THE ORIGIN OF THE TRIASSIC CLAY ASSEMBLAGES OF EUROPE WITH SPECIAL REFERENCE TO THE KEUPER MARL AND RHAETIC OF PARTS OF ENGLAND

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[Plates 1–5, pullout 1]

CONTENTS

Hypotheses are reviewed on the origin of the magnesium-rich Triassic clays which characterize the Germanic facies of western Europe and north Africa. Relations between clay minerals, megafacies and stratigraphy are described from 28 localities in the Triassic Keuper Marl, Tea Green Marl and Rhaetic sediments of England. Two clay mineral assemblages are recognized: (1) a detrital assemblage of mica with minor chlorite which occurs throughout all the sediments investigated, and (2) a neoformed assemblage of magnesium-rich clay minerals with a limited occurrence related to certain megafacies cycles which resulted from the transgression and regression of the Alpine facies into the Germanic facies; this assemblage includes sepiolite, palygorskite, chlorite, smectite, corrensite and irregular mixed-layer smectite/mica† and smectite/chlorite minerals. The clay mineral neoformations resulted from reactions between the water masses in which the Germanic and Alpine facies were deposited. Controlling the distribution and types of minerals neoformed were the general and local variations in the chemistries of the Alpine and Germanic water masses, as well as competition for available magnesium from other mineral-forming reactions.

1. Introduction

The Keuper Marl (?Scythian–Norian) of England represents part of the Germanic facies of the European and north African Trias, which occurs as broad belts on either side of the Alpine facies, separating it from the purely continental areas of sedimentation. The Germanic facies consists predominantly of mudstones with lesser amounts of siltstones and sandstones, and contains considerable deposits of marine evaporite minerals (calcite, dolomite, anhydrite and gypsum, celestite, halite, etc.); it appears to have been deposited subaqueously, often in shallow water, and under arid climatic conditions in a hypersaline environment hostile to organisms. This is in sharp contrast to the open marine environment of the Tethyan Seas in which the Alpine facies was deposited. The highly saline nature of the waters of the Germanic facies is thought to have resulted from the continual evaporation of seawater as it migrated into this arid zone from the Tethyan Seas.

In Europe and north Africa the Germanic facies appears first in the Permian and comes to an end with the deposition of the Rhaetic, a series of shallow-water sediments that mark a transitional phase between the restricted hypersaline facies of the Trias and the open marine facies of the overlying Jurassic. In central Europe the Germanic facies interdigitates at various horizons with the Alpine facies (Muschelkalk), but the latter does not obviously extend westwards into England or Ireland.

Fine-grained silicate minerals are abundant within the sediments of the Germanic facies and consist of an extraordinarily varied assemblage of magnesium-rich clay minerals. This includes sepiolite, palygorskite, corrensite, allevardite, irregular mixed-layer minerals, smectite and chlorite. In France and Germany these clay assemblages have been among the main interests

† See page 626 for the definition of this use of the oblique stroke.

of clay mineralogists. Jacques Lucas at Strasbourg and Friedrich Lippmann at Tübingen in particular, have done much to elucidate their mineralogy, distribution and origin.

These investigations have been concerned both with the description of the mineralogical variation within the clay assemblages of the Keuper Marl and Rhaetic of England, and with its relation to variations in facies, lithologies, faunas and palyno-floras. This paper is divided into four parts. The first summarizes the history of research on the origin of the Triassic clays of Europe and north Africa. The second includes new data on the clay mineralogy, carbonate mineralogy and lithological sequences of the Keuper Marl and Rhaetic of parts of England; the third part is the interpretation of this new data; and the fourth part is the consideration of the origins of the European and north African Triassic clays in the light of this interpretation. The palyno-floral investigations have been carried out by M. J. Fisher and the results of these are being published separately (Fisher, in preparation).

2. Origin of Triassic clays

The main hypotheses for the origins of the Triassic clay assemblages of Europe and north Africa can be grouped into two schools: the French and the German. These are characterized not only by different approaches but also by differences in mineral assemblages. Irregular mixed-layer smectite/chlorite has never been recorded from the German Trias, whereas it is frequently recorded from the French, Spanish, Moroccan and English Trias: whether this is a real mineralogical difference or only one of interpretation and sample preparation cannot yet be decided. In France, sampling over wide areas has elucidated the general relations between mineralogical variation, lithology and palaeogeography, resulting in the transformational hypothesis of Lucas (1962), since revised by Lucas & Ataman (1968). In contrast, German research covers local but much more detailed studies of limited parts of the Triassic sequence.

(a) *French school*

Lucas (1962) argued that open, poorly crystalline illite with minor amounts of chlorite were originally supplied to the Triassic hypersaline seas from the continents. The margins of these seas were relatively dilute, affected by the run-off from the continents, but as the detritus was carried farther out it entered waters of increasingly high salinity due both to increased evaporation and to distance from the effect of continental run-off. Depending on the distance travelled and the time that the detritus was suspended in the seawater, the poorly crystalline detritus was transformed to differing degrees by reaction with the cation-rich seawater. Lucas claimed that the following two mineral series could be followed from the edge of the continent into the centre of the hypersaline basins:

dioctahedral degraded illite
↓
open illite
↓
irregular mixed-layer smectite/mica
↓
corrensite
↓
irregular mixed-layer chlorite/swelling chlorite
↓
well crystalline trioctahedral chlorite

dioctahedral degraded illite
↓
well crystallized illite

These transformational reactions involved the uptake of various cations by the degraded detritus causing their aggradation. They had to compete with other sedimentary processes for the available ions in solution, and in particular with the precipitation of carbonates and halite. In both carbonate and halite facies the silicate minerals have undergone less extensive transformation than might have been expected from their palaeogeographic positions.

More recently Lucas & Ataman (1968) have presented a particularly lucid account of the transformational hypothesis as applied to the Jura Basin. The total amount of magnesium in the sediments remains constant across the basin although the concentration of this element in the clay fraction increases towards the centre. However, the absolute volume of clay decreases basinwards and this suggests that there were no salinity gradients in the main part of the basin, and the decreasing amount of suspended detritus allowed a more complete aggradation from the same magnesium concentration in the hypersaline waters.

Krumm (1969) and Dunoyer de Segonzac (1969) suggest that these transformational reactions took place not so much during transportation but mainly during the initial stages of burial, when there was more time for the continental detritus to equilibrate with the sediments' porewaters.

(*b*) *German school*

The major achievement of the German school lies in their detailed local studies of clay–sediment relations at restricted horizons in the Trias of Germany. Many of these researchers (Becker 1965; Echle 1961; Heling 1963, 1965; Kulke 1969; Lippmann & Savaşçin 1969; Lippmann & Schlenker 1970; Schüle 1974) have suggested that part of the Triassic clay assemblages originated during diagenesis by transformation of phyllosilicate detritus or by neoformational reactions. However, attempts to synthesize the various hypotheses into a single one applicable to the European Trias have not been successful. Complications occur because different diagenetic reactions characterize the porous sandy sediments and the less porous argillaceous sediments. For example, Heling (1963) and Kulke (1969) have paid particular attention to the Stubensandstein, and they have demonstrated, petrographically, the post-depositional development of kaolinite, sudoite, and sudoite–montmorillonite and mica–montmorillonite mixed-layer minerals. Kaolinite, sudoite and sudoite–montmorillonite mixed-layer minerals do not occur typically in the argillaceous sediments which are characterized by the presence of magnesium-rich clay minerals. It is necessary to consider only those studies carried out on predominantly argillaceous sediments.

Echle (1969) was first to realize the scale of magnesium enrichment involved in the formation of the magnesium-rich Triassic clays, basing his conclusions on observations made on the Rotewand and the Steinmergel Keuper. He argues that the magnesium-rich clays were formed during the phase of brine evaporation in which gypsum was being precipitated, and in which the magnesium contents of the brine increased from $2\ g\ l^{-1}$ to $16\ g\ l^{-1}$: if the original detrital sediment had an initial porosity of 50 % its porewaters during this phase of evaporation would have contained between 1000 and 8000 g magnesium per cubic metre of sediment. Echle points out that his samples contained at a minimum 15000 g magnesium per cubic metre of sediment (magnesium in both clay minerals and carbonate minerals is included); this is 2–15 times as much as would be expected if the original porosity was 50 %, and the sediment gained its magnesium by fixing the total amount of this element in the pore solutions. In order to explain this excess, three possibilities were suggested: (1) the original detritus was already very rich in magnesium; (2) the initial porosity of the sediment was much higher than 50 %; (3) the sediment gained magnesium by continuous extraction from the porewaters in an open system connected to the overlying brine: the amount of magnesium fixed within the sediment would have then been controlled mainly by the rate of sedimentation.

Details of the reactions involved in the post-depositional development of the magnesium-rich clays have been suggested by Lippmann and his students. Lippmann & Savaşçin (1969) recognized petrographically the post-depositional development of corrensite in association with potassic feldspar and quartz in the highly gypsiferous Gipskeuper near Böblingen. These authors conclude that all three neoformed minerals resulted from the interaction of the magnesium-rich porewaters with detrital mica, and suggest the two following reactions:

$$\text{detrital mica} + Mg^{2+}\text{-rich pore solutions} \rightarrow \text{corrensite} + K^{+}_{aq},$$

$$K^{+}_{aq} + SiO_2 + Al_2O_3 \rightarrow \text{K feldspar}.$$

Schlenker (1971) and Schüle (1974) have noted a consistent association between the presence of swelling interlayers in mica and the absence of corrensite in the clay assemblages from the Gipskeuper and Buntemergel. Schlenker suggests that this association resulted from the lack of potassium enrichment of the porewaters of the sediment by Lippmann's corrensite-forming reaction. When corrensite has developed in the sediment, the potassium released during its formation has preferentially reconstituted the open mica (with swelling interlayers) before taking part in the precipitation of potassic feldspar. Schlenker suggests also that the chlorite in these clay assemblages developed by reaction of the magnesium-rich pore solutions with mica or smectite.

3. Keuper Marl and Rhaetic of parts of England

The Germanic facies of the Permo-Triassic of England, Scotland and Ireland consists of a thick series of red sediments (up to 3000 m proved in the Prees Borehole, Cheshire; Colter & Barr 1975). The lower part of this sequence is made up predominantly of sandstones intercalated with minor mudstones, and these pass upwards into a series of variable thickness, consisting predominantly of mudstones with occasional horizons of sandstone. The uppermost part of this facies is marked by the Tea Green Marl, a thin sequence of greenish grey dolomitic mudstones, which are overlain by the Rhaetic sediments. The Keuper Marl is a lithological formation used to include this predominantly mudstone upper division and the Tea Green Marl of the British Permo-Triassic sequence. The various sandstone horizons of this Germanic facies are laterally impersistent, and not surprisingly there is considerable difficulty in defining the lower limit of the Keuper Marl. Stratigraphically the Keuper Marl is poorly known; however, it includes stages in addition to those present in the type Keuper of Germany.

The Rhaetic has a similar extent to the Keuper Marl and can be divided lithologically into a lower and upper division. The lower is characterized by dark shales, whereas the upper contains a considerable number of carbonate-rich beds. The base of the Rhaetic is usually well defined and consists of a single or series of minor erosion surfaces at the top of the Tea Green Marl. The Rhaetic averages about 23 m in thickness. The lithofacies of the upper division of the Rhaetic and its relation to the overlying Lias show significant lateral variation in the areas discussed in this paper.

On the south Devon coast the upper part of the Rhaetic is separated from the Lias by the

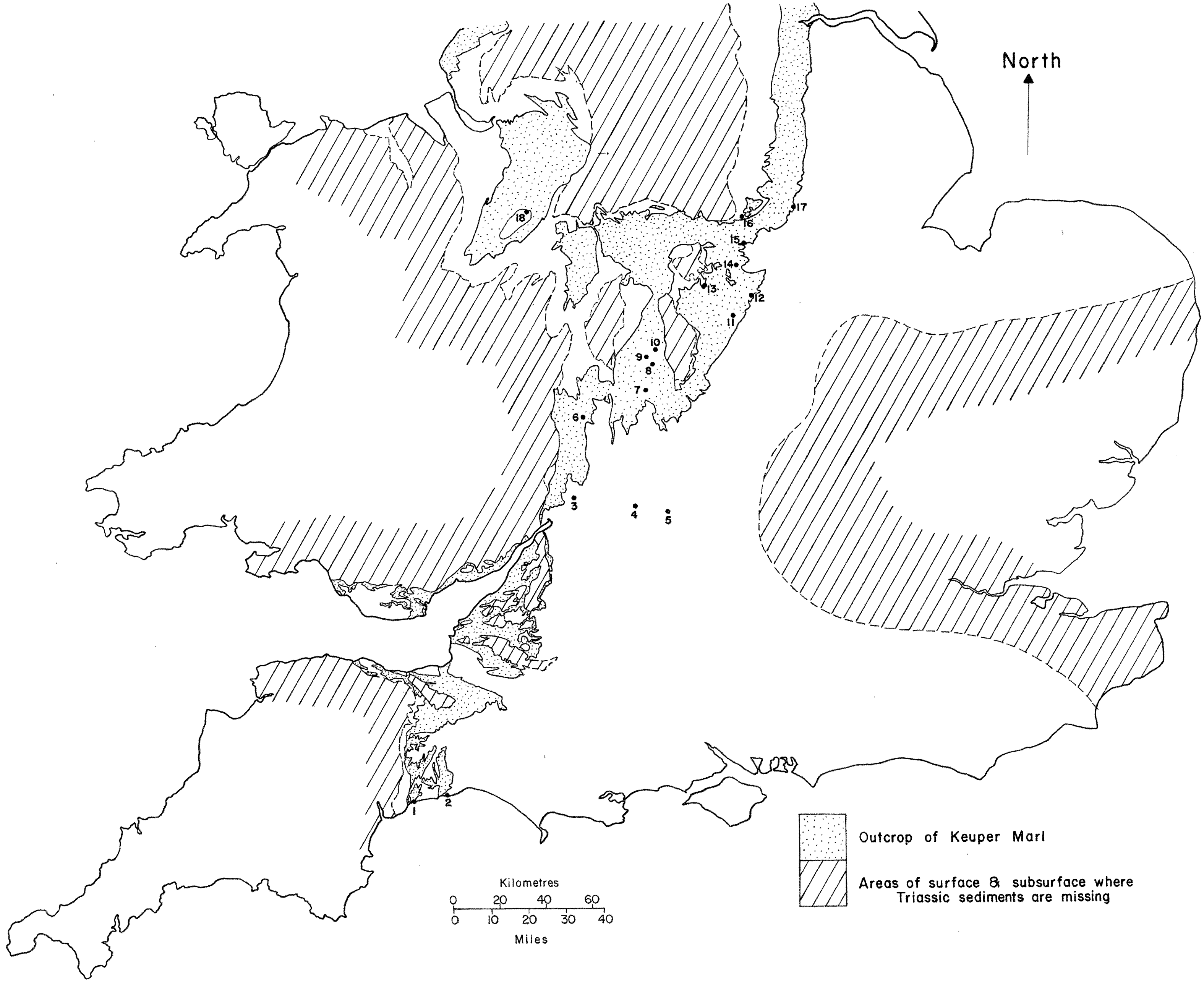


Figure 1. Distribution of Keuper Marl at outcrop and at subsurface in England. Localities: 1, Sidmouth to Branscombe; 2, Seaton to Charton; 3, Westbury-on-Severn; 4, Stowell Park; 5, Upton; 6, Warndon; 7, Henley-in-Arden; 8, Knowle; 9, Solihull; 10, Bickenhill; 11, Croft; 12, Leicester; 13, Ibstock; 14, Loughborough; 15, Bunny; 16, Nottingham; 17, Staunton-in-the-Vale; 18, Wilkesley.

carbonate-rich White Lias. In the Midlands, the Lias rests directly on the upper Rhaetic or on a thin development of the White Lias. In parts of Lincolnshire, Yorkshire and the North Sea, Kent (1953, 1970) has described a red mudstone facies between the top of the Rhaetic black shale and the base of the Lias.

(*a*) *Megafacies*

The spatial relations of the different lithologies in the Keuper Marl and Rhaetic allow their grouping into three megafacies, defined by both lithology and fossil content. Each megafacies is named after the typical lithology: the mudstone, carbonate and sandstone megafacies. Relations between the three megafacies are consistent: the sandstone megafacies is separated from the mudstone megafacies by the carbonate megafacies.

On the south Devon coast there are three cycles of megafacies: the Dunscombe, Weston, and Bindon cycles, in ascending order. Each cycle consists of a carbonate–sandstone–carbonate sequence in which the base of the sandstone megafacies is an erosion surface. The three units of any particular cycle are referred to as the lower carbonate group, the sandstone group, and the upper carbonate group. The three cycles of megafacies are separated by thicknesses of the mudstone megafacies, referred to as Mudstones I, II and III in ascending order.

The three megafacies cycles are best developed in southwest England. The Dunscombe Cycle is only recognized on the south Devon coast. The Weston Cycle is interpreted as being continuous with the Arden Sandstone Group of Matley (1912), which extends northwards into Warwickshire. The Bindon Cycle occurs over most of Britain.

Details of the three megafacies are considered below.

(i) *Mudstone megafacies*

The mudstone megafacies constitutes a very large proportion of the Keuper Marl. It is characterized by unbedded mudstones, dominantly reddish brown with occasional greenish-grey horizons; small greenish-grey specks and blebs are common throughout, tending to be concentrated at various horizons. Differential weathering reveals variation in the massive mudstones and allows their division into poorly defined units, varying in thickness from tens of centimetres to tens of metres. Horizons occur of (*a*) shaley mudstone or fine alternations of mudstone and sandstone up to 10 m thick; (*b*) thin, bedded or unbedded sandy horizons with erosional bases up to 40 m thick; if bedded they are associated with ripple marks, shrinkage-cracked mudstones and pseudomorphs of halite hopper crystals. Beds of mudstone and sandstone often show great lateral persistence with little obvious lithological variation. Dolomite and calcite are present in varying proportions, occurring as small euhedral rhombs scattered throughout the mudstone or filling the pore-space of the sandstones. Bands of dolomite nodules (15 cm in maximum dimension) are occasionally present. Gypsum is common either as lines of nodules parallel to the bedding, as scattered nodules, or intimately dispersed throughout the mudstone. Fish eyes are hard, black spherical or irregularly shaped masses containing various radioactive minerals (Ponsford 1954; Elliott 1961; Ford 1968) surrounded by a halo of greenish-grey mudstone: these are common at some levels.

This megafacies contains the main deposits of marine evaporite minerals other than carbonates. The evaporites have a general lateral distribution.

Celestite occurs as large nodular masses in the Bristol area (Nickless, Booth & Mosley 1975), and probably developed within the sediment after deposition.

In the Midlands, gypsum and anhydrite occur in continuous beds up to 3 m thick, which extend laterally for 1 or 2 km and pass into horizons of large nodules; not all horizons of gypsum or anhydrite nodules are associated with continuous beds of these minerals. Little is known about the formation of these calcium sulphate deposits, although the apparent lack of depositional structures within continuous beds and the form of the nodular bodies suggest development within the sediment during diagenesis.

In the Midlands fine laminae of dolomite occur in the mudstone at various horizons in the Radcliffe and Harlequin formations.

There are thick deposits of halite in the mudstone megafacies in various parts of England (Warrington 1974). They are best developed in basinal regions.

The mudstone megafacies is poorly fossiliferous. The only records of shelly fossils are *Lingula* in the Waterstones of Nottinghamshire (Rose & Kent 1955), and from the old British Petroleum pumping Station at Staunton, north–northwest of Gloucester (Professor L. R. Moore, personal communication). The occasional spore assemblages (Warrington 1970*a*, *b*, 1971; Smith & Warrington 1971; Fisher 1972, in preparation) usually come from fine alternations of sandstones, siltstones and mudstones.

(ii) *Carbonate megafacies*

The carbonate megafacies is characterized by clays and mudstones, dolomitic and calcitic limestones and marls, and conglomerates. The clays and mudstones are grey, greenish grey, black, reddish brown and purple; the limestones and marls are buff or grey. Fine laminae, averaging about 10 mm thick, are common, each consisting of an upward fining unit topped by an erosional or sharp surface. The conglomerates contain clasts of mudstone, clay and marl. Evaporite minerals, other than carbonates, are infrequent although small gypsum nodules occur but are restricted to a few horizons. Poor exposure has not allowed the lateral persistency of individual beds to be determined; however, certain horizons are continuous for at least some hundreds of metres.

Within a megafacies cycle, the uppermost part of the carbonate group immediately underlying the sandstone group often contains thin, carbonaceous-rich horizons and traces of glauconite.

Considerable variation occurs in the proportion of carbonate-rich to carbonate-poor lithologies in this megafacies. The Dunscombe and Weston cycles and the upper part of the Bindon Cycle are dominated by carbonate-poor sediments, while the Lower Carbonate Group of the Bindon Cycle is characterized by carbonate-rich sediments.

The invertebrate fauna is sparse. *Euestheria* occurs occasionally in the uppermost part of the Lower Carbonate Group of the Dunscombe Cycle, and commonly in the Lower and Upper Carbonate groups of the Bindon Cycle.† Soft bodied in-sediment faunas are absent, whereas palynomorph assemblages (Fisher, in preparation) are common.

(iii) *Sandstone megafacies*

The sandstone megafacies shows considerable variations in lithology at different horizons. In the Dunscombe and Weston cycles it consists of a series of sandstones with or without traces of glauconite, intercalated with grey or reddish brown mudstone. The mudstones are often penetrated by sandstone dykes which can sometimes be seen arranged in a polygonal pattern.

† In the Bindon Cycle, the Lower Carbonate Group includes the Tea Green Marl and Grey Marls and the Upper Carbonate Group includes the Cotham Beds.

These dykes usually originate from the overlying sandstone, although, less frequently, from the underlying one. Individual beds are not persistent laterally and may vary in thickness and lithology over tens of metres.

The base of the sandstone groups of the Dunscombe and Weston cycles rest on a well-defined mudstone surface in which the burrows and feeding traces of an extensive soft-bodied in-sediment fauna are preserved. The Sandstone Group of the Bindon Cycle, equivalent to the Westbury Beds, consists of black shales with laminae of fine sand and siltstone resting on the burrowed top surface of the Lower Carbonate Group. Lithologies intermediate between these two extremes occur at Warndon 1 (see later) in the Sandstone Group of the Weston Cycle.

Traces of invertebrate fossils are not uncommon. In the Dunscombe Cycle four types of trace fossils have been recorded while *Euestheria* has only been found at the base of the Sandstone Group. In the Weston Cycle, trace fossils are abundant and include *Chondrites*, a form thought to be restricted to the marine or marine-brackish milieu: *Euestheria* is again common in the lower part of the Sandstone Group. At a number of localities in Warwickshire (Shrewley; Shelfield) and Worcestershire (Inkberrow) poorly preserved molluscs have been found; they have been named as *Thracia*(?) *brodei*, *Nucla*(?) *keuperina* and *Pholodomya*(?) *richardsi* by Newton (1894) and are considered by Matley (1912) to be of marine origin: Cox (in Rose & Kent 1955) considered these molluscs to be too poorly preserved for generic identification. The Sandstone Group of the Bindon Cycle contains large numbers of lamellibranchs, including *Rhaetavicula contorta*, *Chlamys*, *Pseudomonotis*, *Palaeocardita* and *Placunopsis*, suggesting a rather restricted marine environment. Palynomorph assemblages are common indicating deposition in a relatively non-oxidizing environment (Fisher, in preparation).

(iv) *Interpretation of megafacies and megafacies cycles*

The three megafacies are interpreted as representing different milieux of deposition and intrinsic diagenesis. The mudstone megafacies was deposited in a hypersaline environment, the carbonate megafacies in an environment intermediate between hypersaline and normal marine, whilst the sandstone megafacies was laid down under brackish to normal marine conditions.

Each megafacies cycle is interpreted as the result of a transgression and regression of the normal marine environment (Alpine facies) into the hypersaline environment of the Germanic facies. Depositional structures suggest that the upward passage from the mudstone through the carbonate into the sandstone megafacies is associated with considerable increase in the energy of the depositional processes, possibly related to a shallowing of the water. Each cycle is symmetrical on a broad scale but in detail shows asymmetry. The passage from the lower carbonate group to the sandstone group is very sudden and marked by an erosion or subaerially exposed surface; transitional lithologies between these two megafacies are not preserved, although the very top of the lower carbonate group may show evidence of marine influence with glauconite and *Euestheria*, suggesting that the water shallowed very rapidly and the originally subaqueous sediments were exposed subaerially and eroded. The sediments of the sandstone group laid down on this well-defined surface contain the greatest evidence of marine influence in the cycle. The lithology of the sandstone group changes upwards and, in contrast to the lower transgressive half of the cycle, is transitional to the upper carbonate group, hence reflecting a gradual decrease in the energy of the depositional processes and possibly an increase in water depth. The sudden change of the depositional environment occurring at the base of the sandstone group is thought to have been caused by tectonism affecting the general relation between sea level and the depositional surface.

Upwards through the Keuper Marl of the Devon coast, the sandstone group of each succeeding megafacies cycle shows greater influence of an open marine environment, and this is correlated with the increasing extent of each succeeding cycle.

(v) *Clay and carbonate mineralogy of megafacies cycles*

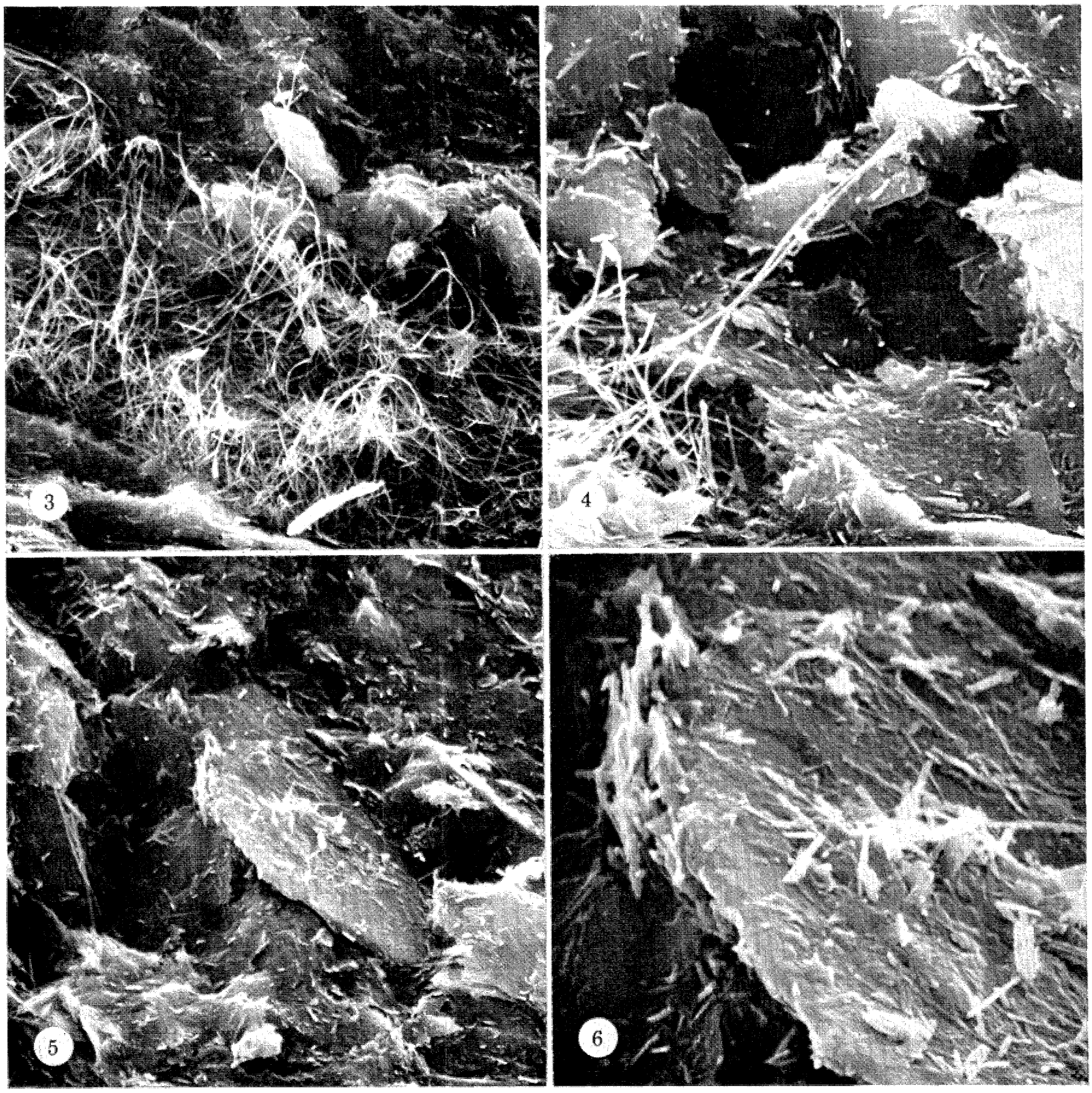
Detailed relations between the distribution of clay minerals, carbonate minerals and the megafacies cycles have been studied only in the Keuper Marl of the south Devon coast. These are discussed below, whereas general relations are considered in a later section.

Clay mineralogy. About 140 samples were selected from the south Devon Keuper Marl to represent both obvious and cryptic variation in lithology. Their clay fractions (less than 2 μm effective settling diameter) were analysed by X-ray diffraction with the analytical procedures and nomenclatorial scheme described in appendix 1. Various mixtures of mica, chlorite, smectite/mica, smectite/chlorite, sepiolite and palygorskite make the clay fractions of these samples. All samples contain mica and chlorite in approximately the same ratio, although in the cyclic sediments the proportion of chlorite tends to be lower. The distribution of the other minerals, with the exception of palygorskite, is related closely to the occurrence of the Dunscombe and Weston cycles. The change from sediments of the mudstone megafacies to the sandstone megafacies, through the carbonate megafacies, is associated with marked changes in the clay assemblages. This is best seen in Mudstone I and the overlying Lower Carbonate and Sandstone groups of the Dunscombe Cycle. In the upper part of Mudstone I, smectite/mica appears in the clay assemblages and becomes generally more abundant upwards. At a higher horizon within the Mudstone sepiolite appears, becoming more abundant upwards, and this is associated with a general decrease in the amount of smectite/mica. The lower part of the Lower Carbonate Group of the Dunscombe Cycle is similar to the top of the underlying Mudstone I, and contains assemblages with conspicuous amounts of sepiolite; the upper part of this group contains much less sepiolite, whereas in some samples smectite/mica is abundant. The overlying Sandstone Group contains clay assemblages of only mica and chlorite. The same sequence of changes in the clay assemblages occurs in reverse as one passes upwards from the Sandstone Group, through the Upper Carbonate Group and into Mudstone II. The mineralogy of Mudstone II is incompletely known; however, the various changes in the clay assemblages in the upper part of the Dunscombe Cycle and between the Weston Cycle and the underlying Mudstone II can be fitted into the pattern of changes recorded in the more fully exposed parts of the sequence.

Palygorskite has a pattern of distribution unrelated to the other clay minerals; it is restricted to certain horizons in Mudstone III.

Three samples (De 241, 242 and 168; figures 34 and 37) are interpreted as containing smectite/chlorite; they are all from dark grey to black finely laminated mudstones occurring just below the base of the sandstone groups. The first two are from the top of the Lower Carbonate Group of the Dunscombe Cycle; the third is from the very top of the Lower Carbonate Group of the Weston Cycle.

Correlation between clay mineralogy and individual lithologies is poor. None of the lithologies has a characteristic clay mineralogy. Only smectite/chlorite is restricted to a particular lithology.



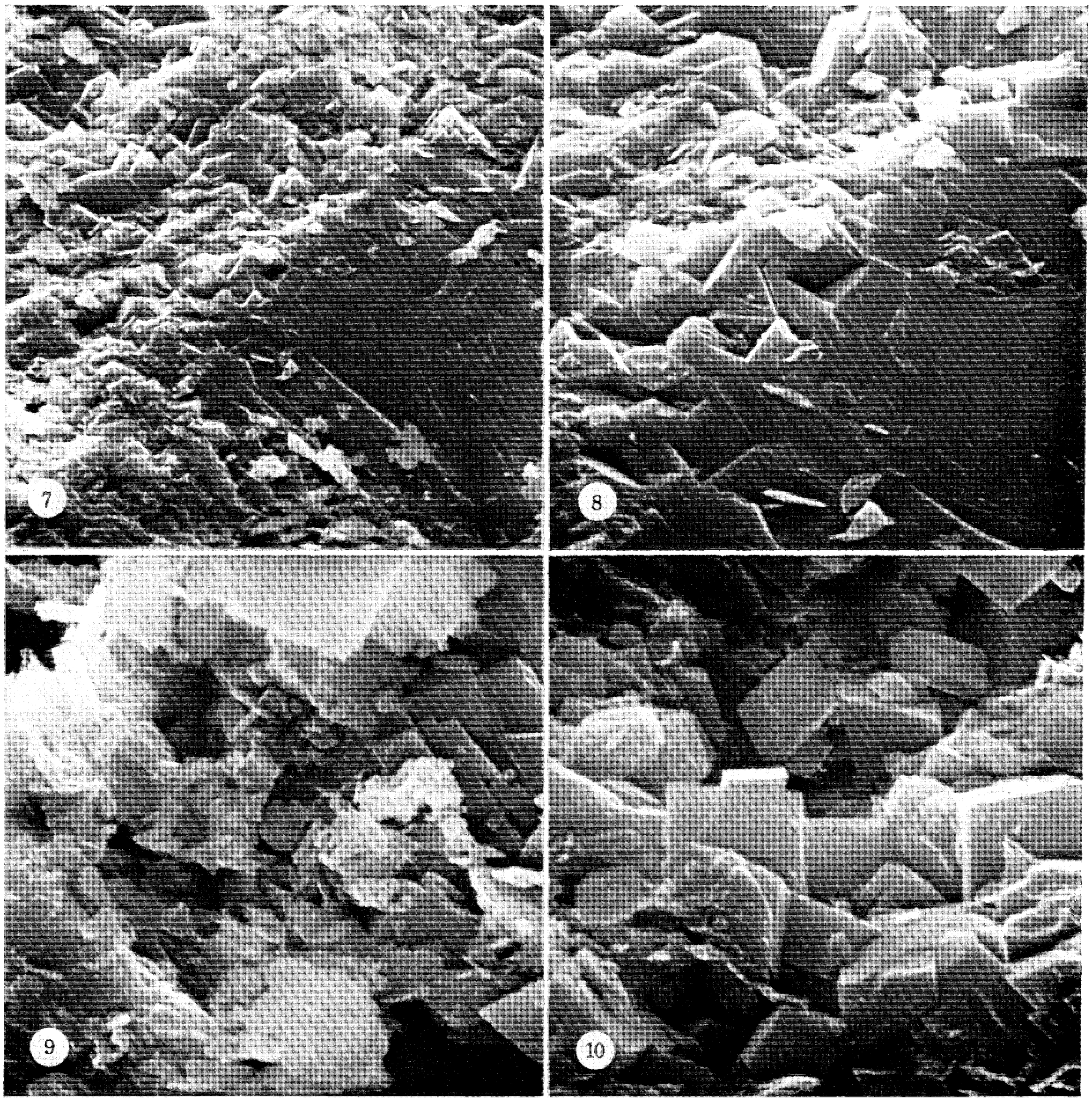
Reddish brown mudstone (De 227) from the Lower Carbonate Group of the Dunscombe Cycle; see Figure 33 for horizon and locality.

FIGURE 3. Long fibres of sepiolite forming a loose tangled mass filling a void. (Magn. × 1980.)

FIGURE 4. Long loose fibres and dense fibrous mats of sepiolite with large irregular plates of mica and/or chlorite and carbonate rhombs. (Magn. × 4400.)

FIGURE 5. Large plates of mica and/or chlorite encrusted with short and long fibre sepiolite. Dense mats of sepiolite occur in the lower portion of the micrograph. (Magn. × 2640.)

FIGURE 6. Detail of figure 5 showing a large plate coated with short fibre sepiolite. (Magn. × 8800.)



Dolomitic limestone (De 154) from the Upper Carbonate Group of the Dunscombe Cycle; see figure 34 for horizon and locality.

FIGURE 7. Contact zone of the coarsely crystalline dolomite (lower right) and the matrix of dolomite and calcite (upper left). (Magn. × 1080.)

FIGURE 8. Detail of figure 7 showing carbonate rhombs enclosed in the coarsely crystalline dolomite. (Magn. × 3000.)

FIGURE 9. The matrix with rhombohedral carbonates and irregular plates of smectite–mica. (Magn. × 4300.)

FIGURE 10. Intimate association of rhombohedral carbonates and smectite–mica. (Magn. × 5760.)

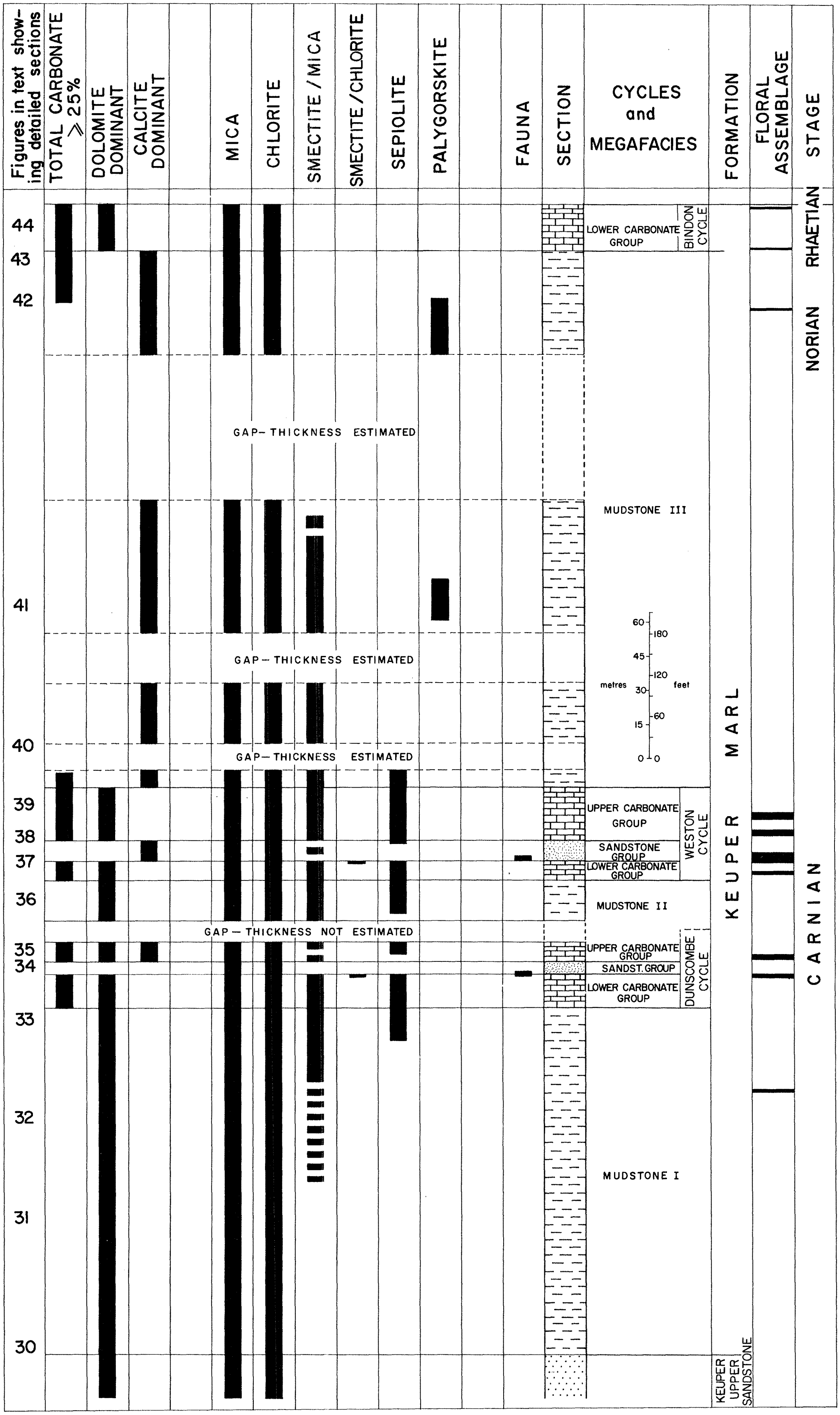


FIGURE 2. Summary of the Keuper Marl, south Devon coast.

General relations between clay mineralogy and megafacies in the south Devon Keuper Marl are summarized in figure 2; detailed relations are illustrated in figures 30–43.

Carbonate mineralogy. The dolomite–calcite ratios and the amounts of these two carbonates in the whole rock have been determined in nearly all samples which have been analysed for their clay mineralogy, and various other samples. The method of analysis is described in appendix 2. The results are summarized in figure 2, and are shown in detail in figures 30–43. A close relation exists between the carbonate minerals and the megafacies. There is a gradual upward increase in the total carbonate contents of the mudstone groups. Mudstones I and II are dominated by dolomite, whereas Mudstone III is dominated by calcite. The Lower and Upper Carbonate groups of the Dunscombe and Weston cycles, and the Lower Carbonate Group of the Bindon Cycle have high carbonate contents dominated by dolomite. The sandstone groups, as far as the limited number of samples can be generalized, have low carbonate contents dominated by calcite.

(vi) *Petrography of megafacies*

Detailed petrographic studies have been undertaken on six samples from the mudstone and carbonate megafacies of the Keuper Marl of the south Devon coast. These samples, which are described below, represent some of the typical lithologies making up these two megafacies.

Sample De 227 is a reddish-brown mudstone from the Lower Carbonate Group of the Dunscombe Cycle (see figure 33 for horizon). The sample disintegrates readily into small blocky fragments with maximum dimensions of some 10–12 mm. The clay fraction consists of mica, chlorite and sepiolite. The petrography is illustrated in figures 3–6, plate 1. Sepiolite is conspicuous by its fibrous habit, occurring either as long fibres in tangled masses infilling voids, or as shorter fibres coating large flakes of mica or chlorite, or in fibrous mats. Textural relations suggest that the sepiolite was precipitated within the pore space of the sediment after deposition.

Sample De 154 is a buff laminated limestone from the Upper Carbonate Group of the Dunscombe Cycle (see figure 34 for horizon). Each lamina, averaging 7–14 mm in thickness, is graded, fining upwards, and consists largely of a mixture of dolomite (48 %) and calcite (10 %). Grey botryoidal masses of coarsely crystalline, nearly pure dolomite are conspicuous and are often restricted to the lower part of the laminae; on weathered surfaces these masses are very

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Description of plate 3

Grey marl (De 80) from the Upper Carbonate Group of the Weston Cycle; see figure 38 for horizon and locality.

Figure 11. General view showing abundant loose fibres and fibrous mats of sepiolite obscuring a matrix of large plates of mica and/or chlorite. A carbonate rhomb is partially visible in the lower right hand corner. (Magn. × 990.)

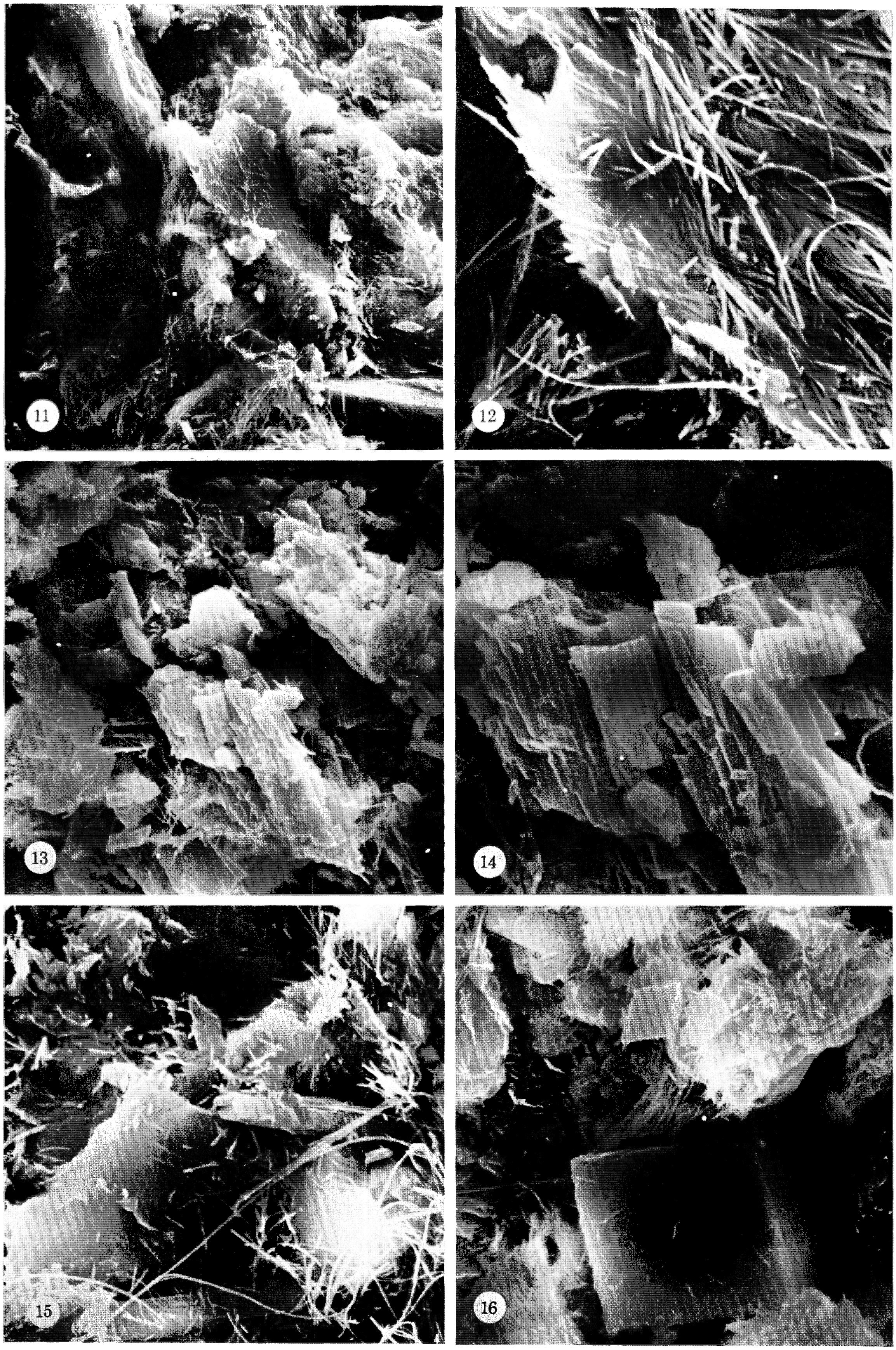
Figure 12. Detail of figure 11 showing a dense mat of fibrous sepiolite. (Magn. × 7920.)

Figure 13. Intergrowth of euhedral gypsum (?) and sepiolite in a void. (Magn. × 675.)

Figure 14. Detail of figure 13. (Magn. × 2640.)

Figure 15. Large plate of mica or chlorite with elongated crystals of gypsum (?) and fibrous sepiolite. (Magn. × 4400.)

Figure 16. Rhombohedral carbonates in juxtaposition with sepiolite and small possibly irregular plates of smectite–mica. (Magn. × 7040.)



FIGURES 11–16. For description see opposite.

(*Facing p.* 560)

Description of plate 4

Dolomitic marly limestone (De 72) from the Upper Carbonate Group of the Weston Cycle; see figure 38 for horizon and locality.

Figure 17. General view of rhombohedral carbonates and masses of small irregular plates of smectite–mica. The latter may coat and obscure larger particles. (Magn. × 5000.)

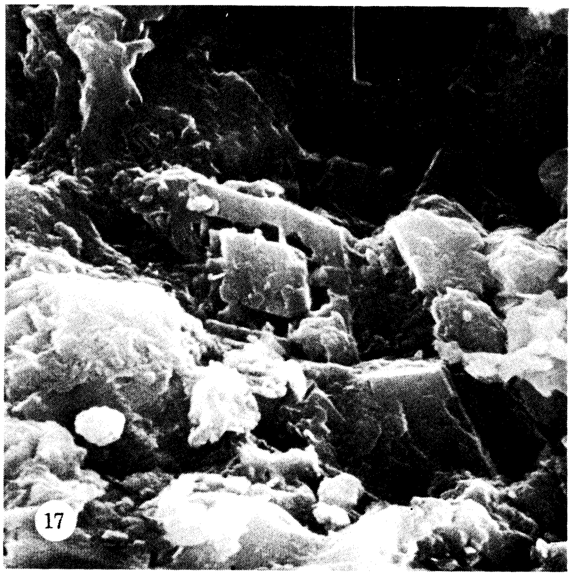
Figure 18. Detail of figure 17. A hollow zone in a rhombohedral carbonate (dolomite?) encrusted with plates of smectite–mica. (Magn. × 15000.)

Figure 19. General view of large plates of mica and/or chlorite encrusted with smectite–mica plates. (Magn. × 5300.)

Figure 20. Detail of figure 19. (Magn. × 16230.)

Figure 21. Euhedral gypsum (?) projecting into an empty void. (Magn. × 10000.)

Figure 22. Thin irregular plates of smectite–mica in juxtaposition with a rhombohedral carbonate. (Magn. × 15450.)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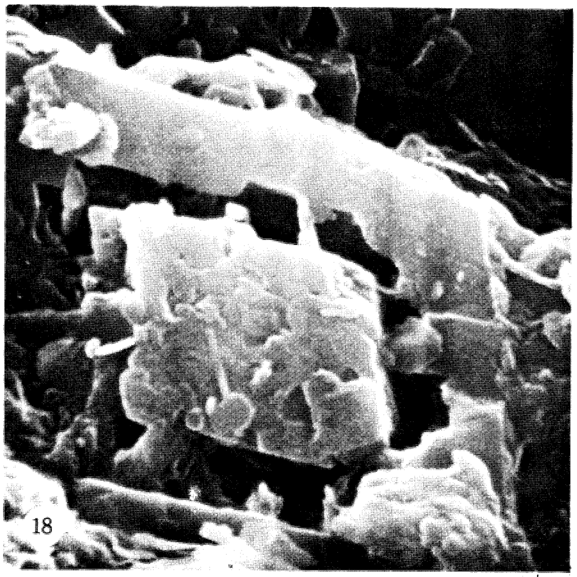
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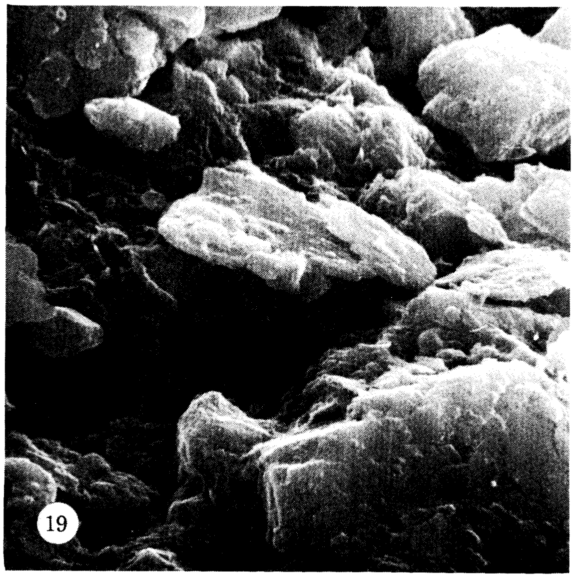
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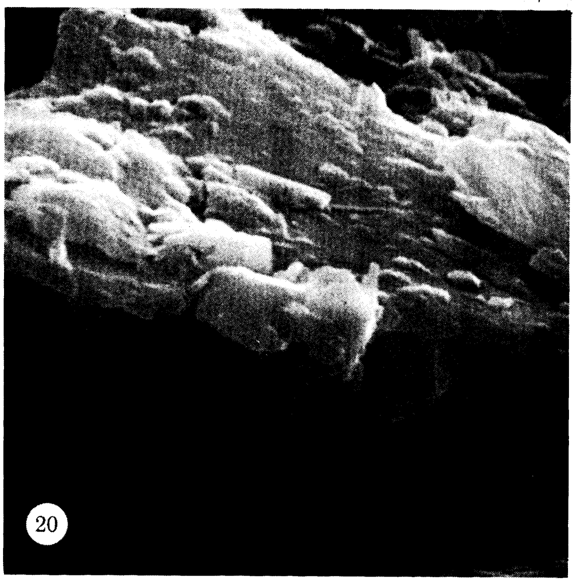
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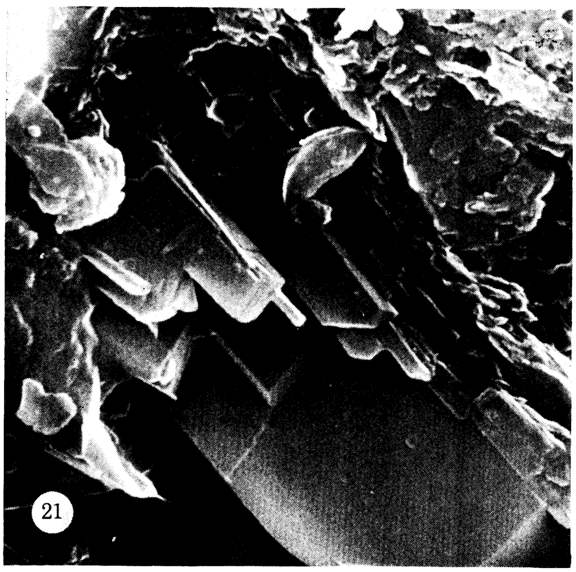
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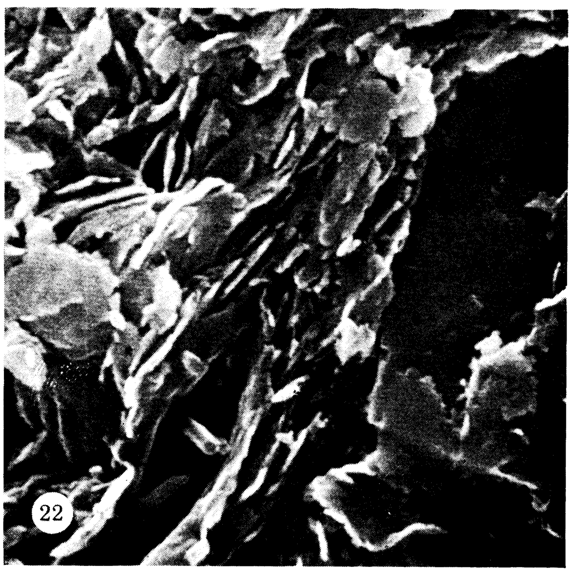
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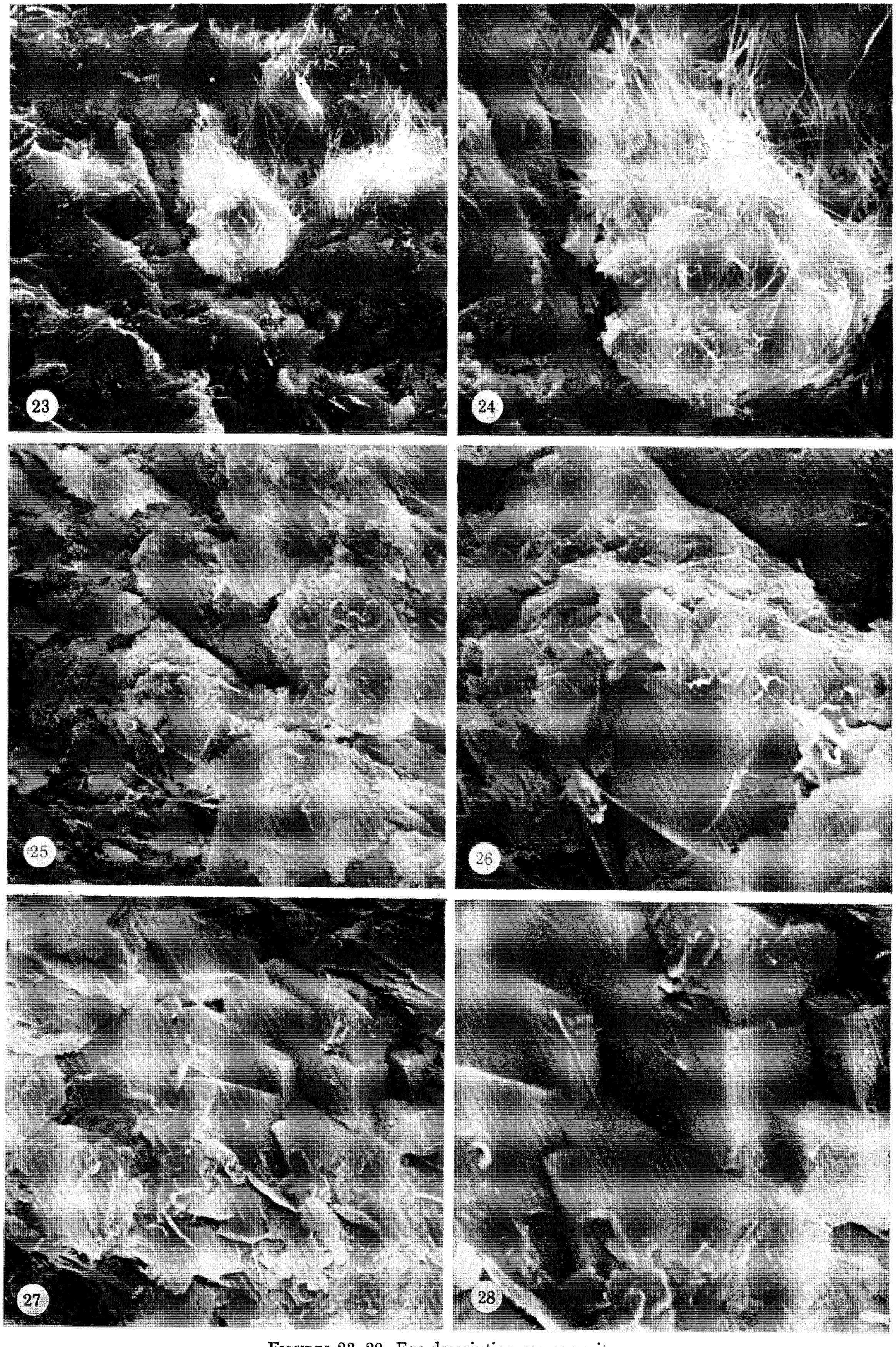

FIGURES 23–28. For description see opposite.

prominent. The clay fraction consists of mica, chlorite and smectite-mica. The petrography is illustrated in figures 7–10, plate 2. The buff limestone laminae consist of loose intergrowths of rhombohedral carbonates and clay minerals, whereas the dolomite masses reflect the later growth of large dolomite crystals in the coarser more porous parts of the laminae.

Sample De 80 is a greenish grey marl from the Upper Carbonate Group of the Weston Cycle (see figure 38 for horizon). Calcite and dolomite in approximately equal proportions make up about 25 % (by mass) of the sediment. The clay fraction is of mica, chlorite, sepiolite and smectite-mica. The petrography is illustrated in figures 11–16, plate 3. Sepiolite is conspicuous by its fibrous habit, occurring in voids, coating surfaces of larger grains, and as mats. Aggregates of euhedral gypsum (?) (figures 13 and 14) and carbonate occur. Smectite-mica could not be identified in the micrographs. The textural relations of the sepiolite, carbonates and gypsum (?) suggest their precipitation within the sediment after deposition.

Sample De 72 is a pale grey marl from the Upper Carbonate Group of the Weston Cycle (see figure 38 for horizon). Dolomite is the only carbonate present, making up 27 % (by mass) of the sediment. The clay fraction consists of mica, chlorite and smectite-mica. The petrography is illustrated in figures 17–22, plate 4. The smectite-mica occurs as aggregates made up of small, thin ragged crystals. These aggregates often occur without obvious textural relations to other minerals or to the pore space of the sediment. Coating surfaces of large clay flakes (mica and/or chlorite) and carbonate minerals are small platy crystals, possibly of smectite-mica. Rhombohedral crystals of carbonate are common and may contain a hollow zone dividing the crystals into an inner and outer region. Elongated, euhedral crystals (? gypsum) occur as outgrowths into voids or scattered through the sediment. The euhedral form of the carbonates and ? gypsum and the coating of smectite-mica on the large clay flakes suggest post-depositional crystallization of these minerals.

Sample De 77 is a grey laminated marly limestone from the Upper Carbonate Group of the Weston Cycle (see figure 38 for horizon). Each lamina is graded, fining upwards, and has an average thickness of 5–7 mm. Dolomite makes up 28 % by mass of the sediment. The clay fraction consists of mica, chlorite, sepiolite and smectite/mica. The petrography is illustrated in figures 25–28, plate 5. Texturally there are intimate intergrowths between dolomite, sepiolite and smectite/mica suggesting their post-depositional precipitation.

Sample De 128 is a massive reddish-brown marly mudstone from Mudstone III (see figure 42

Description of plate 5

Reddish brown mudstone (De 128) from Mudstone III; see figure 42 for horizon and locality.

Figure 23. Tangled masses of palygorskite in a mica and chlorite matrix. (Magn. × 1760.)

Figure 24. Detail of figure 23 showing both loose and dense packing of the fibrous palygorskite. (Magn. × 4400.)

Grey marly limestone (De 77) from the Upper Carbonate Group of the Weston Cycle; figure 38 for horizon and locality.

Figure 25. General view showing dolomite rhombs, long fibres of sepiolite and thin irregular plates of smectite–mica. (Magn. × 1750.)

Figure 26. Detail of figure 25 showing relation between rhomb, sepiolite, smectite/mica and a large plate of mica and/or chlorite. (Magn. × 5750.)

Figure 27. Intergrown dolomite rhombs in a matrix of sepiolite and smectite/mica. (Magn. × 3450.)

Figure 28. Detail of figure 27. (Magn. × 7320.)

for horizon). Approximately 9 % calcite and 7 % dolomite (by mass) are present in the sample. The clay fraction is of mica, chlorite and palygorskite. The petrography is illustrated in figures 23–24, plate 5. Palygorskite is conspicuous by its fibrous nature occurring as irregular tangled masses filling voids and coating the surfaces of the other mineral grains, suggesting that it crystallized after the deposition of the sediment.

4. Detailed description of Keuper Marl and Rhaetic

New data on the clay mineralogy, carbonate mineralogy and lithologies of the Keuper Marl and Rhaetic from 28 localities are presented in diagrammatic form. The generalized sequences of the Keuper Marl in the various areas studied are shown in figure 29.

(a) *South Devon coast*

Sidmouth–Bindon Cliff, Axmouth (grid references SY130873–272894). Generalized sequence figure 2, detailed sequence figures 30–43. A nearly complete section through the Keuper Marl was investigated in exposures in the following cliffs (from west to east): Salcombe Hill, Maynard's, Higher and Lower Dunscombe, Weston, Coxe's, Berry, Branscombe West, Haven and Bindon. Additional comments concerning these cliff exposures are given in appendix 3.

Charton Bay (figure 44). A cliff section in the west part of the Bay (grid reference SP 900300) exposes a sequence in the Lower Carbonate Group (Tea Green Marl) of the Bindon Cycle.

(b) *Oxfordshire*

Upton borehole (*Geological Survey of Great Britain*) (figures 45–46). The borehole was situated 494 m (540 yards) south 35° west of Taynton Church (grid reference SP 23151313). It penetrated the complete sequence of the Keuper Marl and the underlying Keuper Sandstone. The stratigraphy has been described by Worssam (1963); a summary section is shown in figure 29. Clay analysis was restricted to the Keuper Marl and the top of the Keuper Sandstone.

(c) *Warwickshire, Worcestershire and Gloucestershire*

Jackson's Brickworks, Bickenhill (figure 47). A worked pit situated immediately south of the A 45 road, about 1800 m, 73° east of north from Bickenhill Church (grid reference SP 205829). The top of the section is a small distance below the base of the Arden Sandstone Group. Sample 62 AT of Freeman (1964; personal communication) came from this locality.

Solihull (figures 48 and 51). A disused pit on the east side of the A 41 road, just south of the River Blythe (grid reference SP 164789): in 1969 it was being filled in very rapidly. Stratigraphically the section is in the lower part of the Keuper Marl immediately overlying the Arden Sandstone Group. Keeling's (1956) sepiolite-rich samples came from this locality.

Knowle Brick Co. Ltd, Mill Lane, Bentley Heath (figures 49 and 51). A worked pit situated on the east side of the railway line in the south part of Bentley Heath (grid reference SP 164757). Stratigraphically the section is in the lower part of the Keuper Marl overlying the Arden Sandstone Group. Sample 62 AS of Freeman (1964; personal communication) came from this locality.

Henley-in-Arden (figure 50). An overgrown roadside section on the north side of the B 4095 road, approximately 0.9 km east of its junction with the A 34 road south of Henley-in-Arden (grid reference SP 167654). The section is in the Arden Sandstone Group and the immediately underlying Keuper Marl.

Arden Forest area (figure 52). Occasional samples were collected from temporary roadside exposures: their geographical and stratigraphical locations are shown in a geological map (figure 51) of the area based upon Matley's (1912) map and sheet no. 54 (Old Series) of the Geological Survey. Samples War 15–20 are from the upper division of the Keuper Marl, War 33 is from the Arden Sandstone Group, and War 32 is from the upper part of the Lower Keuper Marl.

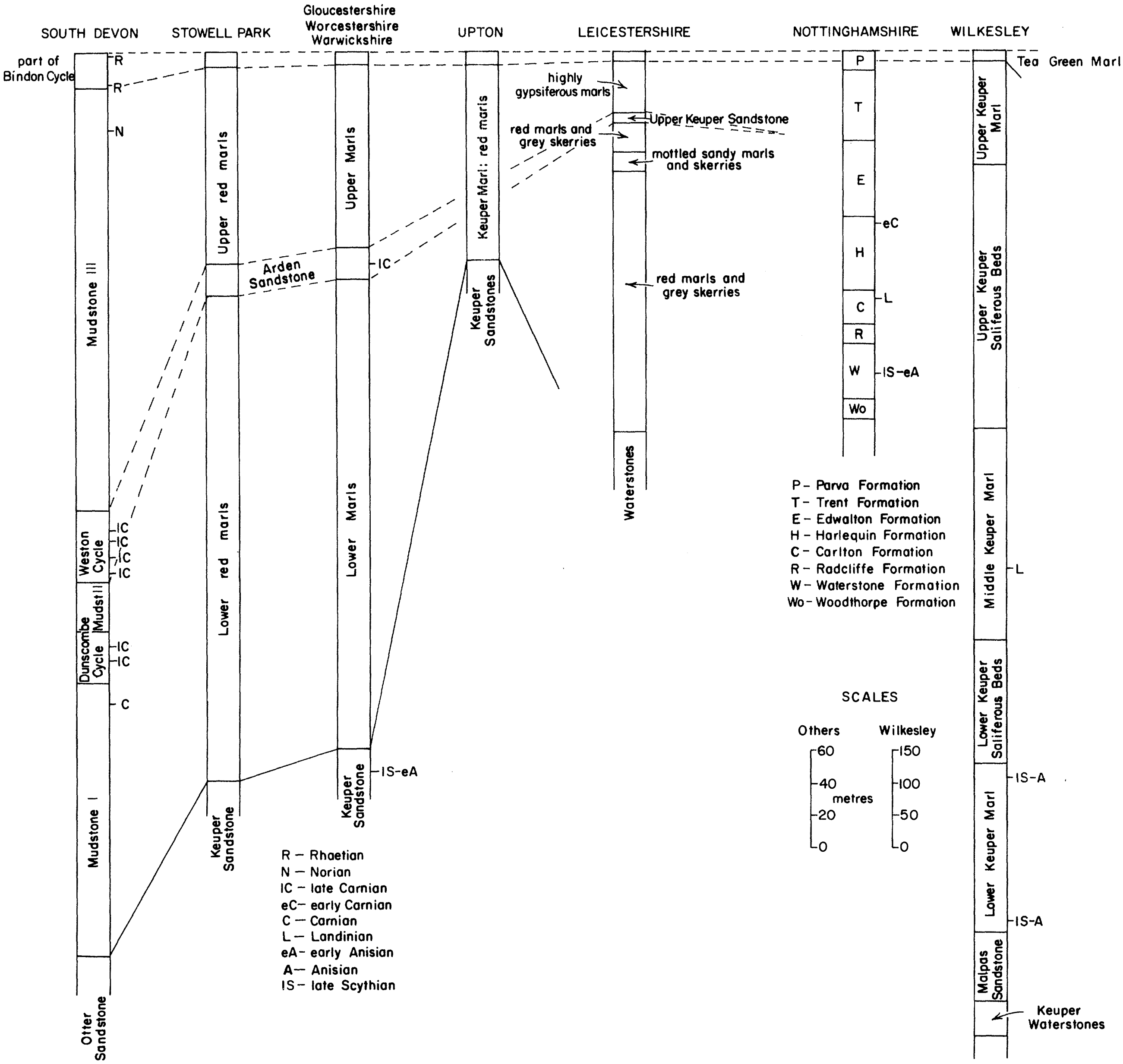

FIGURE 29. Generalized sequences in the Keuper Marl of England from the areas investigated. The following sources of data have been used: south Devon, this paper; Stowell Park, Green & Melville (1956); Gloucestershire, Worcestershire and Warwickshire, Matley (1912); Upton, Worssam (1963); Leicestershire, Bosworth (1912); Nottinghamshire, Elliott (1961); Wilkesley, Poole & Whiteman (1966). Biostratigraphy based on palynomorph assemblages from Warrington (1970*b*, 1971) and Fisher (1972, in preparation).

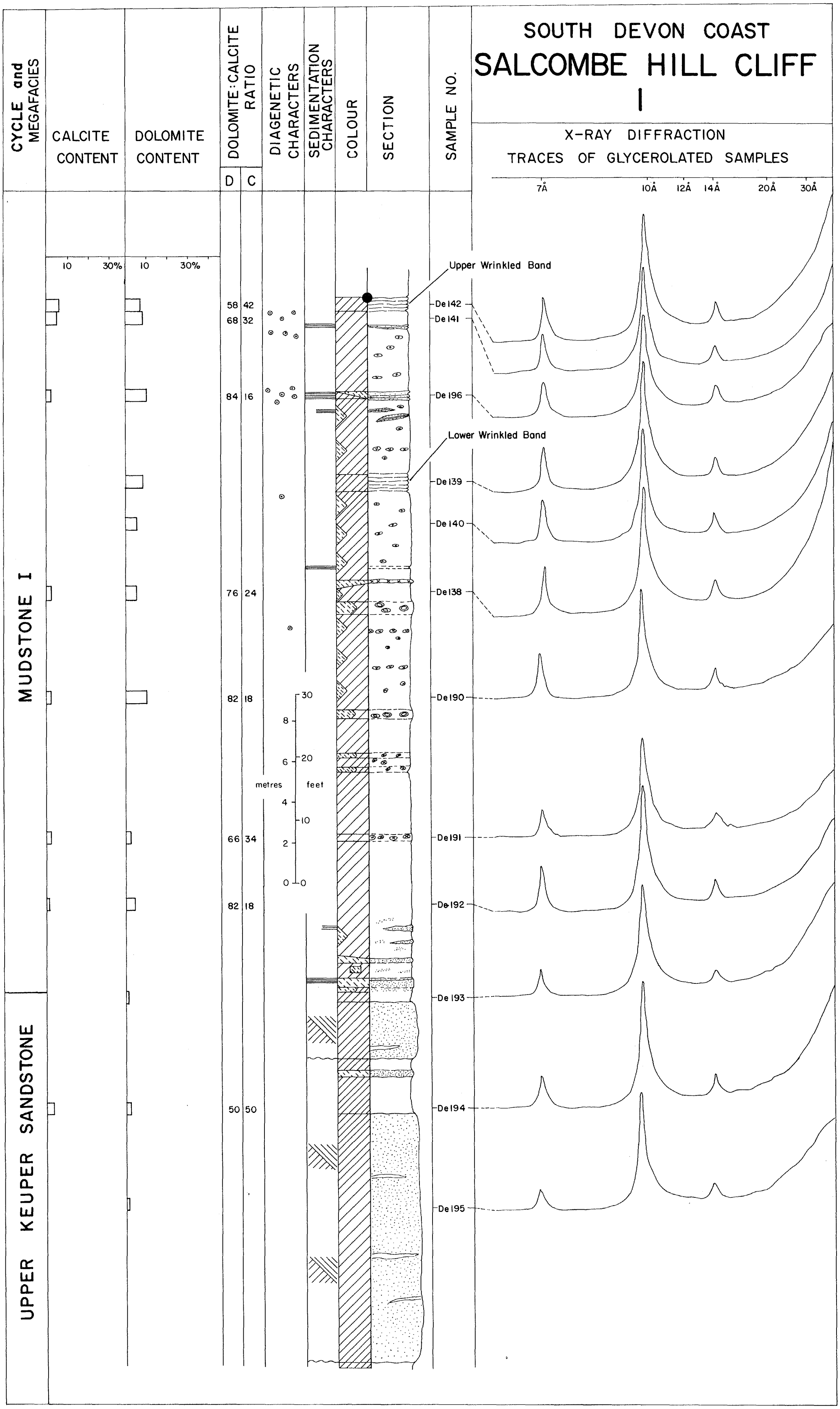

FIGURE 30. Lower part of the Salcombe Hill Cliff section. See figure 96 (pullout 1) for key.

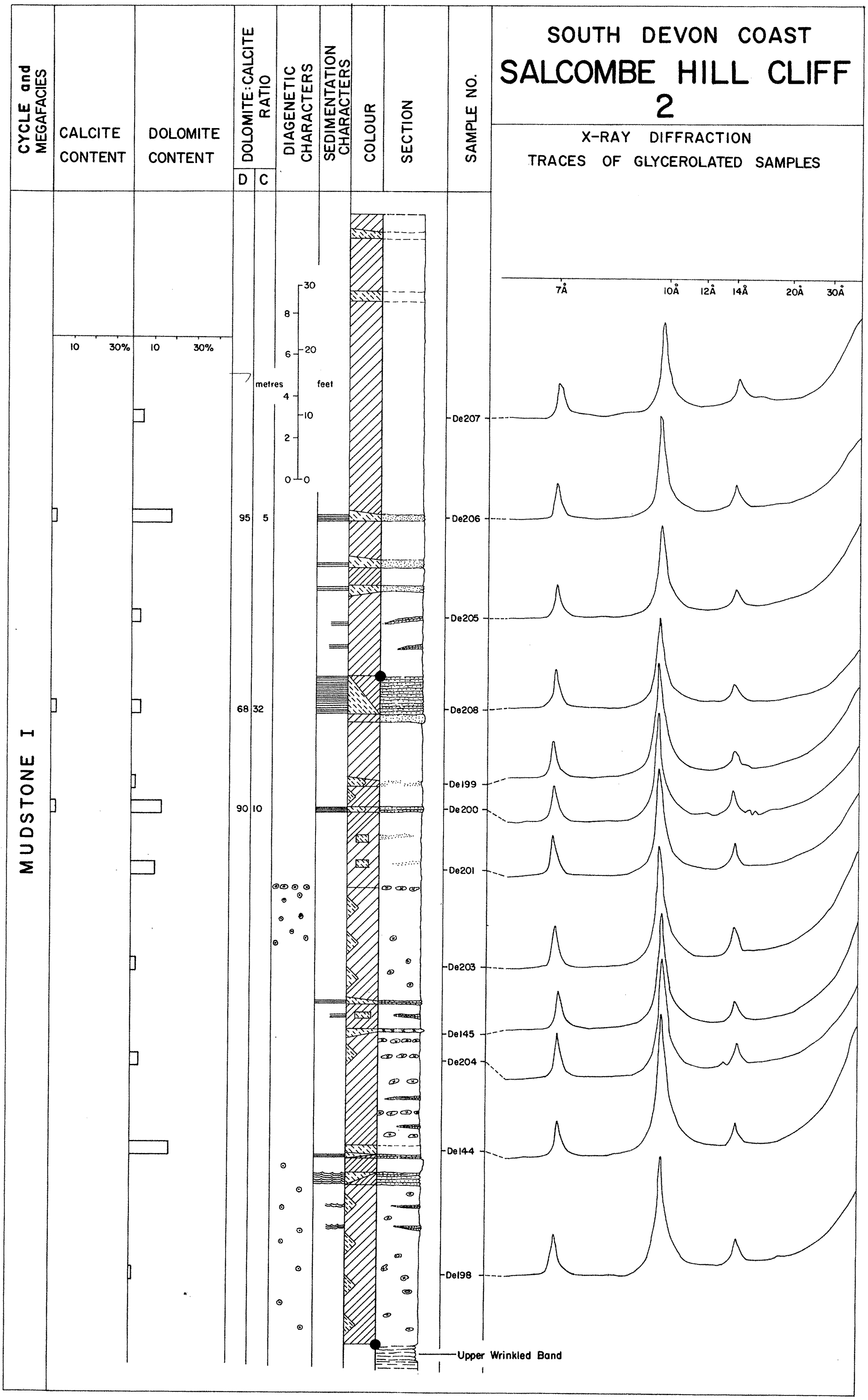

FIGURE 31. Upper part of the Salcombe Hill Cliff section continued from figure 30. See figure 96 for key.

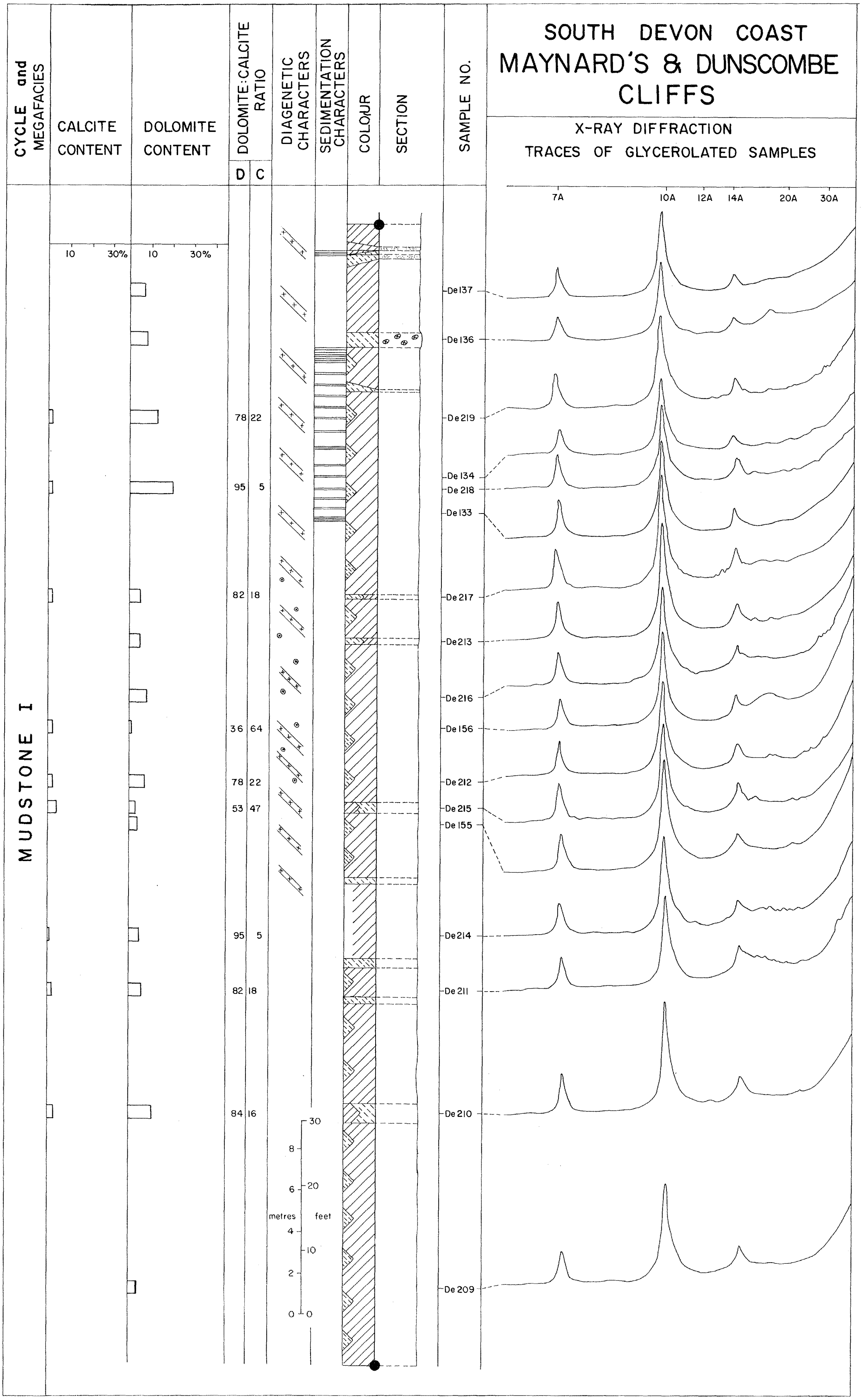

FIGURE 32. Section in Maynard's and Dunscombe Cliffs. See figure 96 for key.

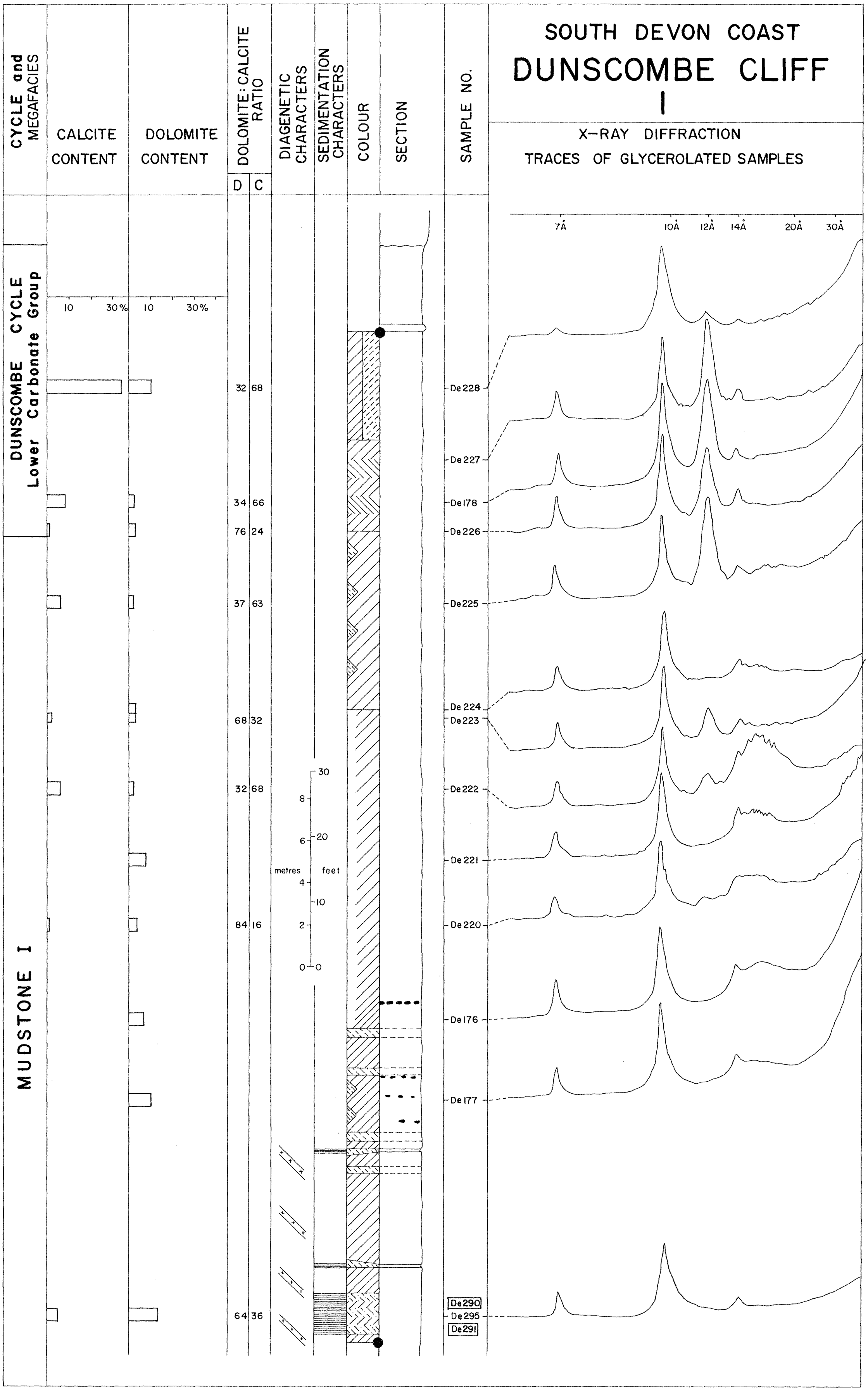

FIGURE 33. Lower section in Dunscombe Cliff continued from figure 32. See figure 96 for key.

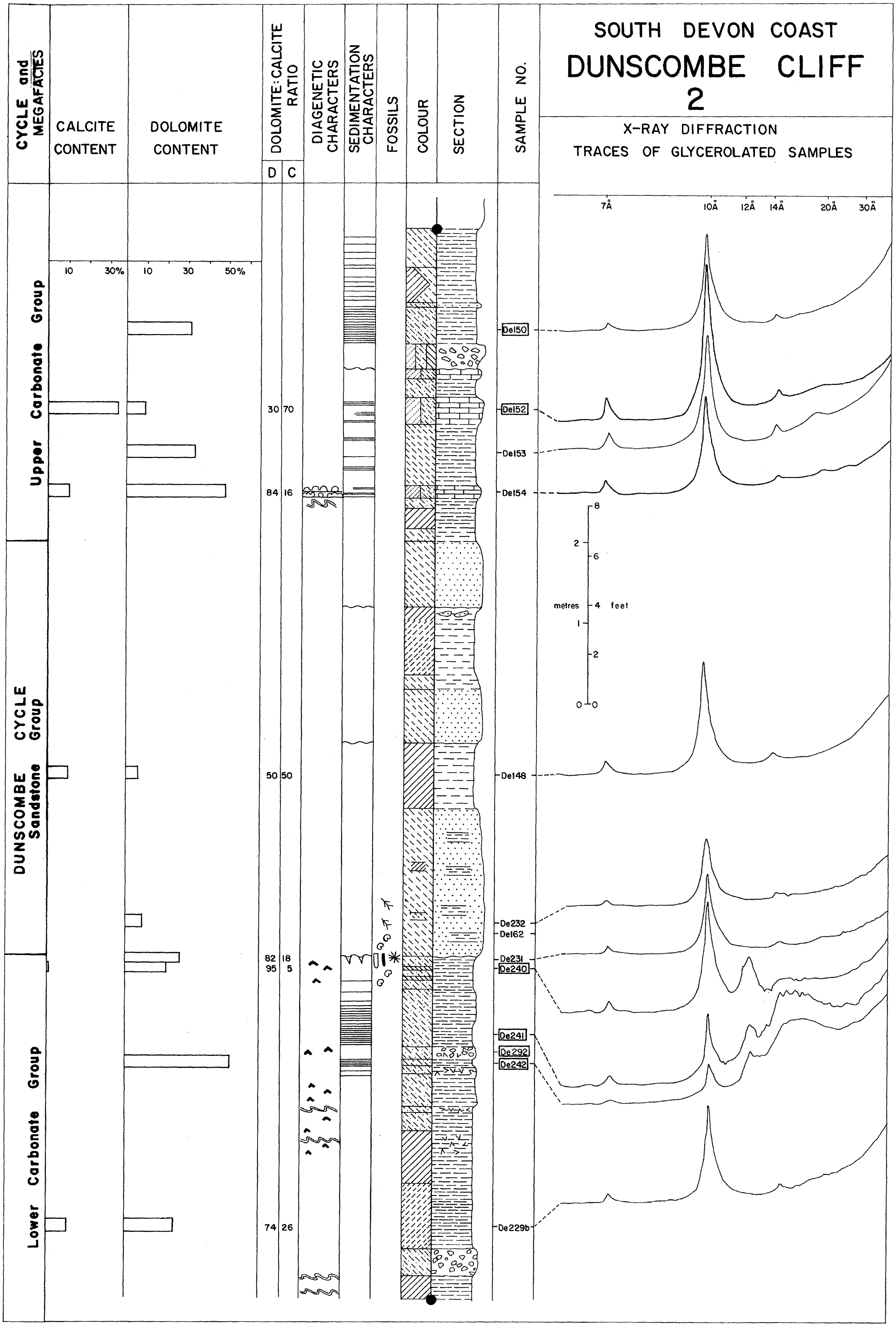

FIGURE 34. Middle section in Dunscombe Cliff continued from figure 33. See figure 96 for key.

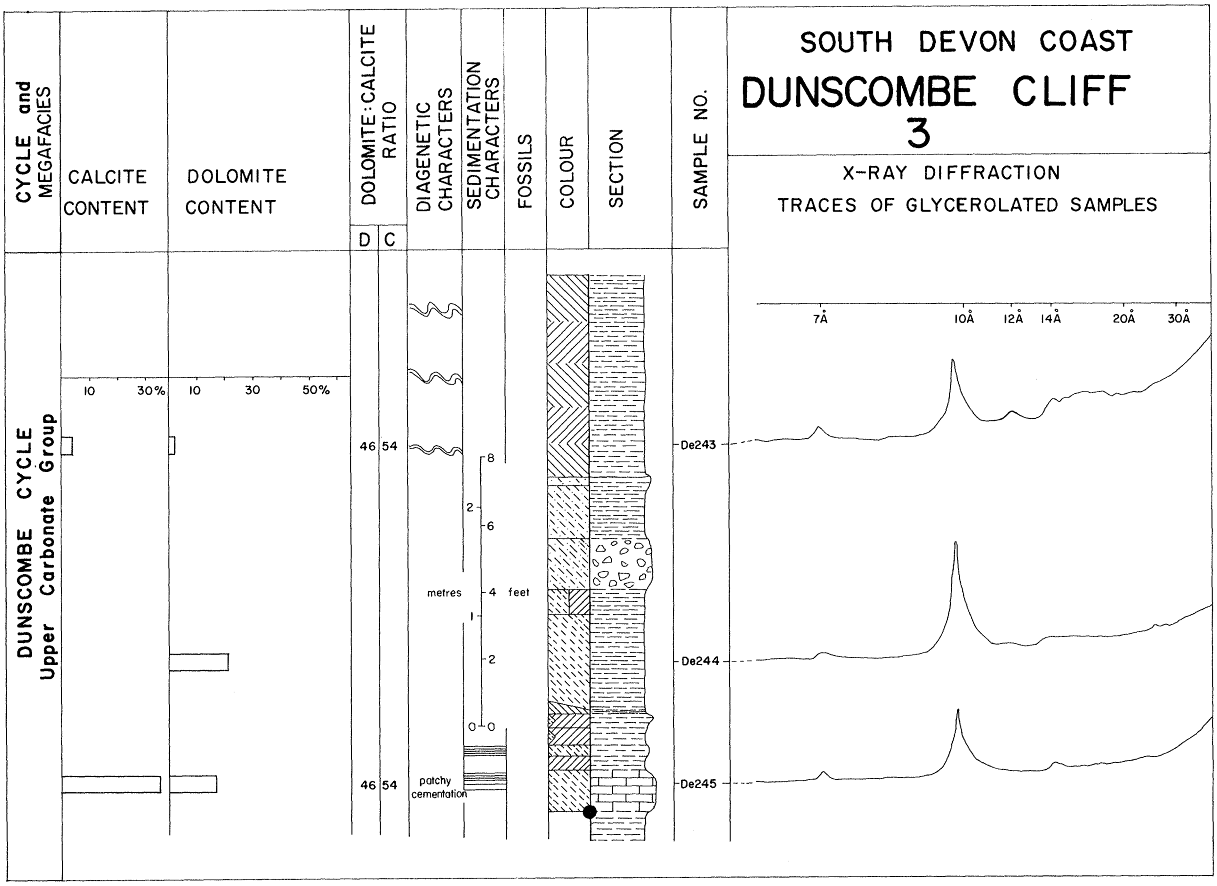

FIGURE 35. Upper section in Dunscombe Cliff continued from figure 34. See figure 96 for key.

Warndon 1 (figure 53). A road cutting on the west side of the B 4084 road, about 200 m from the motorway flyover (M 5) at Warndon (grid reference SO 895567). The section is in the Arden Sandstone Group.

Chondrites is common in some sandy layers.

Warndon 2 (figure 54). A recently grassed-over pit from which samples were obtained by excavation (grid reference SO 895574). The section is in the Arden Sandstone Group and possibly part of the underlying Keuper Marl. This locality is the Coneybury Wood borrow-pit of Dumbleton & West (1966).

Warndon 3 (figure 54). Minor road excavations situated on the east side of the B 4084 road about 300 m from the M 5 motorway flyover at Warndon (grid reference SO 908621). The section is in the top of the Lower Keuper Marl.

Stowell Park borehole (*Geological Survey of Great Britain*) (figures 55–58). The borehole was situated in Stowell Park, 46 m (50 yards) west of the Fosse Way and 869 m (950 yards) north by west of Coln St Denis Church. It penetrated the full thickness of the Keuper Marl (448 m; 1470 feet), which has been divided into four lithological units by Green & Melville (1956); a summary section is shown in figure 29.

Westbury-on-Severn (figure 59). The section is exposed in the cliffs on the northern bank of the River Severn at Strand (grid reference SO 716131). It spans the Rhaetic Formation, Tea Green Marl and uppermost part of the Keuper Marl.

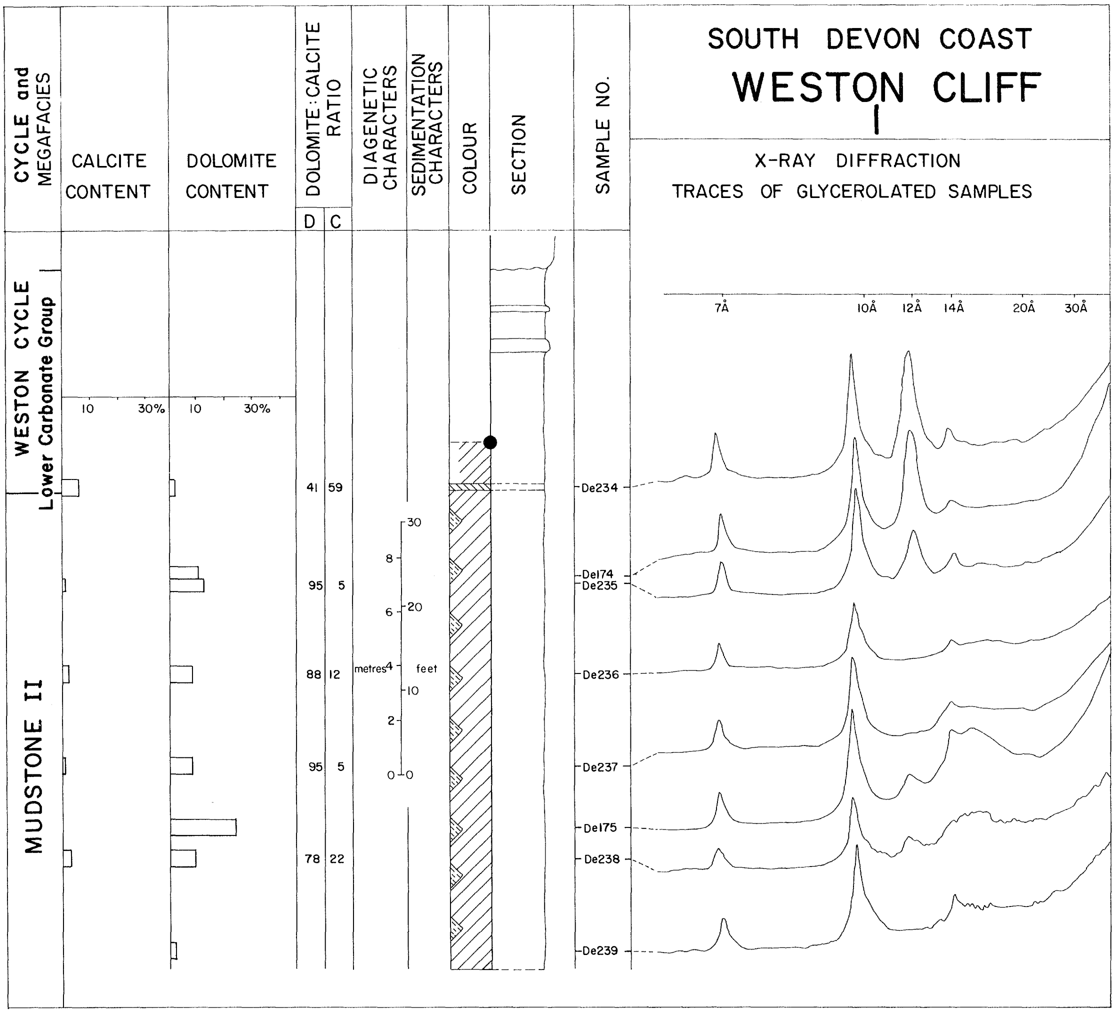

FIGURE 36. Lower section in Weston Cliff. See figure 96 for key.

(*d*) *Leicestershire*

Ibstock (grid reference SK 405110) (figure 60). In 1969 two adjacent pits were being worked: A 'lower clay zone' was being excavated in an older and lower pit, while a 'middle clay zone' was being worked in a younger and upper pit. The thickness of the unrecorded part of the sequence between the top of the lower pit and the base of the upper pit is probably some few metres.

Croft (grid reference SP 512965) (figure 61). This quarry, worked for granite to great depths by the English China Clay Company, shows the contact between the Precambrian granite and the Keuper Marl. Bosworth (1912, pp. 26–29) has described in great detail how the Keuper Marl is banked up against the hills of the granite basement. He identified an Upper Keuper Sandstone in the uppermost part of the Keuper sequence; this is still accessible and bears no resemblance to the Arden Sandstone Group.

Loughborough (figure 62). A large overgrown pit located 200 m northeast of the A 6 road bridge over the main railway line in south Loughborough (grid reference SK 546184); it is now completely disused, although in 1969 Keuper Marl was being worked in the south part of the pit. This locality is mentioned by Bosworth (1912, fig. 1).

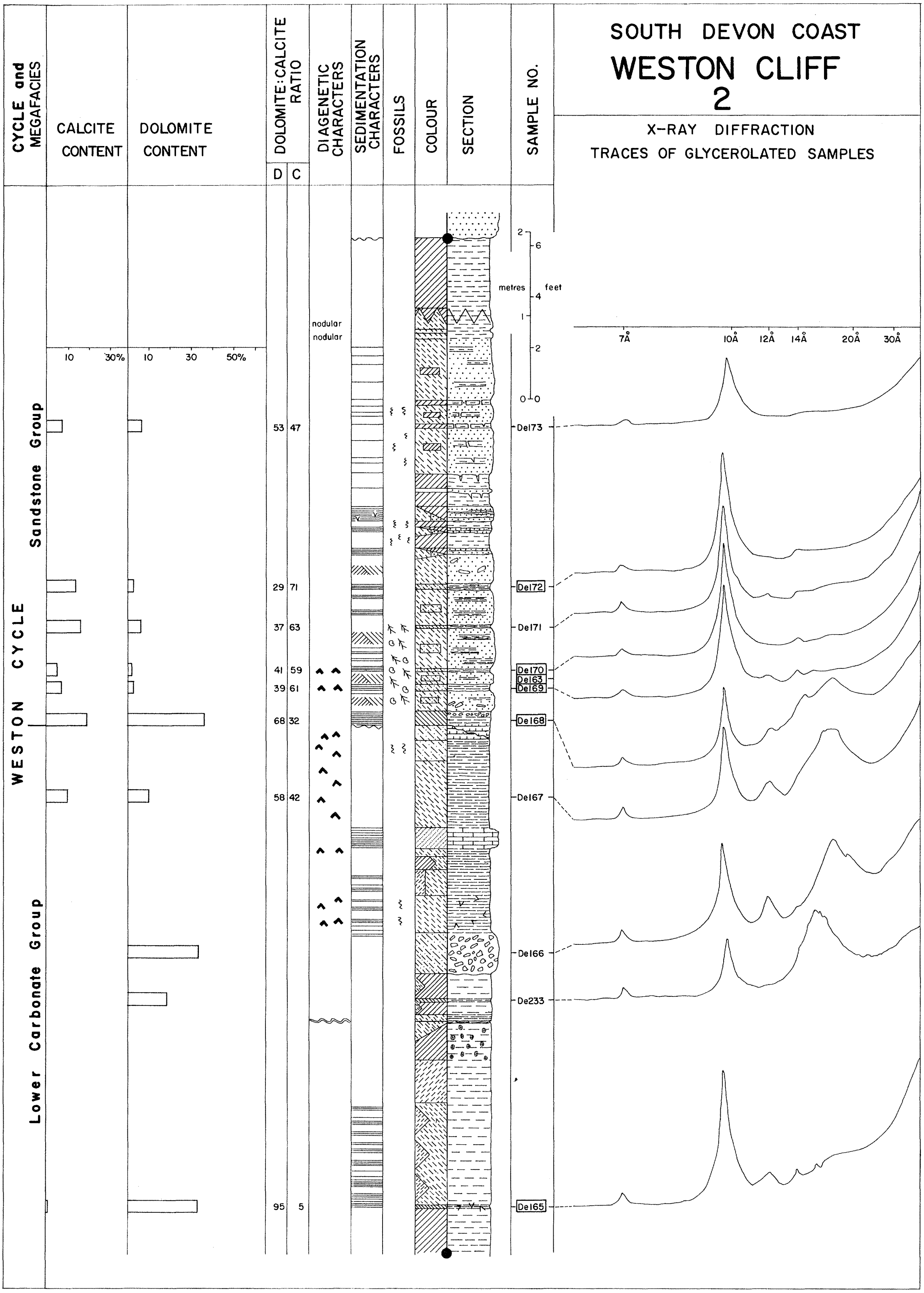

FIGURE 37. Lower middle section in Weston Cliff continued from figure 36. See figure 96 for key.

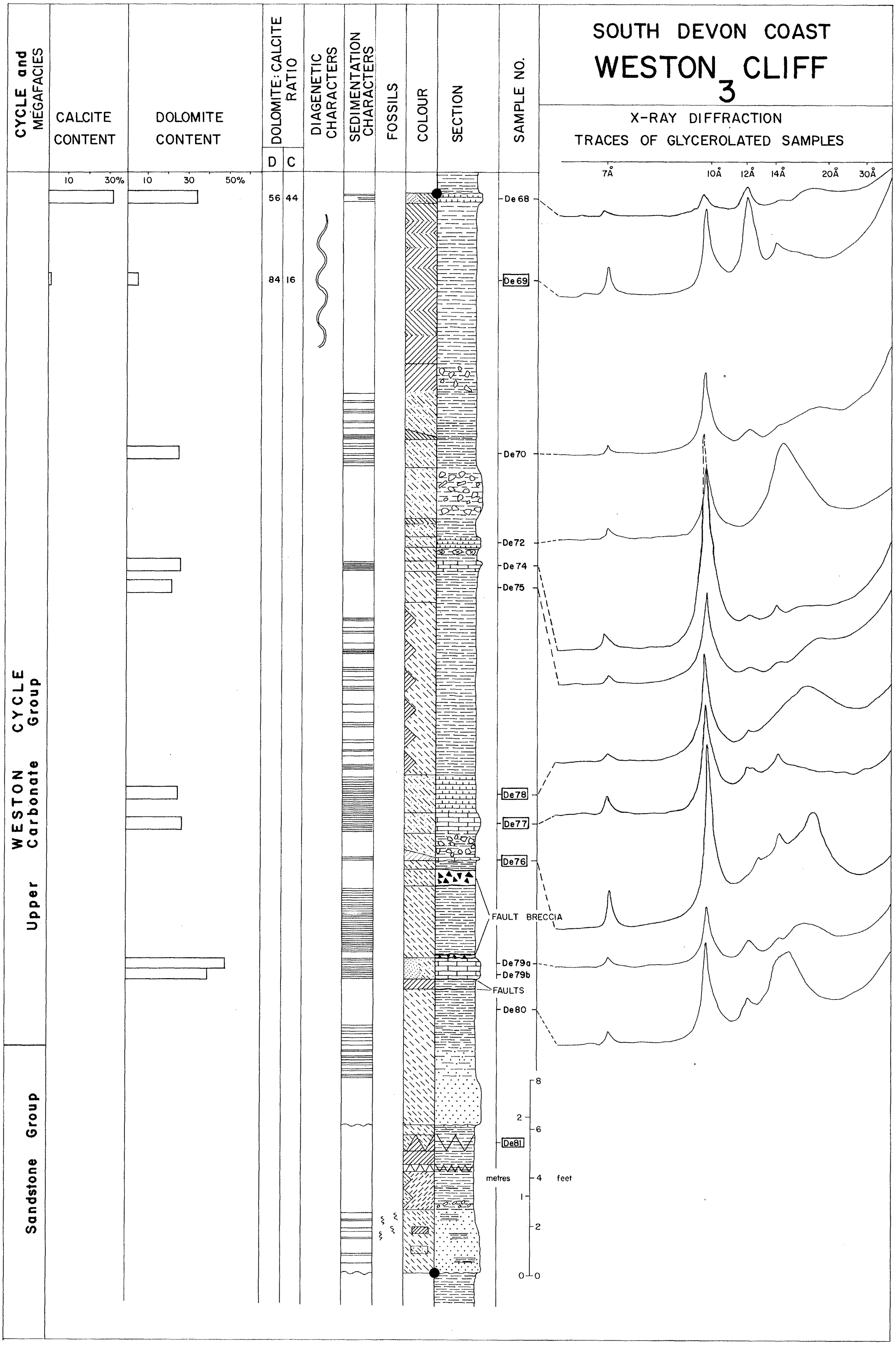

FIGURE 38. Upper middle section in Weston Cliff continued from figure 37. See figure 96 for key.

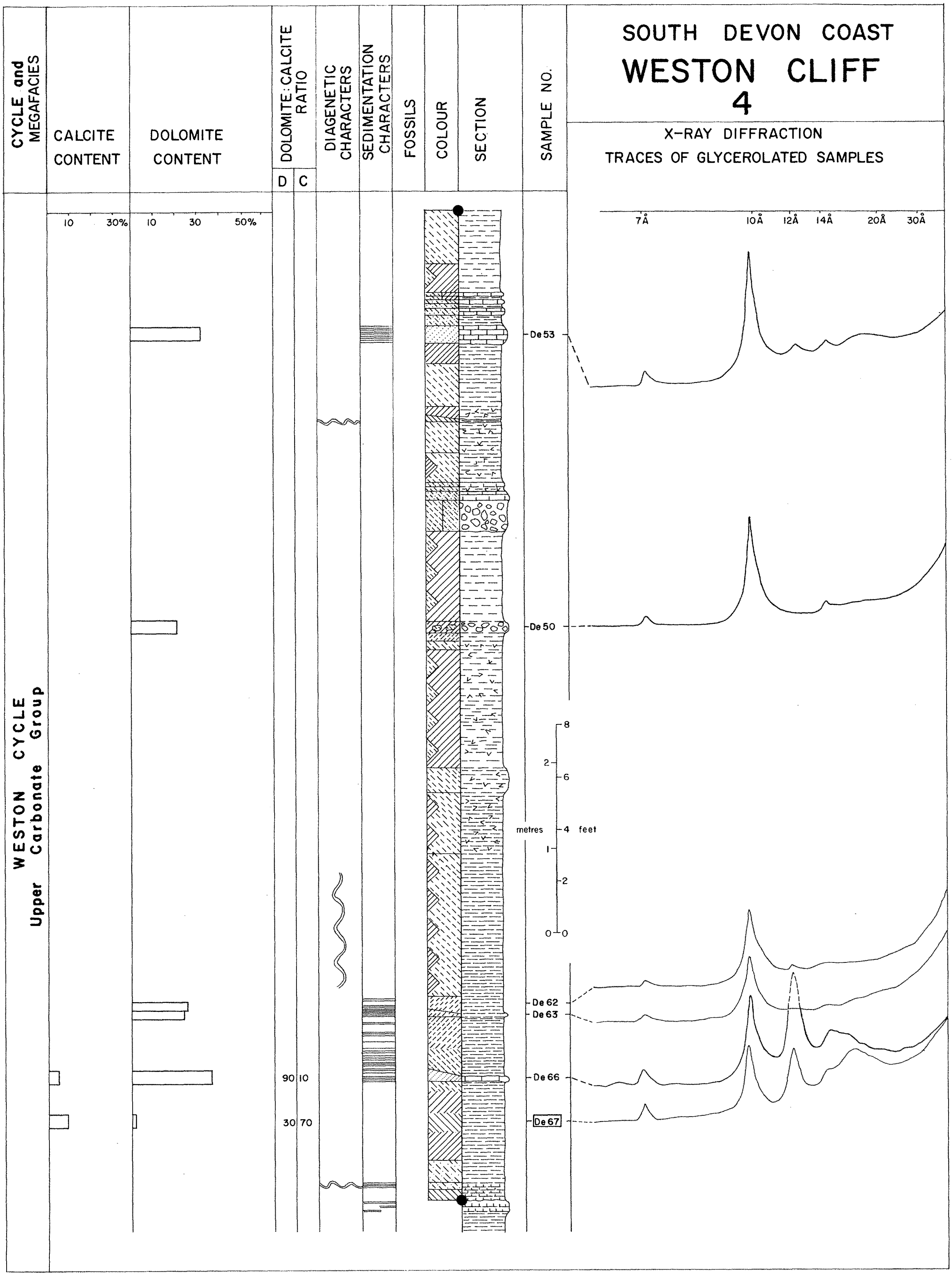

FIGURE 39. Upper section in Weston Cliff continued from figure 38. See figure 96 for key. The X-ray diffraction trace of untreated sample De 66 is shown.

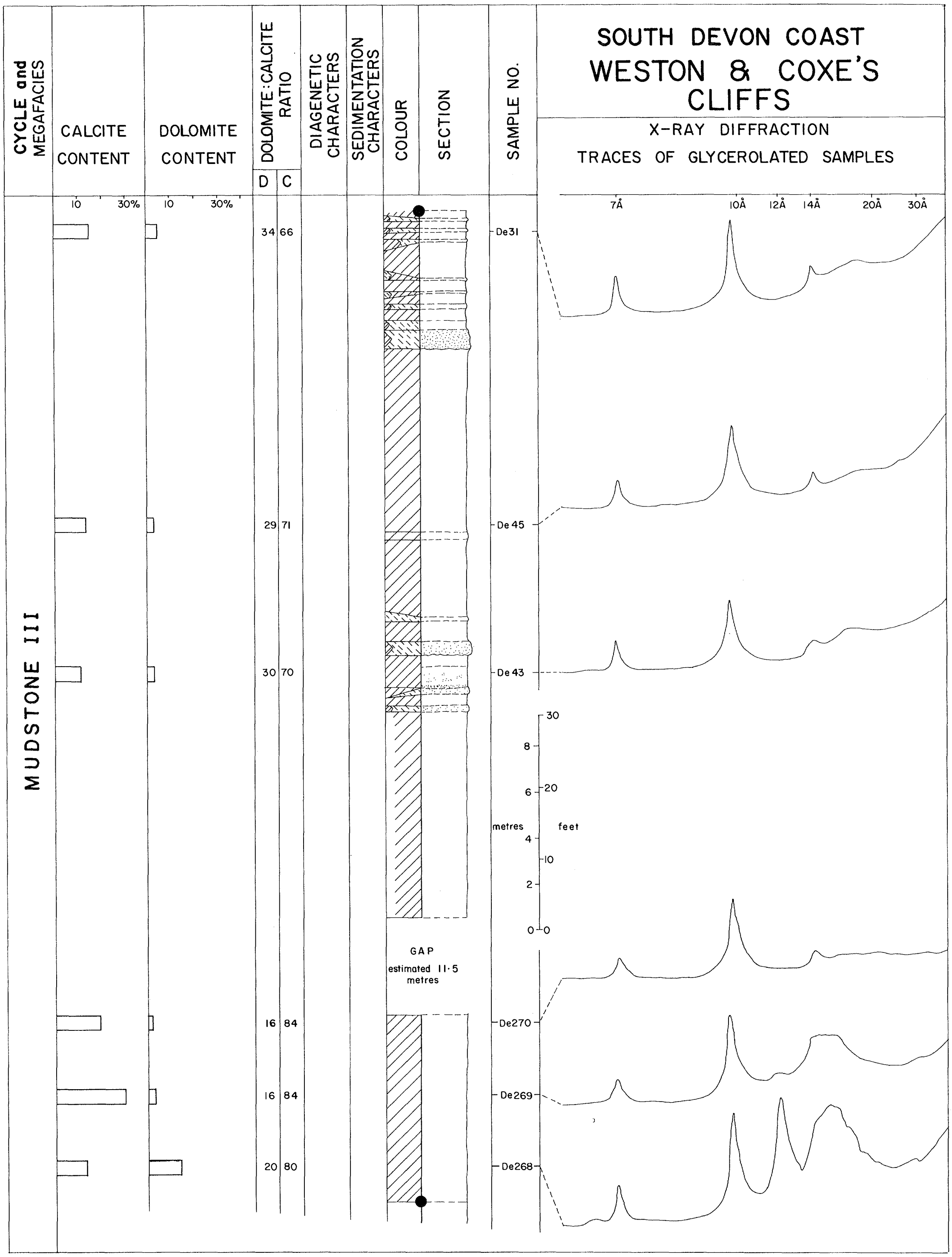

FIGURE 40. Section in Weston and Coxe's Cliffs continued from figure 39. See figure 96 for key.

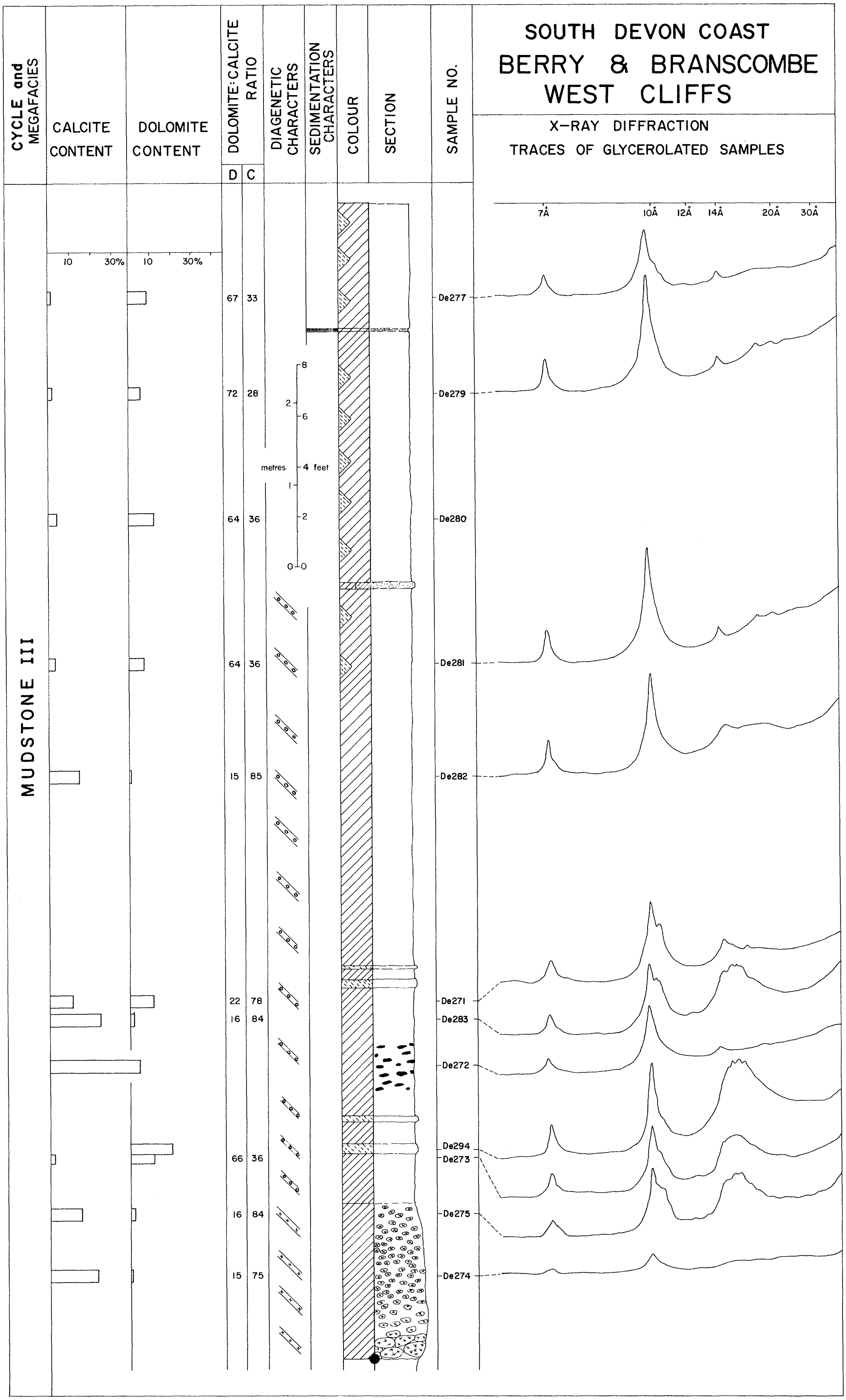

FIGURE 41. Section in Berry and Branscombe West Cliffs: there is a 16 m gap between the bottom of this section and the top of the section in figure 40. See figure 96 for key.

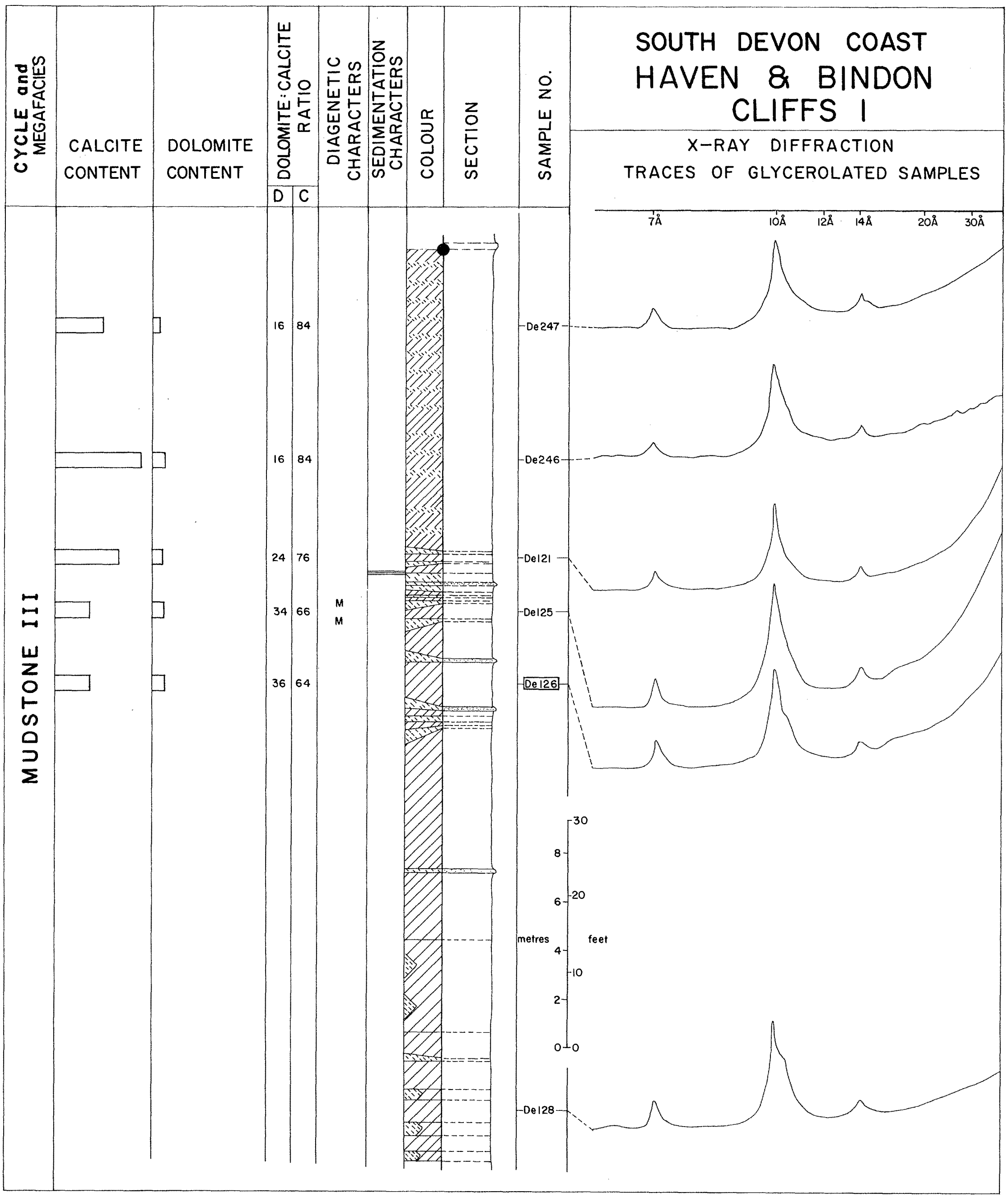

FIGURE 42. Lower section in Haven and Bindon Cliffs. See figure 96 for key.

Leicester 1: *Gypsy Lane Brickworks, northeast Leicester* (figure 63). A worked pit situated 800 m north of the hospital at New Humberstone (grid reference SK 616070) was mentioned by Bosworth (1912, pp. 66–9) and Taylor (1968, pp. 160 and 172). The section is of reddish brown mudstone with beds and nodule bands of gypsum, and is overlain by greenish grey shaly mudstone, probably part of the Tea Green Marl.

Leicester 2: *New Star Brick Co. Leicester* (figure 64). This overgrown pit, worked in 1969, is 1.4 km, 14° east of north from the New Humberstone Hospital (grid reference SK 616075). This is probably the Star Brickworks of Bosworth (1912, p. 67) where he records a gypsum-free horizon of the 'Highly Gypsiferous Marls'.

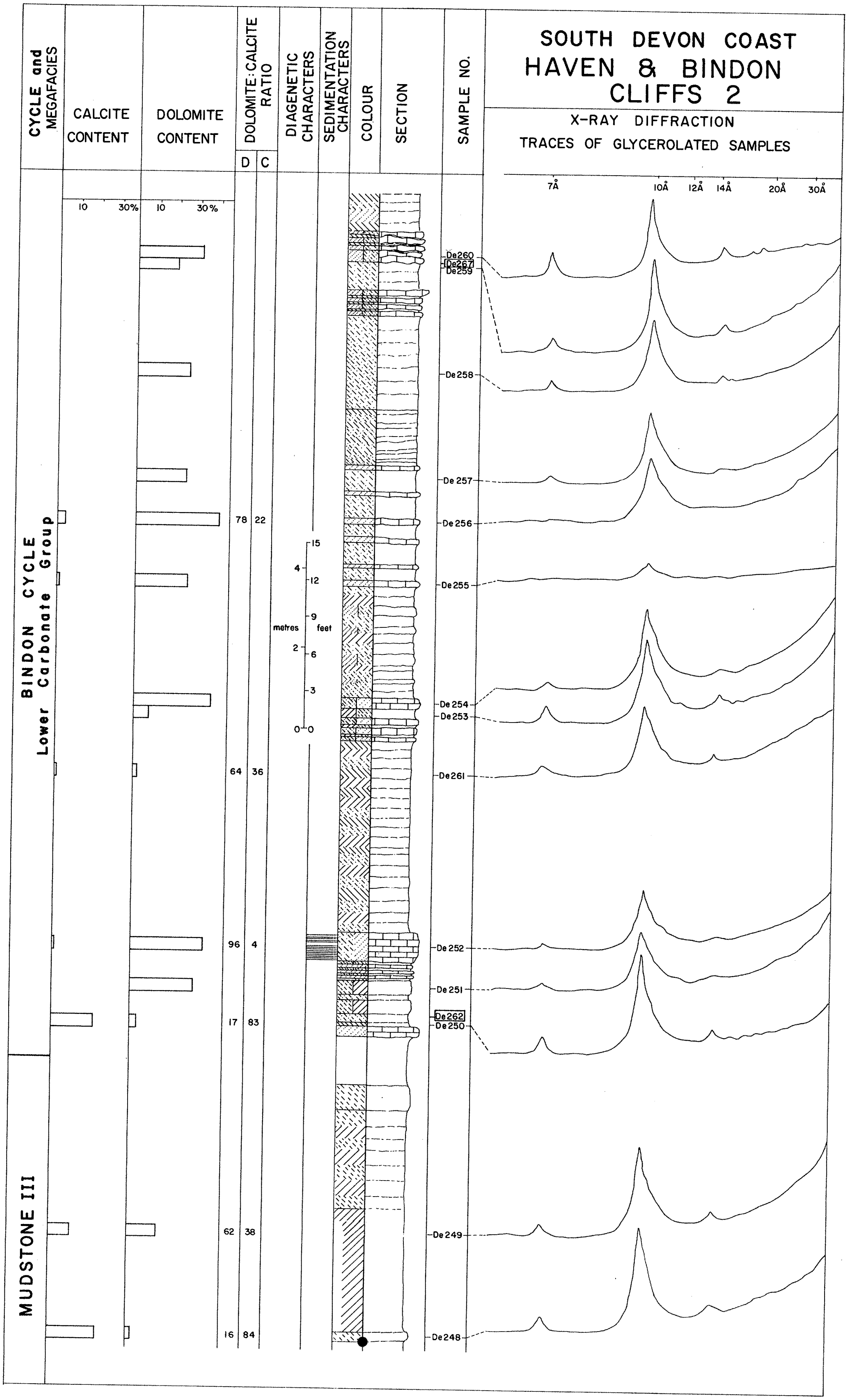

FIGURE 43. Upper section in Haven and Bindon Cliffs continued from figure 42. See figure 96 for key.

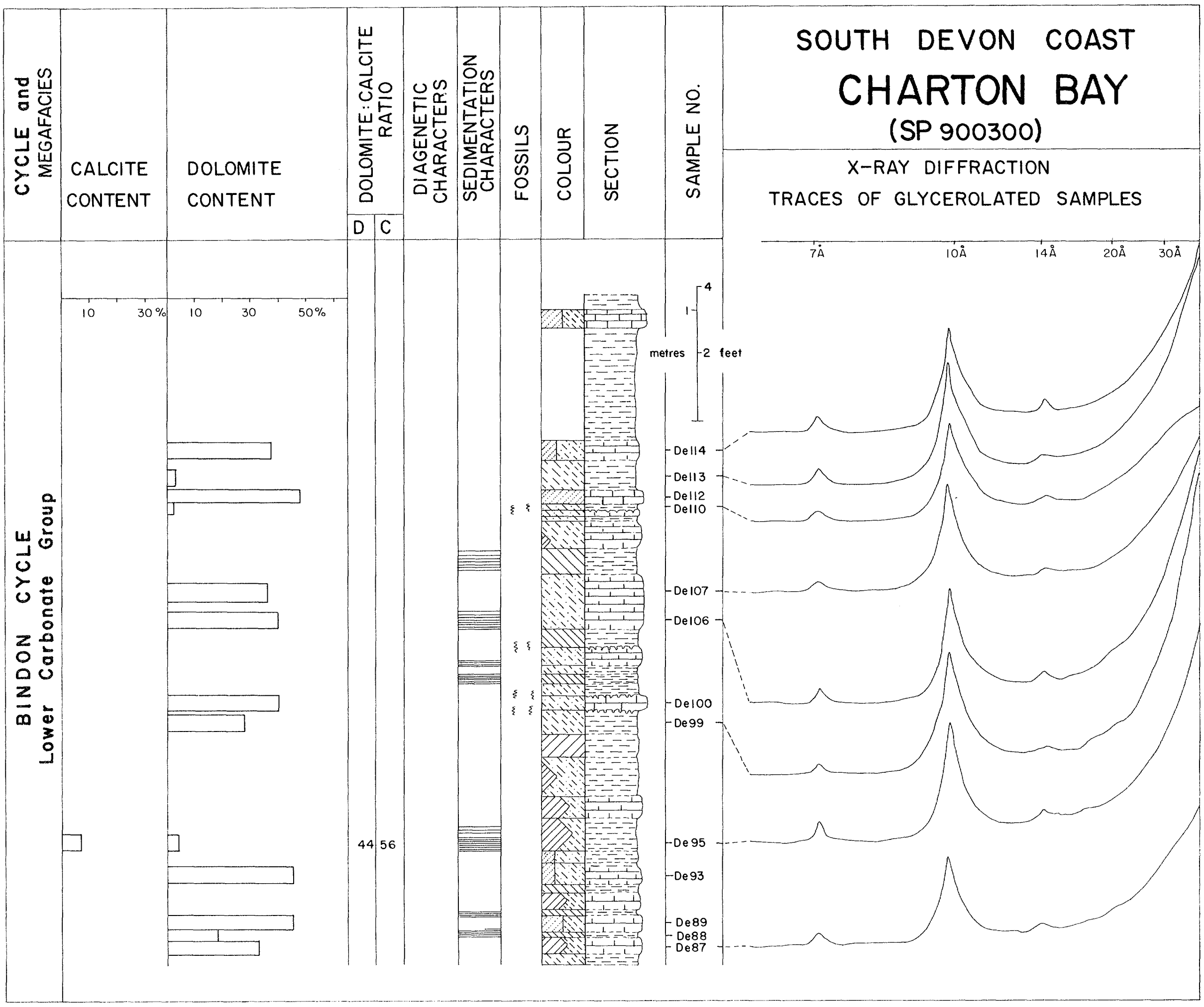

FIGURE 44. Section in Charton Bay. See figure 96 for key.

(e) *Nottinghamshire*

Staunton-in-the-Vale gypsum pit (figure 65). A worked pit located about 8.5 km south of Newark-on-Trent on the east side of the Kilvington road (grid reference SK 804445). The section consists of massive reddish brown mudstone with thick gypsum bands and is included in the Trent Formation (Elliott 1961, p. 222; Taylor 1968, p. 272).

Cropwell Bishop gypsum pit (figure 66). A worked pit on the north side of the Cropwell Bishop–Stragglethorpe road (grid reference SK 675358): mentioned by Elliott (1961, p. 222) and by Taylor (1968, p. 172). In 1969 it was still being worked and showed a section in the reddish brown mudstones of the Trent Formation containing bands of gypsum. There was no evidence that these gypsum bands were of depositional origin. According to Elliott (1961, p. 222), this gypsum comes from 14 m (45 feet) below the base of the Parva Formation.

Windmill Hill Marl pit, Cotgrave (grid reference SK 644358) (figure 67). The section recorded is from the west part of the disused pit. The sequence according to Elliott (1961, p. 222) belongs to Beds 2 and 3 of the Trent Formation. This is one of the few localities in Nottinghamshire at which sepiolite has been found.

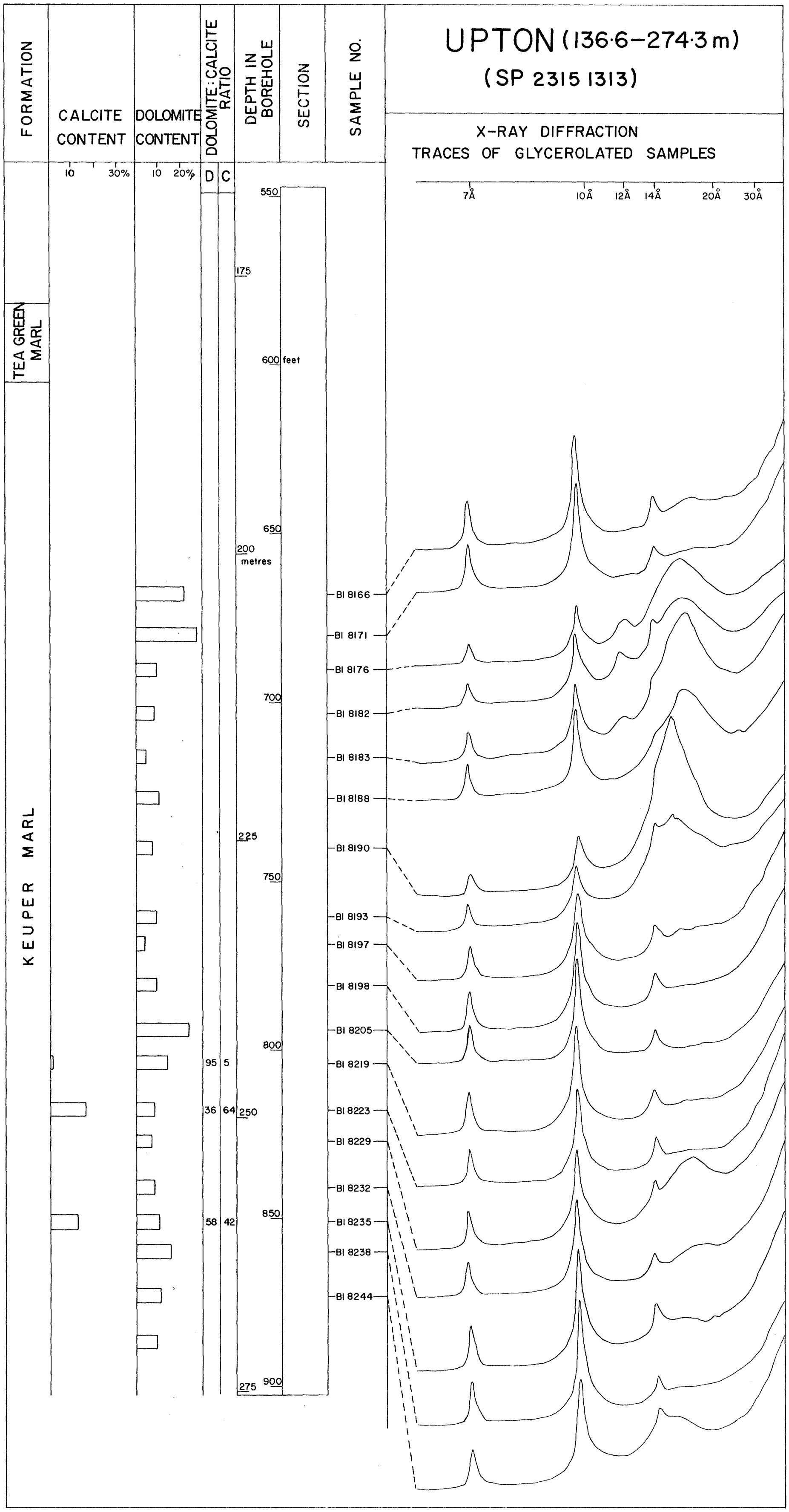

FIGURE 45. Clay and carbonates in the Keuper Marl of the Upton borehole between 136.6 and 274.3 m depth.

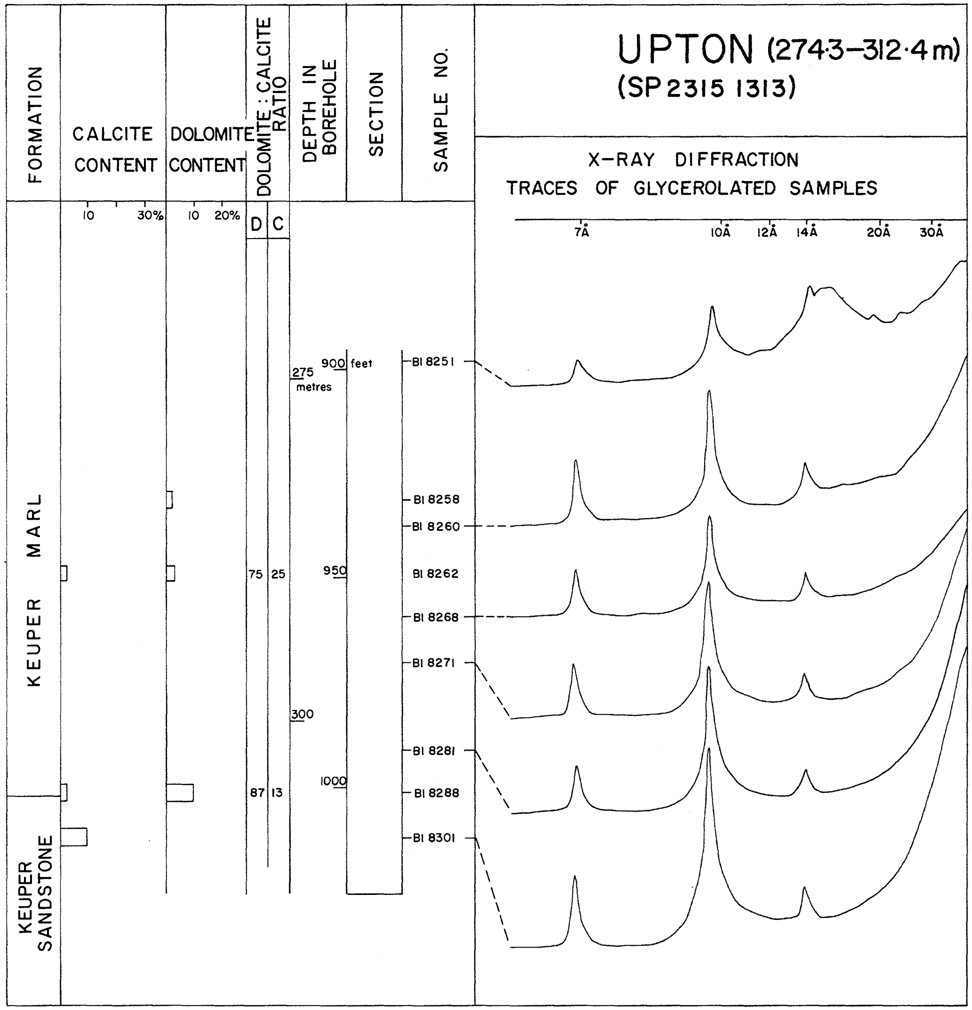

Figure 46. Clays and carbonates in the Keuper Marl of the Upton borehole between 274.3 and 312.4 m depth.

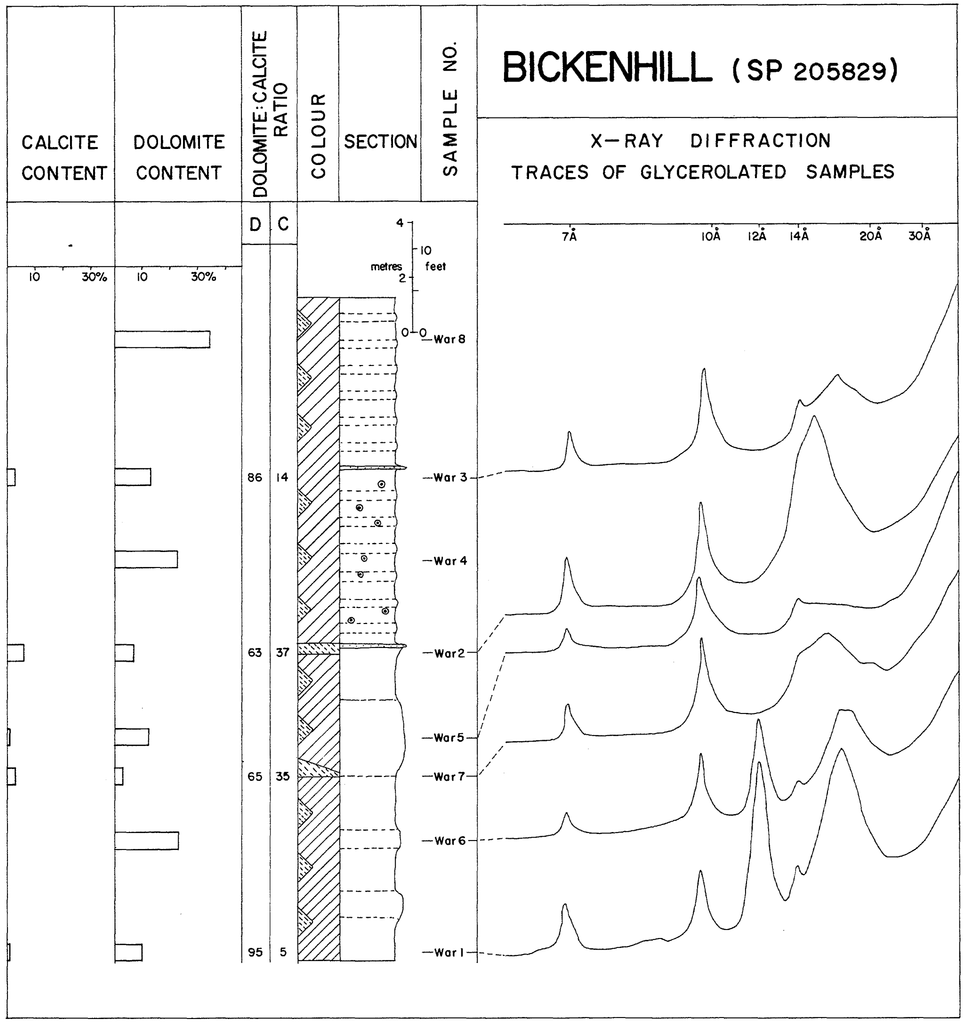

Figure 47. Keuper Marl at Bickenhill, Warwickshire. See figure 96 for key.

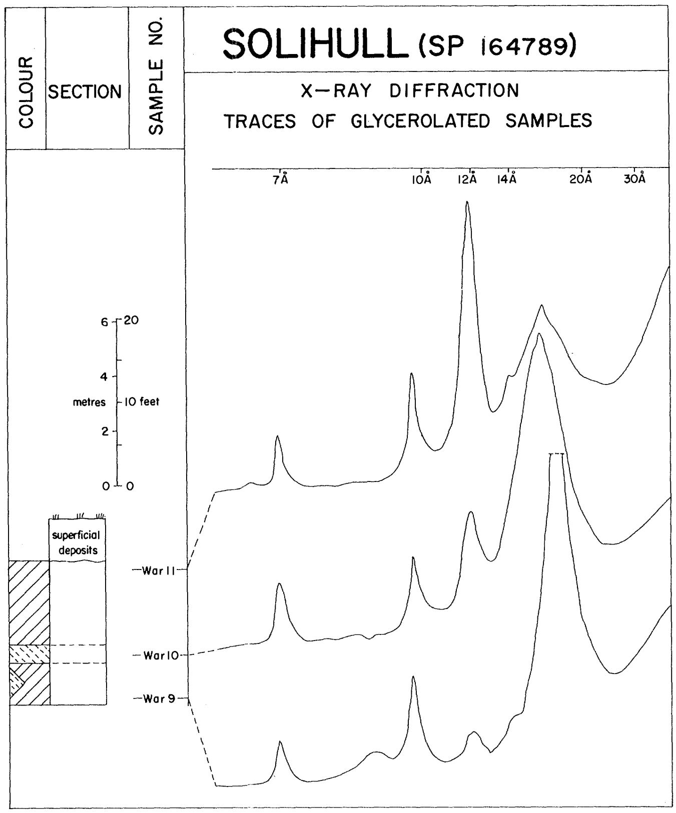

FIGURE 48. Keuper Marl at Solihull, Warwickshire. See figure 96 for key.

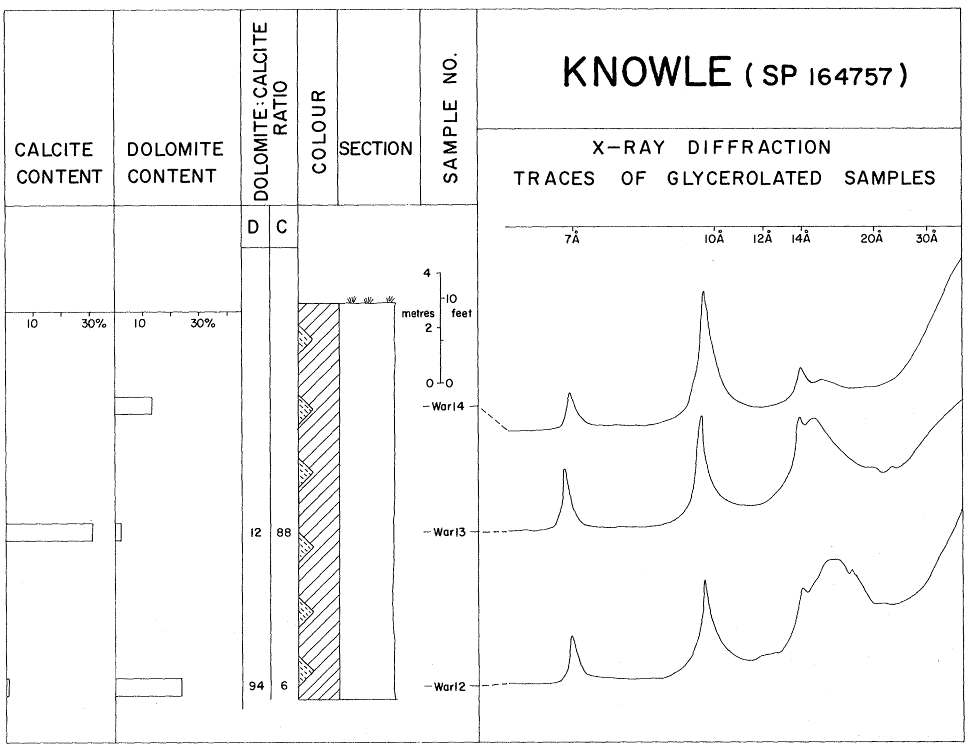

FIGURE 49. Keuper Marl at Knowle, Warwickshire. See figure 96 for key.

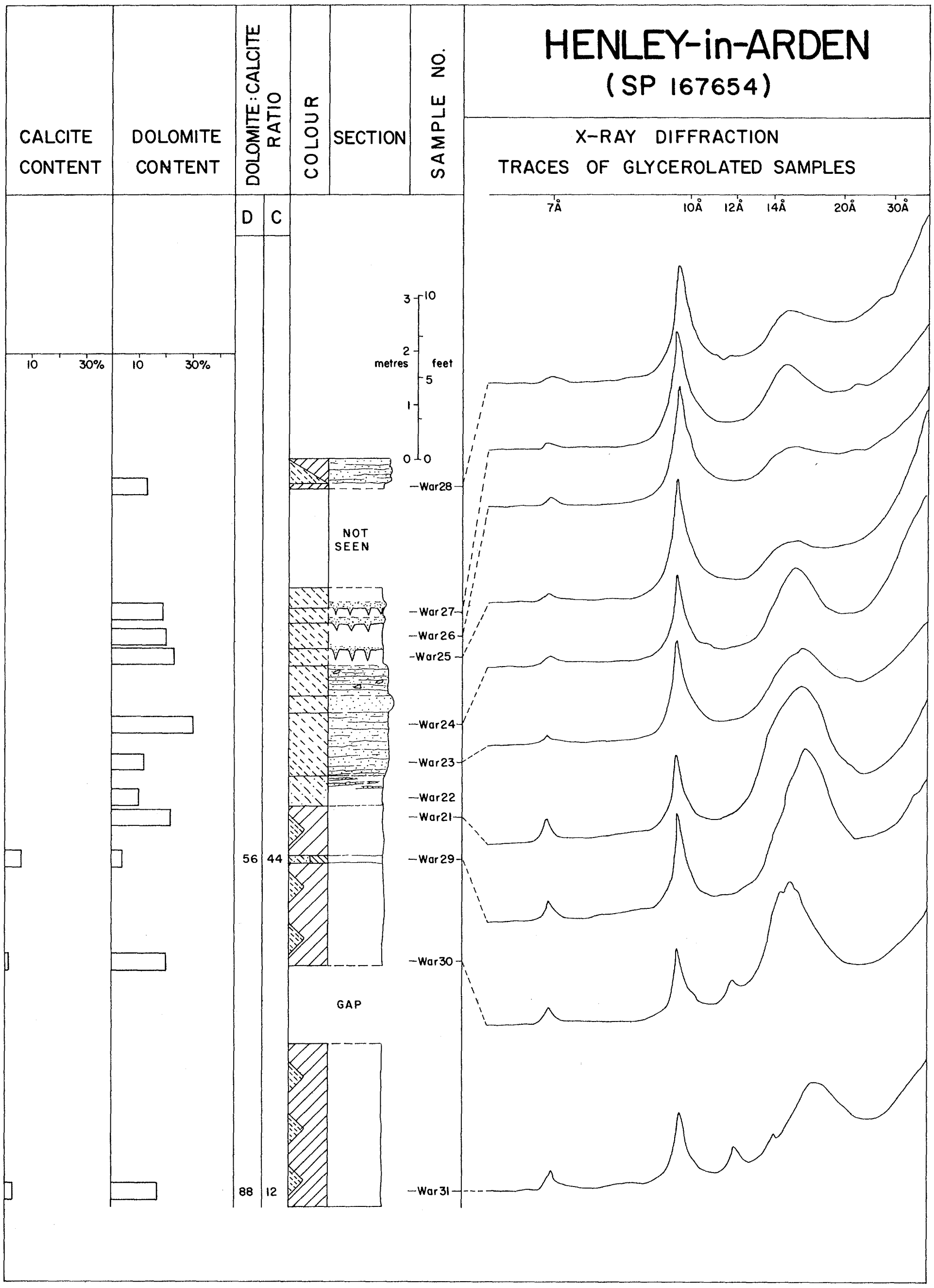

FIGURE 50. Keuper Marl (Arden Sandstone Group) at Henley-in-Arden, Warwickshire. See figure 96 for key.

Edwalton Hill Brickworks (figure 68). A disused pit situated south–southwest of Nottingham, adjacent to the railway and immediately west of the A 606 road (grid reference SK 589363), was mentioned by Elliott (1961, p. 220). In 1969 a section was recorded in the lower green-bed belt and Cotgrave Skerry of the Edwalton Formation.

Bunny brick and gypsum pit (figure 69). A worked pit situated immediately east of the A 60 road near Bunny, about 10.5 km south of Nottingham (grid reference SK 581286) was mentioned by Taylor (1968). In 1969 an upper and lower pit were being worked. The sequence,

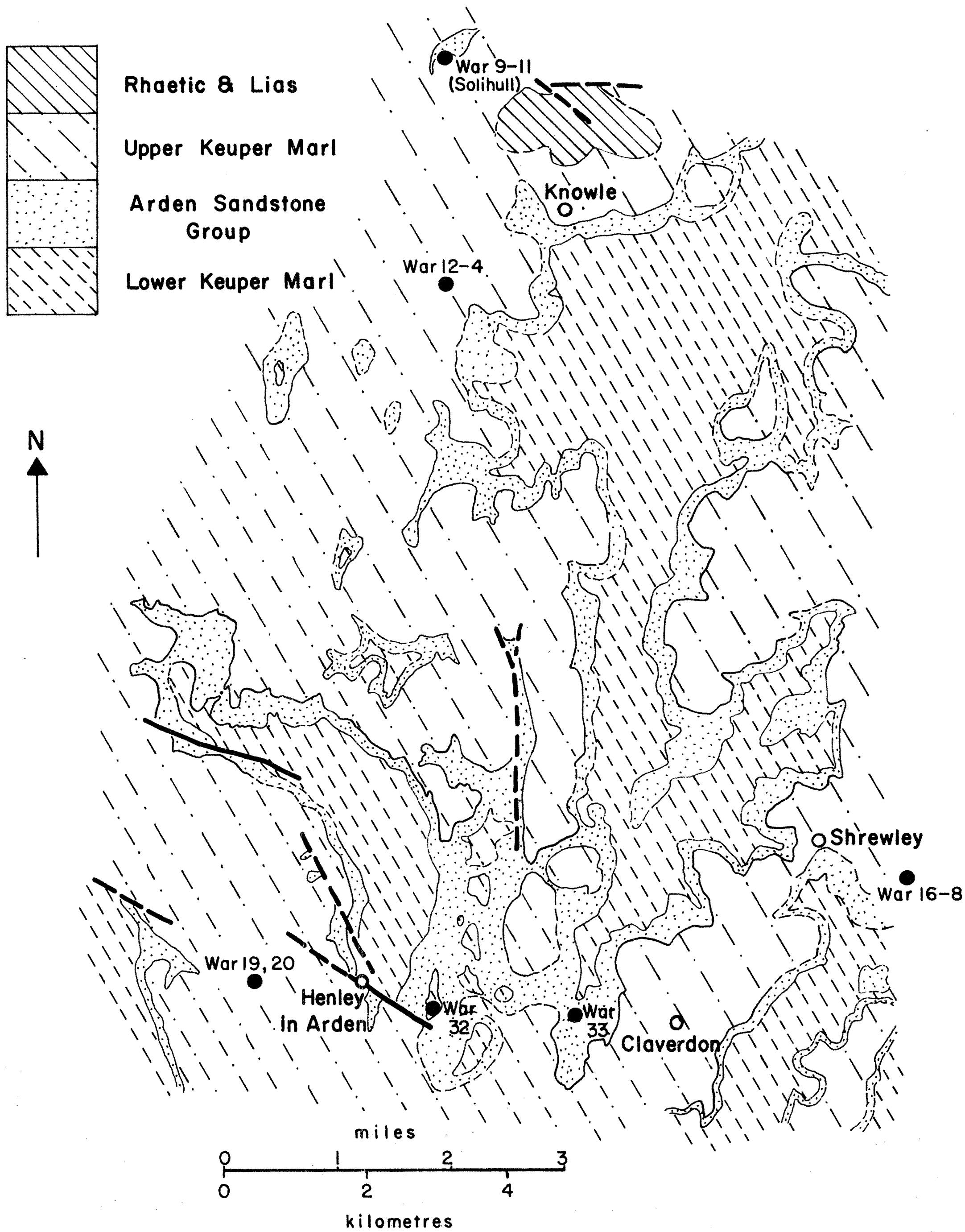

FIGURE 51. Geological map of the Arden Forest area; sample locations shown.

probably in the Trent Formation, consisted of reddish brown mudstone containing bands of large nodules and continuous beds of gypsum.

Owthorpe: Woodman's Cottage borehole no. 11 (*N.C.B.*) (figure 70). The borehole was located 1043 m, 37° west of south from St Margaret's Church, Owthorpe (grid reference SK 666325). It penetrated the basal part of the Lias, the Rhaetic and the Keuper Marl as far as the base of the Parva Formation. The lithological section was recorded by Mr Raisbeck of the N.C.B.

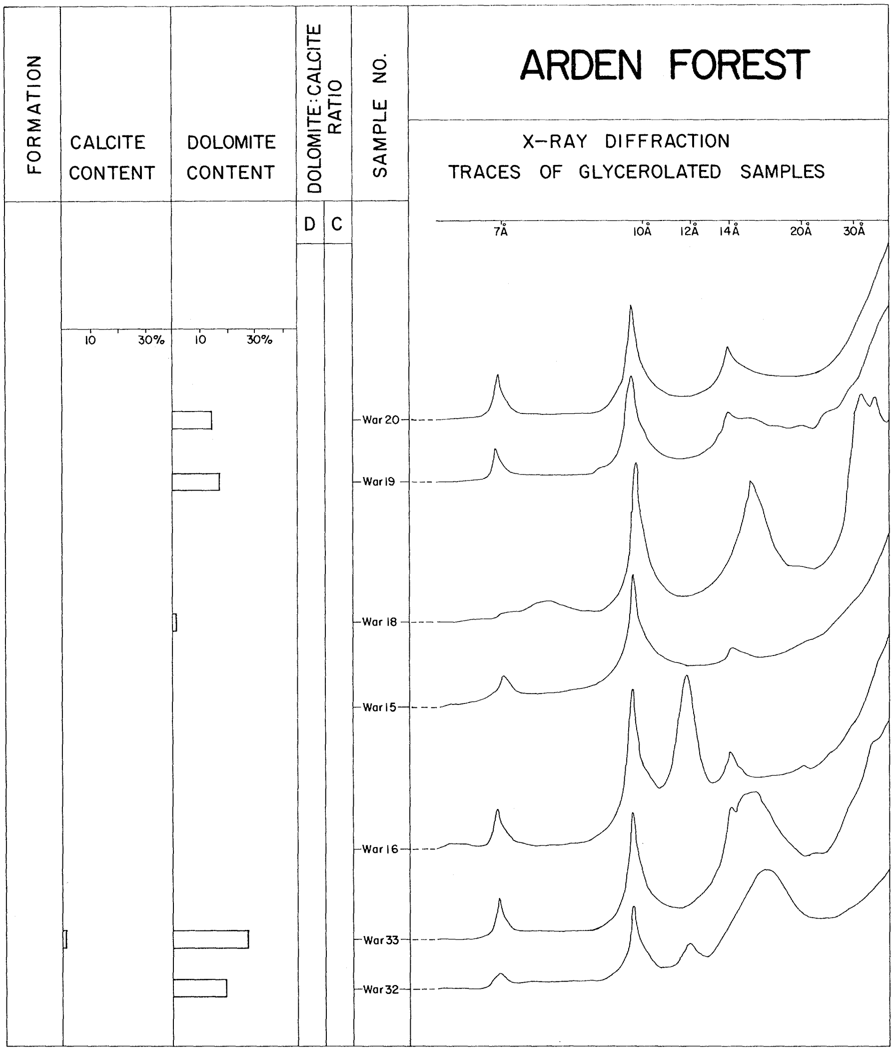

FIGURE 52. Clays and carbonates in the Keuper Marl of the Arden Forest area.

Radcliffe Barn Farm borehole no. 2 (*N.C.B.*) (figure 71). The borehole was sunk approximately 274 m east of Radcliffe Barn Farm, Radcliffe-on-Trent (grid reference SK 659382). It penetrated the Cotgrave Skerry of the Edwalton Formation and the upper part of the Harlequin Formation. The lithological section was recorded by Mr Raisbeck of the N.C.B.

Clipston: Blackberry Hills borehole no. 7 (*N.C.B.*) (figures 72 and 73). The borehole was situated 832 m, 35° east of south from St John's Chapel, Clipston (grid reference SK 638333). It started in the lower part of the Parva Formation and penetrated to the base of the Hollygate Skerry in the upper part of the Edwalton Formation. Sepiolite was recorded from the base of the Trent Formation in sample Nott 74. The lithological section was recorded by Mr Raisbeck of the N.C.B.

Cropwell Bishop borehole (*N.C.B.*/*I.G.S.*) (grid reference SK 67730 35473) (figures 74 and 75). A sequence from the upper part of the Edwalton Formation to the base of the Keuper Series was investigated. The lithological sequence in figures 74 and 75 showing the provisional assignment of Elliott's subdivisions was communicated by Dr Warrington (I.G.S.).

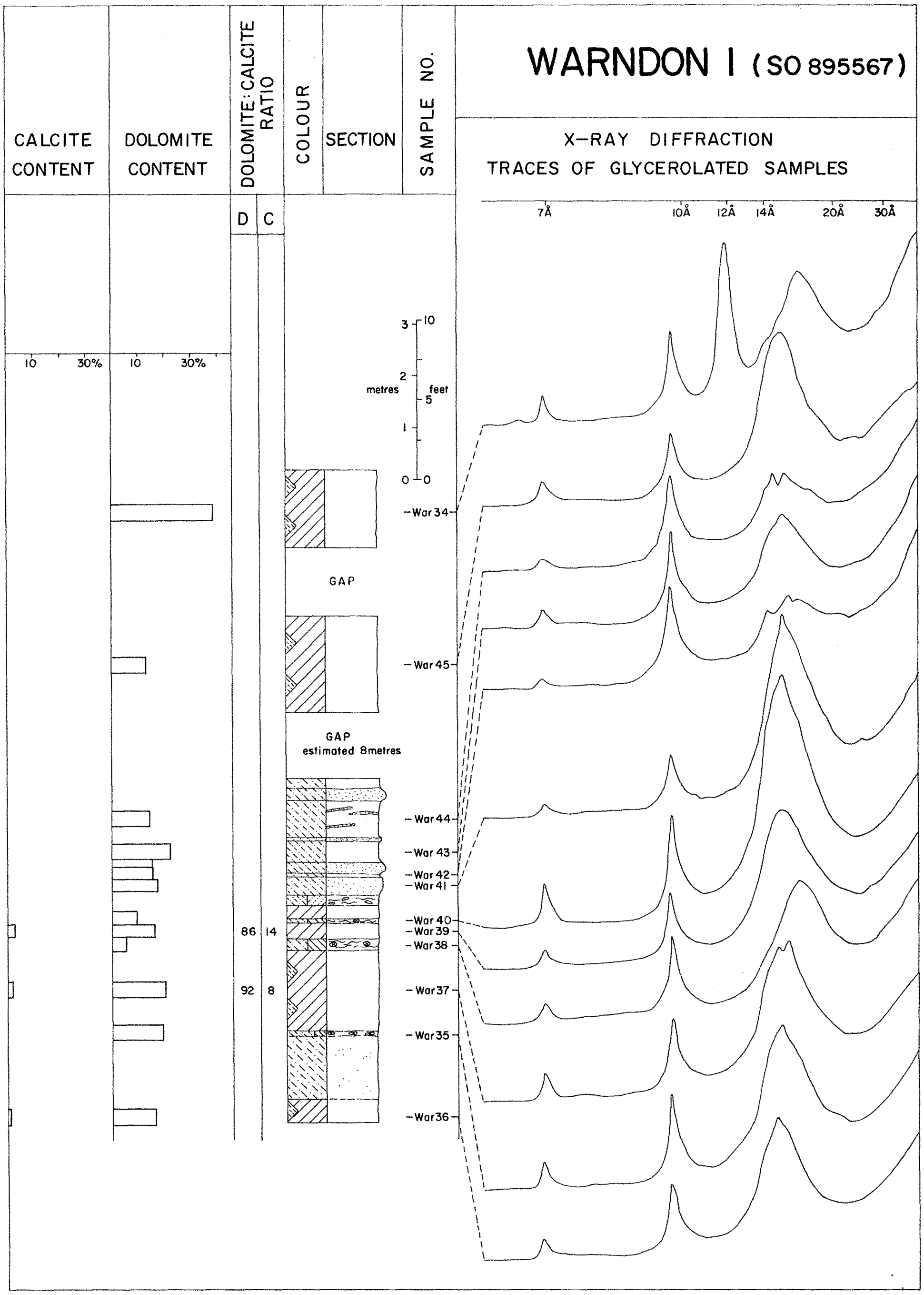

FIGURE 53. Keuper Marl (Arden Sandstone Group) at Warndon 1, Worcestershire. See figure 96 for key.

(*f*) *Cheshire*

Wilkesley borehole (*Geological Survey of Great Britain*) (figures 76–79). The drilling site was 397 m (430 yards) north of the road junction at Wilkesley (grid reference SJ 62864144). The borehole penetrated the complete Keuper Marl sequence of the Cheshire Basin, and the lithological log has been described by Poole & Whiteman (1966, pp. 114–135); a generalized section is illustrated in figure 29.

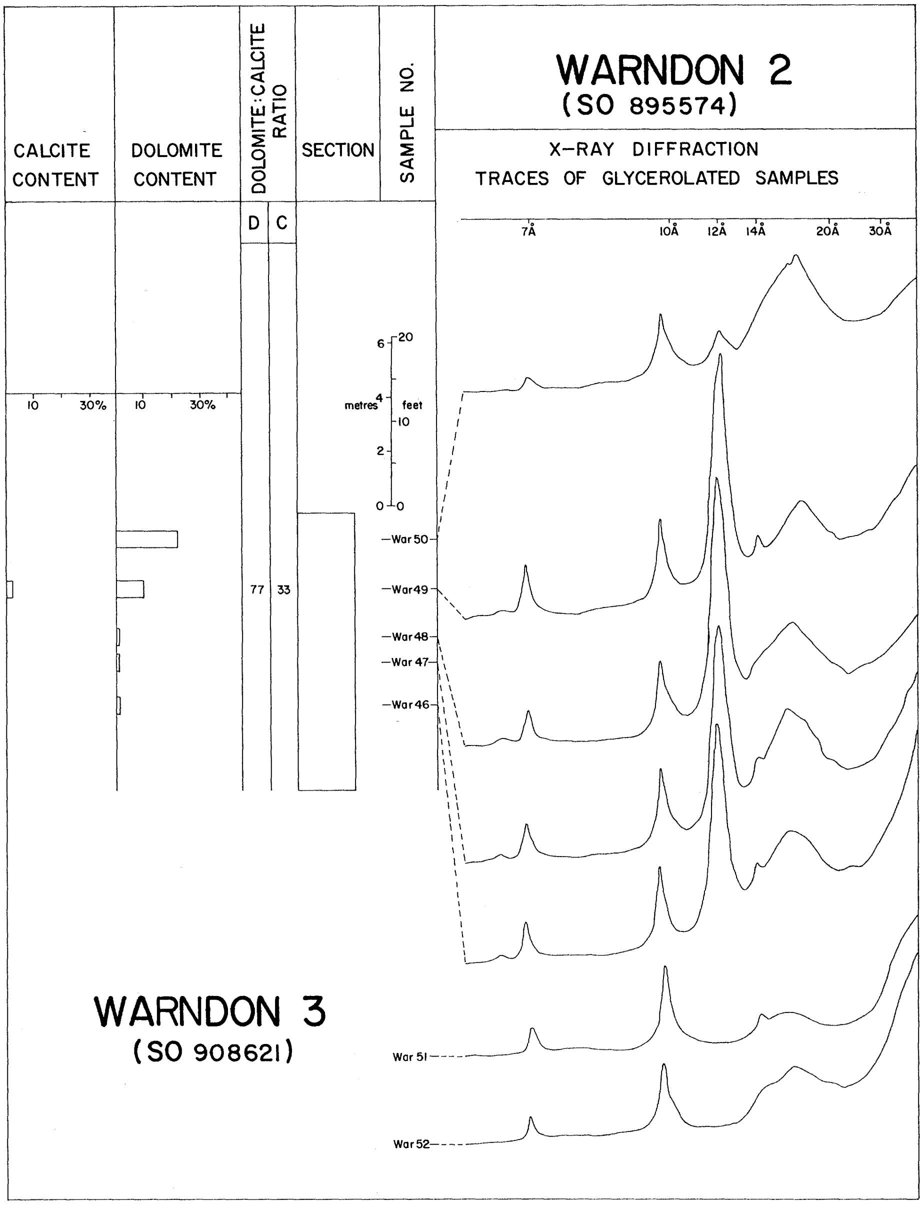

FIGURE 54. Keuper Marl at Warndon 2 and 3, Worcestershire. See figure 96 for key.

5. Relations between clay minerals, evaporites and megafacies

The relations between clay assemblages and the distribution of evaporite minerals and megafacies are demonstrated in eleven horizontal sections (figures 80–90) through the Keuper Marl between the Devon coast and the Cheshire Basin. These horizontal sections are unrepresentative in that they consider only those portions of the Keuper Marl which have been investigated in this study. They do not attempt to show the thickness and lithological variations that occur between the investigated sections.

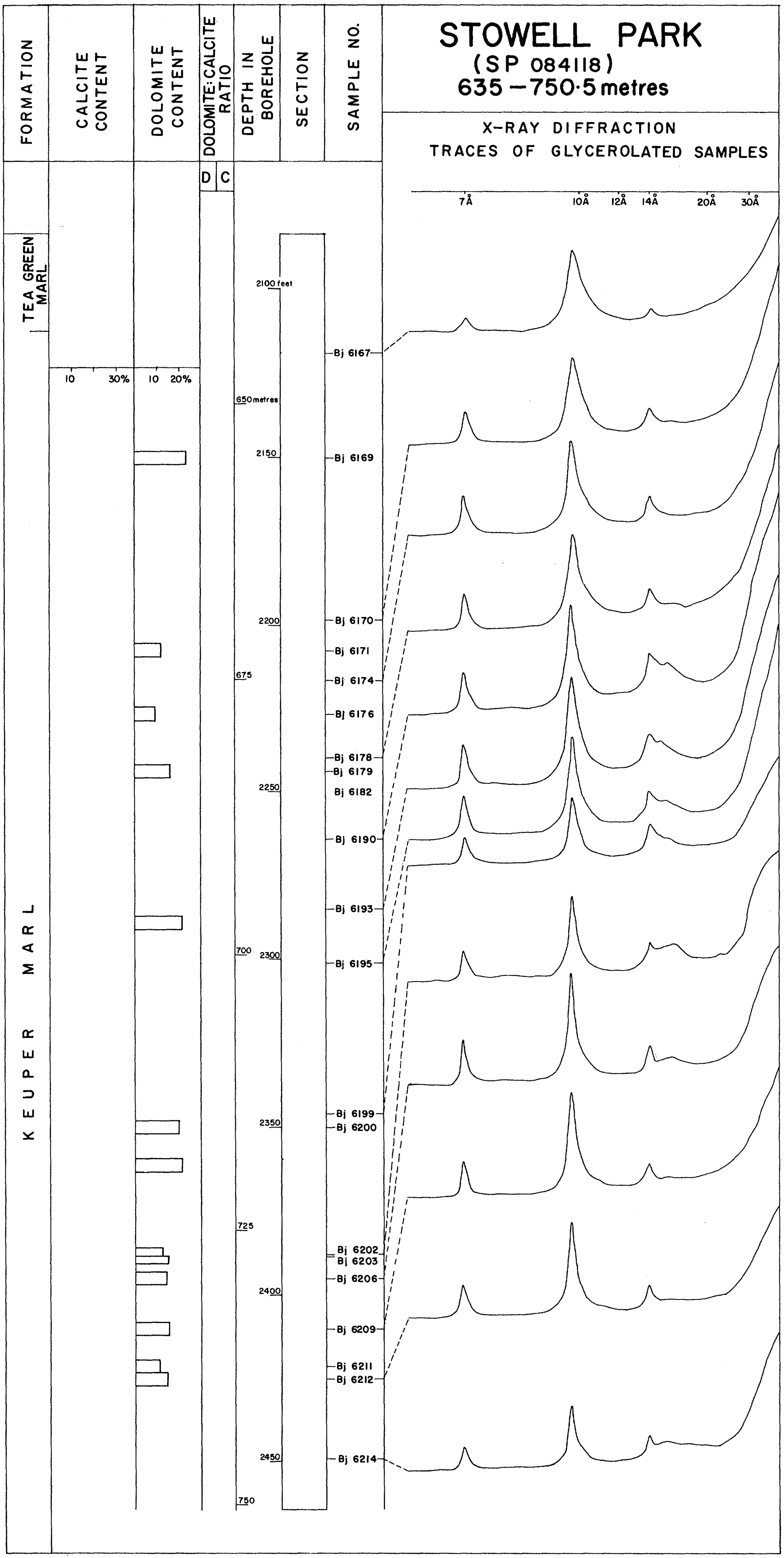

FIGURE 55. Clays and carbonates in the Keuper Marl of the Stowell Park borehole between 635 and 750.5 m depth.

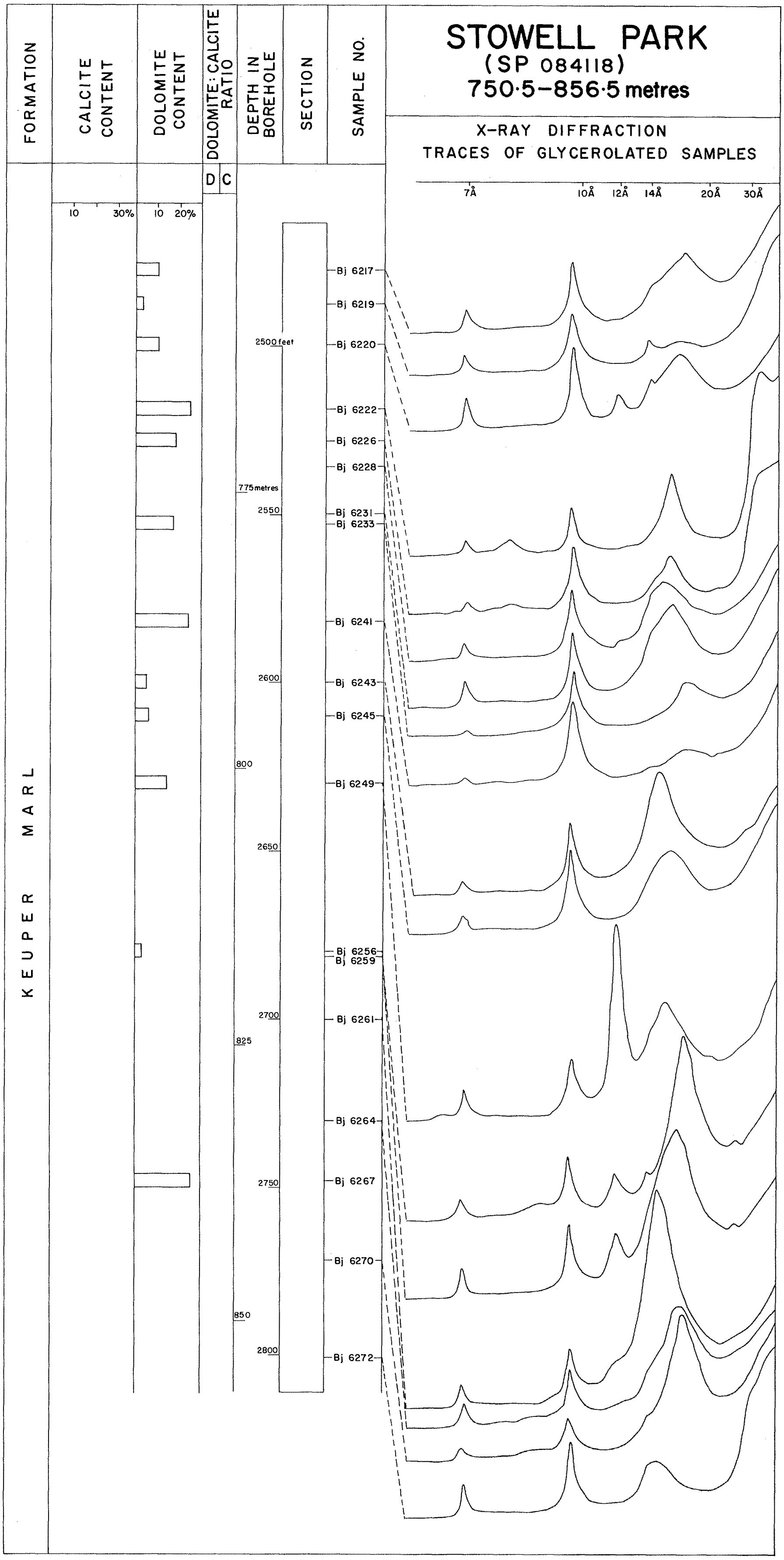

FIGURE 56. Clays and carbonates in the Keuper Marl of the Stowell Park borehole between 750.5 and 856.5 m depth.

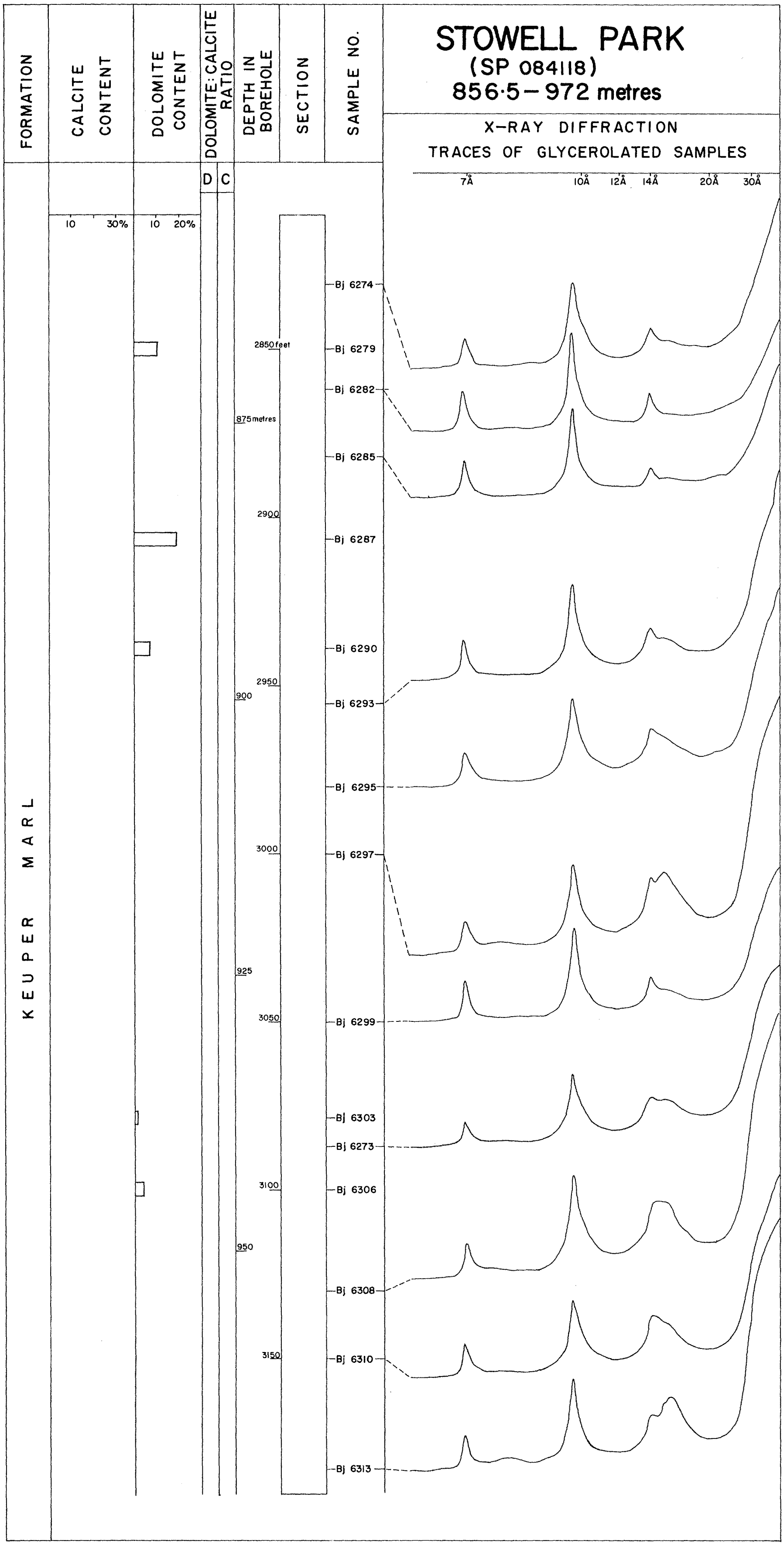

FIGURE 57. Clays and carbonates in the Keuper Marl of the Stowell Park borehole between 856.5 and 972 m depth.

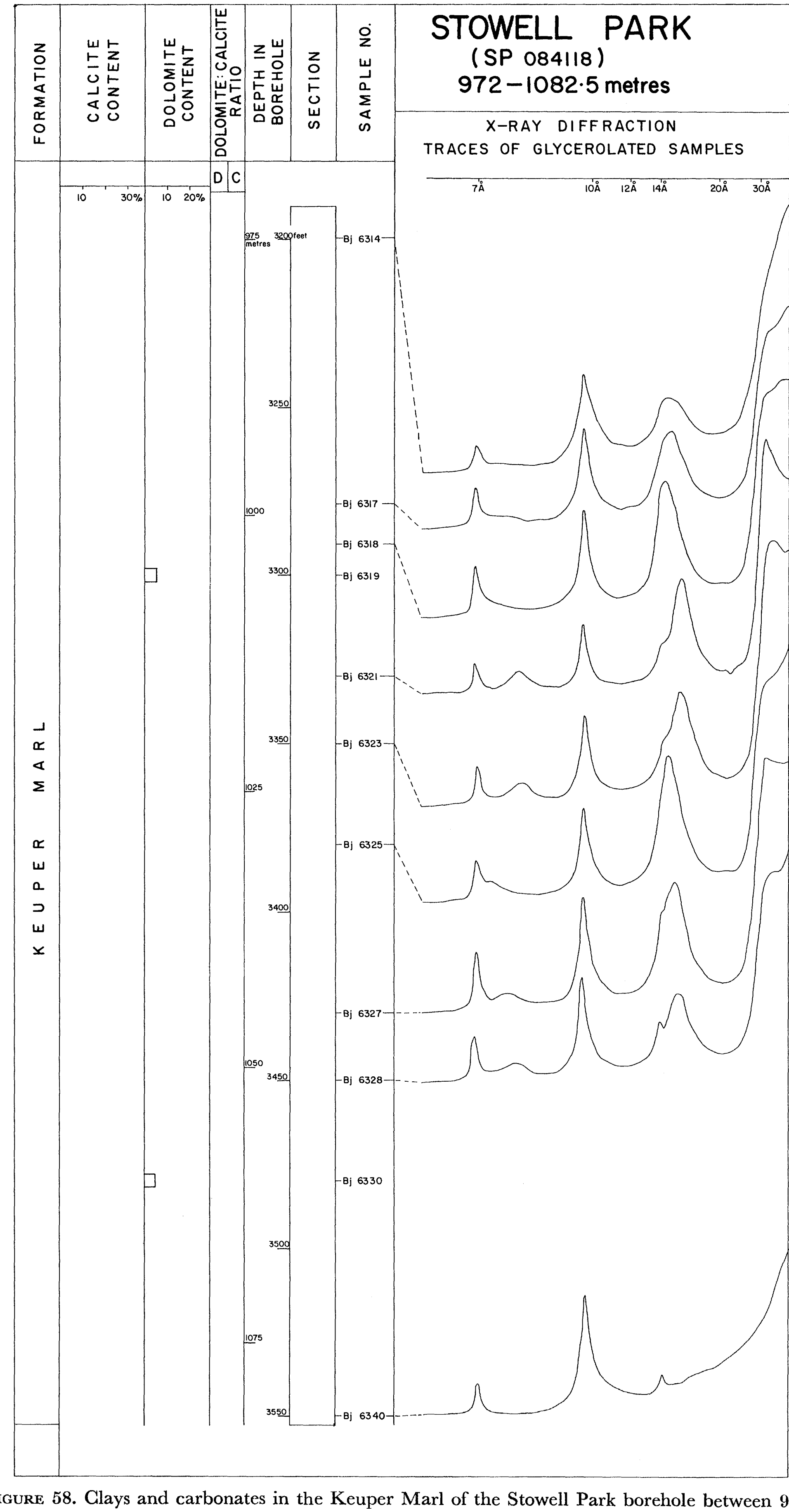

FIGURE 58. Clays and carbonates in the Keuper Marl of the Stowell Park borehole between 972 and 1082.5 m depth.

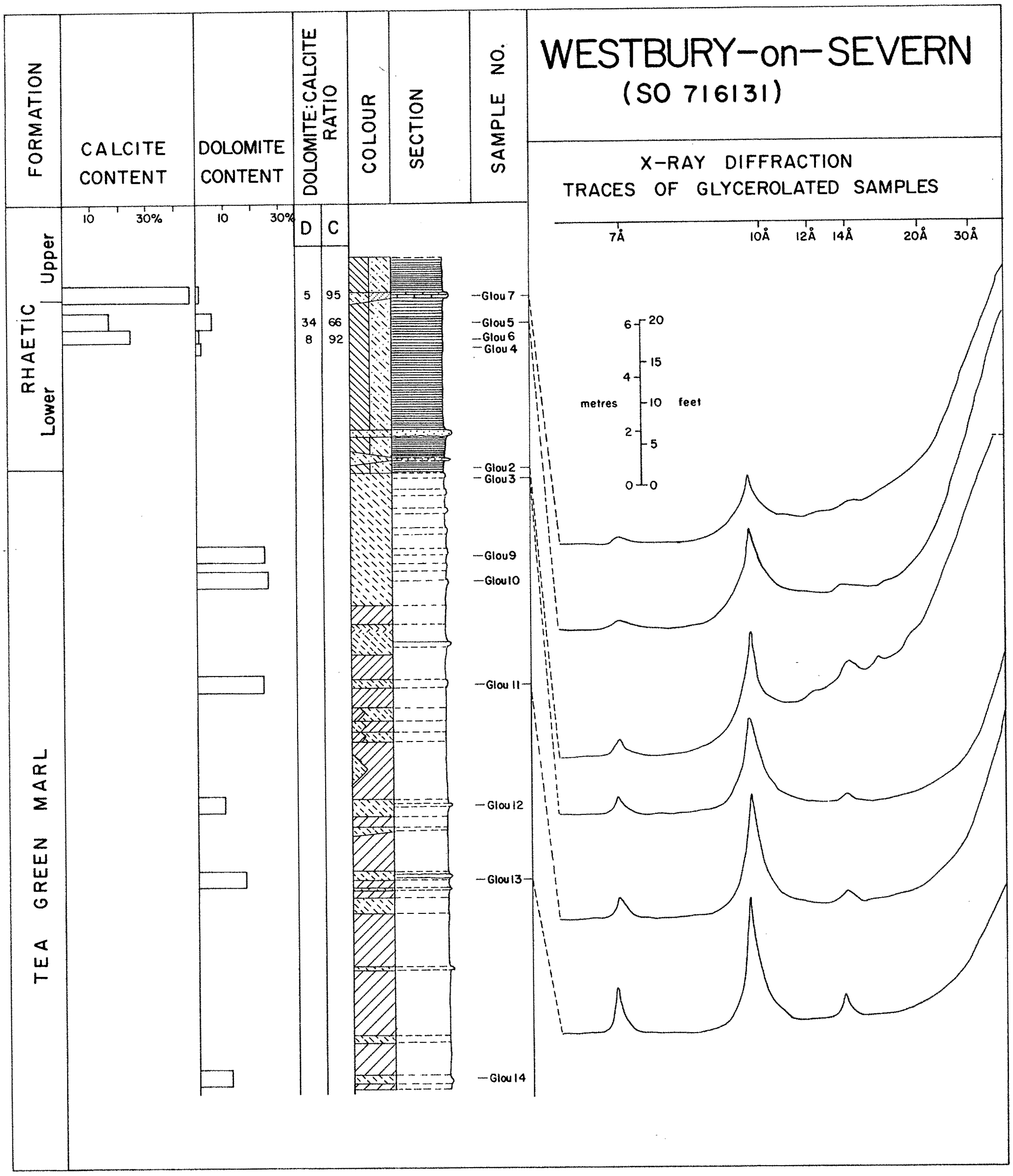

Figure 59. Keuper Marl and Rhaetic at Westbury-on-Severn. See figure 96 for key.

(a) *Evaporites*

The cyclic sediments contain evaporite carbonate minerals but no major deposits of gypsum or anhydrite, or of any other evaporite minerals, whereas the mudstone megafacies may contain abundant non-carbonate evaporites.

Within the mudstone megafacies there is a general northward zonation of the evaporite minerals (figure 80). In south Devon the evaporite minerals are dominated by carbonates; these carbonates decrease northwards and major deposits of celestite, anhydrite and gypsum, and halite appear in this order. Within the carbonates there is a northward replacement of calcite by dolomite (figures 81, 82). High carbonate contents are abundant in, but not restricted to, the carbonate megafacies of the sediment cycles.

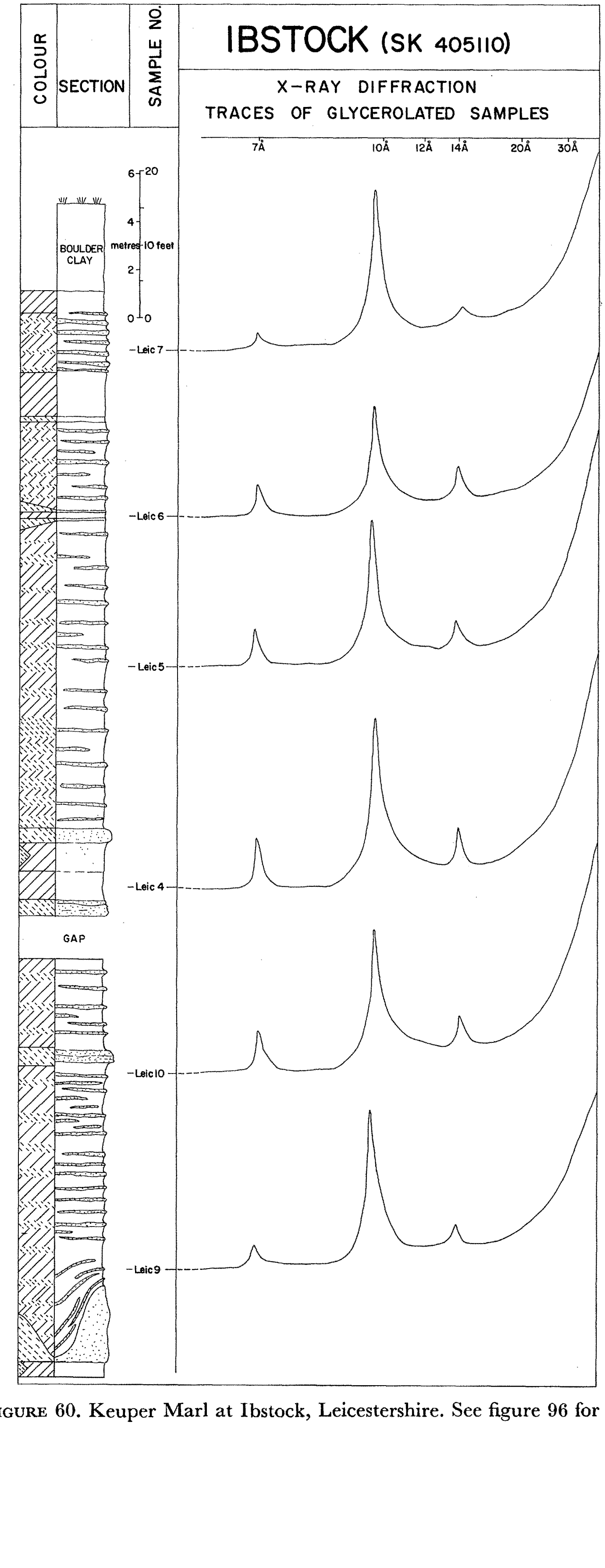

FIGURE 60. Keuper Marl at Ibstock, Leicestershire. See figure 96 for key.

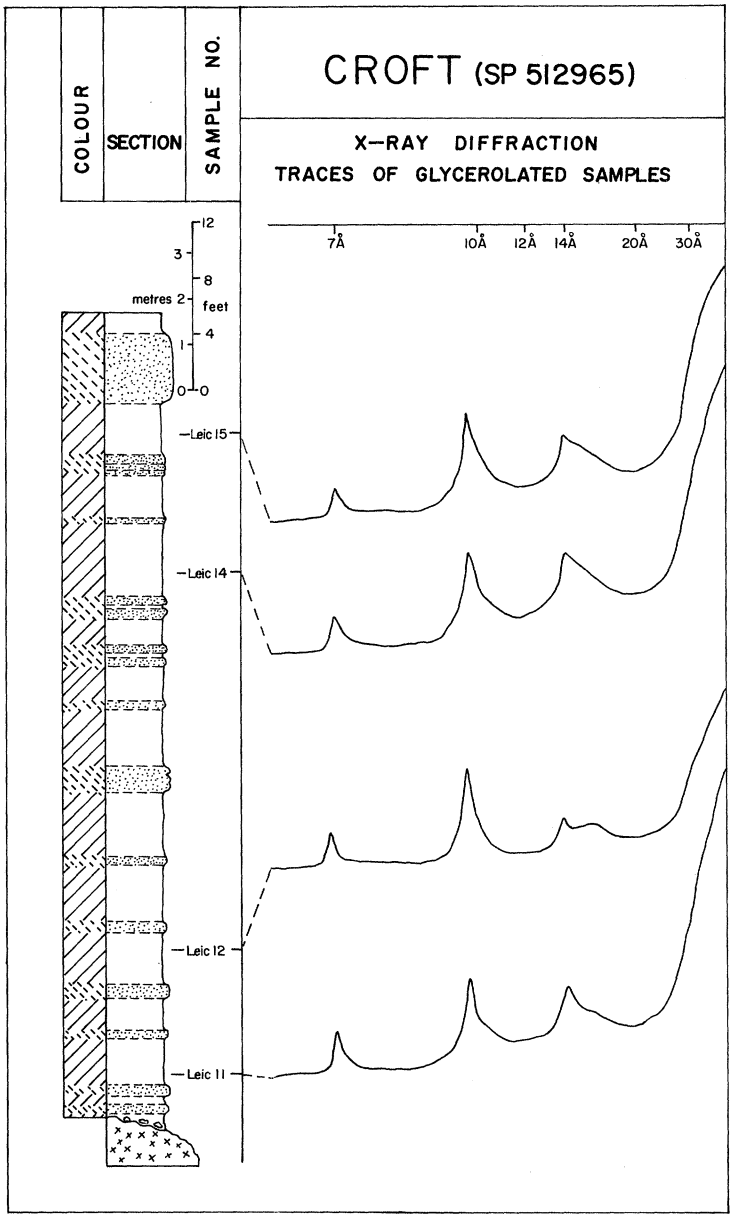

FIGURE 61. Keuper Marl at Croft, Leicestershire. See figure 96 for key.

(*b*) *Clay minerals*

The analytical methods used are described in appendix 1.

(i) *Qualitative analysis*

The distribution of clay minerals suggests that there are two well-defined assemblages. The first is the matrix assemblage, which has been recorded in all samples. It consists of mica and chlorite in approximately the same ratio, although there are some gradual regional variations. On the south Devon coast the proportion of chlorite is particularly low in the cyclic sediments, and some parts of the mudstone megafacies. Northwards there is a general increase in the

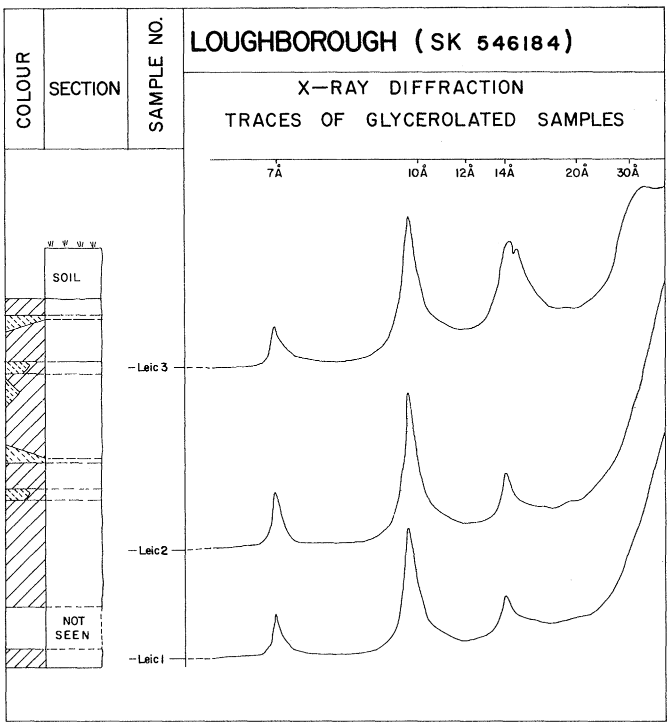

FIGURE 62. Keuper Marl at Loughborough, Leicestershire. See figure 96 for key.

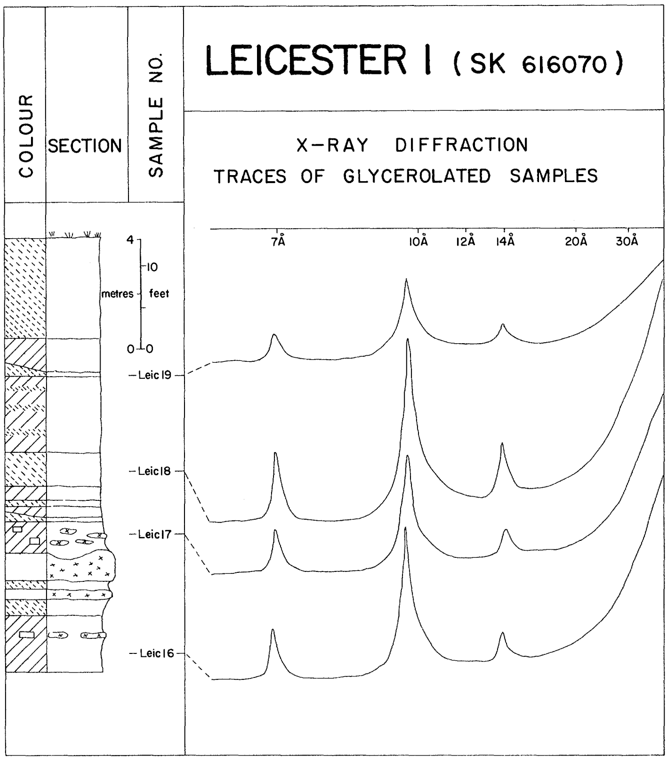

FIGURE 63. Keuper Marl at Leicester 1. See figure 96 for key.

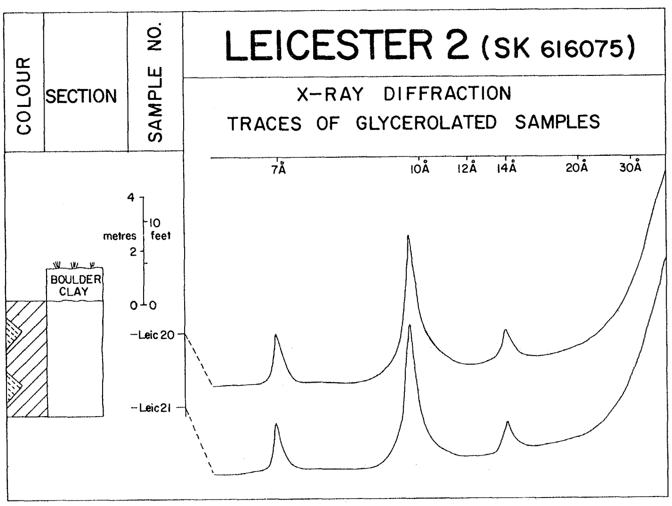

FIGURE 64. Keuper Marl at Leicester 2. See figure 96 for key.

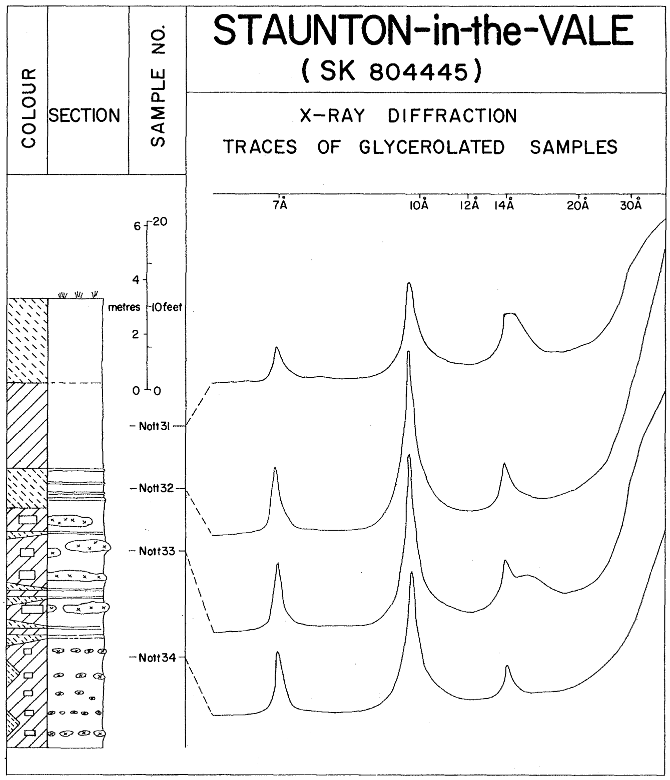

FIGURE 65. Keuper Marl (Trent Formation) at Staunton-in-the-Vale, Nottinghamshire. See figure 96 for key.

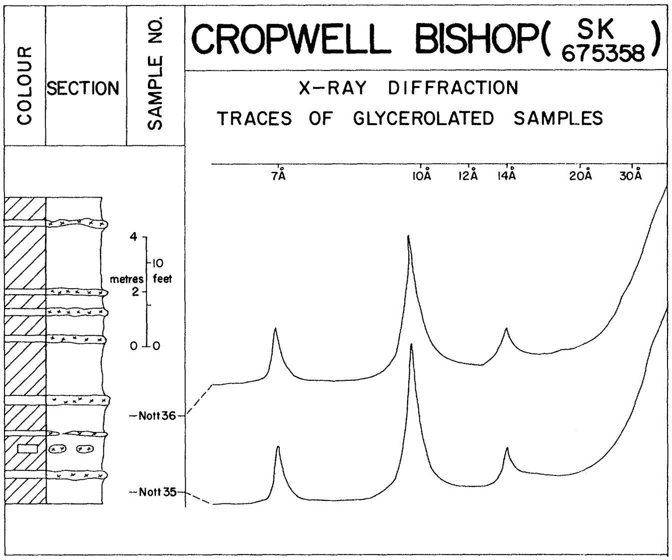

FIGURE 66. Keuper Marl (Trent Formation) at Cropwell Bishop, Nottinghamshire. See figure 96 for key.

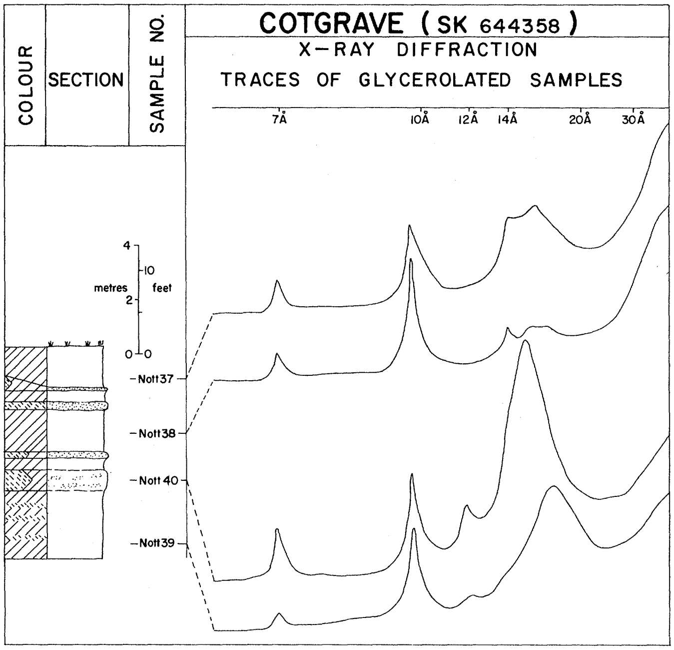

FIGURE 67. Keuper Marl (Trent Formation) at Cotgrave, Nottinghamshire. See figure 96 for key.

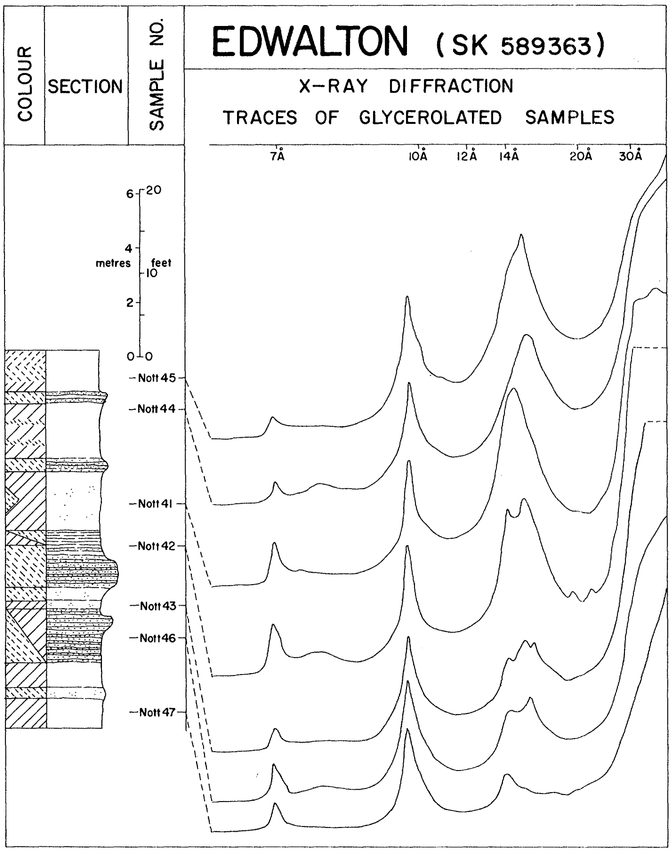

FIGURE 68. Keuper Marl (Edwalton Formation) at Edwalton, Nottinghamshire. See figure 96 for key.

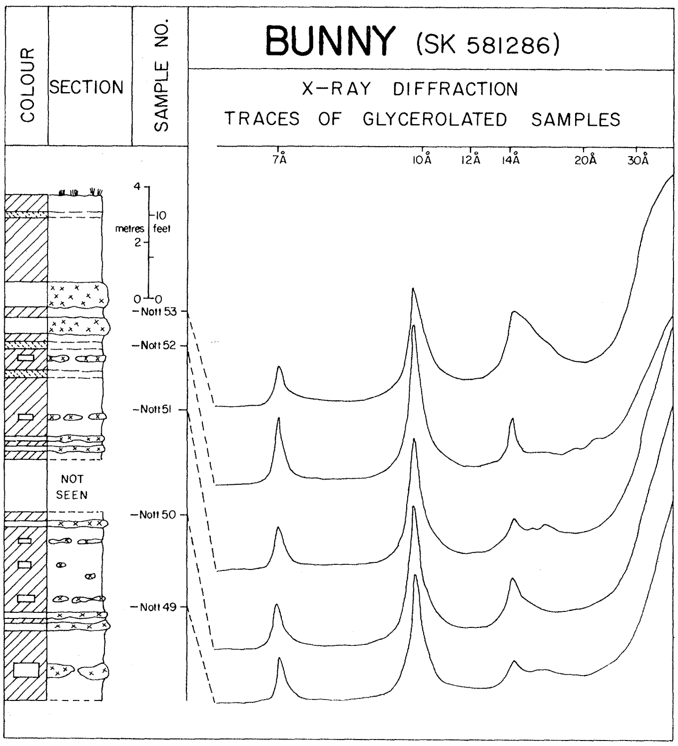

FIGURE 69. Keuper Marl (Trent Formation) at Bunny, Nottinghamshire. See figure 96 for key.

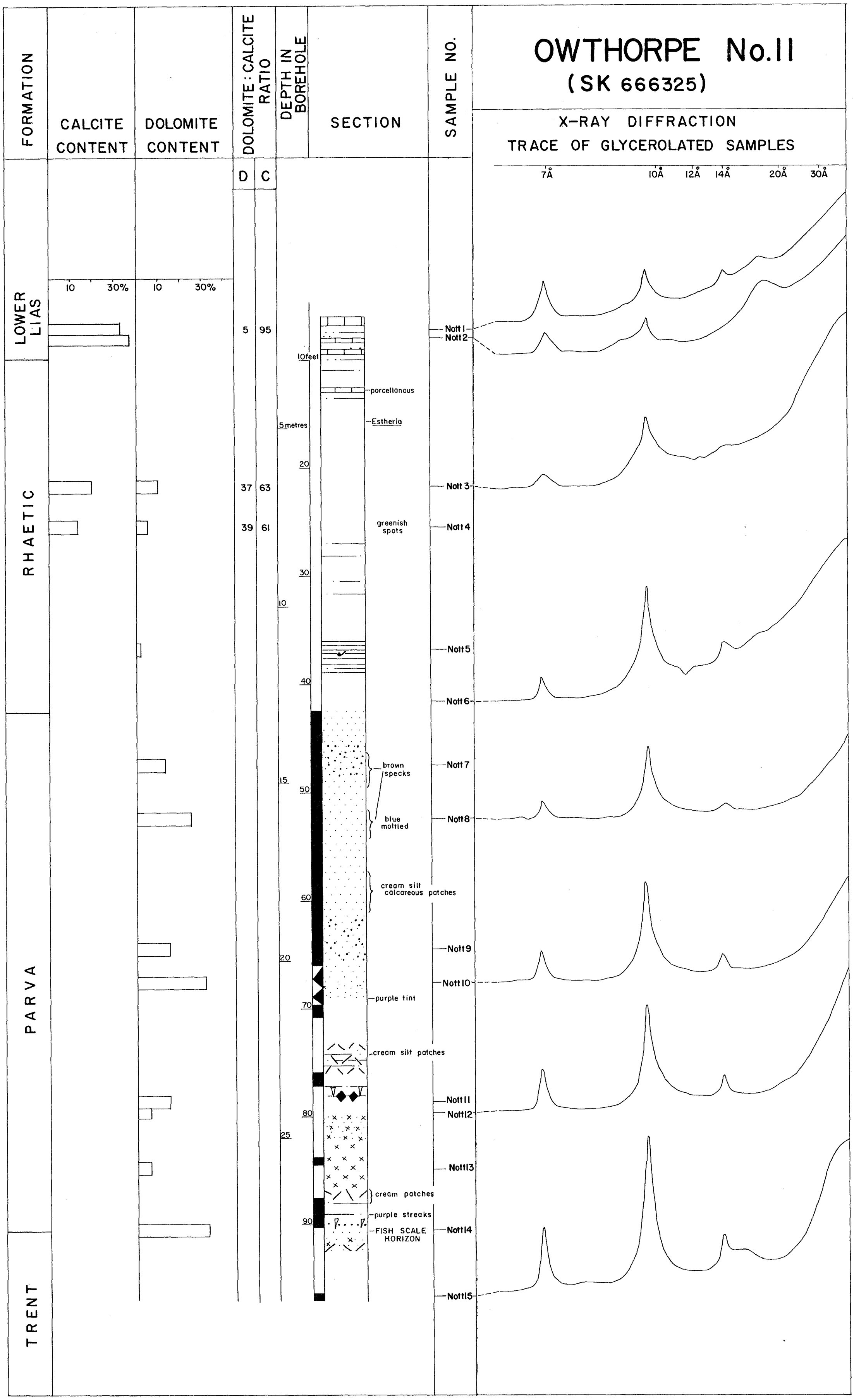

FIGURE 70. Keuper Marl (Rhaetic to top of Trent Formation) in Owthorpe borehole no. 11, Nottinghamshire. See figure 96 for key.

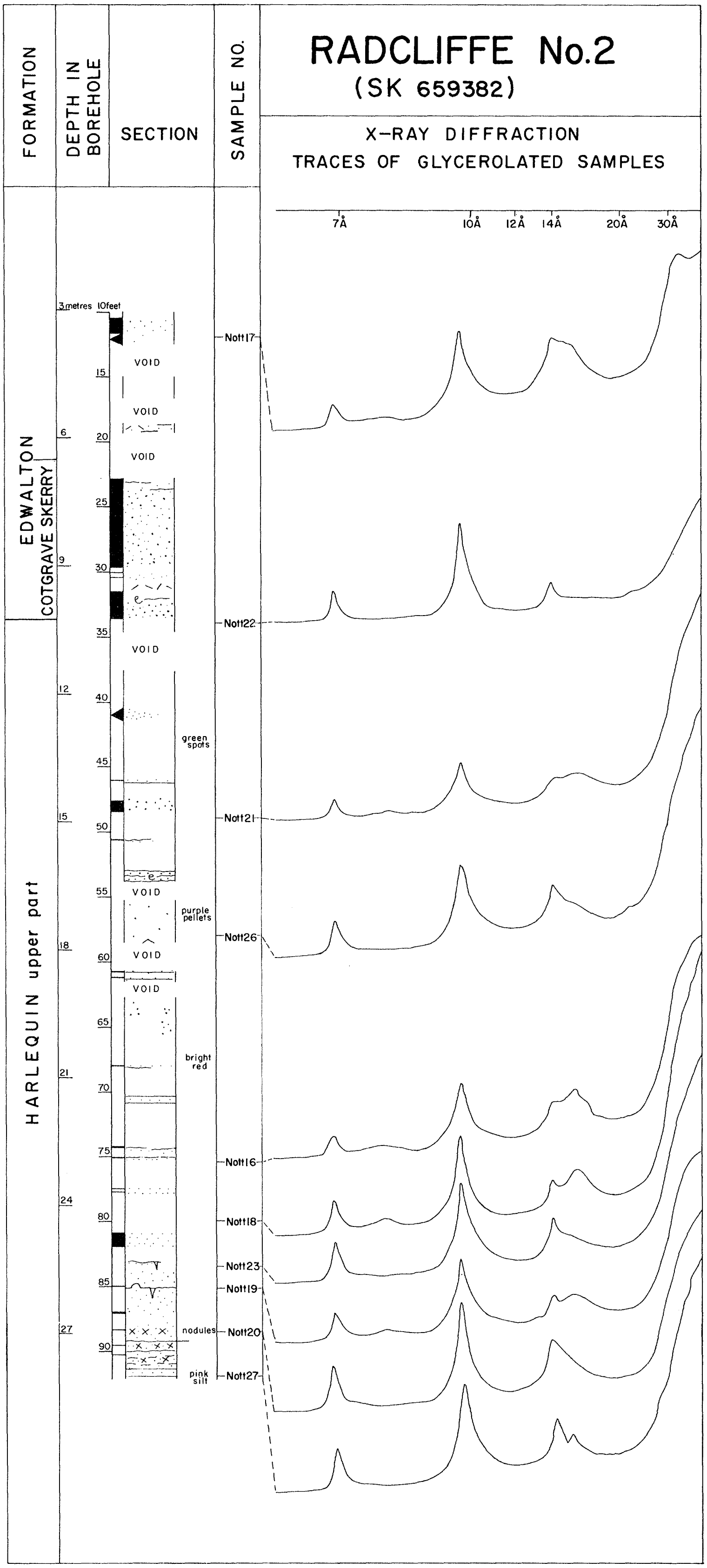

FIGURE 71. Keuper Marl (Edwalton to Harlequin Formation) in the Radcliffe borehole no. 2, Nottinghamshire. See figure 96 for key.

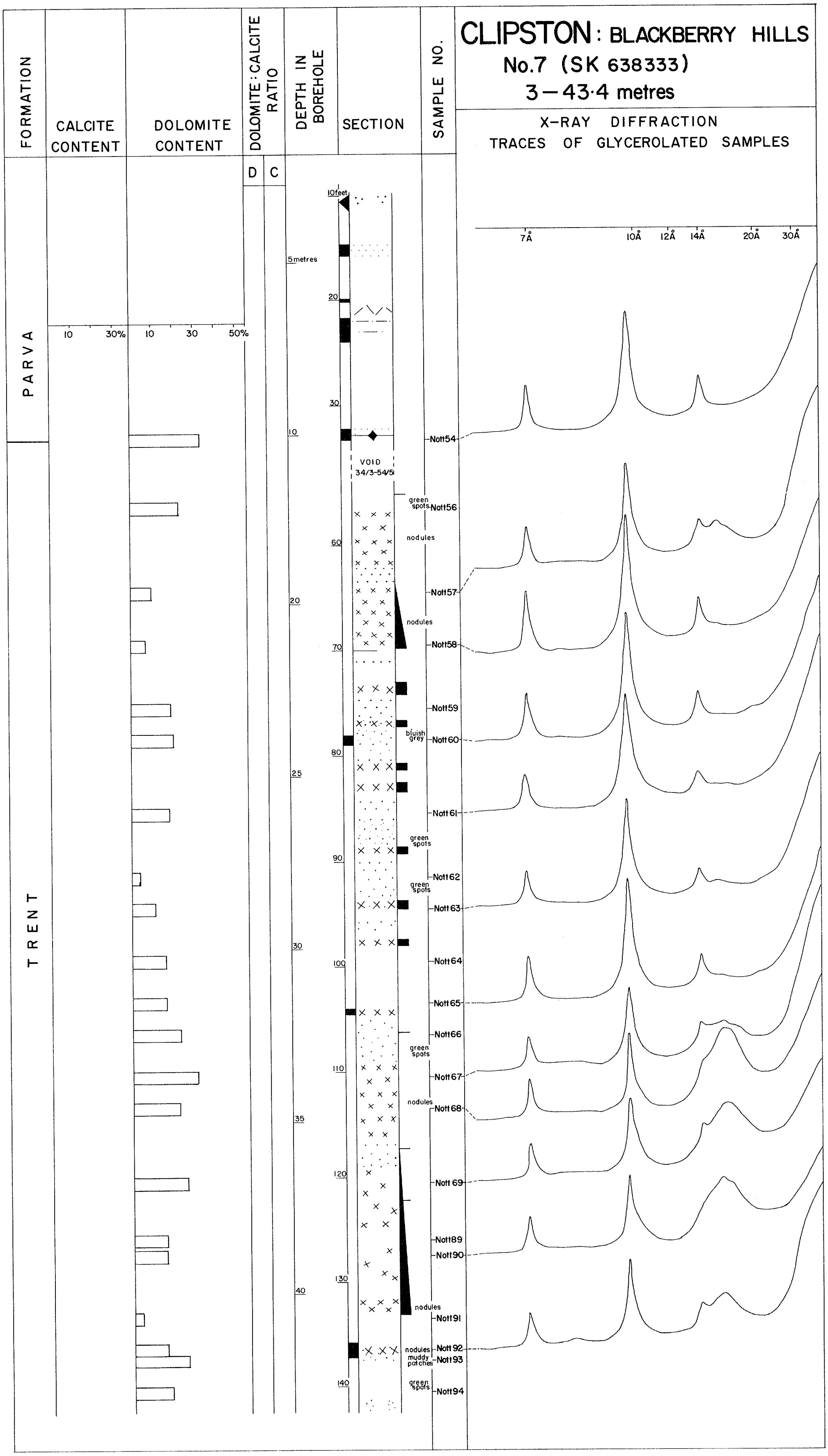

FIGURE 72. Keuper Marl (Parva to Trent Formation) between 3 and 43.4 m depth in the Blackberry Hills borehole no. 7, Clipston, Nottinghamshire. See figure 96 for key.

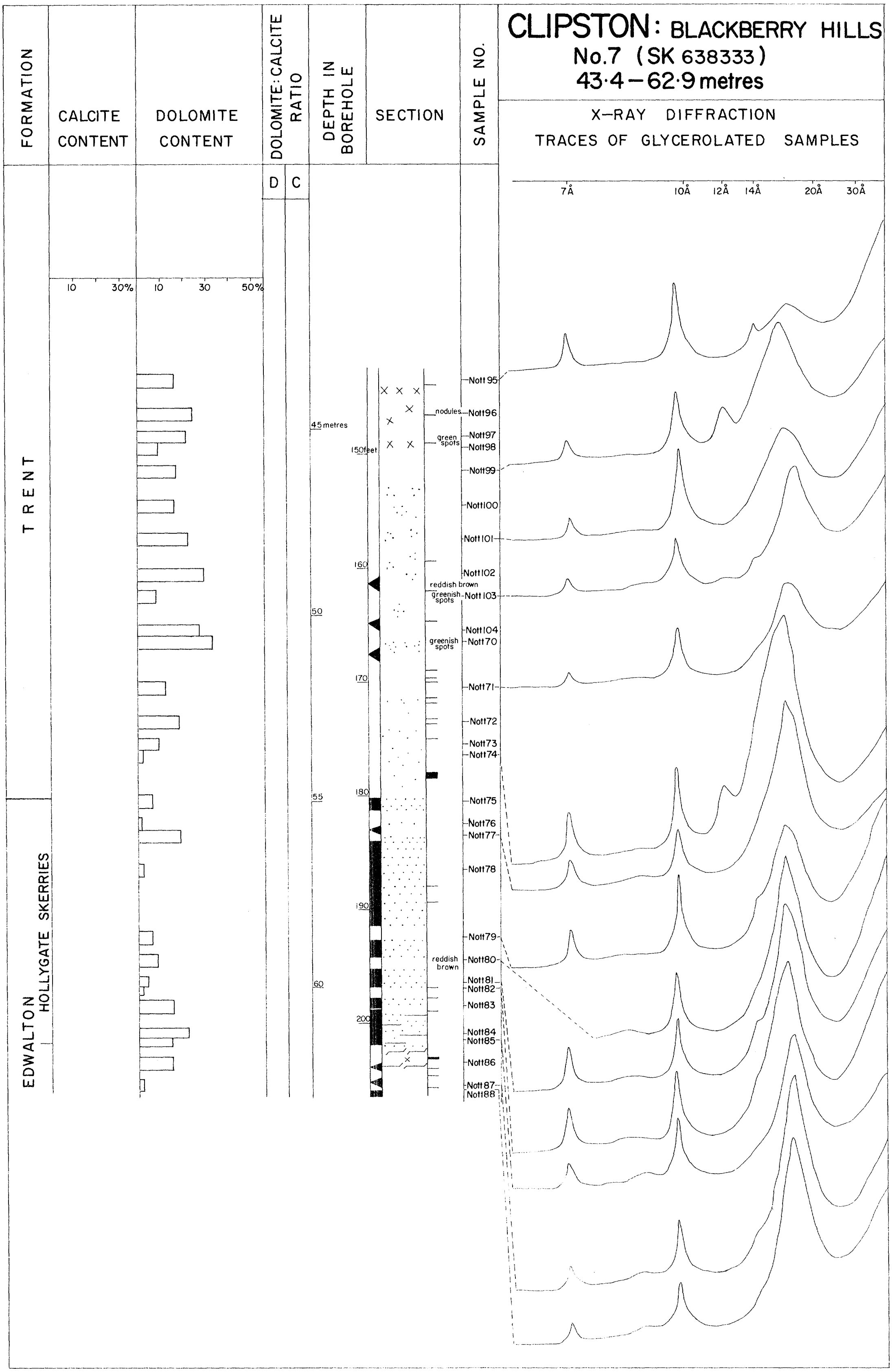

FIGURE 73. Keuper Marl (Trent to Edwalton Formation) between 43.4 and 62.9 m depth in the Blackberry Hills borehole no. 7, Clipston, Nottinghamshire. See figure 96 for key.

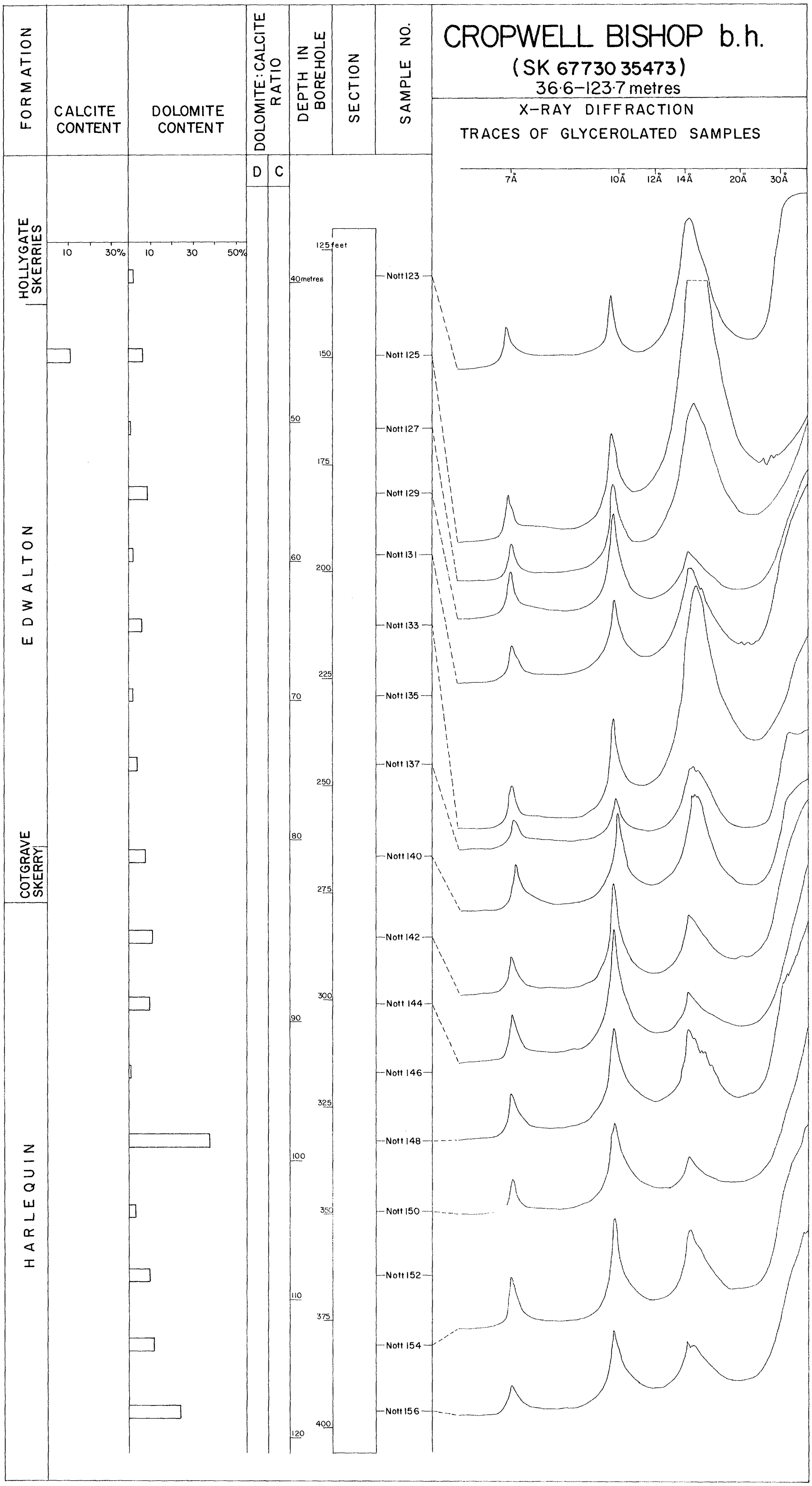

FIGURE 74. Clays and carbonates from the Keuper Marl (Edwalton to Harlequin Formation) in the Cropwell Bishop borehole between 36.6 and 123.7 m depth.

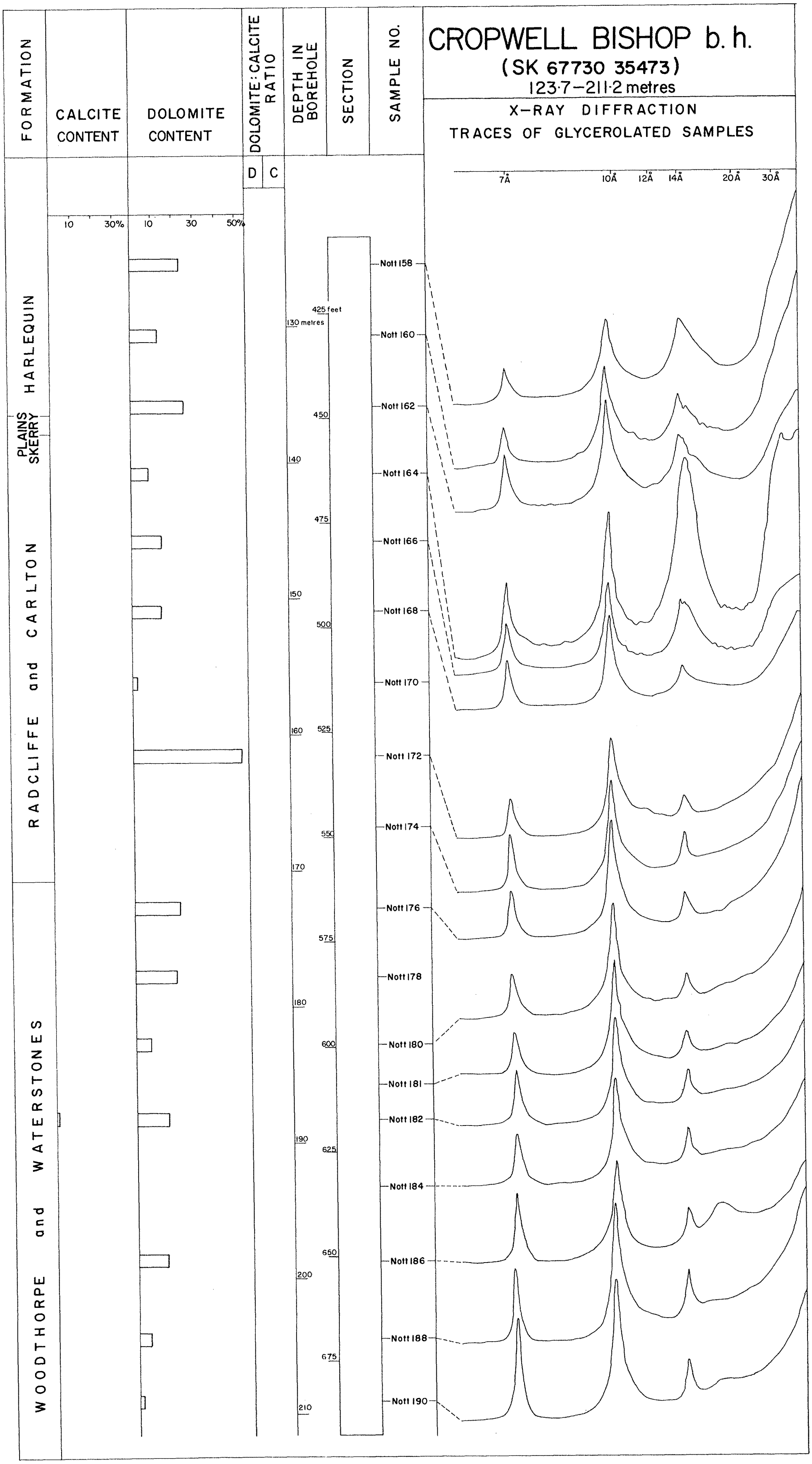

FIGURE 75. Clays and carbonates from the Keuper Marl (Harlequin to Woodthorpe Formation) in the Cropwell Bishop borehole between 123.7 and 211.2 m depth.

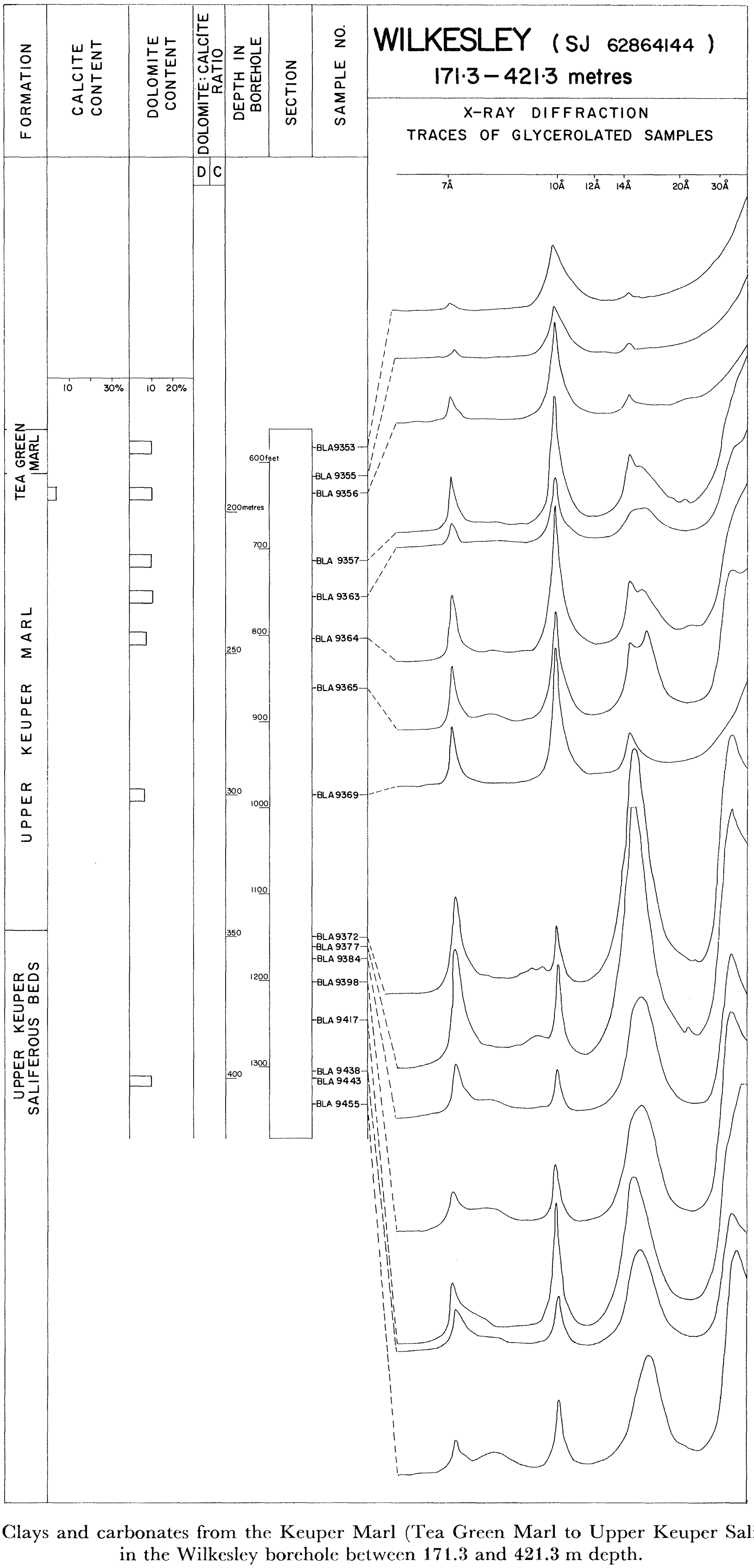

FIGURE 76. Clays and carbonates from the Keuper Marl (Tea Green Marl to Upper Keuper Saliferous Beds) in the Wilkesley borehole between 171.3 and 421.3 m depth.

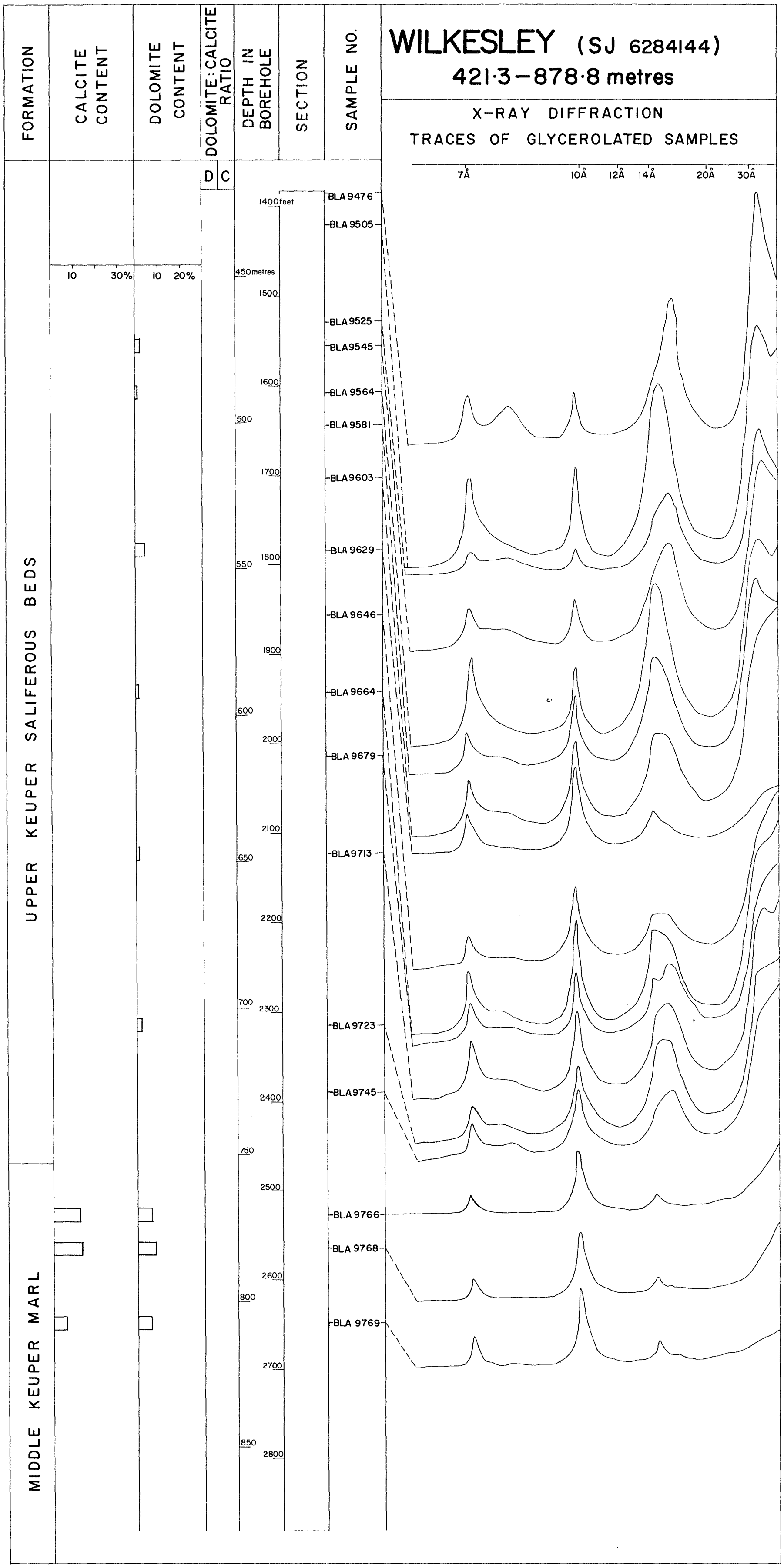

FIGURE 77. Clays and carbonates from the Keuper Marl (Upper Keuper Saliferous Beds to Middle Keuper Marl) in the Wilkesley borehole between 421.3 and 878.8 m depth. The grid reference for the Wilkesley borehole should read SJ 62864144.

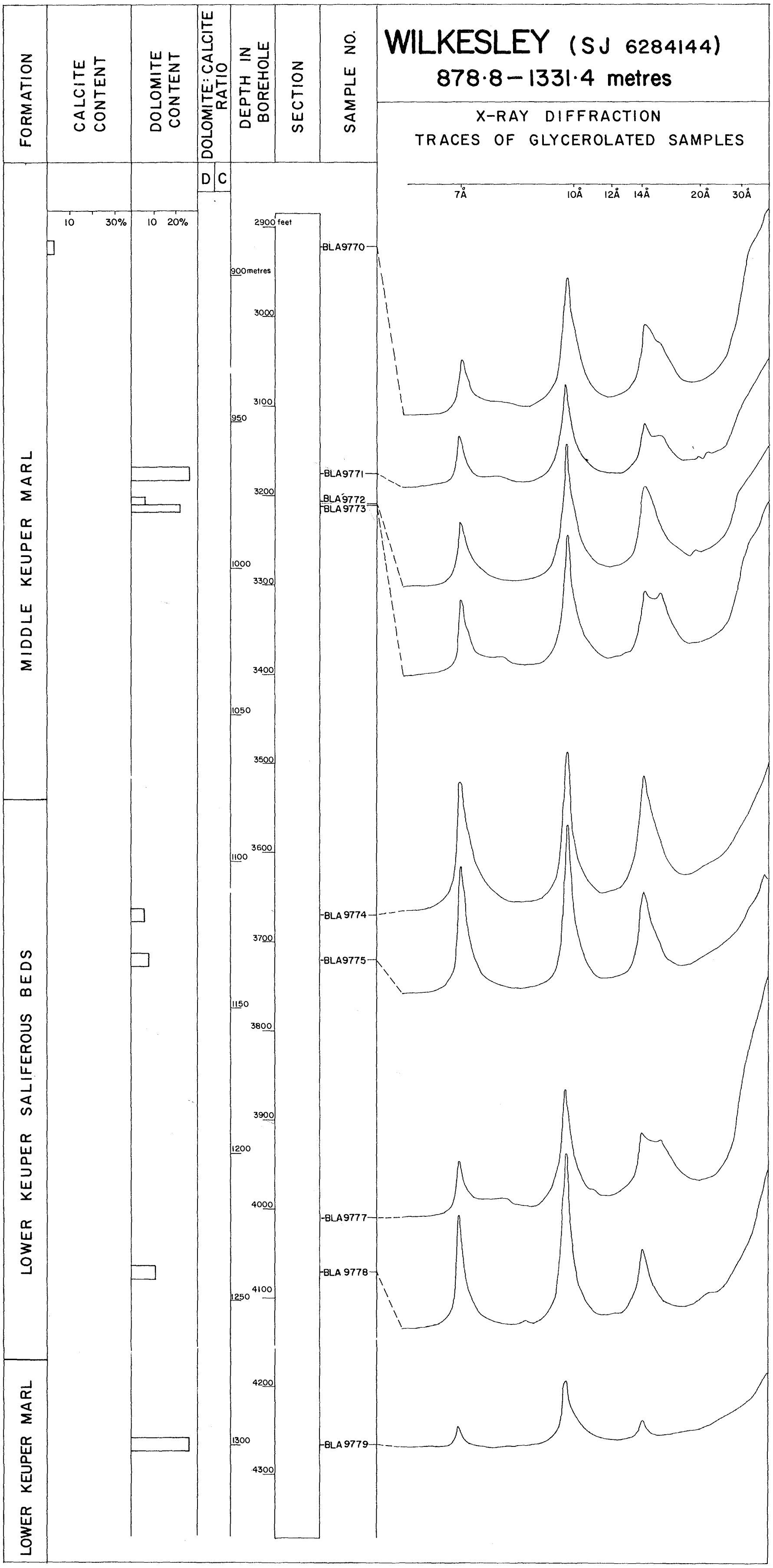

Figure 78. Clays and carbonates from the Keuper Marl (Middle Keuper Marl to Lower Keuper Marl) in the Wilkesley borehole between 878.8 and 1331.4 m depth. The grid reference for the Wilkesley borehole should read SJ 62864144.

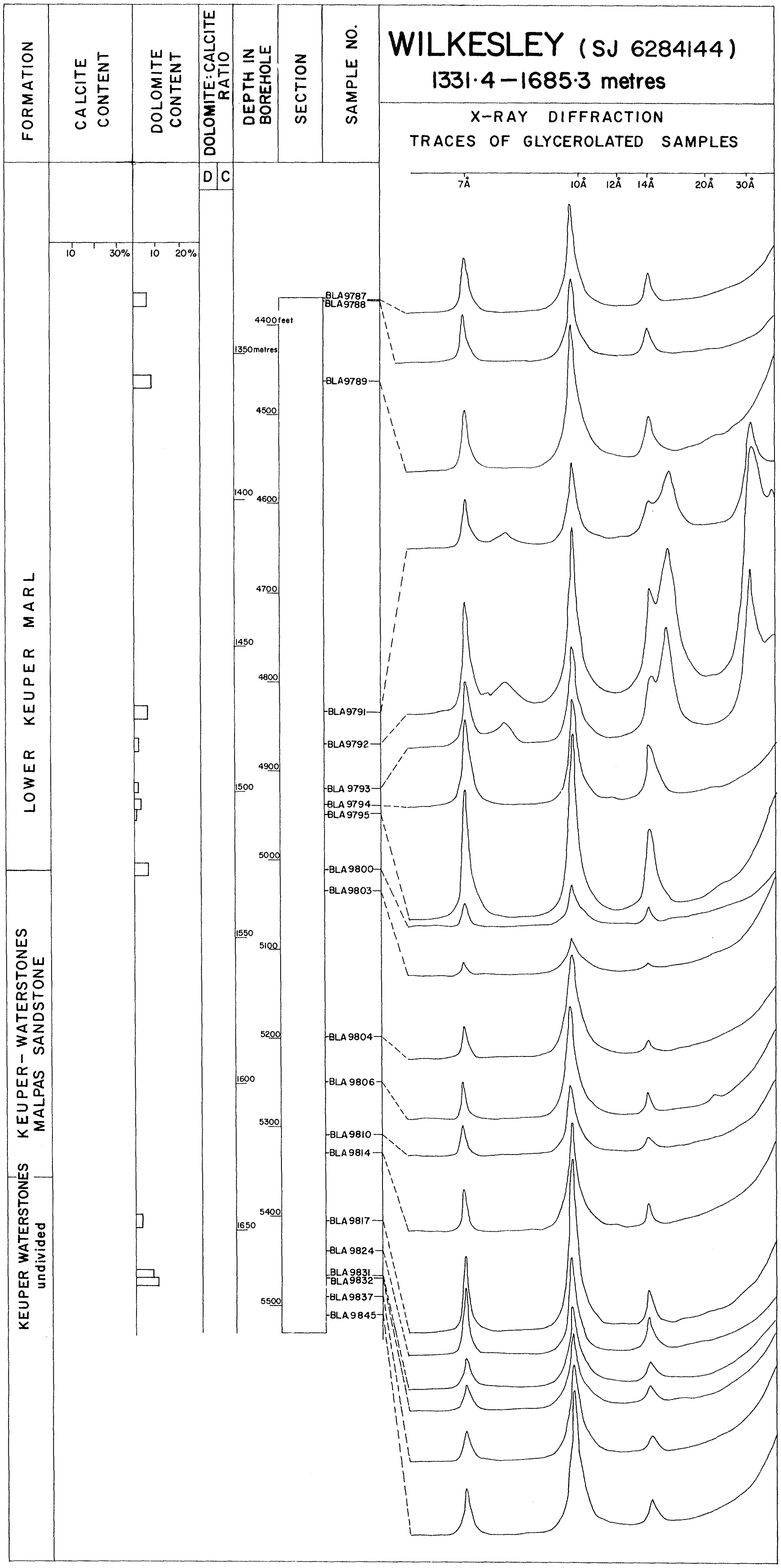

FIGURE 79. Clays and carbonates from the Keuper Marl (Lower Keuper Marl to Keuper Waterstones) in the Wilkesley borehole between 1331.4 and 1685.3 *m* depth. The grid reference for the Wilkesley borehole should read SJ 62864144.

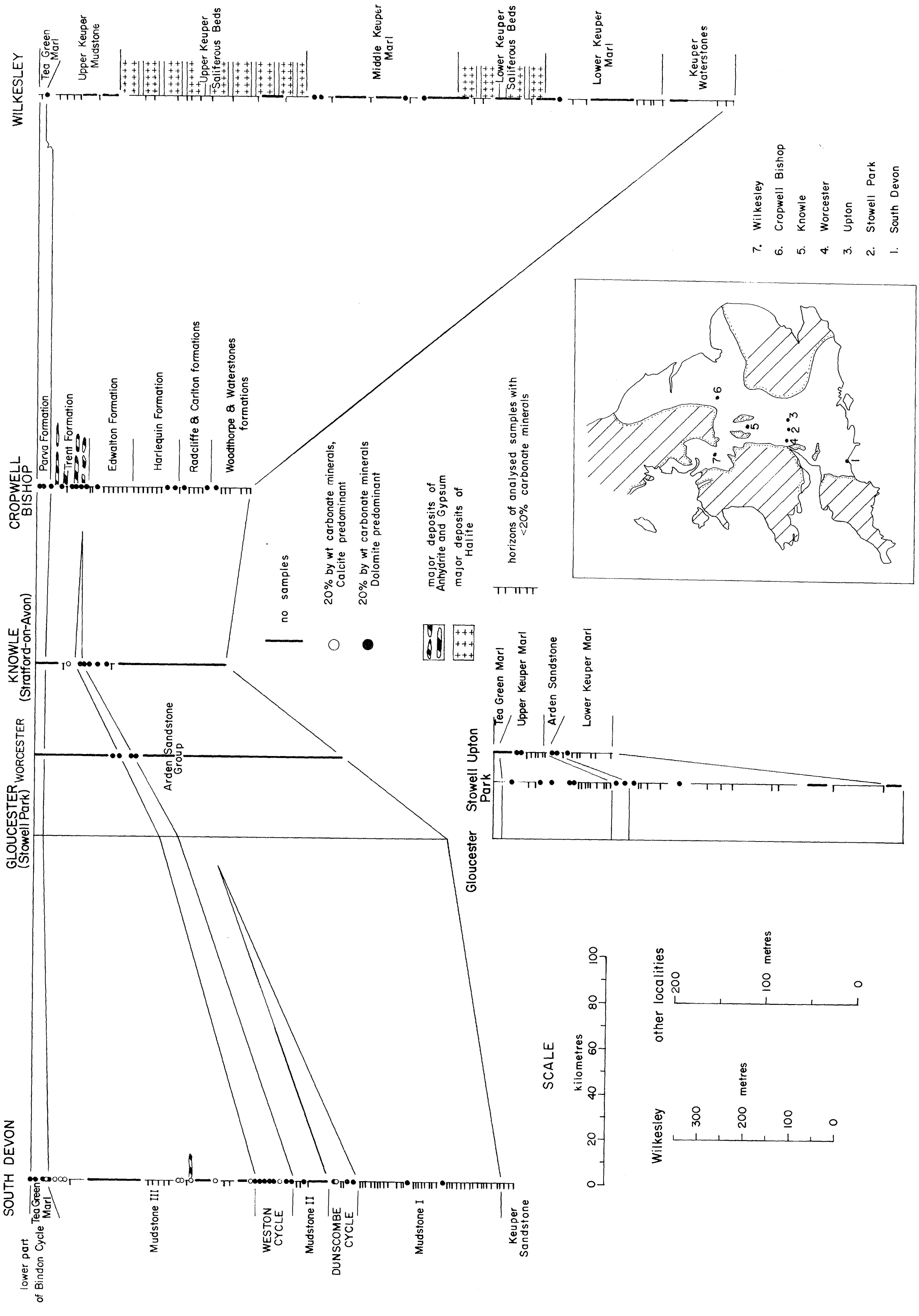

FIGURE 80. Distribution of evaporites in the Keuper Marl.

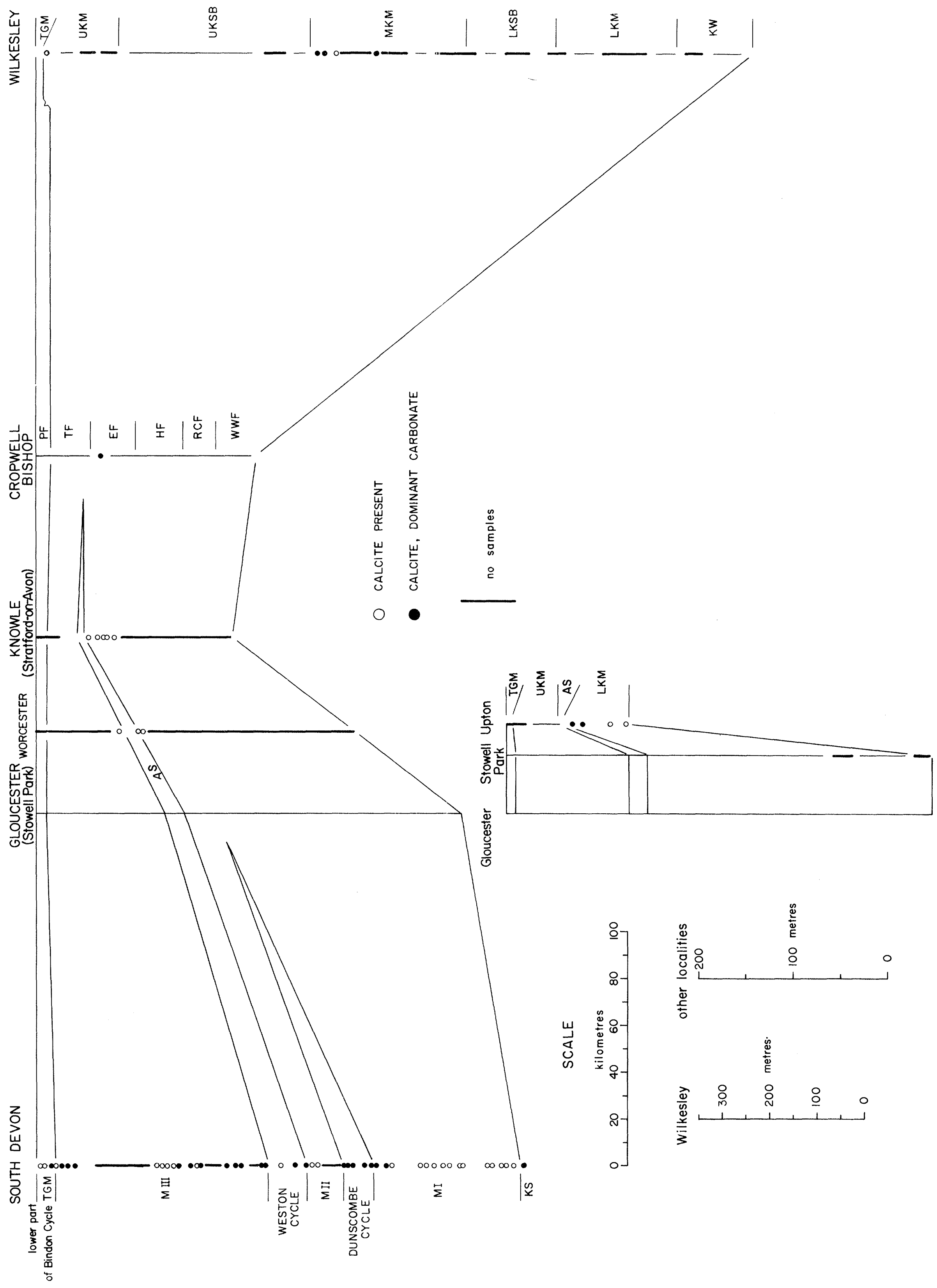

FIGURE 81. Distribution of calcite in the Keuper Marl.

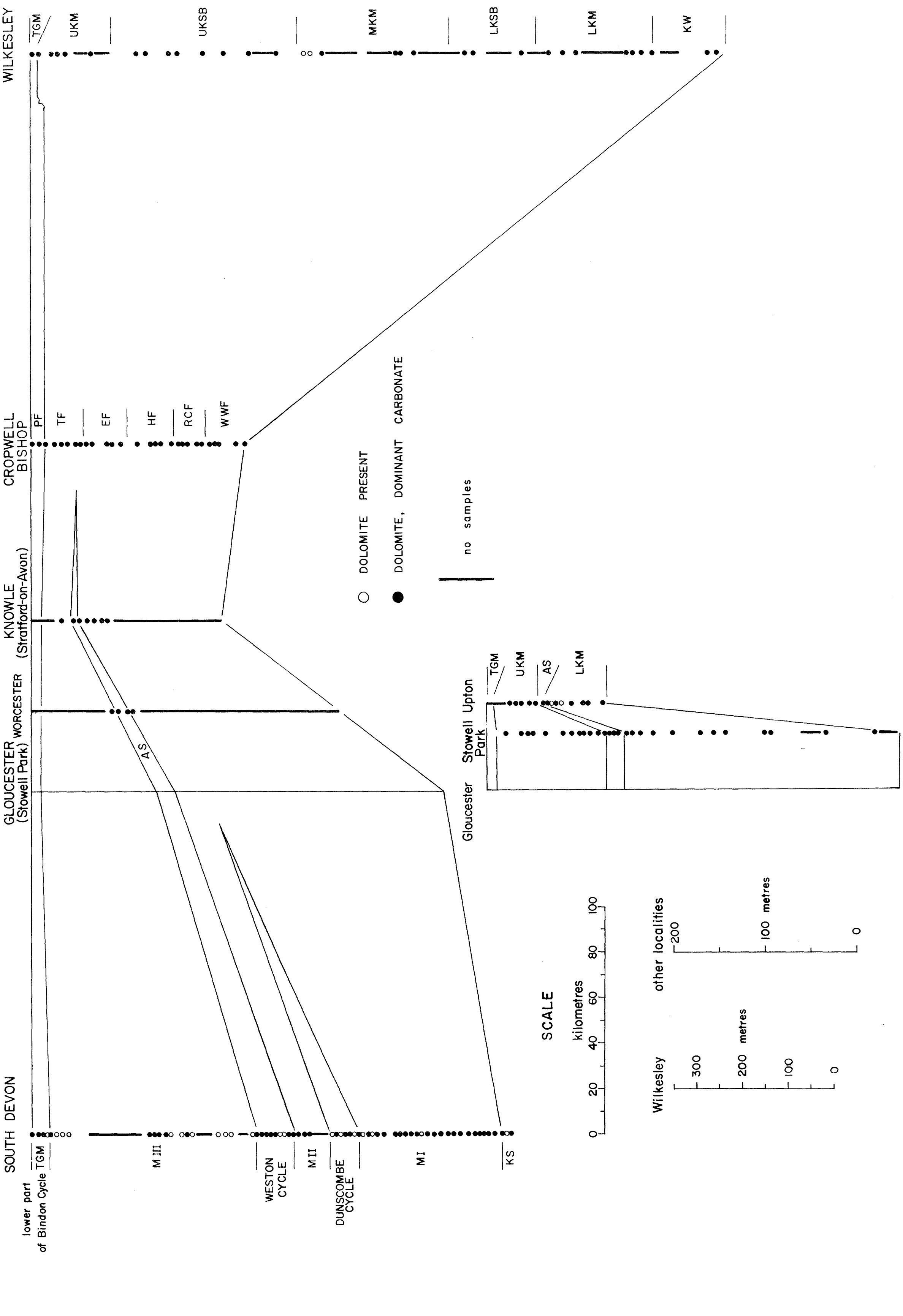

FIGURE 82. Distribution of dolomite in the Keuper Marl.

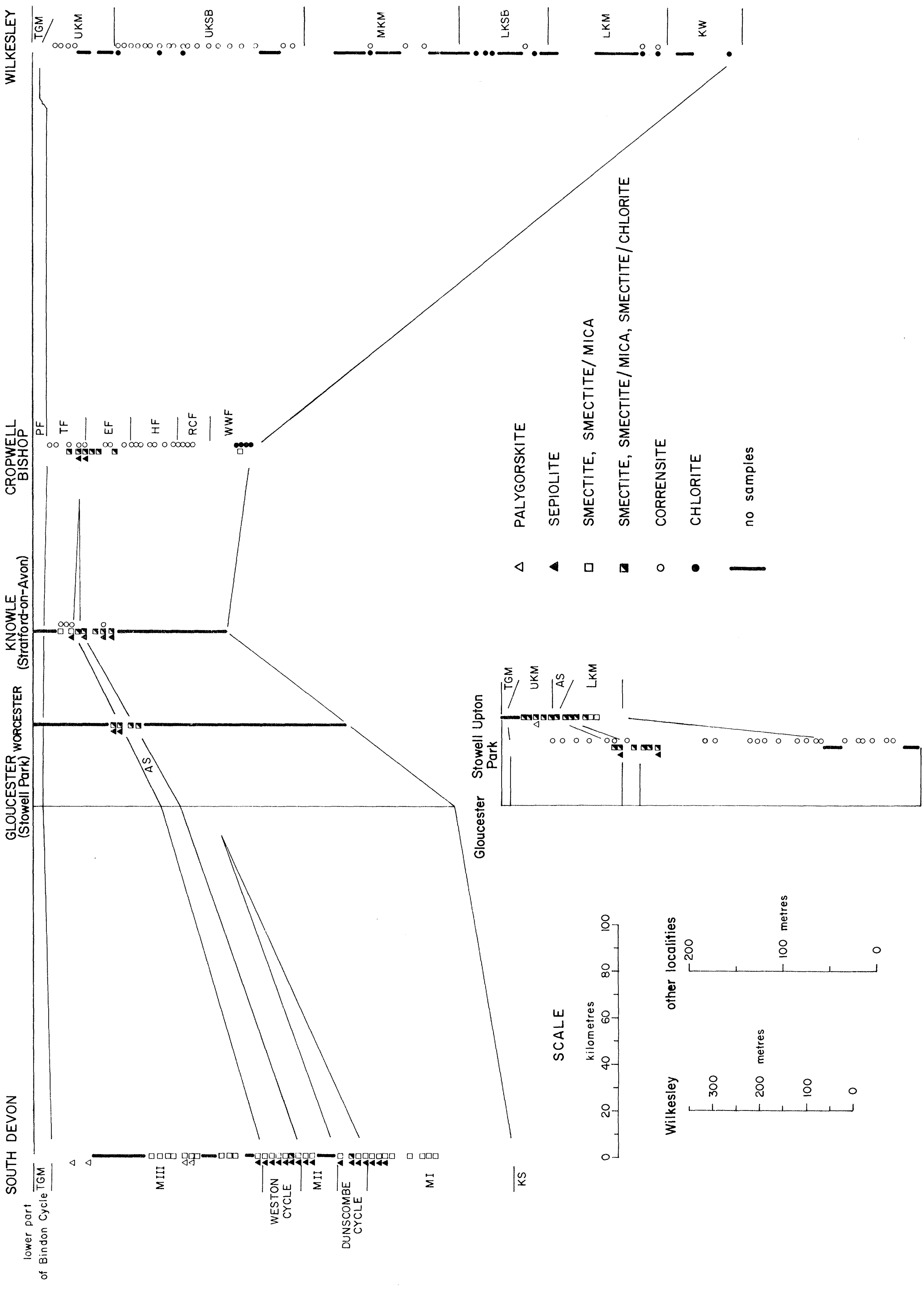

FIGURE 83. Distribution of exotic clays in the Keuper Marl.

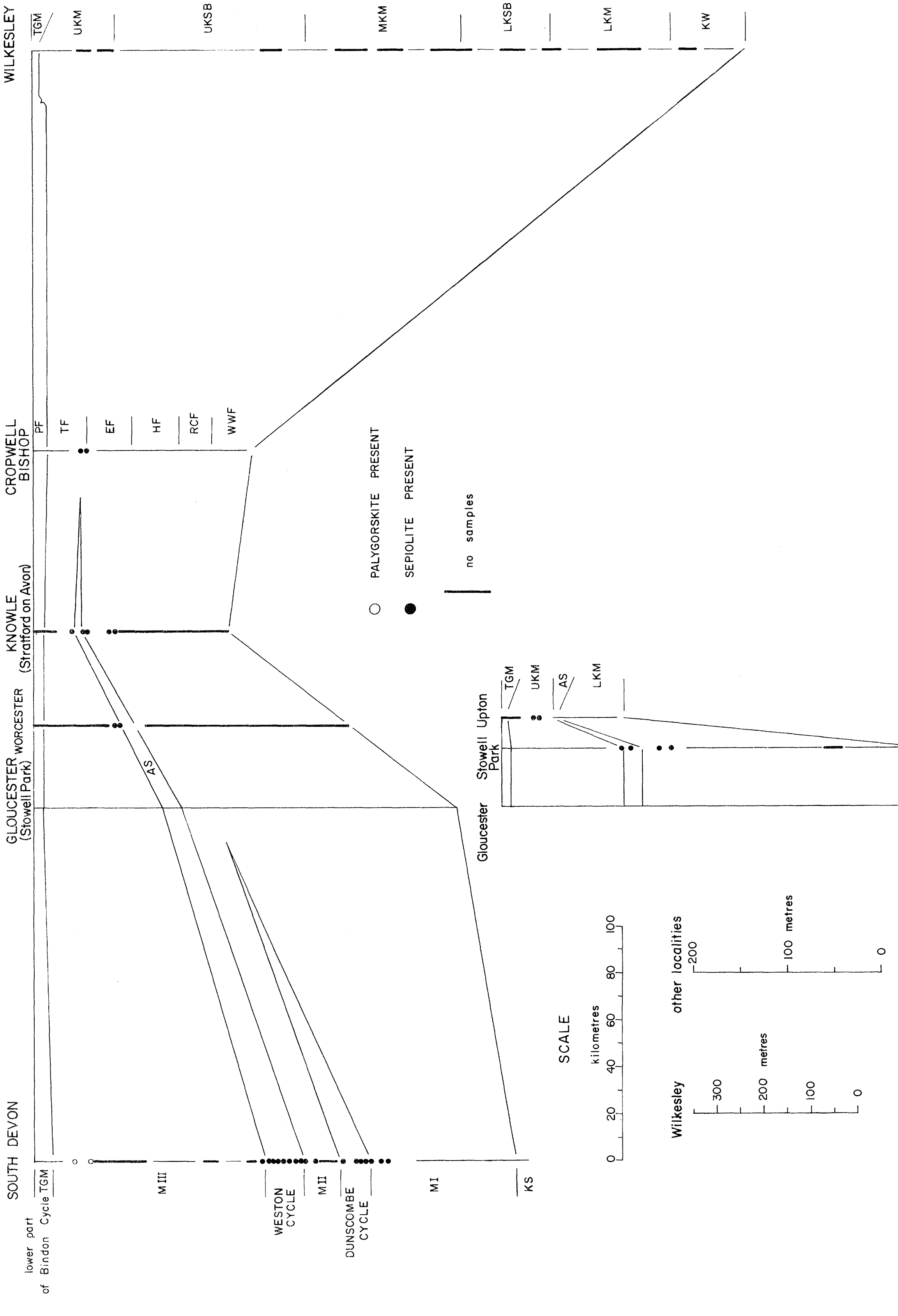

FIGURE 84. Distribution of sepiolite and palygorskite in the Keuper Marl.

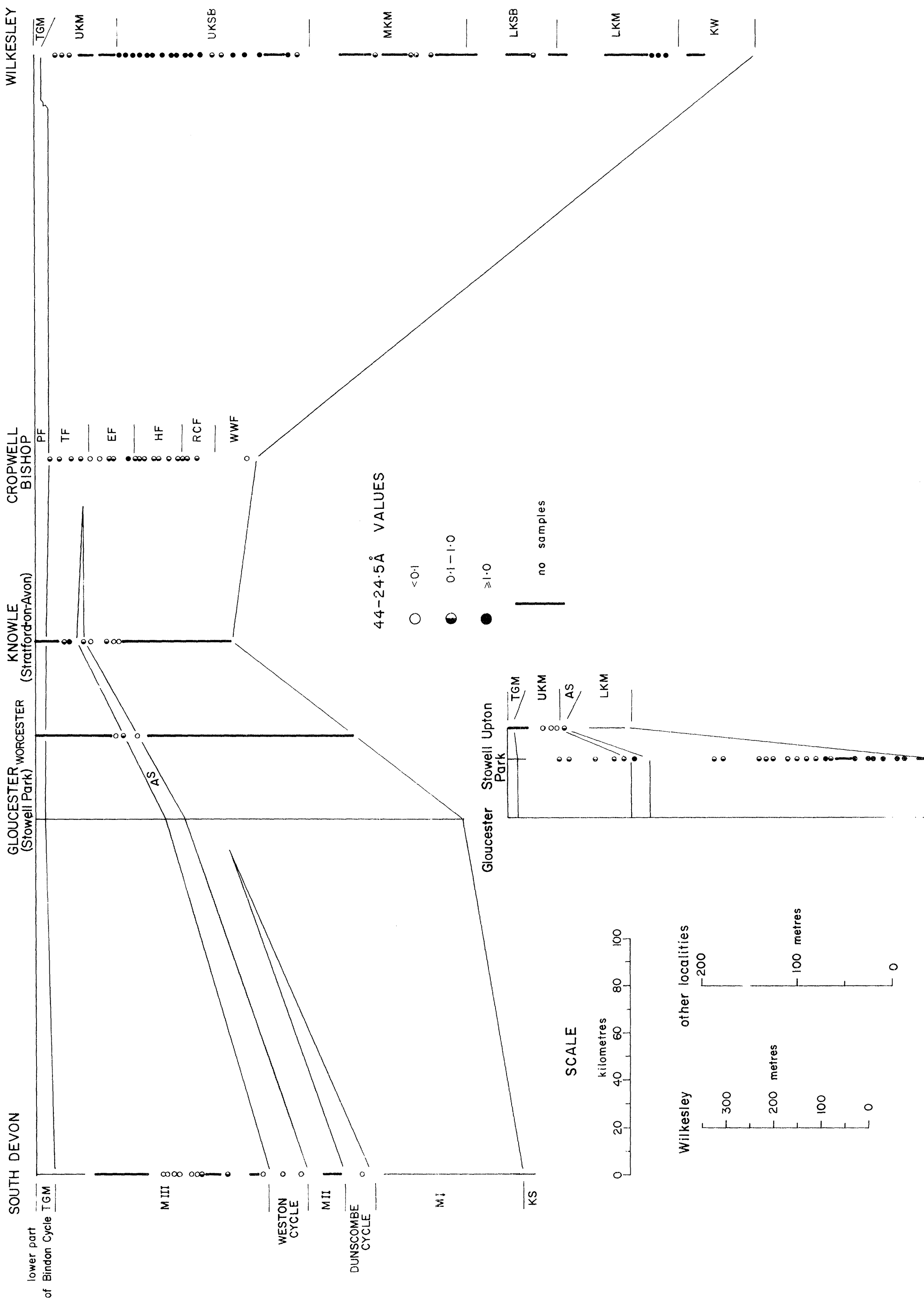

Figure 85. Distribution of 44–24.5 Å values in the Keuper Marl.

proportion of chlorite. At various levels in the Keuper Marl of the Cheshire Basin there occur abnormally high contents of chlorite and these are thought to result from the addition of another type of chlorite which belongs to the second clay assemblage (appendix 1, X-ray analysis).

The second or exotic assemblage of minerals has a much more restricted distribution, being only recorded from a relatively small number of samples. The assemblage includes the following minerals: sepiolite, palygorskite, smectite, smectite/mica, smectite/chlorite, corrensite and chlorite. In any one sample only a few of these minerals may be present, but their overall distribution within the Keuper Marl shows well-defined patterns. Sepiolite occurs in a zone associated with the cyclic sediments (figure 84). Smectite and smectite/mica are closely linked with the Weston and Dunscombe cycles on the Devon coast; northwards, these two minerals extend through a much greater proportion of the mudstone megafacies and are increasingly replaced by smectite/chlorite and corrensite. Corrensite increases from the Midlands into the Cheshire Basin at the expense of smectite/chlorite. Palygorskite occurs in a few samples in Mudstone III on the south Devon coast (figure 84). These relations are demonstrated in figure 83.

(ii) *Quantitative non-mineralogical analysis*

This is summarized in figures 85–90. Each circle may represent more than one sample, the number depending upon the distance between individual samples. A single circle covers a thickness of 10 m in the Wilkesley borehole and of 5 m at other localities. Details of the interpretation are discussed below.

Values of 44–24.5 Å† (representing corrensite) have a marked northerly distribution with high values being mainly restricted to the northern part of the mudstone megafacies (figure 85).

Values of 24.5–15.8 Å show a general northward increase (figure 86). There are particularly high values associated with the Weston Cycle and the adjacent mudstone megafacies; this is also well seen in the lower half of the Trent Formation and the upper part of the Edwalton Formation in the Midlands; an equivalent concentration occurs in the upper part of the Upper Keuper Saliferous Beds. Comparison of figure 86 with figures 85 and 87 shows that these high values are caused by smectite and micaceous smectite in south Devon, by smectite/chlorite in the Midlands, and by corrensite in the Cheshire Basin.

Values of 15.8–13.0 Å show a general northward increase (figure 87) which is related to the same mineral distribution pattern responsible for the high 24.5–15.8 Å values. However, there are additional high values in the Midlands and the Cheshire Basin which are related to high concentrations of chlorite; comparison of figures 87 and 89 illustrates this.

High 13.0–11.05 Å values are associated with the Dunscombe and Weston cycles on the south Devon coast, the mudstones into which these two cycles pass in the Midlands, and in Upper Keuper Saliferous Beds in the Cheshire Basin (figure 88). They are caused by sepiolite on the south Devon coast, Gloucestershire, Worcestershire and Warwickshire. In Nottinghamshire, smectite/mica and corrensite are responsible, whereas in the Cheshire Basin only corrensite is responsible.

Values of 7 Å, reflecting chlorite, show a well-defined pattern (figure 89). The cyclic sediments and sometimes the immediately adjacent mudstone megafacies have low values, whereas the main body of the mudstone group has higher values. Particularly high values occur in the Midlands and in the Cheshire Basin.

† 1 Å = 0.1 nm = 10^{-10} m.

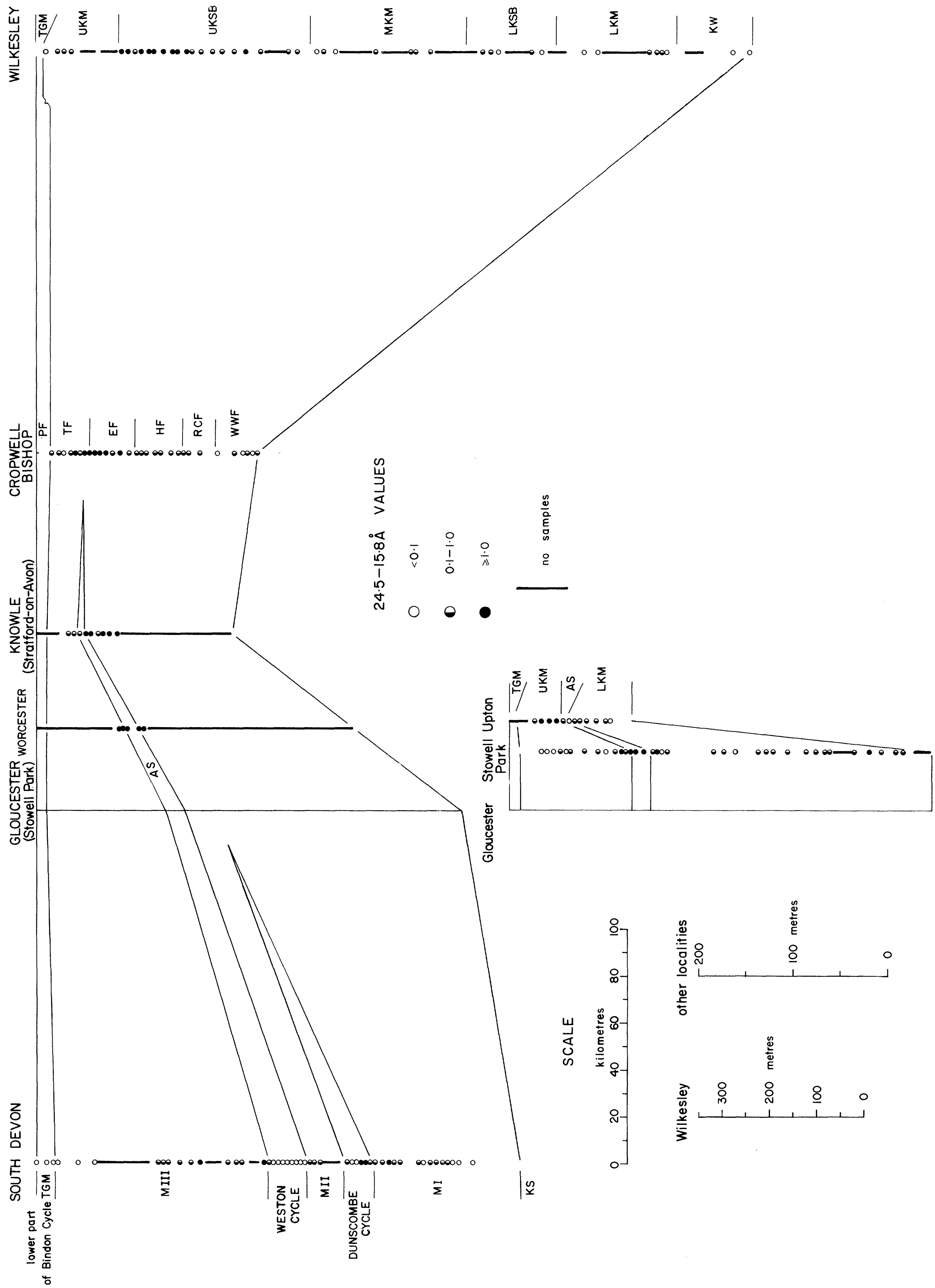

FIGURE 86. Distribution of 24.5–15.8 Å values in the Keuper Marl.

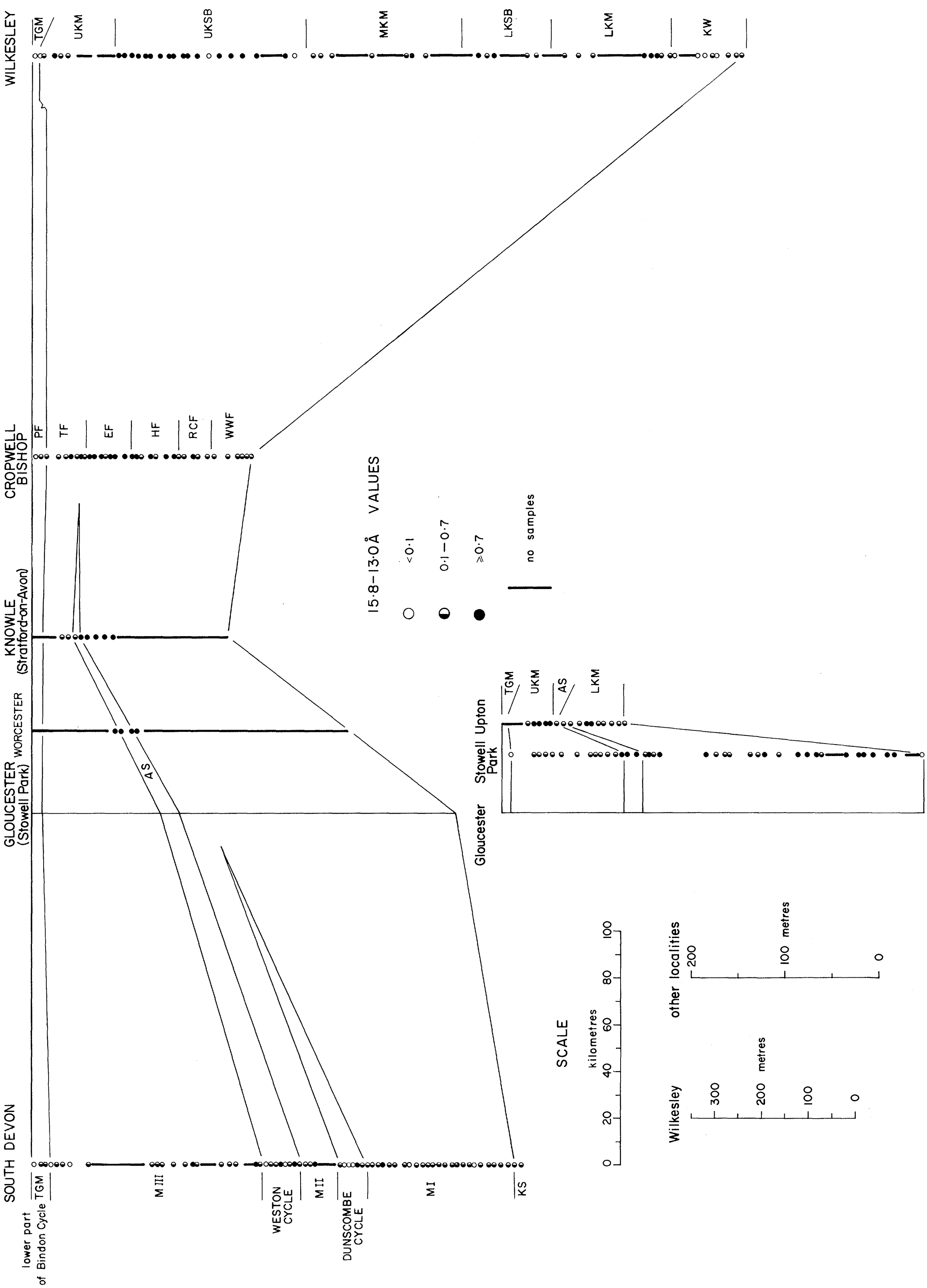

FIGURE 87. Distribution of 15.8–13.0 Å values in the Keuper Marl.

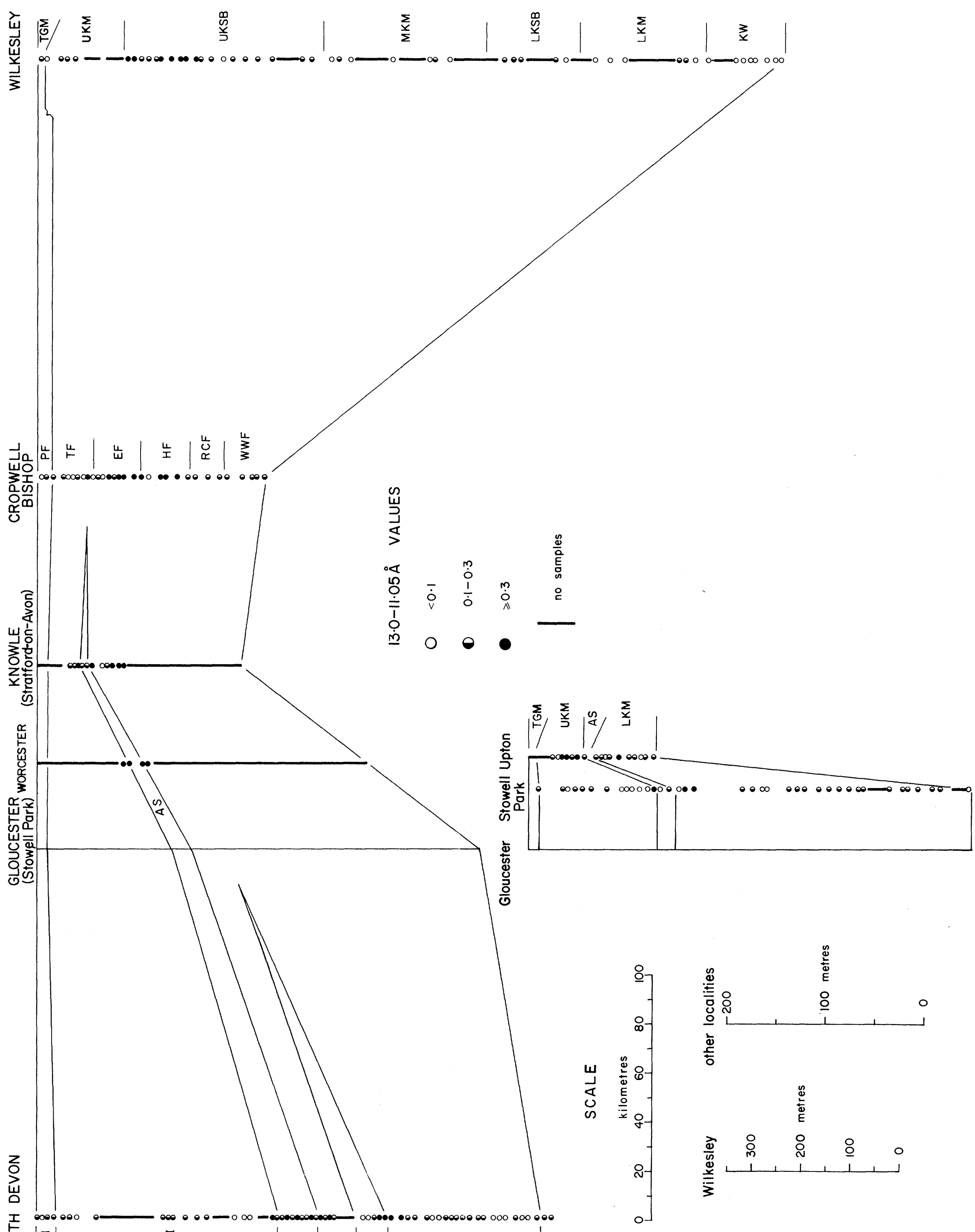

Figure 88. Distribution of 13.0–11.05 Å values in the Keuper Marl.

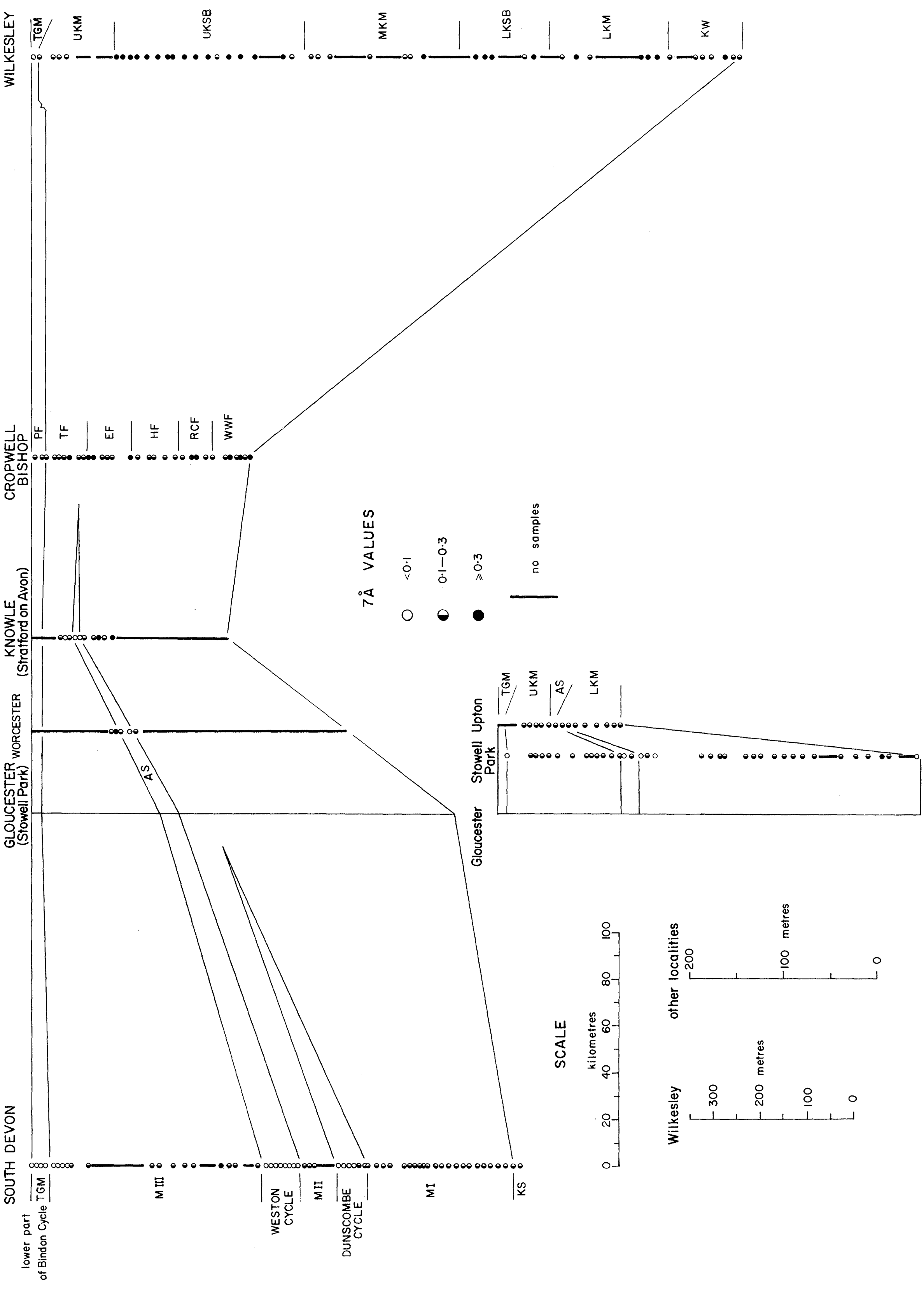

FIGURE 89. Distribution of 7 Å values in the Keuper Marl.

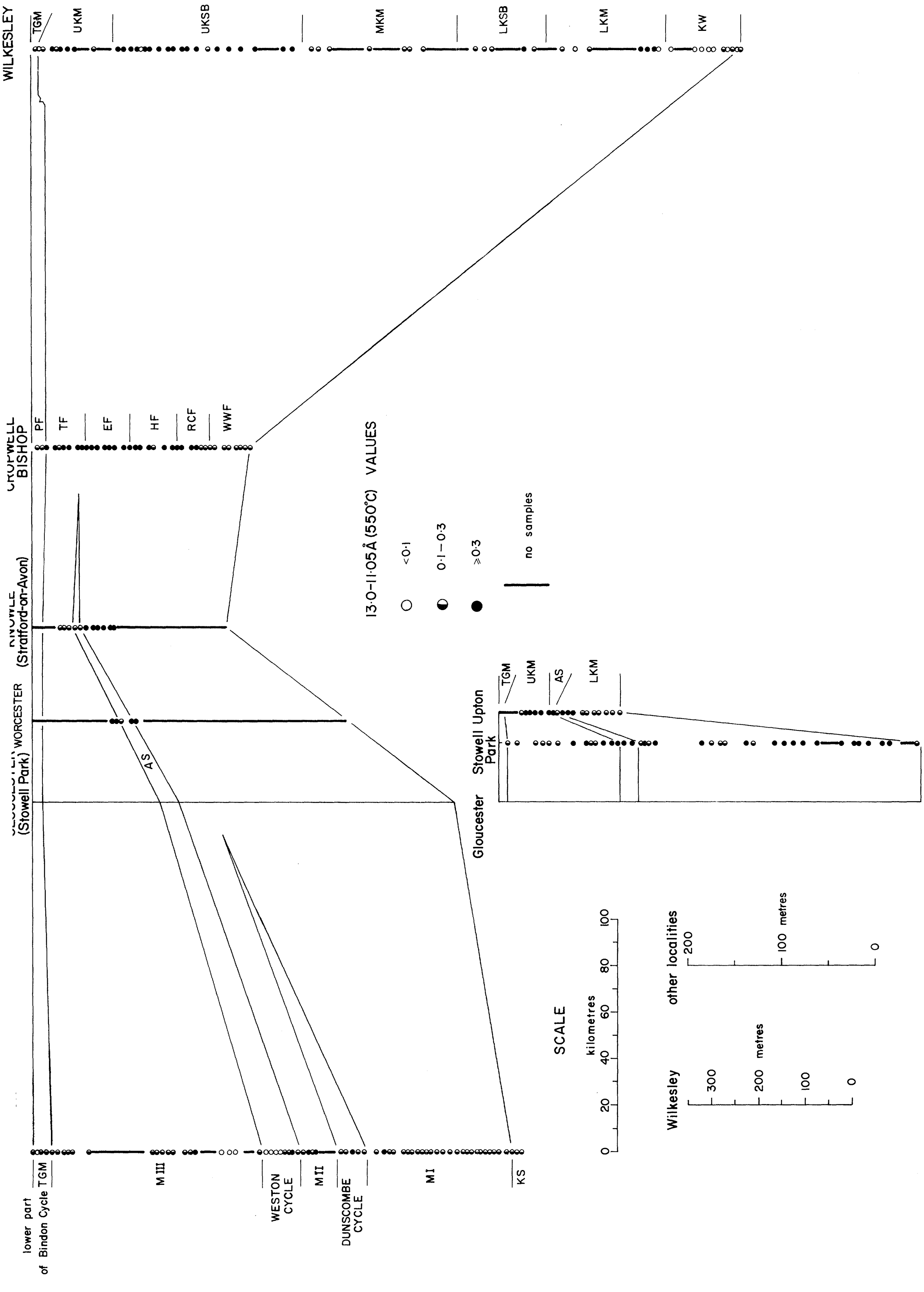

FIGURE 90. Distribution of 13.0–11.05 Å (550 °C) values in the Keuper Marl.

There is a general northward increase in the proportion of high 13.0–11.05 Å (550 °C heated) values (figure 90). The occasional high values on the Devon coast are related to residual peaks of sepiolite and of smectite/chlorite minerals. In the Midlands the 001 of smectite/chlorite and the 002 of corrensite cause the high values, whereas in the Cheshire Basin the 002 of corrensite is largely responsible.

6. Interpretation

The first question to be considered is whether the relations within the clay assemblages of the Keuper Marl and Rhaetic, and between these assemblages and other features of the sediments, can be satisfactorily explained by either the French or the German hypotheses discussed earlier.

There are superficial resemblances between the lateral mineralogical changes in the Keuper Marl and the mineral series described by Lucas (1962) from the Jura in particular. In detail, however, comparison is unsatisfactory. Of particular interest in Keuper Marl samples is the absence of clay mineral phases representing the mineralogical intermediate stages between the detrital assemblage of mica and chlorite, and the clay minerals of the exotic assemblage with which they may be associated. The mica and chlorite of the detrital assemblage occur invariably as distinct phases in samples containing the exotic assemblage. This indicates that the exotic assemblage has not been formed by transformation reactions from the detrital assemblage.

Other marked differences are of lesser significance: these include the absence of chlorite-dominated assemblages in the Keuper Marl and Rhaetic in England, and the absence in France of a relation between sepiolite and the lateral mineral series.

The corrensite-forming reaction put forward by some German researchers (Lippmann & Savaşçin 1969; Lippman & Schlenker 1970; Schüle 1974) is equally unsatisfactory in explaining my findings. There is no evidence that the corrensite in the Keuper Marl was formed by a neoformational reaction between detrital mica and magnesium-rich solutions. If this reaction had occurred there should be, for example, a decrease in the amount of mica relative to chlorite as the proportion of corrensite increases. This relation has not been recorded for corrensite or for any other member of the exotic clay assemblage. The only way by which the clay interrelations in the Keuper Marl can be explained by this mechanism is to assume that (1) the mica and chlorite of the matrix assemblage are of detrital origin, (2) the detrital mica and chlorite were broken down in such a way that their relative proportions remain constant, and (3) exotic clays were formed by reaction between the components released in the breakdown of silicate detritus and the magnesium-rich porewaters of the sediment. The second assumption however, is unsatisfactory. Experimental work (Ferrell & Grim 1967; Grim 1968, pp. 434–448; Ross 1969; Carstea, Harvard & Knox 1970) on the decomposition of clay minerals under different conditions at low temperatures suggests that mica and chlorite are unlikely to decompose at exactly the same rate under similar conditions. Krumm's (1969) suggestion of a relation between the salinity and alkalinity of the environment and the type of clay developed does not fit the pattern of clays found in the Keuper Marl and Rhaetic.

An alternative hypothesis is put forward here. I have demonstrated that there are two well-defined clay assemblages within the Keuper Marl: a matrix assemblage of mica and chlorite, and an exotic assemblage made up of a number of minerals including sepiolite and various mixed-layer minerals. Of particular importance in interpreting the origin of these assemblages are their relations to the lithology and megafacies.

The clearest relations have been recorded from the Devon coast where there is conspicuous correlation between the mineral assemblages and the Dunscombe and Weston cycles (figure 2). The Bindon Cycle does not show this correlation and possible reasons for this are discussed later. Smectite/mica and sepiolite of the exotic assemblage are arranged symmetrically about the sandstone groups of both the Dunscombe and Weston cycles. This arrangement indicates that the factors controlling the distribution of these exotic clays are connected closely with the interplay between the environments of the Alpine and Germanic facies. The general lack of correlation between the exotic clay minerals and the more conspicuous aspects of the lithologies making up the different megafacies suggests that their occurence had little to do with the physico-chemical conditions responsible for the more normal aspects of the sediments.

It might be suggested that this distribution of clays was caused by the mixing of detritus from these two environments, the smectite and smectite/mica belonging to the Germanic facies and the sepiolite to the Alpine facies.

According to present records, sepiolite does not occur except as traces in the Alpine facies, and, similarly, smectite and smectite/mica do not occur in the main part of the Germanic facies of the Devon coast. This hypothesis is consequently untenable and a neoformational origin for the minerals of the exotic assemblage is the only possibility.

The unlikelihood that the ions, necessary for these neoformations, have originated from the dissolution of the mica and chlorite of the detrital assemblage has already been discussed. The ions came therefore from solution or from non-crystalline gels in the waters of both the Germanic and Alpine facies. These two water masses must have had very different chemistries, and the various members of the exotic assemblage were precipitated in the mixing zone between them. This might have happened in two ways: (1) non-crystalline gels were first precipitated and these crystallized later both during deposition and after their inclusion within the sediment during intrinsic diagenesis; (2) clay minerals were crystallized either directly from solution during deposition, or from the porewaters of the sediment. There is petrographic evidence, illustrated in Plates 1–5, that some of these clays (sepiolite, palygorskite, some of the smectite or smectite/mica) were formed in the sediment after burial but for the greater part of the exotic assemblage such evidence is not available.

In the Keuper Marl the lateral mineralogical variations in the exotic assemblages parallel the lateral zonation of evaporite minerals. The following general associations occur: sepiolite, palygorskite and smectite/mica with calcite and dolomite, smectite/chlorite with calcium sulphate, and corrensite and chlorite with halite. These relations can be seen by comparing figures 80 and 83. Even better correlation is evident when the total distribution of major evaporite deposits in the Trias of England (Warrington 1974, figs 1 and 2) is considered; then the anomalous occurences of corrensite in the lower part of the Keuper Marl sequence at Cropwell Bishop and at Stowell Park which are not associated with evaporite deposits in the boreholes can be related to proved or probable, adjacent halite deposits. The zonation of evaporites must have been caused by lateral increases in salinity of the hypersaline Germanic facies. On the south Devon coast, detailed petrography has shown that the exotic clays are of neoformational origin, and there can be little doubt that the different assemblages of exotic minerals, into which they pass northwards, are of a similar origin. The conclusion might therefore be drawn that there is a series of evaporitic silicate minerals equivalent to the better known sequence of carbonate, sulphate and chloride minerals associated with the evaporation of seawater. However, this is not substantiated when the general distribution of clay minerals in evaporitic sequences is considered. This suggests that two superficially similar, but genetically unrelated chemical gradients existed in the same body of water. The following model might explain the interrelations.

The lateral gradient in evaporites is caused by a northward increase in the salinity of the water mass in which the Germanic facies was deposited, whereas the lateral sequence of neoformed clay minerals resulted from the movement of the lighter, less saline waters of the Alpine facies over the hypersaline water of the Germanic facies: the neoformed clay minerals crystallized either directly out of solution within, or from gels precipitated out of, the mixing zone at the interface between these two water masses. Variation in their mineral nature was controlled both by the continuous chemical variation of the Alpine water mass through reaction with the water mass of the Germanic facies and by lateral salinity gradients and local variations in the composition of the underlying hypersaline water mass. These local variations in the hypersaline waters might have been caused by fresh-water run-off from surrounding continental areas, and by the presence of submarine mineral springs associated with the widespread post-Hercynian mineralization of the basement during the Permo-Triassic. The waters of the Germanic facies were enriched in silica by two processes: (1) the precipitation of dissolved silica brought into the basin by fresh water; (2) silica introduced by submarine mineral springs or seeps. The general absence of the biological removal of silica from solution as a consequence of the highly saline, hostile environment helped to maintain the high concentration. It is pertinent to recall that sepiolite can be rapidly precipitated out at one atmosphere pressure and at 25 °C by mixing filtered seawater with a weak solution of sodium silicate (Wollast, Mackenzie & Bricker 1968) — a situation little different from that postulated to have occurred between the waters of the Alpine and the Germanic facies in southwest England.

The model put forward to explain the origin of the clays of the Keuper Marl is shown in figure 91.

The Bindon Cycle can be related to a transgression–regression cycle in a manner exactly similar to the Weston and Dunscombe cycles; however, in the sections investigated the Bindon Cycle is not associated with the occurrence of the exotic clay assemblage. This may be explained by (1) the marked differences in the proportion of individual lithologies in its megafacies, and (2) the northward recession of the more saline zones in the Germanic facies during the deposition of the upper part of the Triassic. The Lower Carbonate Group of the Bindon Cycle contains a very much higher proportion of dolomitic sediments than in any other carbonate group of the three cycles. If it is assumed that the cations of the exotic clays are dominated by magnesium as has been found by researchers on the European Germanic facies, then the absence of these clays from the Lower Carbonate Group of the Bindon Cycle could have been caused by dolomite precipitating from solution and effectively starving the silicate-forming processes of magnesium in the manner originally suggested by Lucas (1962). The absence of the exotic assemblage from the Upper Carbonate Group of the Bindon Cycle cannot be explained by this mechanism because no great amount of carbonate minerals occur in its sediments. A likely cause is that the salinity pattern during the regressive phase of the Bindon Cycle had moved farther to the north compared to the immediately pre-transgressive phase of this cycle. Calcite is the only carbonate recorded from the Upper Carbonate Group of the Bindon Cycle in the region studied in this investigation†: this suggests that the salinity was similar to, or even less than, the depositional waters in which the sandstone groups of the Dunscombe and Weston cycles were deposited, in which calcite predominates over dolomite.

† Traces of dolomite have been recorded in this horizon at Westbury-on-Severn (figure 59) and at Owthorpe (figure 70).

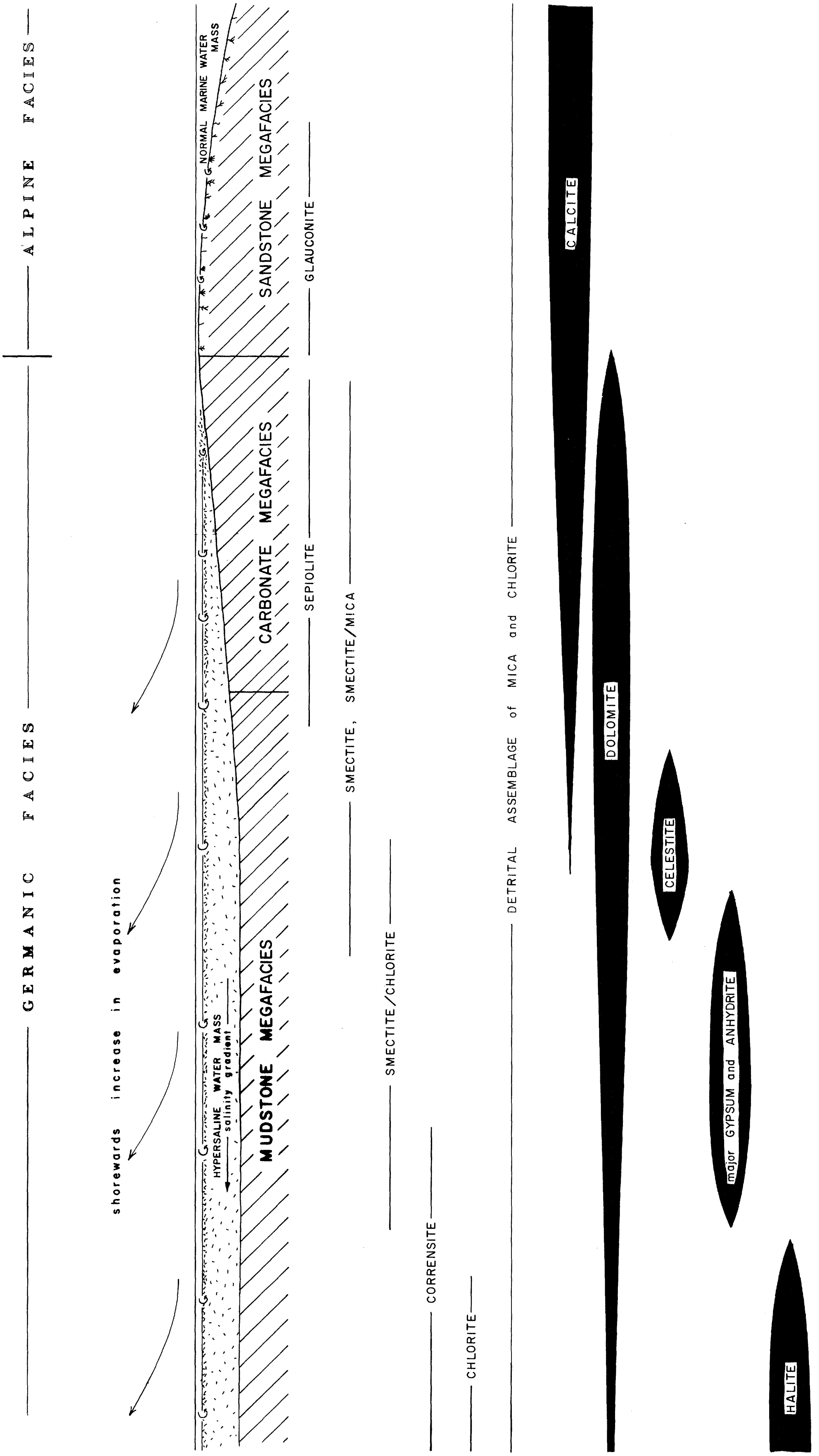

FIGURE 91. Model proposed for the origin and distribution of the Keuper clays.

Farther to the north there is evidence that the salinity increased. Raymond (1955) has recorded the presence of dolomite in the Cotham Beds (= Upper Carbonate Group of the Bindon Cycle) in the Eskdale no. 8 borehole in north Yorkshire. Swelling chlorite, belonging to the exotic assemblage of clay minerals, occurs in these beds as well as in the Lower Carbonate Group (Tea Green Marl) of this cycle (Raymond 1955). These relations between the predominant type of carbonate and the appearance of the exotic assemblage in the Upper Carbonate Group of the Bindon Cycle suggests that if the chemistry of the waters in which the sandstone and carbonate megafacies were deposited were not sufficiently different no appreciable silicate-precipitating reactions occurred. Differences in chloride and sulphate concentrations were probably of little importance compared with the neccessity of enhanced silica concentrations within the waters of the Germanic facies, including the carbonate megafacies. The same pattern of carbonate–exotic clay assemblage relations occur in the upper part of the red mudstone megafacies in the Keuper Marl. On the south Devon coast, Mudstone III is characterized by a predominance of calcite over dolomite in contrast to Mudstones I and II, indicating the encroachment of open marine conditions. The transgressive phase of the Bindon Cycle is not associated with any appreciable development of exotic clays in the top of Mudstone III, such as occurs immediately below the Weston and Dunscombe cycles in Mudstone II and I respectively. In the Midlands, however, an exotic assemblage does occur in the top of the red mudstone megafacies beneath the transgressive phase (Lower Carbonate Group) of the Bindon Cycle; these sediments contain dolomite as the predominant carbonate. These relations suggest that the waters of the Germanic facies had to be sufficiently different in chemistry from the open marine water of the Alpine facies before any clay mineral neoformation would result from their mixing.

7. Conclusions

Evidence suggests that the phyllosilicates of the clay fraction of the Keuper Marl and Rhaetic consist of two assemblages of different origin. The first is a matrix assemblage consisting largely of mica with small amounts of chlorite and this occurs in all the samples investigated. It is of detrital origin and the slight variations in the ratio of these two minerals reflect differences in the various source areas that contributed fine-grained detritus to the area of Keuper Marl sedimentation. In some parts of the Keuper Marl, a second assemblage is superimposed upon this matrix assemblage. This consists of sepiolite, palygorskite, smectite, irregular mixed-layer smectite/mica, irregular mixed-layer smectite/chlorite, corrensite and chlorite. These minerals are of neoformational origin and crystallized within the sediment during its intrinsic diagenesis from either one or a combination of sources: (1) the sediments' pore-solution; (2) amorphous gels precipitated within the environment of sedimentation; or (3) by the reaction of these gels with the pore-solutions of the sediments. The mineral neoformations resulted from the chemical reactions occurring between two water masses, one with a salinity similar to normal seawater, the other with a much higher salinity. The lateral mineralogical variations in the assemblages of neoformed minerals were controlled by the following: the salinity gradients within, and the chemical composition of, the hypersaline seawater; the changing chemical nature of the normal seawater as it reacted with the hypersaline waters; and the rapid removal of magnesium from solution by the precipitation of carbonate minerals.

It has already been argued that the various hypotheses put forward by the French and

German schools find little supporting evidence in my investigation. This implies that there are three different and national explanations for the origin of the Triassic clay assemblages of Europe and north Africa. It is my contention that there is essentially a single hypothesis which will satisfy all the observed relations within the Triassic clays. Neither Lucas's transformational nor Lippman's neoformational hypotheses explain satisfactorily the relations observed in the Keuper Marl. Krumm's summary (1969) of the Trias of Europe and north Africa, although based upon a large number of results varying in quality and emphasis, demonstrates that the minerals belonging to the neoformational assemblage of the Keuper Marl are restricted to the Germanic facies and the immediately adjacent Alpine facies. This suggests that their occurrence may have been related to the movement of normal seawater from the Alpine facies into the Germanic facies to replace the considerable loss of water by evaporation in this arid hypersaline milieu. The less-dense seawater would have flowed across the top of the more dense, highly saline brines and the reactions responsible for the formation of the neoformed silicates would have resulted from the mixing of and reaction between these two water masses. If certain areas of Triassic sedimentation are considered in more detail there arise various difficulties in applying my hypothesis. The best example is the Jura Basin which has formed the cornerstone for Lucas's interpretation. If seawater of normal salinity moved northwestwards from the Alpine facies in the southeast as is suggested by the palaeogeographic reconstruction assumed by Lucas, the sequence of mineral assemblages would in my hypothesis result from salinity gradients completely in reverse of those found in the Keuper Marl. The most saline brines would be closest to the Alpine facies at Laveron and would become less saline towards the outer edge of the Jura Basin.

There is no definite evidence that the Alpine sea had access to the Jura Basin along its southeast margin and it is conceivable that normal seawater was introduced from the northwest – the area assumed by Lucas to be bordering a continental land mass. With this reinterpretation of the palaeogeography, the salinity gradient and its relation to the clay assemblages become similar to that in the Keuper Marl. The transformational series of Lucas could then be explained as a mixture of a detrital matrix assemblage of degraded mica and chlorite showing evidence of minor aggradational transformation reactions and a neoformed assemblage of irregular mixed-layer smectite/mica and chlorite/swelling chlorite, corrensite and much of the well-crystalline trioctahedral chlorite. Evidence of transformation reactions in the detrital assemblage of the English Trias have not been recorded in this investigation. Their absence could result from (1) the lack of near-shore facies in which degraded clay detritus was both deposited and preserved, or (2) degraded clay detritus not being supplied to the Germanic facies.

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Appendix 1. Methods of clay mineralogy

The decalcified clay fractions (less than 2 μm e.s.d.) of about 450 samples were extracted and analysed mineralogically by X-ray diffraction using oriented aggregates. The methods employed are described below.

Sample preparation. Part of each air-dried sample is ground and placed in cold 2 N. acetic acid (buffered at pH 3 with sodium acetate) to dissolve any calcite. Samples consisting largely of halite with small mudstone inclusions are first dissolved in water and then the mudstone is ground wet and subsequently treated for the removal of calcite. As soon as any calcite has dissolved, the sample is washed repeatedly with distilled water to the point of dispersion. It is then shaken with 0.1 % sodium hexametaphosphate solution on a mechanical shaker for 2 h. After an appropriate settling time calculated from the Stokes' formula, a 50 ml sample of the fraction less than 2 μm e.s.d. is collected in a pipette. A portion of this is flocculated with concentrated calcium chloride solution, and is centrifugally compacted. The clear supernatant liquid is poured off and two smears of the compacted clay are made on glass slides using a piece of flexible perspex. The slides are dried slowly in a desiccator over a saturated solution of calcium nitrate (vapour pressure 50 %); the resulting oriented aggregates are used for X-ray analysis.

There was no identifiable acid-attack or mineral alteration of the clays resulting from the method of sample preparation. The rapid flocculation with concentrated calcium chloride before centrifugal compaction and the smear method of aggregate formation avoided any differential mineral segregation, and, in addition, produced excellently orientated aggregates of the calcium-saturated clay fractions.

One of the tests used to differentiate between chlorite and kaolinite is based upon the different rates at which these two minerals dissolve in a mineral acid. The method used is as follows: A portion of the less than 2 μm e.s.d. fraction is boiled gently with 20 % sulphuric acid in a reflux condenser for 20 min. It is then washed free of acid with distilled water, flocculated with concentrated calcium chloride solution, centrifugally compacted, and a single smear slide is made and mineralogically analysed by X-ray diffraction. The presence of a 7 Å peak after this treatment indicates that kaolinite is present – this mineral is resistant to the acid treatment – whereas chlorite dissolves.

X-ray analysis. Analysis by X-ray diffraction was carried out on the orientated aggregates of the clay fraction by using the Philips diffractometer (PW. 1050/25) and X-ray generator (PW. 1009/80), housed in the Department of Mineralogy and Petrology, University of Cambridge. The machine settings were as follows; generator, 20 mA, 40 kV; diffractometer, slits $\frac{1}{4}°$ and 0.1° (receiving), rate of rotation, $\frac{1}{2}°$ $2\,\theta$/min; chart rate, 40 × 20 mm/h; time constant, 4 s; counting rate, 400 count/s. Four runs were made for each sample from 2° to 35° 2θ before and after various thermal and chemical treatments. One smear slide was examined untreated, and then again after being heated over glycerol in an enclosed vessel for 2–$2\frac{1}{4}$ h at 110 °C; this treatment causes minerals containing swelling interlayers to expand. The other smear slide was heated for 2 h in a muffled furnace, first at 440 °C and then at 550 °C. After each heating the slide was cooled in a silica-gel desiccator and then X-rayed.

Analysis of the four or five diffractometer traces from each sample allowed in particular the basal spacings (001) of the different groups of clay minerals to be identified by using the mineralogical data given by Brown (1961) and Lucas (1962). Identification was carried out at group level only.

Lucas's (1962) structural interpretation of the various types of irregular mixed-layer clay minerals found in the European Triassic has been followed, although the British Clay Minerals Group (Brown 1955) polynomial system of nomenclature is still used. For example, a smectitic chlorite is an irregular mixed-layer structure consisting of Te–Oct–Te units with smectitic and chloritic inter-unit spaces, the latter predominating; a smectite–chlorite is an irregular mixed-layer structure in which the proportions of smectitic and chloritic inter-unit spaces are approximately equal. The use of an oblique stroke between two mineral names (e.g. smectite/chlorite)

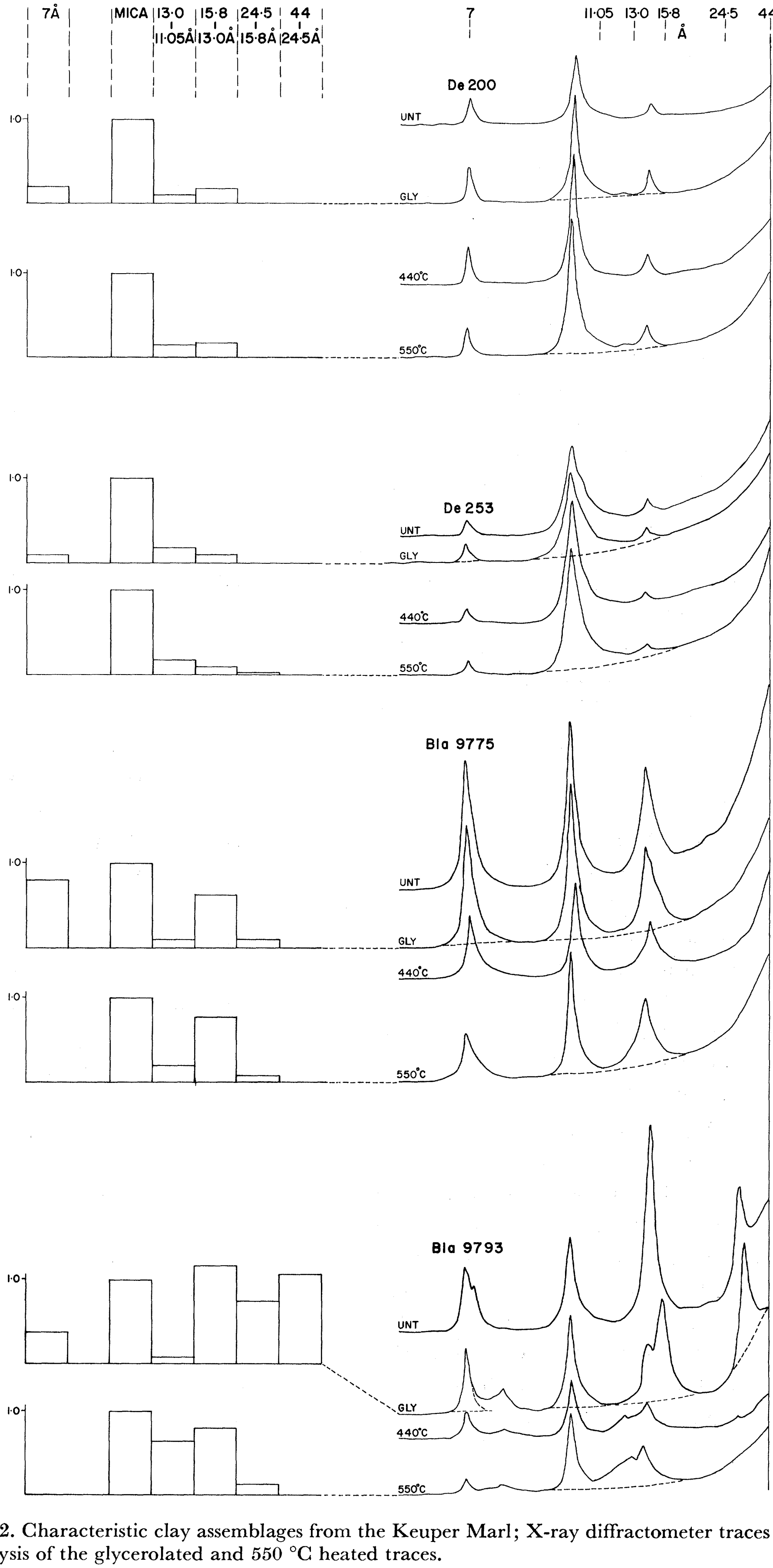


FIGURE 92. Characteristic clay assemblages from the Keuper Marl; X-ray diffractometer traces and quantitative analysis of the glycerolated and 550 °C heated traces.

De 200. Mica and chlorite; Mudstone III, Salcombe Hill Cliff, south Devon coast.

De 253. Mica (with some smectite and/or vermiculite interlayers) and chlorite; Lower Carbonate Group, Bindon Cycle, Haven and Bindon Cliffs, south Devon coast.

BLA 9775. Mica and chlorite; Lower Keuper Saliferous Beds, Wilkesley borehole, Cheshire.

BLA 9793. Mica, chlorite and corrensite; Lower Keuper Marl, Wilkesley borehole, Cheshire.

refers to an irregular mixed-layer mineral in which the proportion of inter-unit spaces is not defined.

Swelling chlorite is a term originally applied by Stephen & MacEwan (1950, 1951) and Honeyborne (1951) to a group of undescribed clay minerals from Keuper Marl samples. The properties of these minerals were related to both chlorite and smectite or vermiculite. Lippmann (1954, 1956), Vivaldi & MacEwan (1960) and Lucas (1962) demonstrated that many swelling chlorites and some closely related minerals consist of chlorite and smectite units showing all degrees of interlayering, ranging from completely random to a perfect alternation of layers, and to this last combination Lippmann (1954) gave the name corrensite. Lucas (1962) restricts the use of the term swelling chlorite to a chlorite-type mineral in which the octahedral layer is incomplete and allows a certain degree of expansion, while still maintaining the heat stability of chlorite. I have applied Lucas's definition to the clay mineral assemblages investigated in this study, and have not recorded this mineral. Swelling chlorites have been identified in the Keuper Marl in recent studies (for example, Dumbleton & West 1966; Davis 1967), but the term has been used probably in the sense of Stephen & MacEwan (1950, 1951) and Honeyborne (1951).

The clay mineral groups identified in this study are considered below.

Mica is identified by the 001 peak at about 9.9 Å in the untreated sample which is unaffected by glycerolation or heat treatment. Sample De 200 (figure 92) shows mica with chlorite. Slight changes in the morphology of this peak may occur on glycerolation and heating, and these are caused by the presence of small proportions of smectitic or vermiculitic interlayers (e.g. sample De 253, figure 92). Chlorite is identified by the 001 peak at about 14 Å; this is unaffected by either glycerolation or heat treatment. It has been argued that chlorites of two origins occur. One is detrital and is present in low concentrations associated with mica forming a background assemblage; the 001 and 002 peaks are unaffected by heating (e.g. samples De 200 and De 253, figure 92). The second is of neoformational origin, and this exhibits on heat treatment a relative decrease in the intensity of the overall X-ray pattern and an increase in intensity of the 002 peak relative to the 001 peak (sample BLA 9775, figure 92, contains mica with both types of chlorite).

Sepiolite is identified by the 110 peak at approximately 11.9 Å which is unaffected by glycerolation or by 440 °C heating. On 550 °C heating this peak either disappears or is much reduced. Sample De 69, figure 93, contains prominent sepiolite mixed with mica, chlorite and mica/smectite. Sepiolite occurs both as long and short fibres (figures 3 and 6, plate 1).

Palygorskite is identified by the 110 peak at about 10.5 Å which is unaffected by glycerolation but disappears with 440 °C heating. The 110 peak may be partially masked by the 001 peak of mica. Sample De 271, figure 93, contains palygorskite mixed with mica and chlorite. This mineral occurs in a fibrous habit (figure 24, plate 5).

Smectite is identified by the presence in the glycerolated sample of the 001 peak at about 17.8 Å, and this collapses to approximately 9.8 Å on heating.

Corrensite, a regular interstratified smectite–chlorite, is identified by the 001 peak at about 29 Å in the untreated sample which expands to 32 Å on glycerolation. On 440 °C heating the diffraction pattern is much reduced and the 002 and 003 peaks are represented by diffused peaks at 12.8 Å and 8.0 Å. On 550 °C heating there are diffused peaks at 12.8 and 7.85 Å. Occasionally a weak diffused peak occurs in the 440 °C trace in the 20–30 Å region, representing the 001 reflexion. Sample BLA 9793, figure 92, contains conspicuous corrensite associated with mica and chlorite.

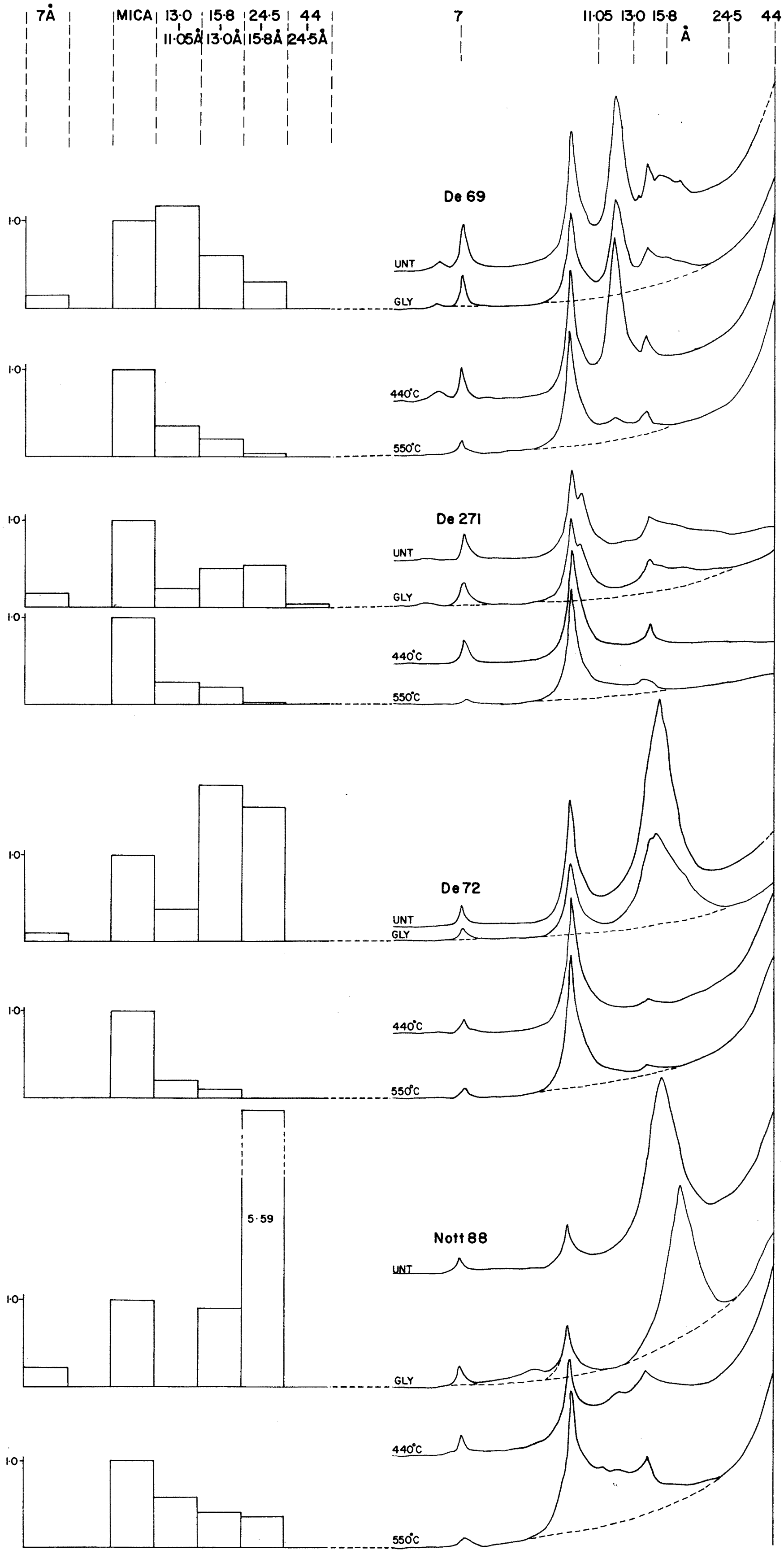


FIGURE 93. Characteristic clay assemblages from the Keuper Marl; X-ray diffractometer traces and quantitative analysis of the glycerolated and 550 °C heated traces.

De 69. Mica, chlorite, sepiolite and smectite/mica; Upper Carbonate Group, Weston Cycle, Weston Cliff, south Devon coast.

De 271. Mica, chlorite, palygorskite, and smectite/mica; Mudstone III, Berry and Branscombe Cliffs, south Devon coast.

De 72. Mica, chlorite and smectite/mica; Upper Carbonate Group, Weston Cycle, south Devon coast.

Nott88. Mica, chlorite and smectite/chlorite; Edwalton Formation, Blackberry Hills borehole no. 7, Clipston Nottinghamshire.

Irregular mixed-layer smectite/mica minerals have 001 peaks between approximately 10 and 17.8 Å in the glycerolated X-ray trace, and these collapse on heating to about 9.8 Å. The proportion of the two types of interlayer is variable. Sample De 72, figure 93, contains a micaceous smectite (the majority of crystallites contain 28 % of mica interlayers) associated with mica and chlorite.

Irregular mixed-layer smectite/chlorite minerals are identified by the presence of 001 peaks in the glycerolated sample between 14 and 17.8 Å which collapse on heating to between 10 and 14 Å. Sample Nott 88, figure 93, contains a chloritic smectite (the majority of crystallites contain 18 % chlorite interlayers) associated with mica and chlorite.

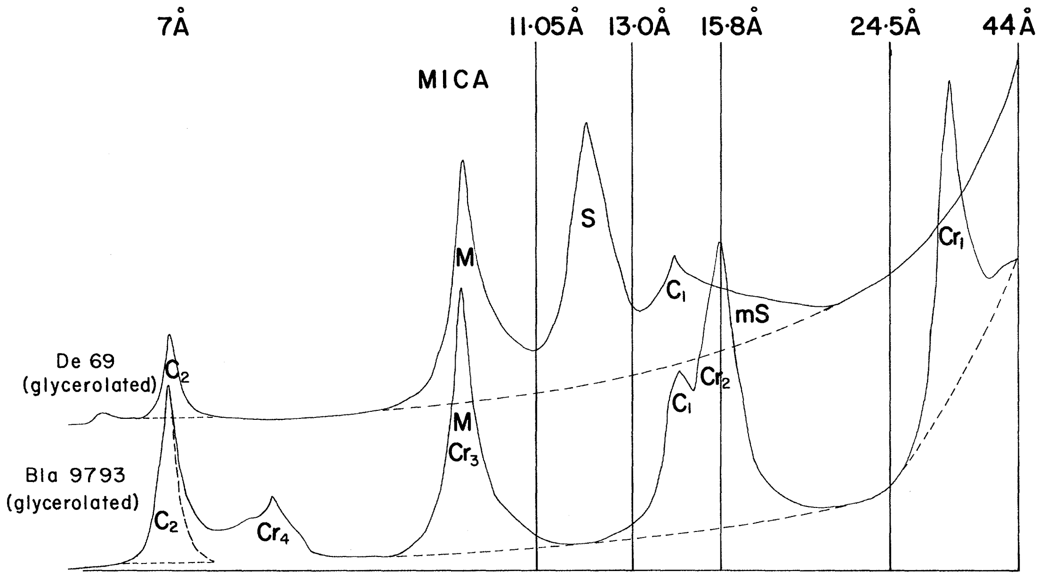


FIGURE 94. Relation of the subdivisions used in quantitative analysis and the mineralogy of two clay assemblages. De 69. mS, 001 of micaceous smectite. C_1, 001 of chlorite. S, 110 of sepiolite. M, 001 of mica. C_2, 002 of chlorite.
BLA 9793. Cr_1, 001 of corrensite. Cr_2, 002 of corrensite. C_1, 001 of chlorite. M, Cr_3, 001 of mica and 003 of corrensite. Cr_4, 004 of corrensite. C_2, 002 of chlorite.

Results of clay mineral analysis are illustrated in two complementary ways. In the first the low-angle portion (2–14° 2θ) of the diffractometer trace of each glycerolated smear is shown and related to the position of its parent sample in the lithological sequence. From this the general variations in the clay assemblages at any particular locality are obvious once the reader has familiarized himself with the different types of clay assemblages shown in figures 92 and 93. This method, however, neither indicates the type of interlayering occurring within the irregular mixed-layer minerals nor allows a more objective and quantitative analysis of mineral assemblages.

The second method is based upon the internal comparison of peak areas. This produces relatively good quantitative assessment of the mineral variation although it does not allow overlapping peaks and the nature of the interlayerings in irregular mixed-layer minerals to be easily deduced. However, with careful use and an understanding of the methods' limitations both these difficulties can be overcome. The method involves analysing the form of the glycerolated and 550 °C heated X-ray traces of each sample between 2° and 14° 2θ by drawing base lines to the traces. The areas of various subdivisions between the base line and corresponding trace are measured and each is proportionally related to the area of the mica peak which is taken as unity. The position of the subdivisions is constant, and they reflect either characteristic peaks of individual minerals or areas of diffraction resulting from two or more minerals. This procedure is illustrated in figures 92–94.† The significance of the various subdivisions is as follows.

Glycerolated trace. The 44–24.5 Å region contains only the 001 peak of corrensite, and therefore variations of this area are a good assessment of the abundance of this mineral.

The 24.5–15.8 Å region may represent (1) the 001 peaks of smectite, micaceous smectite (up to 17 % mica interlayers) and chlorite/smectite (up to 49 % chlorite interlayers), and (2) part of the 002 peak of corrensite.

The 15.8–13.0 Å region may represent (1) the 001 peaks of chlorite, mica/smectite (between 17 and 47 % mica interlayers) and smectite-chlorite (between 49 and 65 % chlorite interlayers), and (2) part of the 002 peak of corrensite.

The 13.0–11.05 Å region may represent (1) the 110 peak of sepiolite, and (2) the 001 peak of smectite-mica (between 47 and 78 % mica interlayers) and mica/chlorite (between 19 and 65 % mica interlayers). Inspection of the glycerolated trace will confirm the presence of sepiolite. High values of this area are nearly always due to sepiolite, this can be seen by comparing figures 84 and 88.

The contribution of any particular mineral to the diffraction region between 24.5 and 11.05 Å can be deduced approximately by examination of the low-angle part of the glycerolated trace and the values for the 44–24.5 Å, the 7 Å peak and the 550 °C heated 13.0–11.05 Å regions. Once the abundance of corrensite, smectite, chlorite and sepiolite are realized there is little difficulty in recognizing the type and approximate quantities of irregular mixed-layer minerals.

The mica peak (11.05 – approx. 8.8 Å) may represent (1) the 001 peaks of mica, chloritic mica (up to 19 % chlorite interlayers) and smectitic mica (up to 22 % smectite interlayers), (2) the 003 peak of corrensite (weak), and (3) the 110 peak of palygorskite. In most samples mica is the sole contributor to this region.

Kandite minerals are absent from the clay assemblages and the 7 Å peak represents 002 of chlorite. There is little interference from other peaks: 004 of corrensite impinges slightly but this has been corrected for where necessary. The relative area of this peak is a good indication of the amount of chlorite, in contrast to its 001 peak at 14 Å which is often masked by other minerals.

550 °C-*heated trace*. The 13.0–11.05 Å region of the 550 °C trace may indicate the extent of mica/chlorite interlayers in irregular mixed-layer minerals. This value represents not only the original mica/chlorite minerals but also structures produced by the collapse of irregular smectite/chlorite minerals and corrensite on heating. Sepiolite may contribute to this area of diffraction as there is often a residual peak, much reduced in intensity, at approximately 12 Å after 550 °C heating. The extent of interference by sepiolite and corrensite can be deduced by inspection of the glycerolated trace.

† This analysis has been carried out on all the samples investigated. The detailed results, as well as the X-ray diffraction diagrams, have been deposited with the Institute of Geological Sciences (Exhibiton Road, London SW7 2DE) where they can be inspected. Figures 85–90 summarize the results.

Appendix 2. Semi-quantitative analysis of calcite and dolomite

The calcite/dolomite ratio of samples was determined by comparison with standard mixtures of pure, finely ground calcite and dolomite by using the X-ray diffraction method outlined by Tennant & Berger (1957).

The approximate amount of calcite and dolomite within a sample was determined by a somewhat similar method except that separate standard mixtures were made up between a typical decalcified sample of Keuper Marl (De 145) with dolomite and calcite. By comparing heights of the most intense peaks of these two carbonates in the sample with those of the standard mixtures, a rough indication of their abundance can be made.

Appendix 3. Sidmouth–Bindon Cliff, Axmouth

In the south Devon cliff-sections 393 m of strata belonging to the Keuper Marl have been examined, representing 81 % of the total thickness of the formation according to my calculations. The only considerable gap, estimated to be 81 m, occurs in the upper part of the succession between the topmost horizon recorded in Branscombe West Cliff and the lowest horizon recorded in Haven Cliff – the part of the Keuper Marl hidden beneath the Cretaceous in the Beer Syncline and those portions that outcrop in the low cliffs between Seaton Hole and Seaton. The Keuper Marl of the latter location, consisting of reddish brown mudstones, has not been investigated.

The thickness of the Keuper Marl is estimated at 487 m; this is based upon three assumptions: (1) the upper part of the Keuper Marl (up to the base of the Rhaetic black shales) at Lyme Regis recorded by Jukes-Browne (1902) from a deep borehole has the same thickness in the Sidmouth–Charton Bay region; (2) the base of Jukes Browne's 'Clays, with beds of gypsum' occurs at the same stratigraphical level as the base of the reddish brown mudstone containing massive gypsum nodules which I have recorded from the cliffs opposite Branscombe Ebb; and (3) no appreciable movement occurred on an inferred fault at Weston Mouth: vertical movement is thought to be in the order of some tens of metres, but as there is no way of estimating the throw, it may be much greater. From the Sidmouth–Branscombe Ebb coastal sections 306 m of strata have been recorded between the base of the mudstone with massive gypsum nodules of Branscombe Ebb and the top of the Keuper Upper Sandstone (Otter Sandstone of Henson 1970), exposed to the east of the mouth of the River Sid. Combining this thickness with Jukes-Browne's figure of 181 m for the sequence between this gypsiferous horizon and the top of the Tea Green Marl, a total thickness of 487 m is obtained for the Keuper Marl.

Salcombe Hill Cliff is delimited to the west by the River Sid and to the east by Salcombe Mouth. Approximately 83 m of strata belonging to Mudstone I were recorded and are shown in figures 30 and 31. The base of the Keuper Marl with its rapid gradation by intercalation down into the Keuper Upper Sandstone is exposed in the extreme western part of the cliff. Pseudomorphs after halite hopper crystals were seen in fallen blocks of the alternating mudstone/sandstone lithology.

Maynard's Cliff and Higher and Lower Dunscombe Cliffs are delimited to the west by Salcombe Mouth and to the east by Weston Mouth. The base of the recorded section, shown in figure 32, starts immediately above the prominent sandstone band, situated some 29.5 m above the Upper Wrinkled Band in Salcombe Hill Cliff, and in the bed of the stream at Salcombe Mouth.

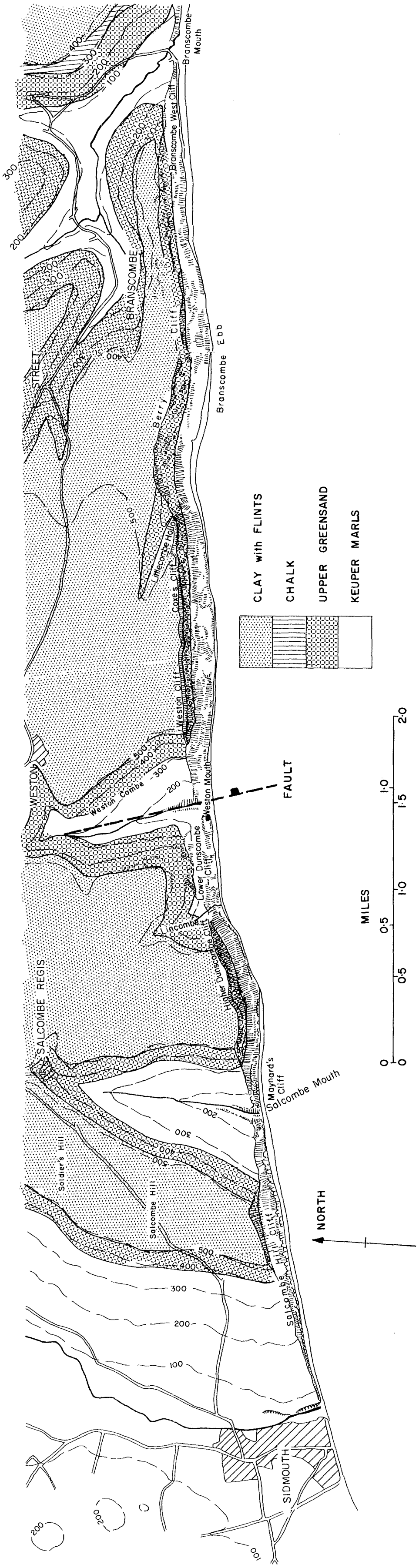


FIGURE 95. Geological map of the Sidmouth–Branscombe region, south Devon, showing localities; based on New Series Geological Survey one inch map, no. 326.

Poor accessibility and obscuring downwash has not allowed the sequence above the prominent sandstone in Salcombe Hill Cliff to be correlated with the succession in Maynard's Cliff. Measurements of 92.5 m of Mudstone I sediments overlain by 28 m of the Dunscombe Cycle were recorded. There is a conspicuous and prominent greenish grey band, 0.66 m thick, situated 5.1 m below the top of the section in figure 32. Some 5.5 m above this band there is a thick zone (1.83 m) of finely laminated grey and reddish brown mudstones and fine sands, that has closer affinities to the sediments of the carbonate group than to the mudstone group.

The sediments of the Dunscombe Cycle were recorded from sections in the upper part of Higher Dunscombe Cliff on either side of the huge slip at the foot of the western part of this cliff. These are shown in figures 33–35. Of special interest is the junction of the Sandstone Group with the Lower Carbonate Group. The topmost mudstone of the latter is penetrated by a series of deep desiccation cracks and the excavations of sediment-working organisms, both of which have been infilled by the basal sandstone of the overlying Sandstone Group. The best location to inspect the sandstone beds of the Sandstone Group is at the foot of the great slips at Higher Dunscombe Cliff: here sandstone blocks are washed out by the sea and are seen to contain thin mudflake conglomerates as well as a wide variety of sedimentary structures (e.g. cross-bedding; ?rainpits; variety of burrows).

The junction of the Upper Carbonate Group with the overlying Mudstone II is not exposed.

Weston and Coxe's Cliffs. Owing to the poor exposure in Lower Dunscombe Cliff the relation between the Dunscombe Cycle and the Weston Cycle is not clear. Combined field relations and stratigraphical, palynofloral and mineralogical data suggest that the Weston Cycle is not the eastward continuation of the Dunscombe Cycle, but two separate cycles separated by an unknown thickness of Mudstone II as originally interpreted by Jeans (in discussion of Wills 1970): Warrington (1971) claims that the sandstone unit in Dunscombe Cliff (= Sandstone Group of Dunscombe Cycle) is the westward continuation of the sandstone unit in Weston Cliff (= Sandstone Group of Weston Cycle). Further details are given in appendix 4.

Behind the beach houses at the foot of the west part of Weston Cliff, 17 m of strata have been recorded belonging to the upper part of the Mudstone II, which in turn are overlain by the basal few metres of the Lower Carbonate Group of the Western Cycle: further to the east a complete sequence through the sediments of the Weston Cycle was recorded. This is shown in figures 36–39. The junction of the Upper Carbonate Group of the Weston Cycle with the overlying Mudstone III was recorded in a slipped mass in the east part of Weston Cliff; a section in Mudstone III was recorded from Coxe's Cliff, the base of this section is 11 m above the top of the Upper Carbonate Group of the Weston Cycle: figure 40 shows these two sections.

There are three conspicuous greenish grey bands in the Coxe's Cliff section and these can be traced along the east part of Weston Cliff. Owing to difficult accessibility it was not possible to examine the upper part of the reddish brown mudstone sequence exposed in Coxe's Cliff.

Berry and Branscombe West Cliffs expose sections in Mudstone III.

Berry Cliff is extensively overgrown and slipped, and only a few small exposures can be inspected. Of particular importance is the occurrence of a horizon, 6–7.5 m thick, of large gypsum nodules and massive gypsiferous reddish brown mudstone: no doubt the very reduced lateral equivalent of Jukes-Browne's (1904) 'Clays, with beds of gypsum'. This was seen *in situ* in a gully in the cliff opposite Branscombe Ebb. The top of this horizon can also be seen in the lower part of the far western portion of Branscombe West Cliff. Large masses of this gypsiferous band litter the foreshore of Branscombe Ebb.

Branscombe West Cliff exposes good sections in the reddish brown mudstone above the gypsum band; these are shown in figure 41. Parts of the mudstone sequence are veined by numerous thin sheets of a flexible, light grey to white material; X-ray analysis of one sample revealed a mixture of palygorskite, celestite and calcite.

The gap between the top of the section in figure 40 and the base of the section in figure 41 is estimated as approximately 16 m.

Haven and Bindon Cliffs provide excellent sections in the upper part of Mudstone III and the overlying Lower Carbonate Group of the Bindon Cycle; these are shown in figures 42–43. A very persistent and conspicuous grey sandstone band occurs about 21 m below the top of Mudstone III, and has been traced along the whole length of Haven Cliff; it is 215 mm thick and is sandwiched between two thin bands of greenish grey mudstone, each about 400 mm thick. The junction of the Lower Carbonate Group of the Bindon Cycle with the overlying Westbury Beds was not seen.

Appendix 4. Dunscombe and Weston Cycles: one or two horizons?

Exposure in Lower Dunscombe Cliff and in the east part of Higher Dunscombe Cliff is poor and does not allow the sediments of the Dunscombe Cycle to be traced with any certainty to the east of Lincombe. In the upper part of the cliff adjacent to the stream descending from Lincombe to the beach, a good section through this cycle is exposed: from here, looking eastwards, it is possible to trace an easterly dipping feature that descends the slipped and highly vegetated face of Lower Dunscombe Cliff towards Weston Mouth. This feature is considered to represent the *in situ* position of the Sandstone Group of the Dunscombe Cycle. From its apparent dip, somewhat higher than the general regional dip of the Keuper, it would be expected to outcrop in the banks or bed of the stream at Weston Mouth. The strata in the vicinity of this stream are considerably disturbed, and it has not been possible to correlate these sections with the Sandstone and the Upper Carbonate groups at Lincombe. It is therefore suggested that a normal fault, downthrowing to the east, of pre-Cretaceous age runs along the floor of Weston Coombe (figure 95).

In contrast, Dr G. Warrington (personal communication) considers that the easterly dipping feature in Lower Dunscombe Cliff represents slipped material of the Sandstone Group of the Dunscombe Cycle. He considers that the regional dip of the Dunscombe Cycle in Higher Dunscombe Cliff, when projected eastwards, would make this cycle continuous with, and therefore the lateral equivalent of the Weston Cycle in Weston Cliff.

My opinion, that the Dunscombe and Weston cycles are two horizons separated by an unknown thickness (in excess of 17 m) of Mudstone II is based also upon detailed comparisons of the lithologies, palynofloras, and clay and carbonate mineralogy of the sediments of these two cycles, which are considered below.

There are considerable differences in the thicknesses of the various lithological groups associated with each cycle. The thickness of the sepiolite-rich zone in the lower carbonate group and the upper part of the underlying mudstone in each cycle is 10 m for the Dunscombe Cycle and 5 m for the Weston Cycle. The Lower Carbonate groups of the Dunscombe and Weston cycles are 13.7 and 8.2 m thick respectively. The Dunscombe Sandstone Group is 5 m thick, while the same group in the Weston Cycle has a thickness of 7 m.

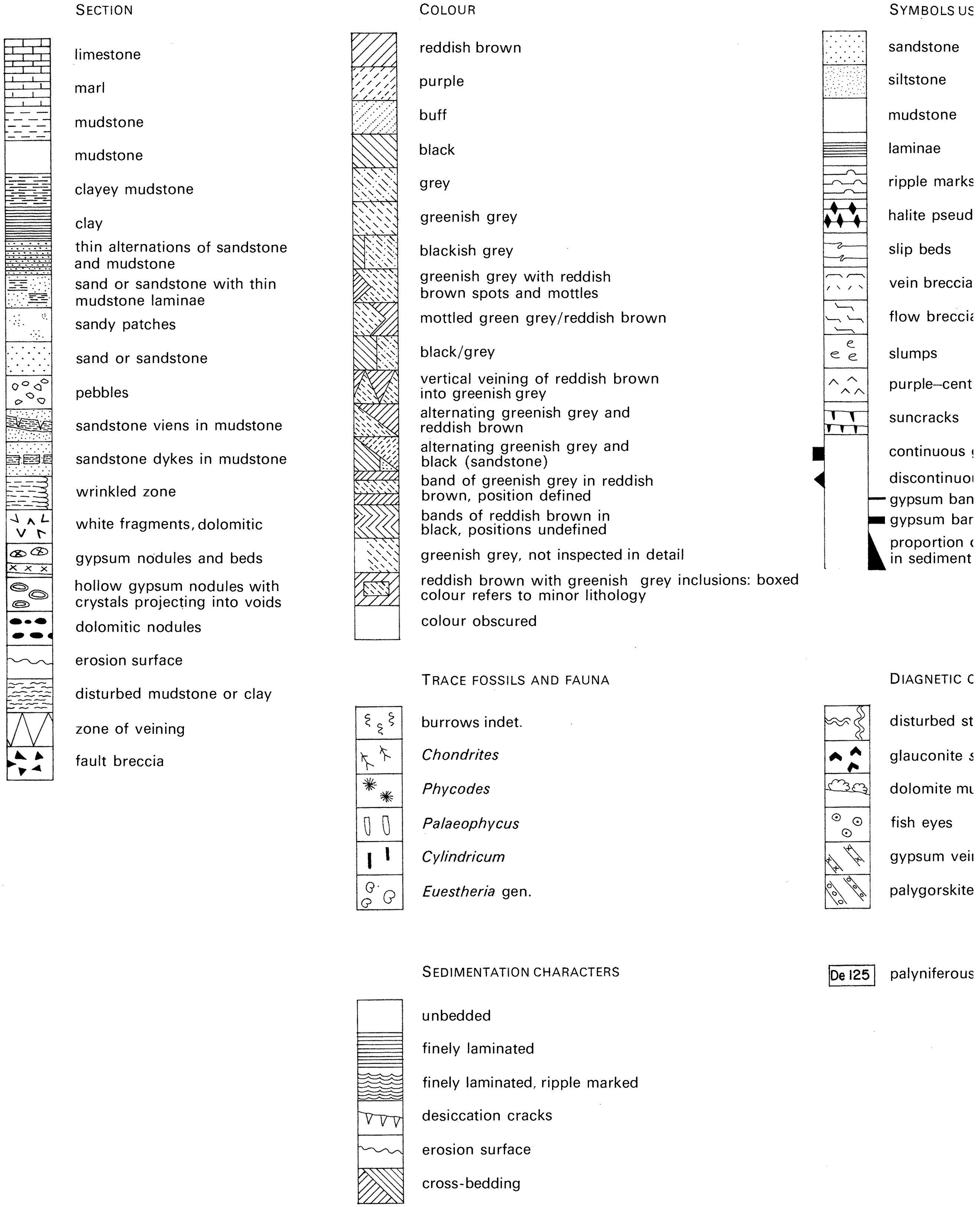
There is general similarity between the lithological sequences in both cycles, although, in detail, there are many conspicuous differences. These can be seen by comparing figures 33–35 with figures 37–39.

Important differences occur in the dolomite–calcite ratios in the different megafacies of both cycles and the associated mudstones. The upper part of Mudstone I is dominated by dolomite, although some calcite-dominated assemblages occur; Mudstone II is completely dominated by dolomite. The Dunscombe Upper Carbonate Group is co-dominated by dolomite and calcite, whereas the same group in the Weston Cycle is characterized by dolomite.

The distribution of palynomorphs within the Dunscombe and Weston cycles shows marked differences. *Botryococcus* is restricted to the Dunscombe Cycle and the Lower Carbonate Group of the Weston Cycle. *Camerosporites secatus* is much more abundant in the Upper Carbonate Group of the Weston Cycle than in the equivalent group in the Dunscombe Cycle. *Cyclogranisporites* spp. *Patinasporites densus* and *Porcellispora longdonensis* are restricted to the Weston, Cycle; *Aratrisporites virgatus*, *Protodiploxypinus gracilis* and *Triadispora plicata* are confined to the Dunscombe Cycle and below.

Assuming that the Weston Cycle is younger than the Dunscombe Cycle, then the palynofloral succession is consistent with that recorded from the more continuously palyniferous Keuper succession recorded by Scheuring (1970) from the Boelchentunnel, Basel.

FIGURE 96. Key to lithological sections. The key used by Mr C. E. Raisbeck for Owthorpe no. 11, Rad
and Blackberry Hills no. 7 is shown.



. 11, Radcliffe no. 2

'MBOLS USED IN FIGURES 70–73

ndstone

tstone

ıdstone

ninae

ıple marks

lite pseudomorphs

p beds

in breccia

ıw breccia

ımps

ırple–centred green patches

ncracks

ntinuous green bed

scontinuous green bed or green mottling

'psum band, less than 5 cms thick

'psum band more than 5 cms thick

oportion of gypsum or anhydrite
sediment (0–100%)

AGNETIC CHARACTERS

sturbed strata

auconite *sensu lato*

ılomite mushrooms

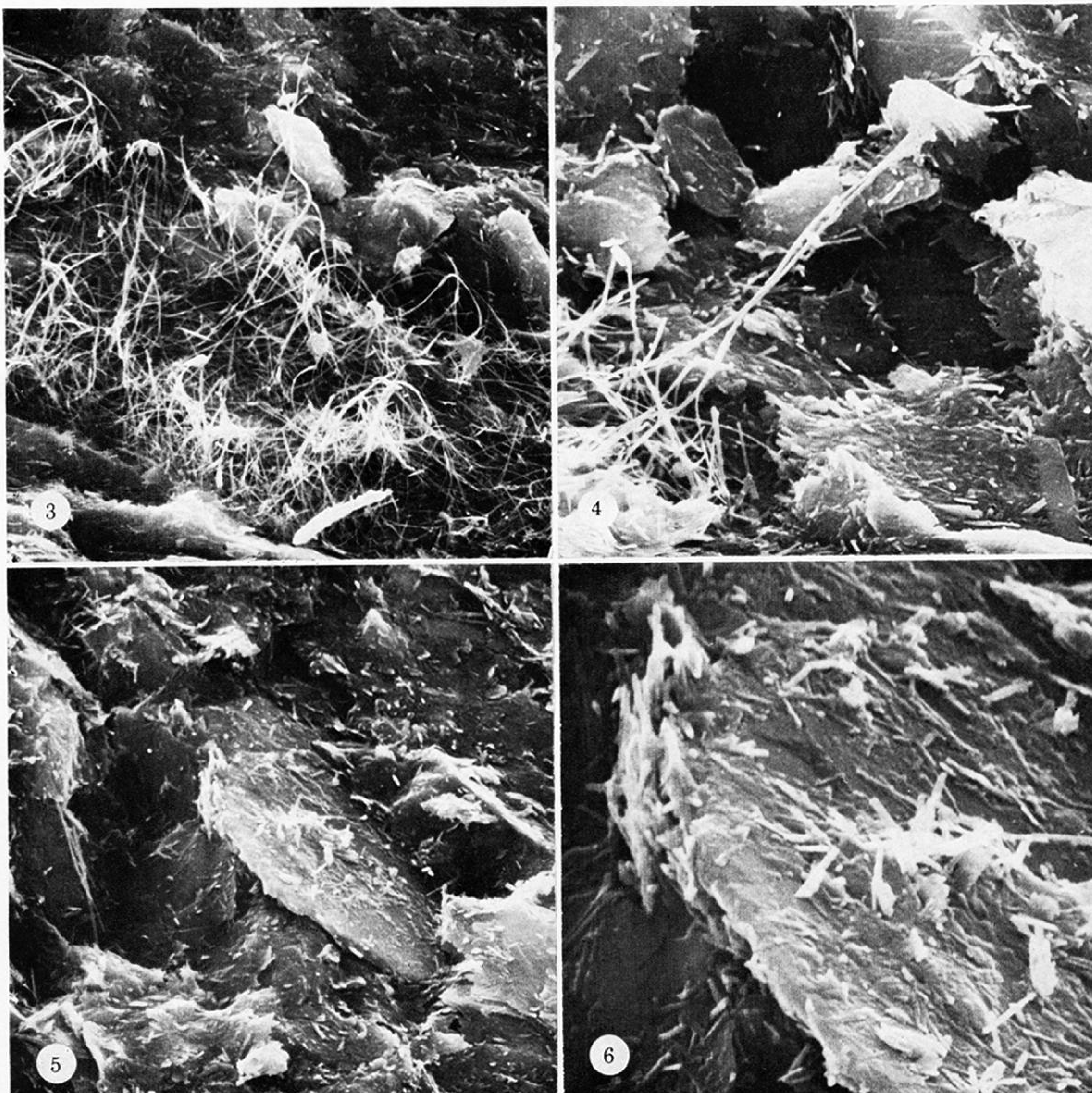
ih eyes

'psum veins

ılygorskite–calcite–celestite veins

ılyniferous sample

(*Facing p.* 636)



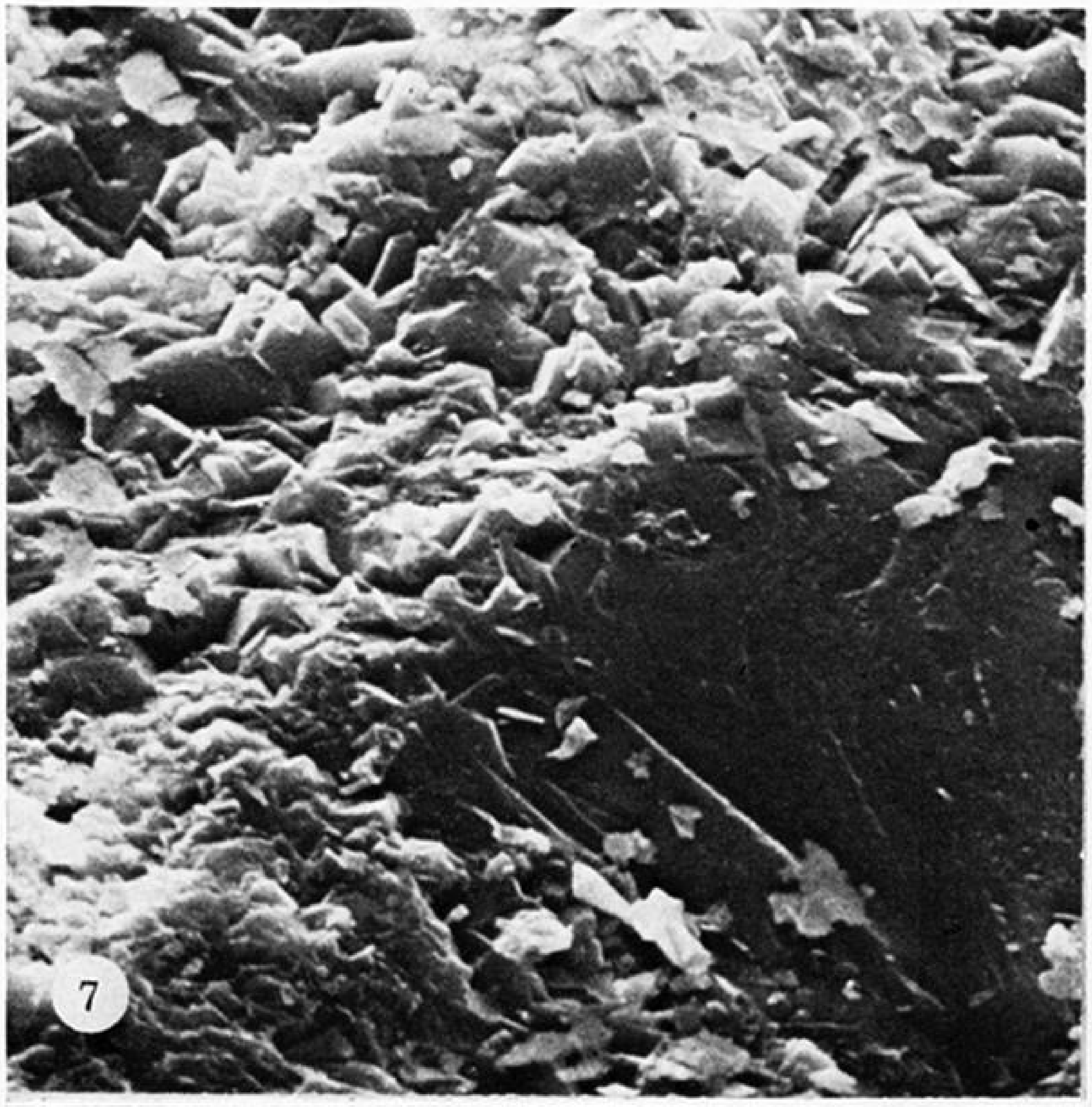
Reddish brown mudstone (De 227) from the Lower Carbonate Group of the Dunscombe Cycle; see Figure 33 for horizon and locality.

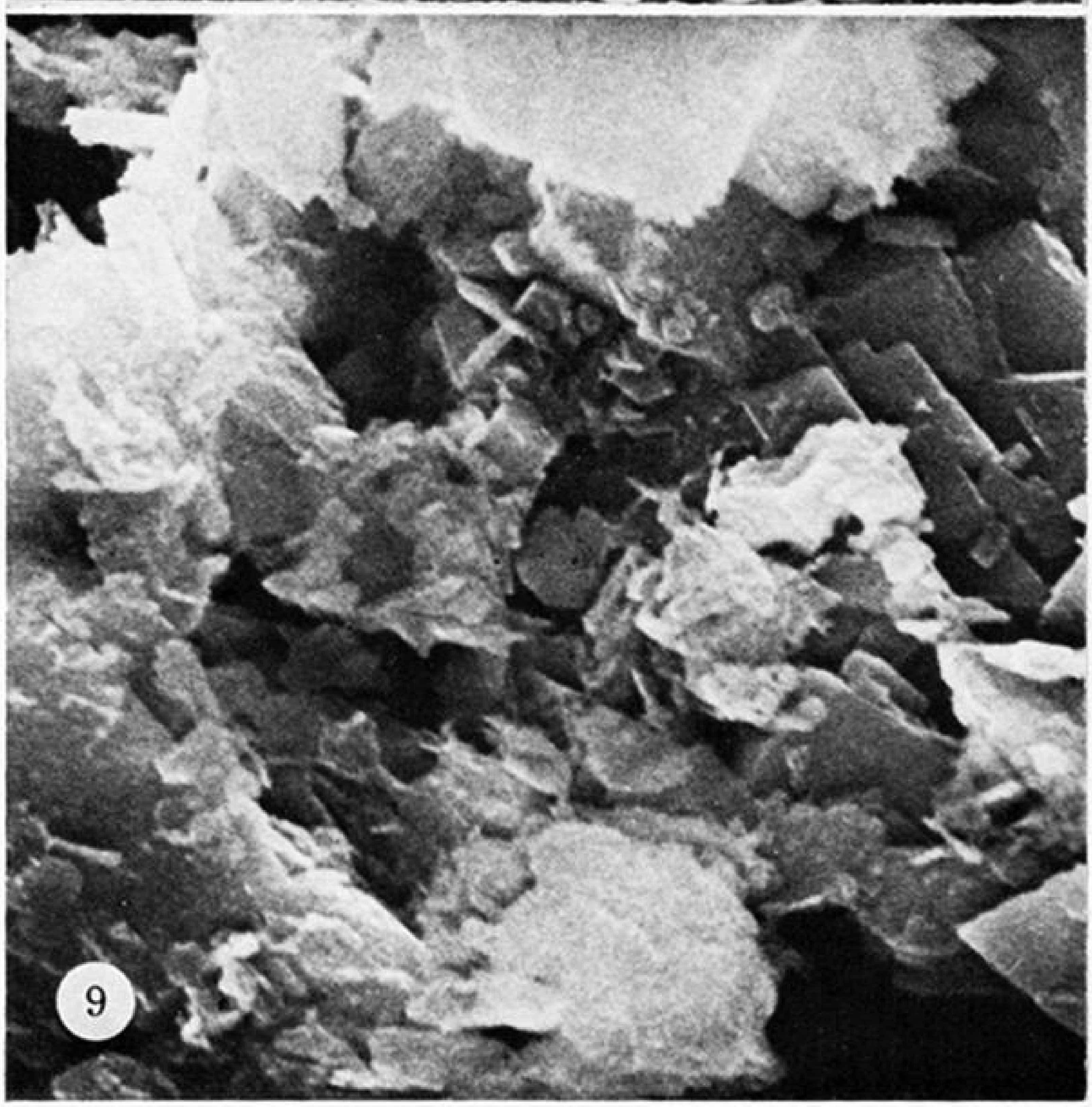
FIGURE 3. Long fibres of sepiolite forming a loose tangled mass filling a void. (Magn. ×1980.)

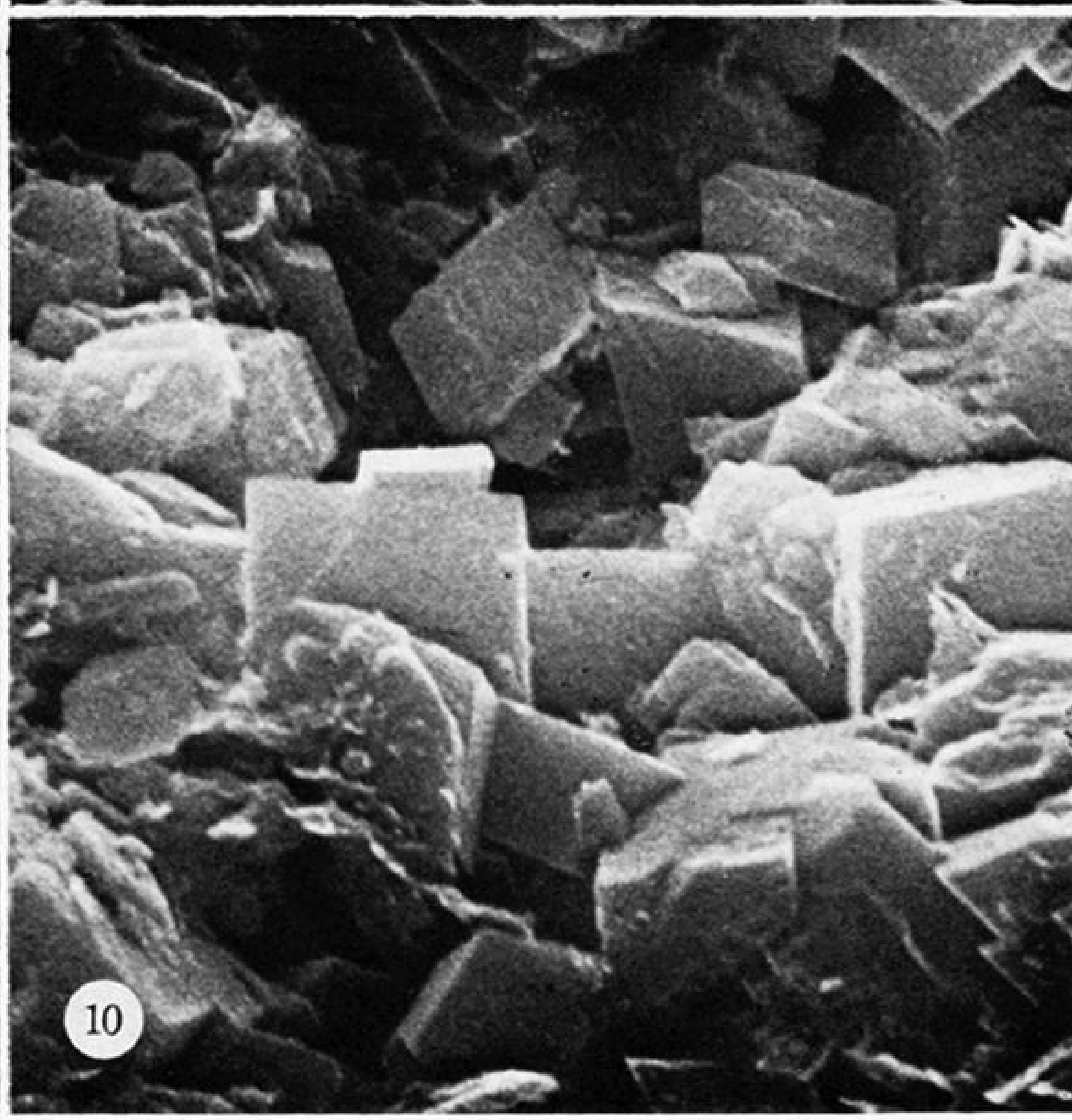
FIGURE 4. Long loose fibres and dense fibrous mats of sepiolite with large irregular plates of mica and/or chlorite and carbonate rhombs. (Magn. ×4400.)

FIGURE 5. Large plates of mica and/or chlorite encrusted with short and long fibre sepiolite. Dense mats of sepiolite occur in the lower portion of the micrograph. (Magn. ×2640.)

FIGURE 6. Detail of figure 5 showing a large plate coated with short fibre sepiolite. (Magn. ×8800.)







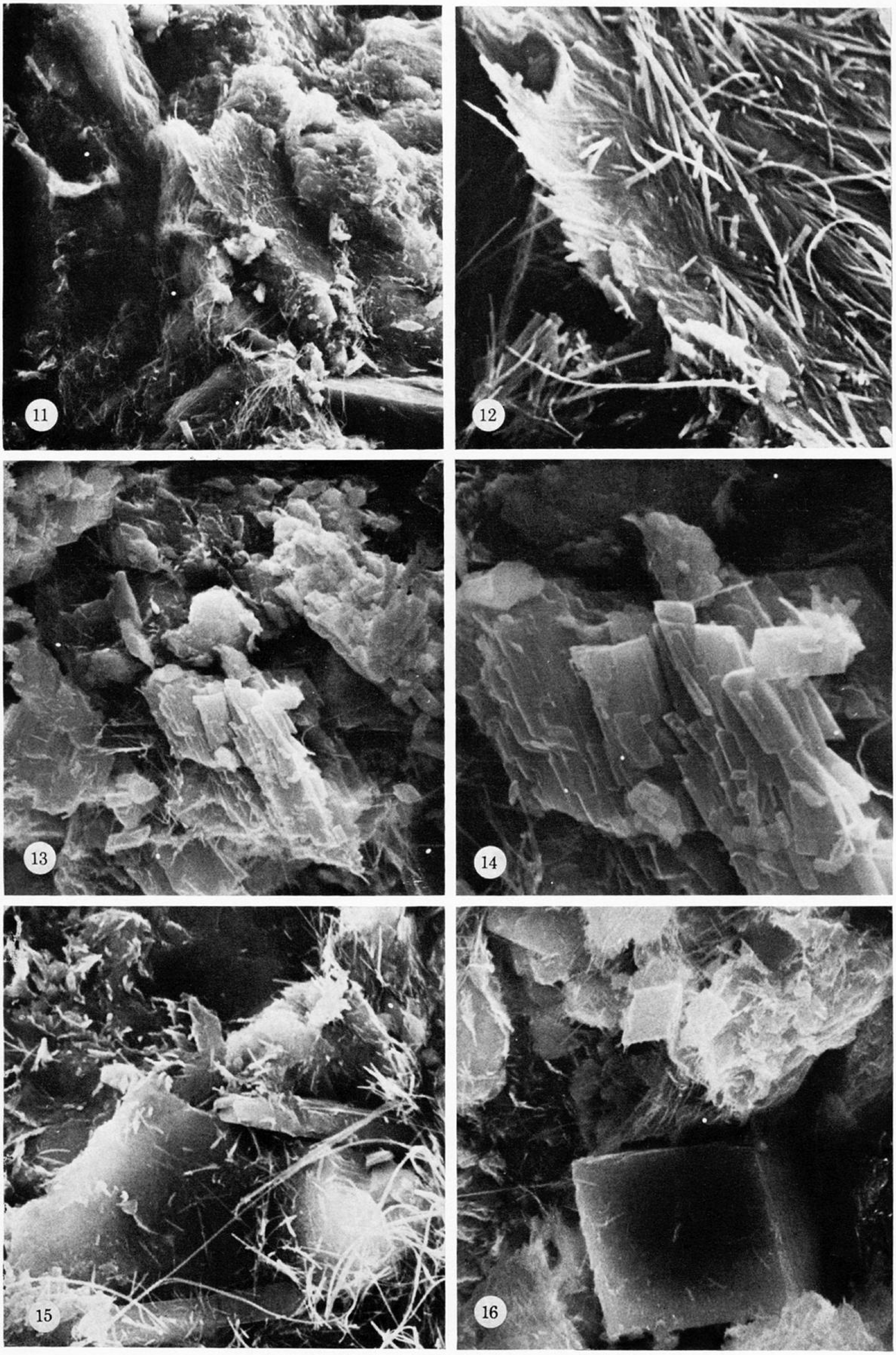
Dolomitic limestone (De 154) from the Upper Carbonate Group of the Dunscombe Cycle; see figure 34 for horizon and locality.

FIGURE 7. Contact zone of the coarsely crystalline dolomite (lower right) and the matrix of dolomite and calcite (upper left). (Magn. × 1080.)

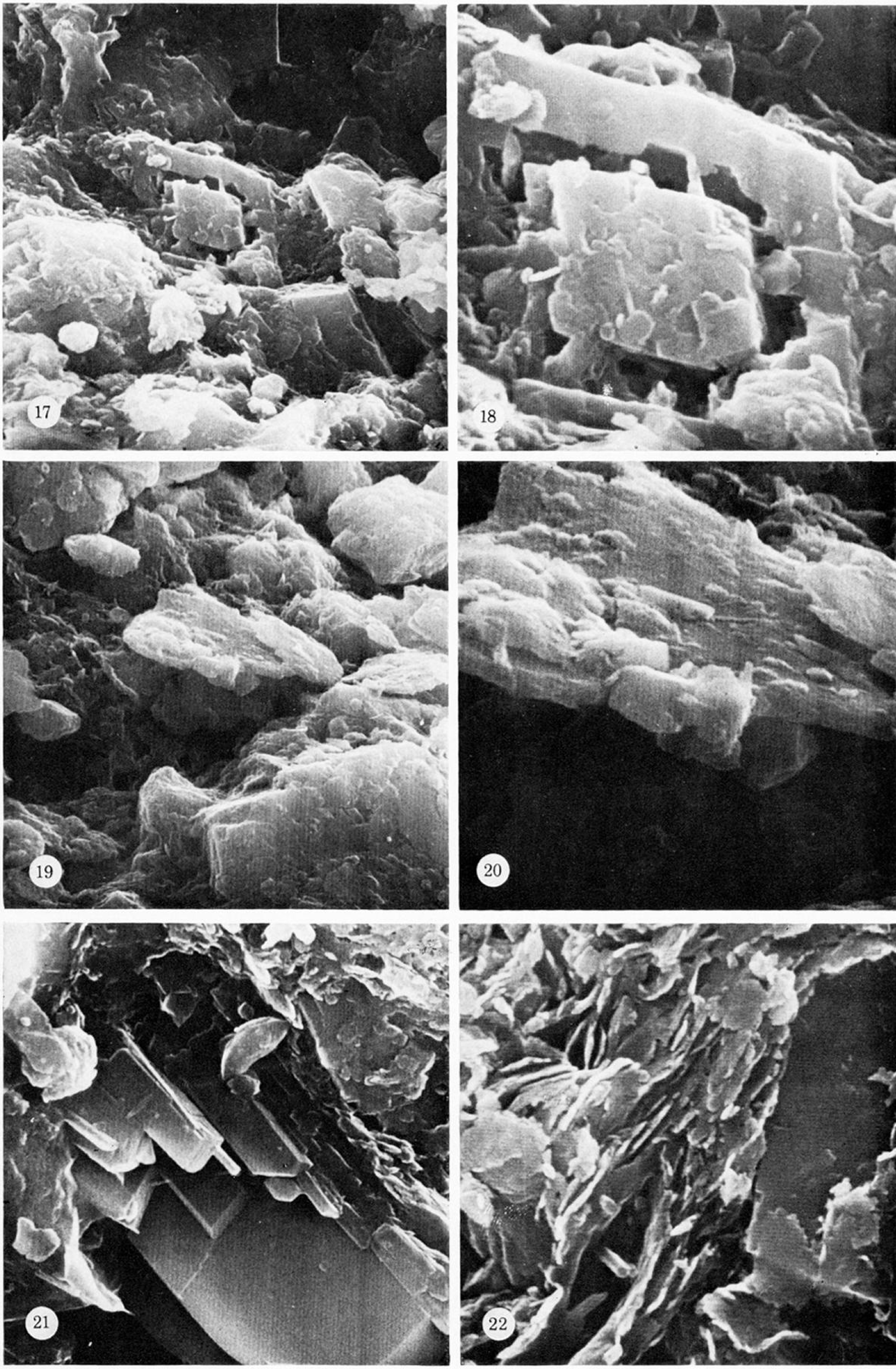
FIGURE 8. Detail of figure 7 showing carbonate rhombs enclosed in the coarsely crystalline dolomite. (Magn. × 3000.)

FIGURE 9. The matrix with rhombohedral carbonates and irregular plates of smectite–mica. (Magn. × 4300.)

FIGURE 10. Intimate association of rhombohedral carbonates and smectite–mica. (Magn. × 5760.)



FIGURES 11–16. For description see opposite.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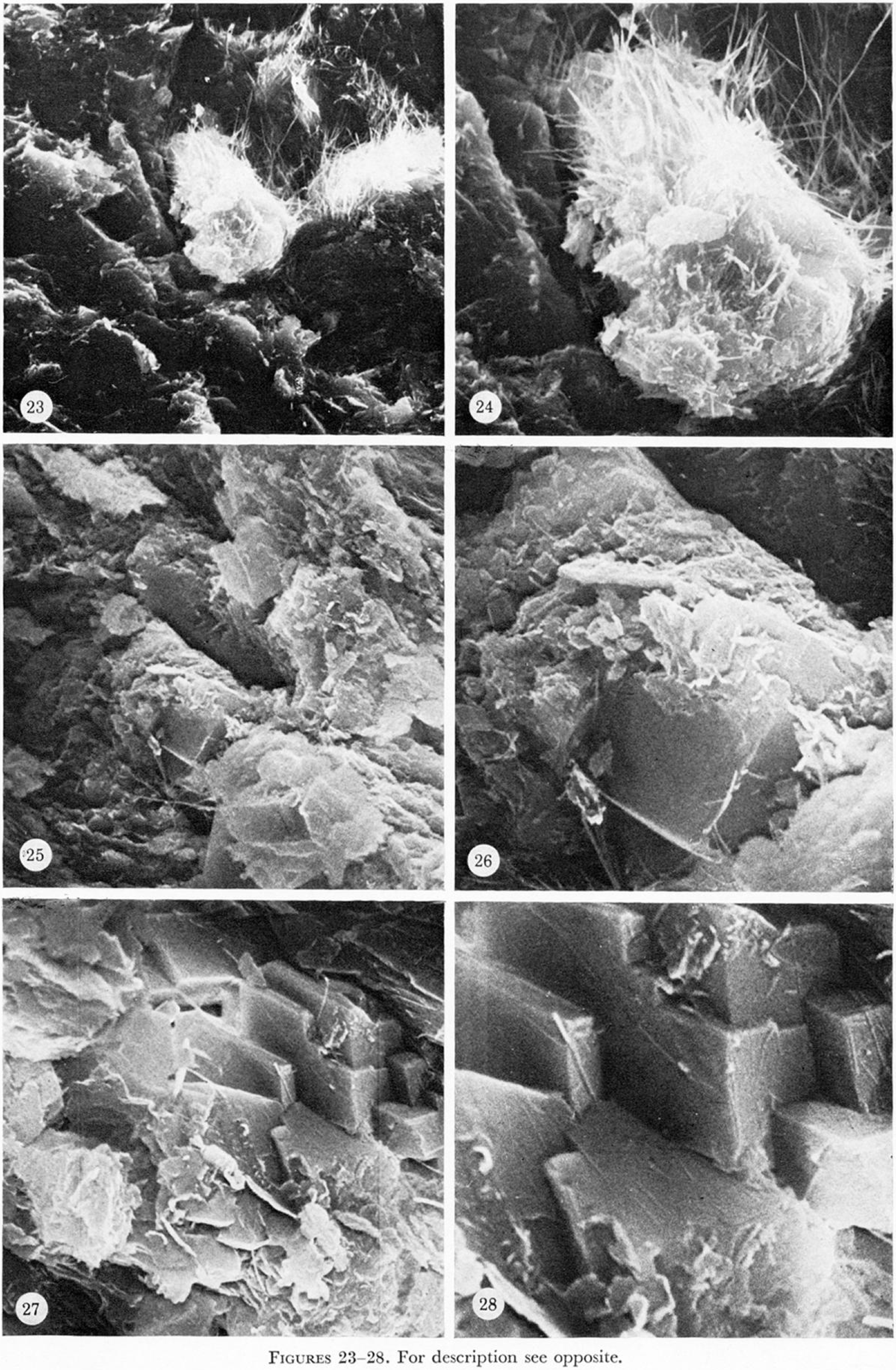

Figures 23–28. For description see opposite.

FIGURE 96. Key to lithological sections. The key used by Mr C. E. Raisbeck for Owthorpe no. 11, Radcliffe no. 2 and Blackberry Hills no. 7 is shown.