3	-5.8	-7.8	-7.3	-8.0	x	-7.3	-6.0
2.10.82	-6.3	-6.3	-7.0	-7.0	-6.0	-7.8	-6.8	-7.4	x	-7.1	-6.1
26.11.82	-6.7	x	-7.4	-7.4	-6.9	x	-7.6	x	x	x	x
1.1.83	-7.4	x	-8.0	-7.1	-7.5	x	-8.2	x	x	x	x
2.2.83	-7.6	-7.8	-8.2	-8.1	-7.5	x	-8.7	x	x	x	x

NOTE: For site abbreviations, see section 3.2.1(e) x = data not available

Table 4.18 $\delta^{18}O$ results for ground and surface waters in the Malham area

Variable	Statistics	Location of measurement: Airehead (North)	Malham Cove	Smelt Mill	Tarn Outflow	Higher Tren House	Knowe Fell	Water-houses
$\delta^{18}O$ (‰)	$\bar{x}$	-7.3	-7.8	-7.5	-7.0	-7.8	-7.5	-7.8
	σ	0.5	0.6	0.3	0.6	0.1	0.6	0.5
	n	25	26	25	27	21	18	25
	CV%	-6.4	-7.4	-4.4	-8.9	-1.4	-8.1	-6.8
Alkalinity (HCO_3^-, ppm)	$\bar{x}$	187	200	271	149	124	151	101
	σ	21	32	42	29	11	47	86
	n	20	18	18	19	19	18	21
	CV%	11.2	15.8	15.6	19.6	8.9	31.4	85.3
Ca^{2+} (ppm)	$\bar{x}$	58	61	82	48	77	48	67
	σ	7	10	13	10	11	19	17
	n	11	12	12	12	11	11	12
	CV%	12.4	17.1	15.9	22.0	14.5	38.7	17.5
Conductivity ($\mu S\ cm^{-1}$)	$\bar{x}$	279	291	384	211	418	228	290
	σ	63	61	76	49	92	60	42
	n	21	20	19	20	19	18	21
	CV%	22.4	20.8	20.0	23.4	21.9	26.4	14.6
Discharge ($m^3\ s^{-1}$)	$\bar{x}$	0.322	0.279	0.040	0.277	-	0.004	0.106
	σ	0.339	0.340	0.043	0.306	-	0.006	0.143
	n	23	20	22	24	-	14	24
	CV%	105.3	121.8	106.3	110.2	-	177.2	135.8
pH	$\bar{x}$	7.3	7.4	8.0	8.2	7.3	7.8	7.3
	σ	0.2	0.2	0.3	0.4	0.2	0.4	0.2
	n	21	20	20	21	20	17	22
	CV%	2.6	2.7	3.8	4.5	2.6	5.2	2.9
Temperature (°C)	$\bar{x}$	7.6	7.5	8.6	8.0	8.2	9.1	7.3
	σ	2.4	0.6	4.7	5.9	1.4	4.6	0.5
	n	24	25	24	26	19	18	25
	CV%	32.0	8.7	54.4	74.8	16.8	51.2	7.2

NOTE: Summary statistics given are mean ($\bar{x}$), standard deviation (σ), number of observations (n) and coefficient of variation (CV%)

Table 4.19 Summary statistics of monthly $\delta^{18}O$ and hydrological/chemical variables: Malham area sampling sites

Location	Date sampled	δ D_{SMOW} °/₀₀
TO	2.11.80	-55
SM	,,	-54
MC	,,	-53
AHN	,,	-48
AHS	,,	-48
TO	29.11.80	-48
GCS	,,	-53
SM	,,	-50
MC	,,	-49
WGC	,,	-51
TO	7.1.81	-47
HTH	,,	-51
WH	,,	-48
AHN	,,	-49
SM	,,	-49
GCS	,,	-50
WGC	,,	-51
MC	,,	-47
TO	31.1.81	-48
MC	,,	-49
SM	,,	-44
AHN	,,	-48
WGC	,,	-53
TO	28.2.81	-49
TO	28.3.81	-53
TO	2.5.81	-54
MC	,,	-65
AHS	,,	-52
TO	6.6.81	-49
MC	,,	-55
TO	28.6.81	-50
MC	,,	-54
TO	26.7.81	-45
WH	,,	-51
TO	3.9.81	-43
TO	2.10.81	-46
TO	1.11.81	-48
KFS	,,	-45
TO	2.12.81	-47
THC(M)	,,	-46
THC(D)	,,	-44
THE(M)	,,	-46
TO	2.1.82	-48
THC(M)	,,	-44
THC(D)	,,	-45
THE(M)	,,	-38
THE(D)	,,	-42
TO	31.1.82	-51
THC(D)	,,	-45
THE(M)	,,	-38
THE(D)	,,	-45
TO	28.2.82	-50
TO	1.4.82	-52
TO	2.5.82	-47
TO	4.6.82	-44
TO	1.7.82	-44
TO	1.8.82	-41
TO	14.9.82	-41
TO	2.10.82	-43
TO	26.11.82	-45
TO	1.1.83	-49
TO	2.2.83	-51

NOTE: For soil moisture samples, (M) indicates sample accumulated over one month, (D) indicates sample extracted in one day

For site abbreviations, see section 3.2.1(e)

Table 4.20 δ D results for ground and surface waters and soil moisture in the Malham area

Date of sampling	Site of sampling $\delta^{13}C_{PDB}$ (‰)							
	AHN	MC	SM	TO	HTH	KFS	WGC	WH
2.10.81								-16.0
1.11.81	-12.9	-15.8	-14.6	-10.3	-14.1	-13.4		-15.7
2.12.81	-12.0			-10.0				-15.1
2.1.82	-12.6	-13.7	-13.3	-9.8				-14.3
28.2.82	-11.9			-8.5	-13.1	-9.0		-13.7
1.4.82	-12.5			-7.7	-13.2			-14.2
2.5.82	-12.8	-12.8	-11.4	-4.8	-13.0	-8.6	-14.6	-13.7
4.6.82	-10.6			-4.4				-13.7
1.7.82	-10.1			-6.0				-15.3
1.8.82	-13.6*			-4.4				-15.1
14.9.82	-12.0			-5.4				-14.3
2.10.82	-10.7			-7.9				-14.7

NOTE: * Sample from AHS (AHN dry)

For site abbreviations, see section 3.2.1(e)

Table 4.21 $\delta^{13}C$ results for Malham area ground and surface waters

MALHAM AREA

Sampling location	Date of sampling	^3H (TU)
WH	3.12.81	25.5
WH	2.1.82	26.7
TO	,,	26.3
WH	31.1.82	29.5
WH	28.2.82	22.9
KFS	,,	36.6
TO	,,	35.0
AHN	,,	34.9
WH	1.4.82	20.0
AHN	2.5.82	29.3
TO	,,	26.1
WH	,,	39.0
WH	4.6.82	43.3
TO	,,	27.2
AHN	,,	31.9
WH	1.7.82	20.3
TO	,,	44.7
AHN	,,	56.2
KFS	,,	33.3
WH	1.8.82	38.0
TO	,,	25.1
AHS	,,	70.8
WH	14.9.82	24.5
TO	,,	30.2
AHN	,,	27.9
WH	2.10.82	28.7
TO	,,	29.0
AHN	,,	25.7

LAMBOURN AREA

Sampling location	Date of sampling	^3H (TU)
WEL	7.11.81	21.6
WEL	18.12.81	14.0
SCE	,,	20.6
WEL	30.3.82	18.8
SCE	,,	24.5
BAG	,,	41.6
SHAW	,,	24.1
WEL	30.4.82	22.3
SCE	,,	16.2
SHAW	,,	42.7
WEL	7.6.82	20.4
WEL	29.6.82	19.4
SCE	,,	38.8
BAG	,,	20.8
SHAW	,,	13.6

NOTE: Measurement error (at 1σ) is 1-3 TU on all samples (including tritium in precipitation in table 4.1)

For site abbreviations, see sections 3.2.1(e) and 3.2.2(e)

Table 4.22 Tritium results for ground and surface waters in the Malham and Lambourn areas

Date of sampling	Site of sampling, $\delta^{18}O_{SMOW}$ (‰)								
	SCE	WEL	BAG	SHAW	MF	NFUG	NFCh	AP	OAK
17.10.80	x	-7.5	x	x	x	x	x	x	x
25.1.81	-7.4	-7.5	-7.3	x	-7.2	-7.6	-7.6	-7.3	-8.1
5.3.81	-7.6	-7.5	-7.2	x	-7.2	x	x	-7.5	-8.0
30.3.81	-7.5	-7.3	x	-7.4	-7.2	x	x	-7.4	-8.2
29.4.81	-7.5	-7.5	-7.3	-7.5	-7.3	x	x	-7.1	-7.9
1.6.81	-7.5	-7.5	-7.3	-7.3	-7.2	-7.5	-7.5	-7.2	-8.2
1.7.81	-7.5	-7.4	-7.2	-7.2	-7.2	x	x	-7.3	-8.2
23.7.81	-7.5	-7.5	-7.4	-7.6	-7.2	-7.4	-7.5	-7.3	-8.2
31.8.81	-7.7	-7.5	x	-7.3	-7.1	x	x	-7.4	-8.2
28.9.81	-7.6	-7.4	x	-7.4	-6.8	-7.1	-7.4	-7.4	-8.0
29.10.81	-7.2	-7.4	-7.2	-6.7	-7.1	x	x	-7.1	-8.0
27.11.81	-7.6	-7.3	-7.3	-7.3	-7.1	-7.5	-7.5	-7.4	-8.2
18.12.81	-7.4	-7.6	-7.4	-7.3	x	x	x	x	x
28.1.82	-7.4	-7.4	-7.4	-7.3	-7.1	-7.5	-7.5	-7.4	-8.2
25.2.82	-7.5	-7.5	-7.3	-7.2	-7.0	x	x	-7.4	-8.2
30.3.82	-7.6	-7.5	-7.3	-7.3	-7.2	-7.3	-7.3	-7.4	-8.2
30.4.82	-7.6	-7.4	-7.4	-7.4	-7.2	x	x	-7.4	-8.2
7.6.82	-7.5	-7.4	-7.4	-7.4	-7.0	-7.5	-7.5	-7.5	-8.1
29.6.82	-7.5	-7.4	-7.4	-7.4	-7.1	x	x	-7.4	-8.2
29.7.82	-7.5	-7.4	-7.5	-7.4	-7.0	x	x	-7.4	-8.2
12.9.82	-7.5	-7.5	-7.4	-7.4	-7.0	x	x	x	-8.1
14.10.82	-7.5	-7.6	-7.6	-7.6	-7.2	x	x	x	-8.2
17.11.81	-7.4	-7.5	-7.4	-7.4	-7.2	x	x	x	-8.2
15.12.82	-7.7	-7.6	-7.5	-7.5	-7.2	x	x	x	-8.3
14.1.83	-7.6	-7.5	-7.5	-7.4	-7.3	x	x	x	-8.3

NOTE: For site abbreviations, see section 3.2.2(e) x = data not available

Table 4.23 $\delta^{18}O$ results for ground and surface waters in the Lambourn area

Variable	Statistics	Source	Location of measurement: Welford	Bagnor	Shaw	Manor Farm borehole	North Farm (UG) borehole	North Farm (UG) borehole	Ashdown Park borehole	Oakash borehole
$\delta^{18}O$ ($^{o}/oo$)	$\bar{x}$	-7.5	-7.5	-7.4	-7.4	-7.1	-7.4	-7.5	-7.3	-8.2
	σ	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1
	n	24	25	21	22	23	8	8	18	23
	CV%	-1.3	-1.1	-1.4	-2.4	-1.8	-2.2	-1.2	-1.4	-1.2
Akalinity (HCO_3^-, ppm)	$\bar{x}$	265	284	326	303	171	291	275	312	398
	σ	14	8	9	8	19	23	15	7	46
	n	22	21	22	21	15	16	15	13	15
	CV%	5.4	2.8	2.8	2.7	11.2	7.9	5.6	2.3	3.0
Ca^{2+} (ppm)	$\bar{x}$	94	102	118	105	59	41	42	121	123
	σ	12	8	13	7	14	40	37	16	6
	n	12	11	12	12	11	10	11	9	10
	CV%	12.6	7.9	11.0	6.8	23.8	97.8	88.3	13.1	5.0
Conductivity ($\mu S\ cm^{-1}$)	$\bar{x}$	459	495	565	450	257	448	436	534	516
	σ	94	89	130	84	43	78	72	130	103
	n	24	24	22	21	15	16	15	13	15
	CV%	20.5	18.0	23.0	18.6	16.9	17.4	16.4	24.4	19.9
Discharge or water level ($m^3 s^{-1}$ or m)	$\bar{x}$	0.193	1.227	0.239	2.084	0.72	1.89	3.23	20.56	54.80
	σ	0.168	0.536	0.112	0.726	0.27	0.74	1.73	3.54	3.39
	n	24	25	25	25	23	21	22	15	20
	CV%	87.3	43.7	46.9	34.9	37.4	38.9	53.4	17.2	6.19
pH	$\bar{x}$	7.3	7.6	7.6	7.8	7.6	8.0	8.0	7.2	7.1
	σ	0.2	0.2	0.2	0.3	0.2	0.3	0.3	0.2	0.1
	n	24	24	22	21	14	15	14	13	14
	CV%	2.1	2.1	2.3	2.6	2.6	3.7	3.9	2.2	1.3
Temperature (^{o}C)	$\bar{x}$	10.0	9.6	9.9	10.0	11.1	10.5	9.7	9.8	9.6
	σ	0.9	2.4	2.5	3.2	2.5	2.0	1.4	0.2	0.2
	n	23	23	22	22	22	20	20	17	22
	CV%	9.3	24.8	25.3	31.5	22.5	19.4	14.2	1.7	2.1

NOTE : Summary statistics given are mean ($\bar{x}$), standard deviation (σ), number of observations (n) and coefficient of variation (CV%)

Table 4.24 Summary statistics of monthly $\delta^{18}O$ and hydrological/chemical variables: Lambourn area sampling sites

Location	Date sampled	δ D ‰ SMOW
WEL	17.10.80	-50
NFCh	25.1.81	-52
NFUG	,,	-51
AP	,,	-50
MF	,,	-48
OAK	,,	-56
WEL	,,	-51
SCE	,,	-53
BAG	,,	-50
OAK	5.3.81	-53
AP	,,	-48
WEL	,,	-52
SCE	,,	-51
OAK	2.4.81	-50
OAK(90)	,,	-50
SHAW	,,	-54
SCE	,,	-52
OAK(70)	,,	-56
OAK(57)	,,	-56
WEL	,,	-52
NFUG(3)	29.4.81	-48
NFUG(20)	,,	-50
NFCh(2)	,,	-51
NFCh(20)	,,	-50
OAK	,,	-52
OAK(53)	,,	-52
OAK(90)	,,	-50
MF(20)	,,	-50
AP	,,	-48
AP(25)	,,	-49
WEL	,,	-49
WEL	1.6.81	-53
WEL	1.7.81	-50
WEL	23.7.81	-52
MF	,,	-50
OAK	,,	-59

NOTE: A number in brackets after a borehole reference indicates a depth sample, with depth below well-head given in metres

For site abbreviations, see section 3.2.2(e)

Table 4.25 δ D results for ground and surface waters in the Lambourn area

Date of sampling	Site of sampling $\delta^{13}C_{PDB}$ (‰)			
	SCE	WEL	BAG	SHAW
29.10.81	-13.6	-13.0		-12.8
27.11.81	-13.6			-12.8
18.12.81	-13.4	-12.6		-12.3
30.3.82	-13.8		-12.9	-12.7

NOTE: For site abbreviations, see section 3.2.2(e)

Table 4.26 $\delta^{13}C$ results for Lambourn area surface waters

Water sampling location for $\delta^{18}O$	Correlation with $\delta^{18}O$ in precipitation									
	Monthly sampling sites			Weekly samples and decay functions						
	FF	MTFC	MV	MTFC	DEC (1_T)	DEC (2_T)	DEC (3_T)	DEC (1_E)	DEC (2_E)	DEC (3_E)
Airehead (North)	.33 + 23	.28 + 25	.35 + 22	.08 - 22	.28 + 19	.31 + 19	.35 + 19	.30 + 19	.32 + 19	.36 + 19
Airehead (South)	.20 - 19	.11 - 21	.28 - 18							
Malham Cove	.24 - 23	-.02 - 26	.29 + 22	.11 - 22	.12 - 19	.13 - 19	.16 - 19	.14 - 19	.17 - 19	.20 - 19
Smelt Mill	.42 ** 22	.34 * 25	.64 *** 21	.50 ** 21	.39 + 18	.43 * 18	.43 * 18	.39 + 18	.43 * 18	.42 * 18
Tarn Outflow	.58 *** 24	.59 *** 27	.59 *** 23	.28 + 23	.35 + 19	.38 + 19	.42 * 19	.36 + 19	.37 + 19	.41 * 19
Higher Tren House	-.26 - 20	-.42 * 21	-.32 * 19	-.22 - 19	-.28 - 15	-.31 - 15	-.32 + 15	-.26 - 15	-.29 - 15	-.29 - 15
Knowe Fell	.35 + 17	.27 - 18	.67 *** 17	.72 *** 17	.77 *** 13	.81 *** 13	.80 *** 13	.78 *** 13	.83 *** 13	.82 *** 13
Waterhouses	.30 + 24	.19 - 25	.26 + 23	.21 - 23	.31 + 19	.31 + 19	.38 + 19	.32 + 19	.31 + 19	.39 + 19
West Great Close	.37 + 16	.07 - 17	.50 * 15							
Great Close Scar	.60 + 7	-.09 - 9	.73 + 5							
Chapel Cave	.78 *** 13	.47 * 14	.55 * 13	.24 - 13						

NOTES : For explanation of decay (DEC) terms, see section 4.3.2(a). For precipitation site abbreviations, see section 3.2.1(e)
Results given are (1) correlation coefficient (r)
(2) significance level of r (for explanation of symbols, see Appendix B)
(3) number of observations

Table 4.27 Correlation of $\delta^{18}O$ in monthly samples of surface, groundwater and cave drips with $\delta^{18}O$ in monthly and weighted weekly precipitation samples : Malham area

Sampling Locations
(Abbreviations)

	AHN	AHS	MC	SM	TO	HTH	KFS	WH	WGC	GCS	CC
Airehead (North) (AHN)	-	.90 *** 20	.61 *** 24	.48 ** 23	.88 *** 25	-.11 - 20	.29 - 17	.54 *** 24	.56 ** 16	.45 - 8	.59 ** 14
Airehead (South) (AHS)		-	.52 ** 20	.36 + 20	.70 *** 21	.32 + 19	.26 - 18	.55 ** 20	.66 ** 14	.47 - 6	.61 ** 14
Malham Cove (MC)			-	.65 *** 25	.40 ** 26	.15 - 20	.51 ** 17	.71 *** 24	.64 *** 17	.89 *** 9	.61 ** 14
Smelt Mill (SM)				-	.51 *** 25	-.28 + 20	.69 *** 17	.63 *** 23	.60 ** 16	.68 ** 9	.51 * 14
Tarn Outflow (TO)					-	-.15 - 21	.21 - 18	.36 * 25	.38 + 17	.40 - 9	.71 *** 14
Higher Tren House (HTH)						-	-.04 - 18	-.01 - 21	.15 - 16	.50 + 7	.48 * 14
Knowe Fell (KFS)							-	.60 *** 18	.84 *** 13	.95 ** 4	.24 - 14
Waterhouses (WH)								-	.67 *** 17	.93 *** 7	.53 * 14
West Great Close (WGC)									-	.90 *** 7	.45 + 11
Great Close Scar (GCS)										-	.93 * 4
Chapel Cave (CC)											-

NOTE: Results given are (1) correlation coefficient (r)
(2) significance level of r (for explanation of symbols, see Appendix B)
(3) number of observations

Table 4.28 Correlation matrix of $\delta^{18}O$ in monthly samples of surface, groundwater and cave drips: Malham area sampling sites

Location of $\delta^{18}O$ measurement

Variable against which $\delta^{18}O$ correlated	Airehead (North)	Malham Cove	Smelt Mill	Tarn Outflow	Higher Tren House	Knowe Fell	Waterhouses
Alkalinity (HCO_3^-, ppm)	-.39 * 20	.13 - 18	.16 - 18	-.69 *** 19	-.09 - 19	.30 + 18	-.22 - 21
Ca^{2+} (ppm)	.02 - 11	.69 ** 12	.63 ** 12	-.69 ** 12	.35 - 11	.46 + 11	.60 ** 12
Conductivity ($\mu S\ cm^{-1}$)	-.04 - 21	.48 ** 20	.42 * 19	-.43 * 20	.35 * 19	.41 * 18	.49 ** 21
Discharge ($m^3\ s^{-1}$)	.21 - 22	.19 - 20	.13 - 22	-.09 - 24		-.83 *** 14	.04 - 24
pH	-.09 - 21	.07 - 20	-.08 - 20	.41 * 21	.17 - 20	.25 - 17	-.25 - 22
Temperature (^oC)	.54 *** 24	.23 - 25	.26 + 24	.76 *** 26	-.07 - 19	.15 - 18	-.03 - 25

NOTE : Results given are (1) correlation coefficient (r)
(2) level of significance of r (for explanation of symbols, see Appendix B)
(3) number of observations

Table 4.29 Correlation results of monthly $\delta^{18}O$ values with hydrological and chemical variables : Malham area surface and groundwaters.

Parameter	February, 1981	July, 1981	Source Used
F_{in}	$0.24 m^3 s^{-1}$	$0.02 m^3 s^{-1}$	measured at Tarn Outflow
δ_{in}	$-7.32^{o}/oo$	$-7.62^{o}/oo$	measured at Waterhouses
δ_L^{ss}	$-7.23^{o}/oo$	$-7.02^{o}/oo$	measured at Tarn Outflow
ϵ	0.0111 (4.4°C)	0.0102 (13.4°C)	FRIEDMAN & O'NEIL (1977) (for measured Tarn temperatures)
h	0.80	0.64	WARD (1976)
δ_a	$-17.4^{o}/oo$	$-10.4^{o}/oo$	estimates using ZIMMERMAN (1979)
δ^*	$-17.39^{o}/oo$	$-10.38^{o}/oo$	calculated value

Table 4.30 Parameter values for the estimation of evaporation from Malham Tarn

Sampling locations (abbreviation)	PPT	SCE	WEL	BAG	SHAW	MF	NFUG	NFCh	AP	OAK
Precipitation (PPT)	-	-.07 - 24	.37 * 24	-.20 - 21	-.02 - 22	.37 * 23	.16 - 8	.03 - 8	-.18 - 18	-.28 + 23
Source (SCE)		-	.13 - 24	.42 * 21	.59 *** 22	.05 - 23	-.64 * 8	-.69 * 8	.64 *** 18	.45 ** 23
Welford (WEL)			-	.29 + 21	.31 + 22	.38 * 23	.16 - 8	-.04 - 8	-.12 - 18	.08 - 23
Bagnor (BAG)				-	.76 *** 19	-.01 - 20	-.47 - 7	-.17 - 7	.38 + 15	.60 *** 20
Shaw (SHAW)					-	.11 - 21	-.25 - 7	.30 - 7	.56 ** 16	.34 + 21
Manor Farm (MF)						-	.73 ** 8	.11 - 8	-.32 + 18	.17 - 23
North Farm (UG) borehole (NFUG)							-	.62 + 8	-.13 - 8	.60 + 8
North Farm (Ch) borehole (NFCh)								-	-.11 - 8	-.01 - 8
Ashdown Park (AP)									-	.55 ** 18
Oakash (OAK)										-

NOTE : Results given are (1) correlation coefficient(s),
(2) significance level of (for explanation of symbols, see Appendix B),
(3) number of observations
Precipitation values are from the composite Lechlade/Warren Down Farm series

Table 4.31 Correlation matrix between $\delta^{18}O$ values in ground and surface waters and in monthly precipitation, in the Lambourn area

Variable against which $\delta^{18}O$ correlated	Location of $\delta^{18}O$ measurement: Source	Welford	Bagnor	Shaw	Manor Farm borehole	North Farm (UG) borehole	North Farm (Ch) borehole	Ashdown Park borehole	Oakash borehole
Alkalinity (HCO_3^-, ppm)	.01	-.04	-.24	.15	-.58	.25	-.45	.34	-.23
	-	-	-	-	**	-	-	+	-
	22	21	18	21	15	5	5	13	15
Ca^{2+} (ppm)	-.34	.44	.14	.50	-.29	.13	.41	-.84	-.30
	-	+	-	*	-	-	-	***	-
	12	11	12	12	11	3	4	9	10
Conductivity ($\mu S\ cm^{-1}$)	-.20	-.08	-.45	.19	-.39	.06	.44	-.25	-.34
	-	-	*	-	+	-	-	-	+
	25	25	19	22	16	6	6	14	16
Discharge ($m^3\ s^{-1}$)	.07	.01	.07	.04	.09	-.34	-.47	-.26	-.07
	-	-	-	-	-	-	+	-	-
	25	25	20	22	24	8	8	16	21
pH	.29	.08	-.15	-.20	.24	-.18	.02	.29	-.03
	+	-	-	-	-	-	-	-	-
	25	25	19	22	15	6	6	14	15
Temperature (°C)	-.06	.10	.13	-.11	.38	.40	-.42	.01	.01
	-	-	-	-	*	-	-	-	-
	24	24	19	23	23	7	7	18	23

NOTE : Results given are (1) correlation coefficient (1), (2) level of significance of (for explanation of symbols, see Appendix B), (3) number of observations.

Table 4.32 Correlation of monthly $\delta^{18}O$ values with hydrological and chemical variables: Lambourn area sampling sites (ground and surface waters)