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Fossil contourites: type example from an Oligocene palaeoslope system, Cyprus

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Abstract: As part of a wider programme on the recognition and decoding of contourite sediments, we propose the adoption of part of the Lefkara Formation on Cyprus as the first in a series of type examples of fossil contourites in ancient series exposed on land. A clear case can be made for interpreting these mainly Oligocene age sediments as carbonate-rich contourites. They combine faint structures due to current action with pervasive bioturbation, typically show cyclic grain size alternation, and have compositional differences from the more easily identifiable calciturbidites. One particularly diagnostic contourite facies is a lenticular, thin-bedded calcarenite–cacisiltite from which the finer bioclastic material and terrigenous clays have been winnowed away. This facies is a well developed condensed unit, which occurs at the same stratigraphic interval throughout Cyprus. Variations in thickness and rates of sedimentation of the contourite units, as well as the presence of widespread hiatuses and alongslope palaeocurrent trends are consistent with drift development on a lower slope apron in the closing Tethys ocean.

Much as geologists would like there to be a simple way to recognize contourites in the field, this is not the case. The processes of contourite accumulation are complex and the resultant features are a subtle combination of different depositional influences. Whereas this is also true of many deep-water facies, turbidites are more commonly easily recognized. It is partly the frustration of being unable to easily identify contourites, coupled with early errors in identification of contourites on land, that has led to 'great controversy over the recognition and interpretation of fossil contourites exposed in ancient series on land' (Stow *et al.* 1998).

In this recent critical review of fossil contourites (Stow *et al.* 1998), only very few ancient examples are accepted as being closely comparable to modern contourites, for which our knowledge is much more extensive. One of those referred to is part of the Palaeogene Lefkara Formation on Cyprus, first outlined by Kahler & Stow (1998). A similar conclusion was reached by Pickering *et al.* (1989), who listed only one example as acceptable – the Cretaceous Talme Yafe Formation in Israel (Bein & Weiler 1976).

The aim of this paper is to document clearly the case for interpreting the mainly Oligocene age carbonate sediments of parts of southern Cyprus as contourites, dominantly calcareous and some siliceous biogenic contourites. We therefore propose that this can be used as a type example of fossil contourites exposed on land.

In presenting the case, we follow the three stage approach to identification as first proposed by Lovell & Stow (1981) and refined by Stow *et al.* (1998). Simply stated, the following criteria must be met:

(1) *Small-scale (outcrop or core):* do the sediments in question have the full range of facies characteristics typical of known modern contourites?
(2) *Medium-scale (formation, region):* do regional trends, sediment distribution and geometry, presence of hiatuses or condensed sequences, and other features, support a bottom current influence?
(3) *Large-scale (system or continent):* is the palaeoceanographic setting as deduced from independent evidence compatible with bottom current activity?

Geological setting

Between Maastrichtian and early Miocene, deep sea sediments of the Lefkara Formation were deposited in the area that is now Cyprus over newly formed (late Cretaceous) ocean crust (Moores & Vine 1971; Robertson 1990). After an initial period dominated by slow pelagic sedimentation, there was a gradual increase in the influx of turbidites derived from the north during the early and middle Eocene. This was followed by a return to slow pelagic deposition and then, during the latest Eocene to early Miocene, by the influence of bottom currents (Kahler 1994; Kahler & Stow 1998). The depositional setting evolved through this period from a relatively deep oceanic basin to a carbonate slope apron system.

Sedimentation was strongly influenced by tectonic activity, including uplift of the Kyrenia Range in northern Cyprus and continued uplift of the Troodos ophiolite core in central Cyprus, as well as the onset of subduction to the south of the island. The palaeoceanographic setting in a closing Tethys seaway is believed to have been a further influential factor, particularly with regard to intensification of bottom current flow.

The Lefkara Formation can be divided into four lithological units (Fig. 1): the Lower Marl, the Chalk and Chert, the Chalk, and the Upper Marl units. Contourites are recognised in the upper parts of the Chalk Unit and throughout the Upper Marls.

Evidence at outcrop (small-scale)

Of the six localities studied in detail by Kahler (1994), the Lymbia Motorway section presented the best evidence for fossil contourites, as described by Kahler & Stow (1998) (Fig. 2). However, the state of this exposure has deteriorated with time. Further detailed investigation has revealed an even better type locality in the Upper Marls (or Upper Marls equivalent) on the western margin of Pissouri Basin near Petra Tou Romiou, in the section referred to as lenticular/fissile micrites by Stow *et al.* (1995). These two sections are documented here as good candidates for type contourite localities (Figs 3 and 4).

Sediment facies and structures

The first appearence of contourites in the Lymbia section is in the upper part of the Chalk Unit. This mainly comprises massive chalks of presumed pelagic origin, but with parts showing faint laminae together with micro-burrowing. Laminae are often isolated and indistinct and no clear structural sequences exist. Higher up, some of the bedded chalks are calcarenitic in grade due to a greater proportion of foraminifers. The overlying Upper

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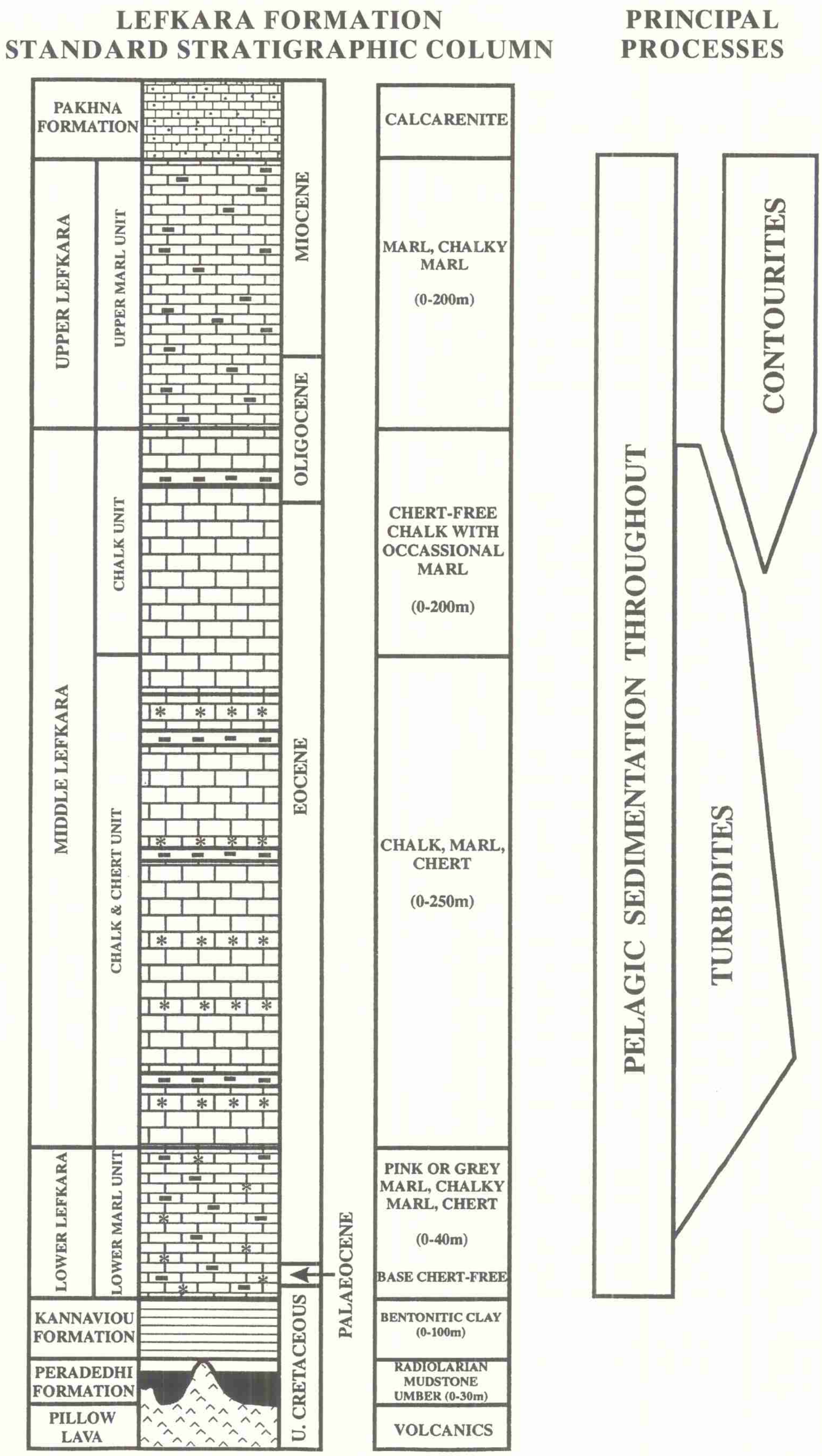

Fig. 1. Lithostratigraphic column for the Lefkara Formation in Cyprus, showing age, lithological units, thickness variation and principal depositional processes.

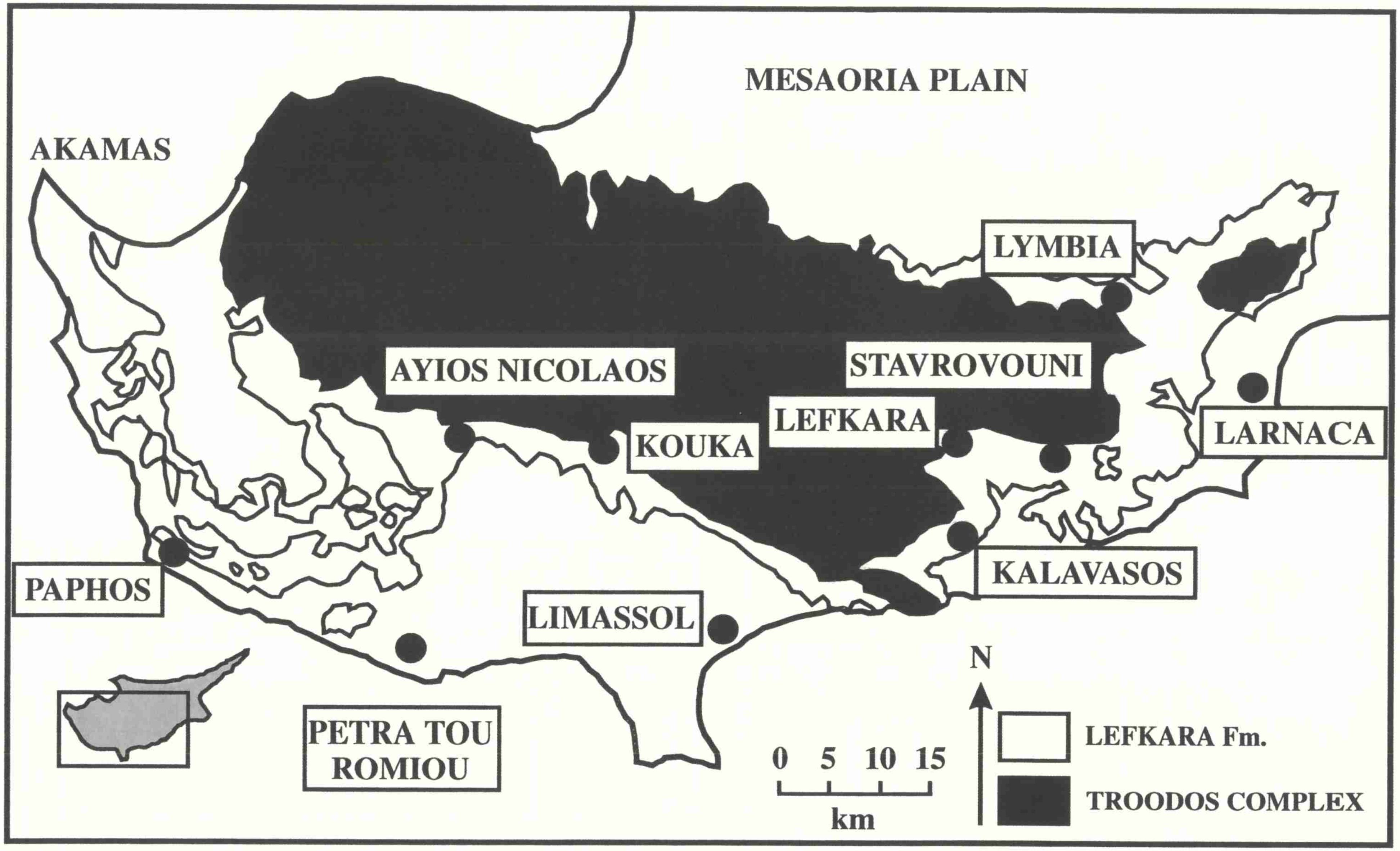

Fig. 2. Simplified geological map of southern Cyprus showing the location of sections studied in detail, as well as principal towns along the south coast.

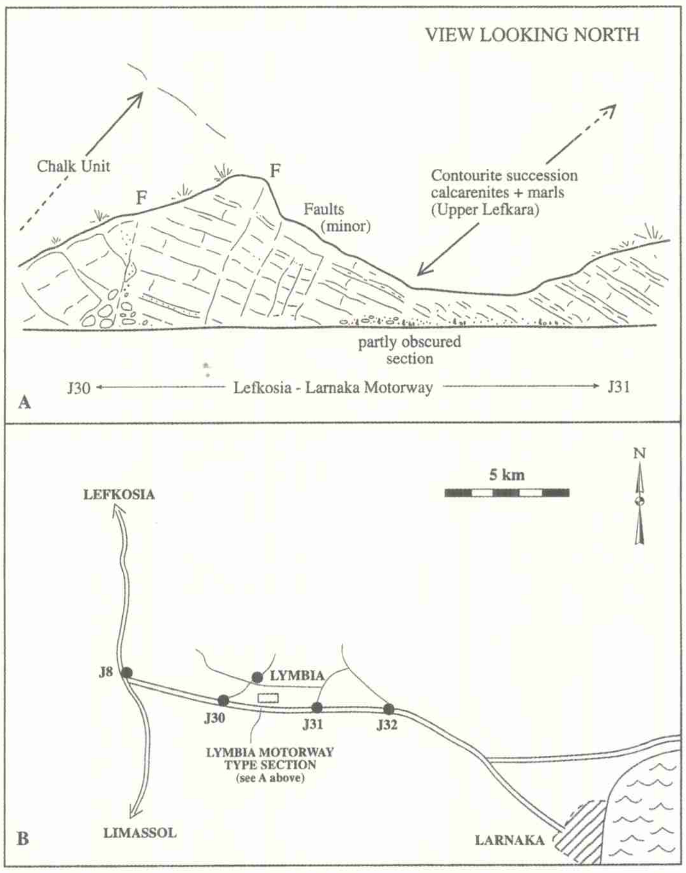

Fig. 3. Locality map and outcrop sketch for Lymbia fossil contourite type section.

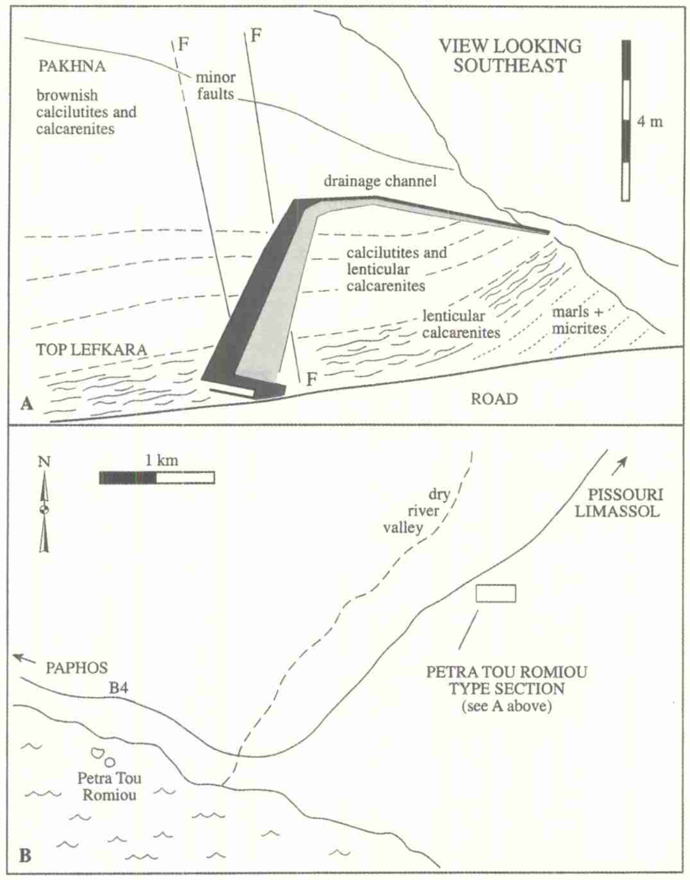

Fig. 4. Locality map and outcrop sketch for Petra Tou Romiou fossil contourite type section.

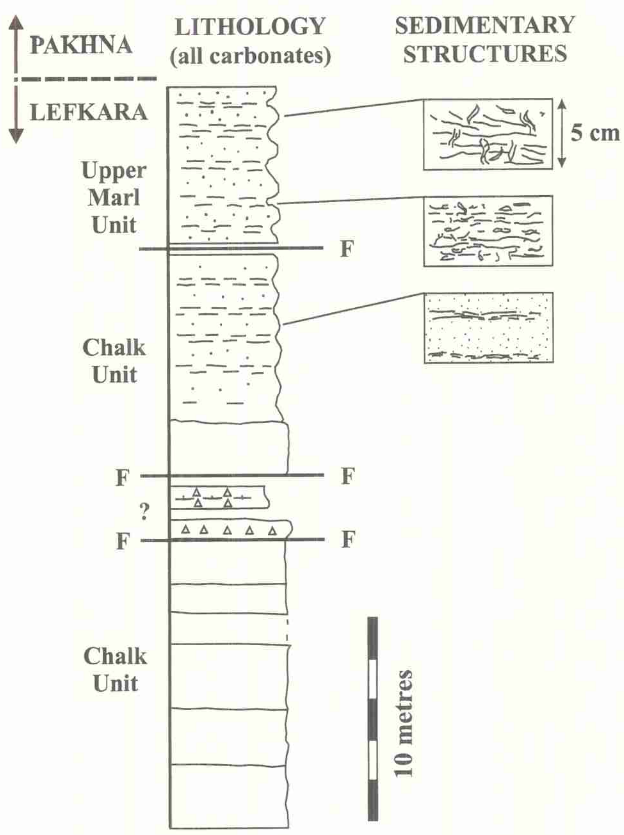

Fig. 5. Logged section of upper Lefkara Formation at Lymbia. The upper part of the Chalk Unit and the Upper Marls Unit show regular calcarenite–calcilutite grain size cyclicity, together with faint indications of lamination and intense bioturbation. Lenticular, thin-bedded calcarenites become more common upwards. This section is now badly weathered.

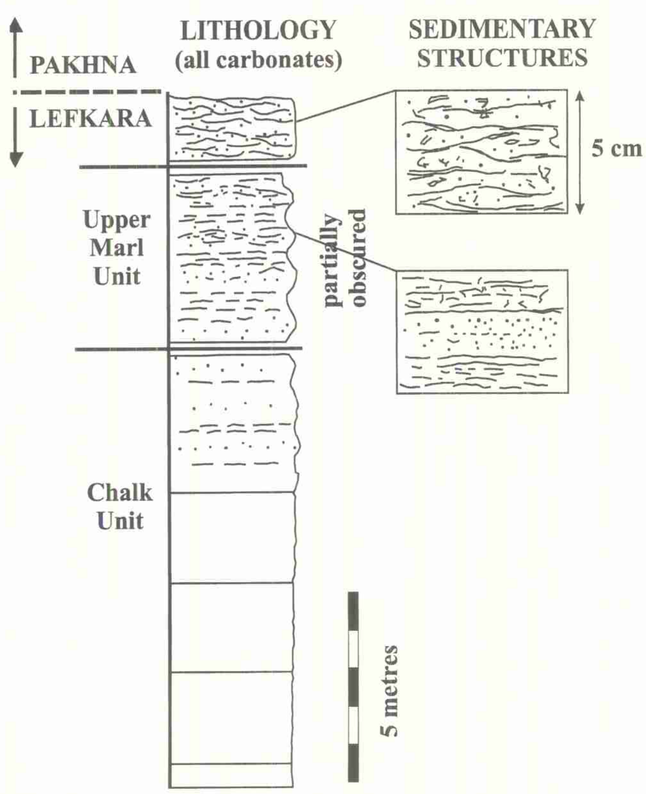

Fig. 6. Logged section of upper Lefkara Formation at Petra Tou Romiou. The upper part of the Chalk Unit and the Upper Marls Unit show regular calcarenite–calcilutite grain size cyclicity, together with faint indications of lamination and intense bioturbation. Lenticular, thin-bedded calcarenites are more common than in the Lymbia section, particularly towrds the top of the Upper Marls unit.

Marl equivalent comprises interbedded marly units (a few dm thick) and chalk or calcarenite units, which contain parallel laminae, cross-laminae and strong bioturbation throughout. No grading or turbidite-like sequences are present, but the cyclic alternation of coarser-grained calcarenites and finer marly calcilutites could be interpreted in terms of the standard contourite model (Stow *et al.* 1986). These features are illustrated in Figures 5 and 7.

The contourite influence at Petra Tou Romiou also begins towards the top of the Chalk Unit with faint lamination and burrowing that passes upwards into a more lenticular-bedded calcarenitic chalk. This is overlain by a poorly exposed mud-rich unit of the Upper Marls followed by a relatively thin interval (< 5 m) of lenticular to fissile bedded micrites and calcarenites. These show faint parallel and cross-lamination in parts as well as bioturbation throughout. They are interpreted as calcilutitic to calcarenitic contourites formed beneath relatively strong bottom currents that winnowed away any finer grained material (Figs 6 and 7). This facies is particularly diagnostic at all the sections examined.

Microfacies

Microfacies analysis of samples from the Lymbia and Petra Tou Romiou sections reveal the sediments to be mainly packed biomicrites (40–60% bioclasts), with the bioclasts dominated by planktonic foraminifers, many of which are fragmented. Associated pelagic facies are mostly sparse biomicrites. The other areas with contouritic sediments identified by Kahler & Stow (1998) show that the contourite microfacies in fact ranges from sparse to packed biomicrites, presumably depending on the strength of the bottom currents involved. In the section at Lefkara, some of the contourites show silicification due to dissolution of radiolarians, together with micro-cross lamination and burrowing.

Fig. 7. Outcrop photographs of fossil contourites from Lymbia (**A–C**) and Petra Tou Romiou (**D–F**) type sections. (**A**) Alternating calcilutite-calcarenite layers reflect cyclic grain-size changes in contourites. Width of section 1.5 m. (**B**) Detail from A showing lenticular, thin-bedded calcisiltites and more weathered calcilutites. Width of section 25 cm. (**C**) Detail from A showing calcilutites with bioturbation and indistinct lamination. Width of section 15 cm. (**D**) Part of the upper lenticular, thin-bedded contourite unit, showing some grain-size cyclicity. Width of section 1.0 m. (**E**) Detail from **D** showing lenticular, thin-bedded, calcarenite contourites. Width of section 20 cm. (**F**) Detail from **D** showing lenticular, thin-bedded, calcarenite contourites. Width of section 15 cm.

Fig. 7(B).

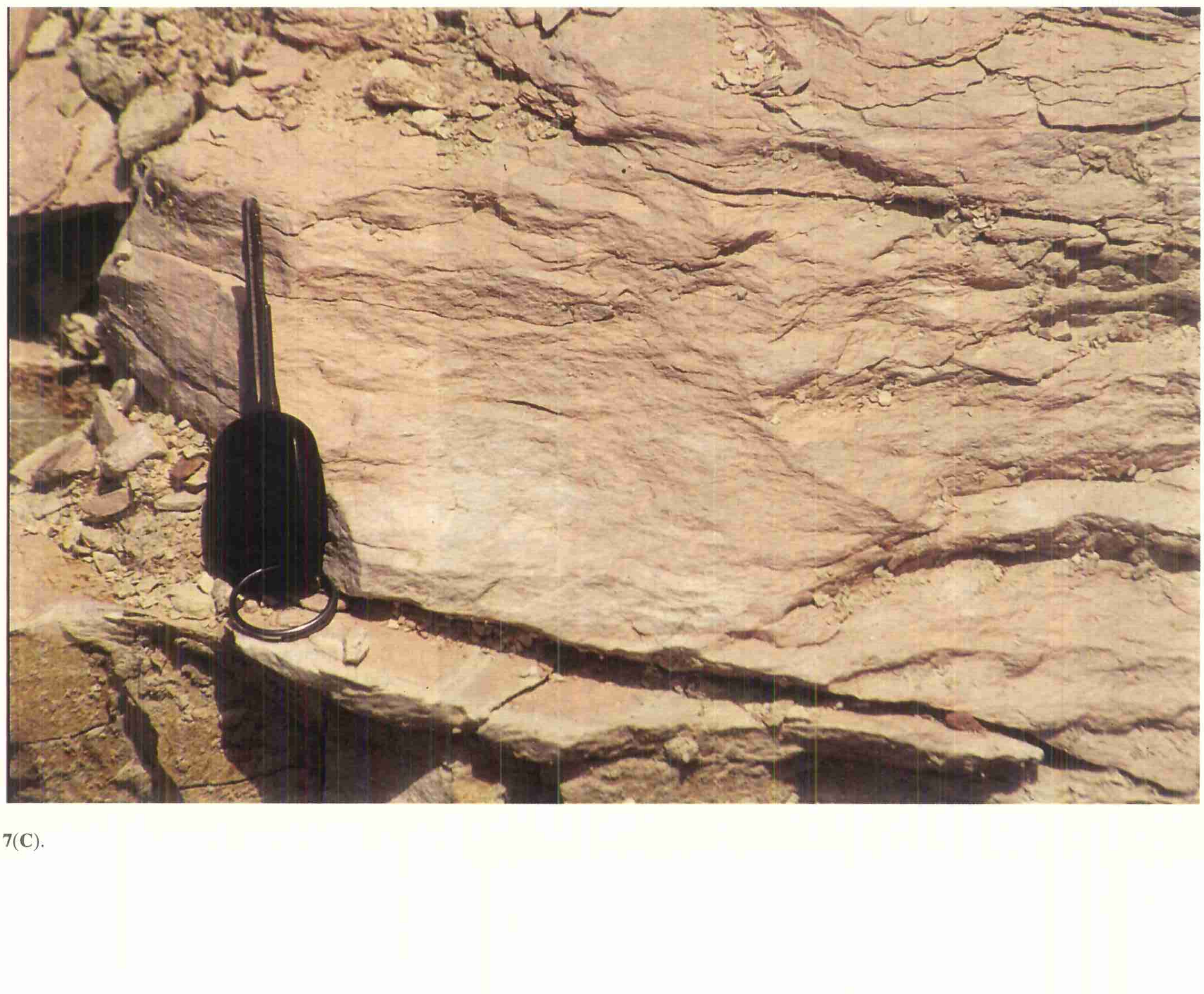

Fig. 7(C).

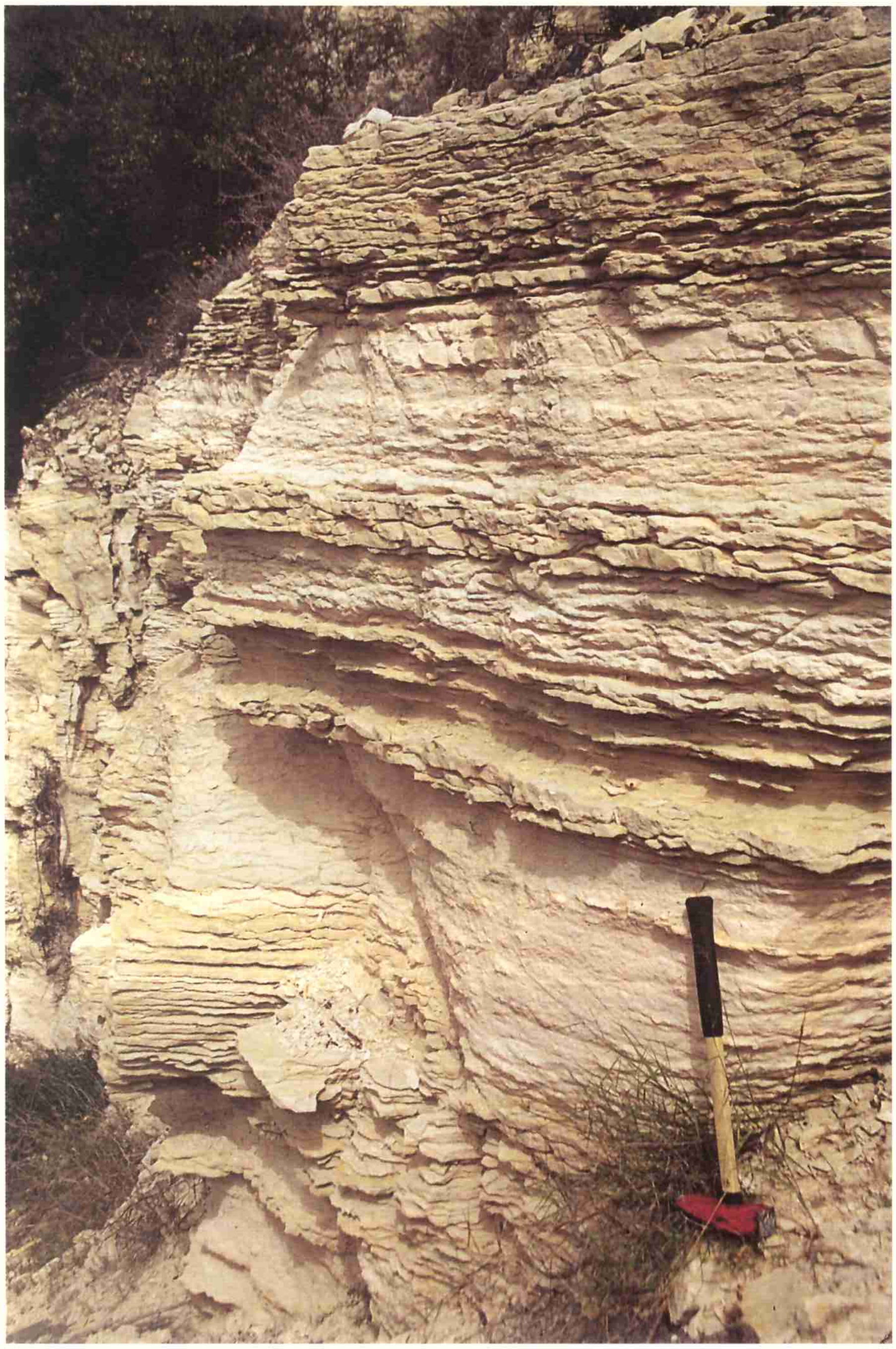

Fig. 7(D).

Textural attributes

Grain size is a less significant parameter in ancient carbonate-rich contourites, in particular, as the high degree of diagenetic alteration can mask any original textural distribution. In the case of the Lefkara contourites, compaction has reduced the sediment thickness by up to 2/3, porosity has markedly decreased, some weaker grains have fragmented and pressure dissolution has led to the partial disappearence of calcareous bioclasts. In contrast, neomorphic processes, mainly inside bioclast voids but partly also within the matrix, have increased grain sizes. SEM studies have shown the matrix to be dominantly 2–3 μm sized rhombohedra, with strongly altered coccolith relics occasionally still visible. Larger bioclasts are planktonic foraminifers and radiolarians 50–500 μm in size.

Certain gross characteristics do probably reflect the original grain size. The beds of lenticular and partly laminated calcarenites are most likely the result of bottom current winnowing, cleaning and sorting during deposition, as well as subsequent enhancement of coarse carbonate spar by diagenetic processes. The cylcic alternation of these beds or units with finer grained marly intervals may also reflect an original grain size oscillation due to fluctuation in current strength.

Composition

The sand fraction of the chalks and marls throughout the Lefkara Formation comprises planktonic foraminifers and radiolarians, with only rare benthics and lithoclasts. In the Chalk and Chert Unit, the once high proportion of radiolarians has been removed by post-depositional remobilization associated with chert diagenesis. In the Chalk Unit, radiolarians tend to dominate over foraminifers, whereas they are almost absent in all material from the Upper Marls. It is possible that these hydrodynamically light microfossils were selectively removed by more active bottom

Fig. 7(E).

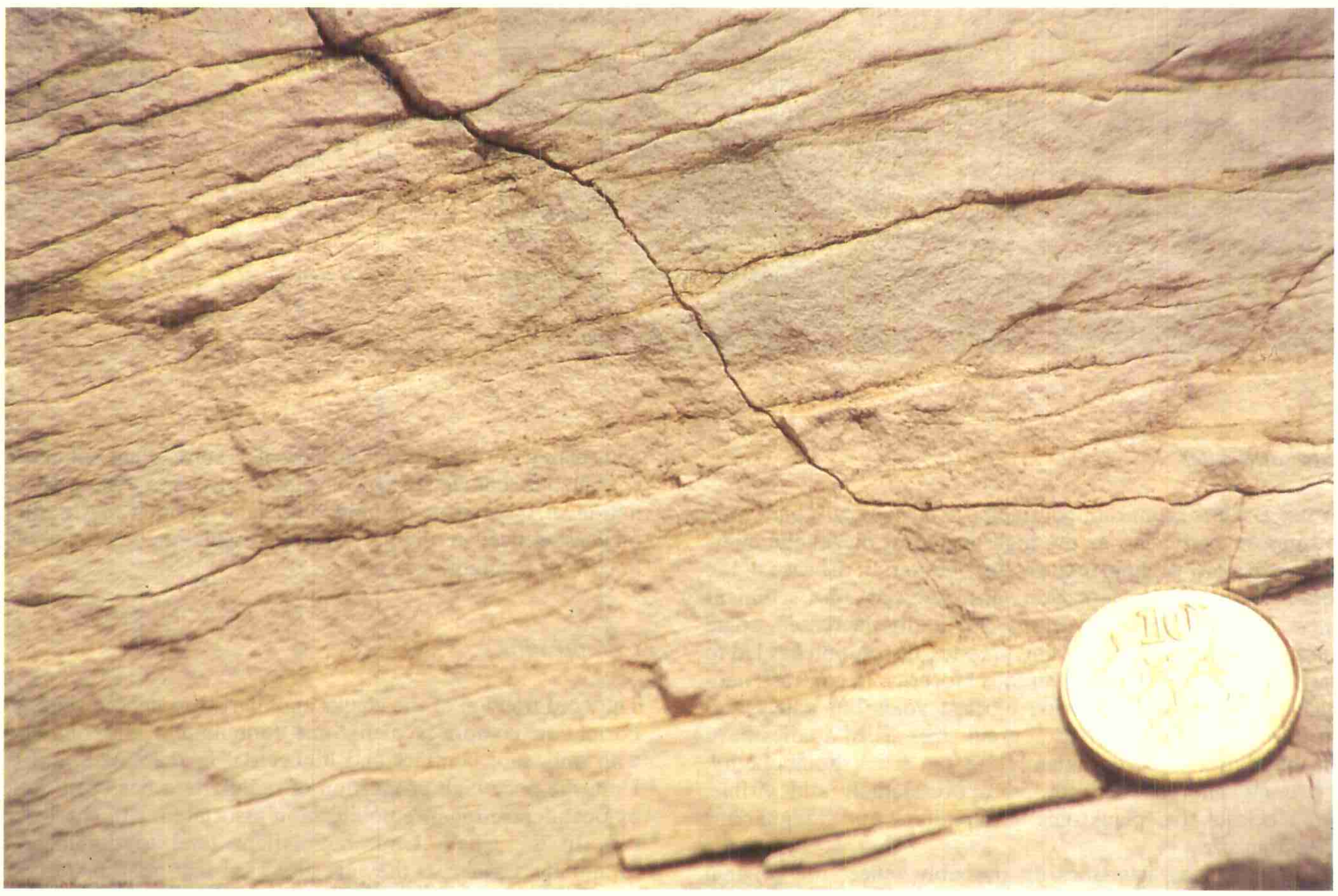

Fig. 7(F).

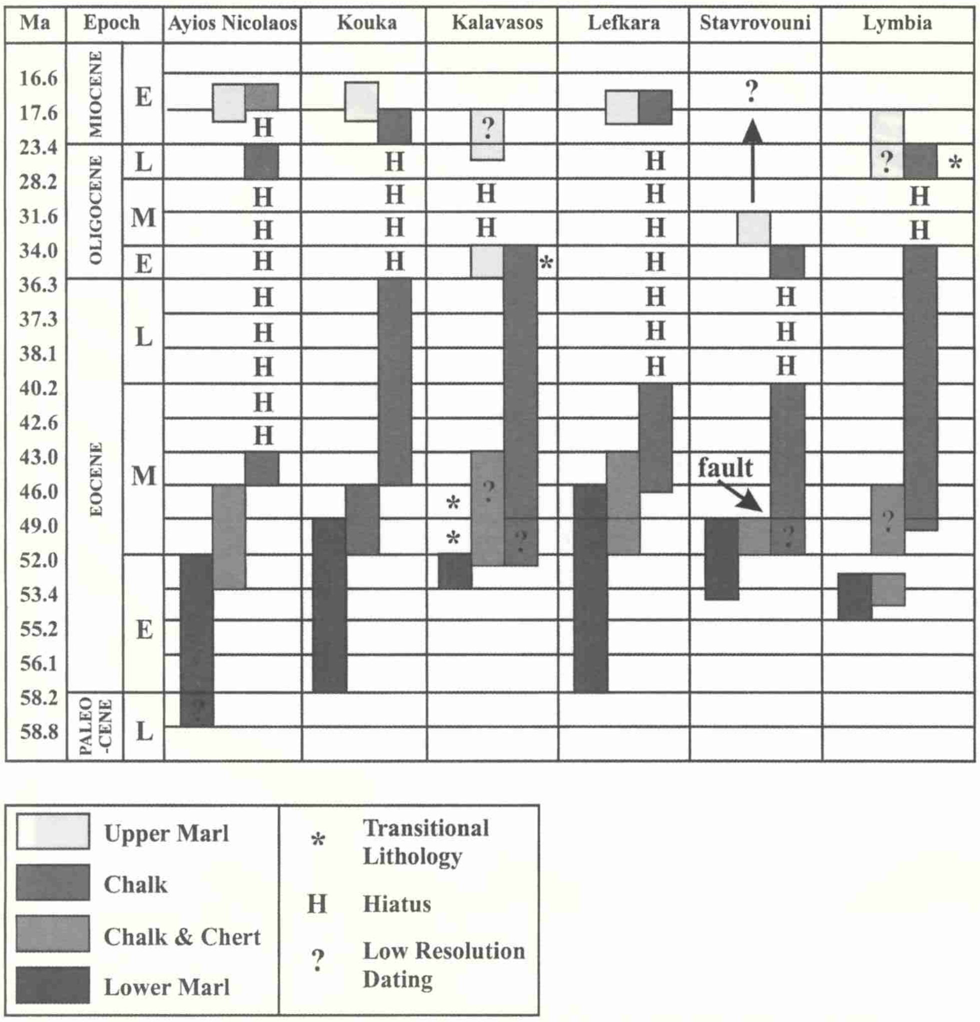

Fig. 8. Stratigraphic correlation of the four lithological units within the Lefkara Formation based on careful biostratigraphic study by Kahler (1994). Note the marked diachroneity of units and the timing and extent of hiatuses.

currents at this time, or that the bottom circulation affected water chemistry promoting their dissolution. Comparatively heavy benthic foraminifers are slightly enriched in the Upper Marls, perhaps as a winnowed residue, together with rather more transported allochems in the Lymbia section especially. There is also notable occurrence of bioclasts reworked from older strata.

In all the contourites studied, as well as in most of the rest of the Lefkara Formation, carbonate content is above 70%, with the exception of some of the diagenetic cherts. The increased clay content of the Upper Marls could be the result of three main factors: (a) an increased flux of terrigenous material in the bottom currents due to increased input from turbidity currents derived from the Kyrenia Range in the north; (b) selective removal of hydrodynamically light microfossils by moderately strong currents; and (c) preferential dissolution due to changes in water chemistry brought about by increased bottom currents. However, particularly strong currents seem to have removed most of the clays leaving only the heavier microfossils to form the calcarenitic contourites. Consistent with an increase in clay is an increase in detrital quartz content in the Upper Marls from the Lymbia section in particular.

Regional evidence (medium-scale)

Thickness variation

Due to lack of exposure and to local faulting, it is not everywhere possible to find a complete section of the Upper Marl unit. We have not yet, therefore, obtained a complete picture of thickness variation of this unit across Cyprus but note, from previous work as well as our own studies, that marked differences do occur, from 0–200 m. Assuming that at least some of this variation reflects original depositional thickness, it further supports the influence of bottom currents in shaping contourite drift sedimentation during this interval, notwithstanding the diachronous nature of the unit (Kahler & Stow 1998).

Maximum thicknesses of the Upper Marls occur on the southern flank of the Troodos Massif, for example in the Mandria–Kouka area, with lesser thickness at Kalavasos (20 m) and the thinnest development at Lymbia and Petra Tou Romiou (< about 10 m). These last are the two sites at which the bottom currents appear to have been strongest.

Sedimentation rates and hiatuses

Based on the detailed dating carried out by Kahler (1994), we can estimate the approximate rates of sedimentation for the contourite intervals of the Lefkara Formation. These vary from < 1 m Ma^{-1} to 17 m Ma^{-1} for the Chalk unit and from 1m Ma^{-1} to 13 m Ma^{-1} for the Upper Marls, all of which indicate slow to extremely slow oceanic accumulation. Clearly, the lower rates apply where the thicknesses are least and bottom current intensity was presumably stronger and hence non-deposition or erosion most likely.

Indeed, hiatuses are evident in all sections where closely spaced biostratigraphic sampling has been carried out (Fig. 8). These are most intense and widespread in the Oligocene, but also occur in the late Eocene and early Miocene, exactly the time period during which contourite accumulation occurs. They are not present during any of the rest of the Lefkara deposition.

Fig. 9. Examples of thin-bedded, lenticular calcarenite contourites from the topmost part of the Upper Marls lithostratigraphic unit within the Stavrovouni (**A**), Lefkara (**B**), and Kalvasos (**C**) sections.

Fig. 9(**B**).

Fig. 9(C).

Facies variation and paleocurrent direction

The contourite facies are clearly calcicontourites, ranging from calcilutites to calcarenites. A distinctive unit (5–15 m thick) of lenticular-bedded and laminated/bioturbated calacarenites occurs at most locations in a stratigraphically equivalent interval, immediately overlying the finer-grained, marl-dominated part of the Upper Marls unit (Fig. 9). We include this facies within the Upper Marls and suggest that it reflects a period of time when bottom currents were stronger over a broad area of deposition, leading to winnowing, non-deposition and development of a condensed sedimentary unit. Calcilutites dominate elsewhere and in other parts of the Upper Marls lithostratigraphic unit.

In general, the contourite influence has occurred subsequent to the main turbidite input. In the western sections examined, turbidites are overlain by pelagic chalks and then, near the top of the Chalk unit, bedded cherty intervals and chalk-marl cycles are interpreted as being influenced by bottom currents. In some of the eastern sections (e.g. at Lymbia and Lefkara), however, an interplay of both downslope and alongslope processes seems likely, with top-cut thin turbidites resulting from bottom current winnowing and erosion.

Whereas palaeocurrent directions for most of the turbidites are mainly NE–SW, consistent with derivation from the Kyrenia Range, Robertson (1976) noted atypical and highly variable current directions towards the top of the succession at Lefkara, some of which were aligned perpendicular to palaeoslope. This favours alongslope reworking of turbidite tops by bottom currents.

Palaeoceanographic setting (large-scale)

The Lefkara Formation as a whole was deposited in a closing small ocean basin, probably in a basin plain to distal slope-apron setting (Robertson *et al.* 1991; Kahler 1994; Kahler & Stow 1998). Palaeowater depth, based on sediment facies, microfossil assemblages and preservation, was in the range of 2000–3000 m. The nearest land lay to the north, now represented by the Kyrenia Range some 25–50 km distant, but which may have been at least twice as far away during the Oligocene. A schematic depositional setting for the late Oligocene to early Miocene is shown in Figure 10.

The nature of bottom circulation in the region during the Oligocene is not well known. However, this period witnessed both constriction of the main Tethyan surface flow from the Indian to the Atlantic Ocean and initiation of circum-Antarctic flow (Haq 1984) (Fig. 11). Whereas earlier in the Palaeogene, bottom waters were made up of warm high salinity water masses generated at low latitudes, by Oligocene time, deep cold water was also being generated at high northern and southern latitudes. For the Cyprus region, it seems most likely that continued constriction of the Tethys seaway led to an intensification of the westward directed Tethys current, which was therefore capable of influencing sedimentation at bathyal depths. Alternatively, there may have been a deep counterflow to the east. Widespread hiatuses have been noted in oceanic sediments worldwide, with maxima in the late Eocene, Oligocene and early Miocene. These are generally linked to climatic cooling, eustatic sealevel lowstand and enhanced bottom circulation (Miller *et al.* 1987).

Tectonic activity in the region, including submergence of the

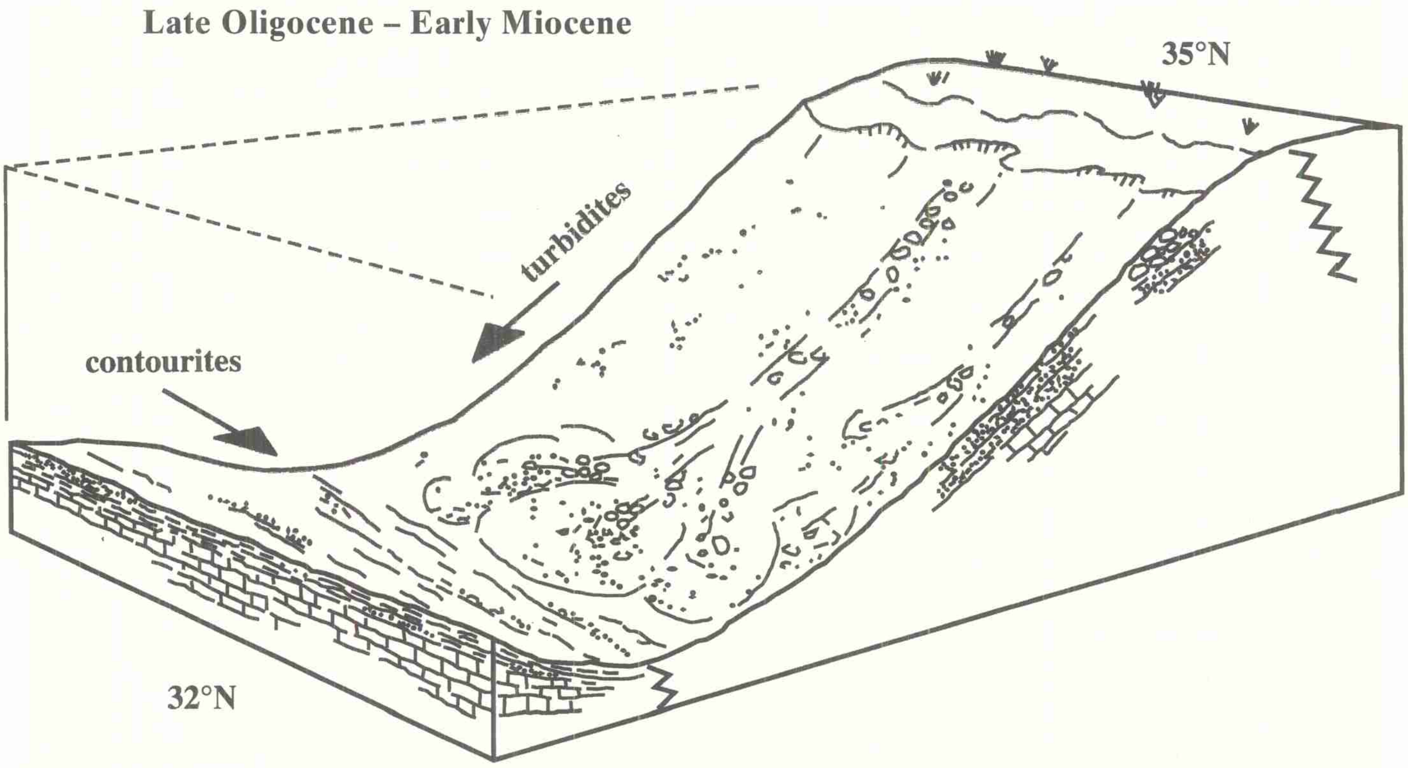

Fig. 10. Inferred depositional setting for the Lefkara Formation during the Oligocene acme of contourite sedimentation. The influence of turbiditity current input was generally less at this time, although some distal turbidites are interbedded with the mainly contourite/pelagite section.

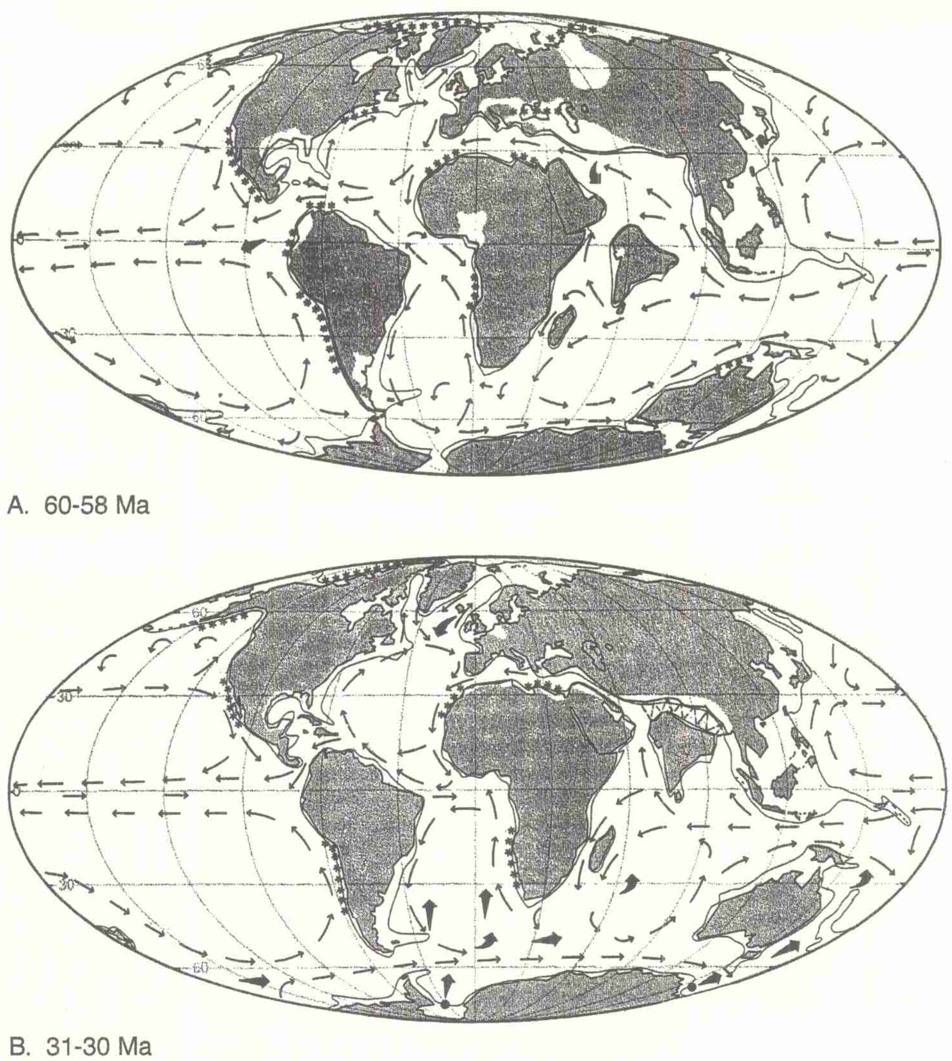

Fig. 11. Palaeogeography, palaeoceans and inferred global palaeocirculation in: (**A**) the early late Paleocene (*c.* 60–58 Ma); and (**B**) the mid-Oligocene period (*c.* 31–30 Ma) (from Haq 1984).

Kyrenia Range, uplift of the Troodos terrane and subduction to the south of Cyprus may also have led to the local intensification of bottom currents due to increased slope gradients (Robertson *et al.* 1991).

Discussion and conclusions

There is considerable evidence that has allowed us to infer bottom current influence on sedimentation during accumulation of the upper parts of the Lefkara Formation in Cyprus. The principal lithostratigraphic units affected are the upper parts of the Chalk and the whole of the Upper Marls, ranging in age from late Eocene to early Miocene with an acme of influence during the Oligocene. A three stage approach to contourite identification has been followed.

(1) The sediments are carbonate-rich contourites that show generally faint structures (in parts only) indicative of current deposition, together with bioturbation throughout. Coarser grained calcarenites and finer grained calcilutites both occur, in some cases in cyclic alternation. Grain fragmentation and reworking of older bioclasts are evident. These features, as well as sediment composition, are notably different from those of Lefkara Formation turbidites, which mainly occur lower in the succession. They show close similarity with calcicontourites described from other 'confirmed' ancient series (Bein & Weiler 1976; Duan *et al.* 1993) as well as with the standard contourite facies model (Stow *et al.* 1986, 1996).

(2) There are marked variations in thickness, accumulation rates and facies of the principal contourite units across the region. Overall, very low sedimentation rates prevail (< 10 m Ma^{-1}), together with distinctive condensed intervals and widespread hiatuses. Locally, palaeocurrent measurements show alongslope reworking of the tops of turbidites. These features are compatible with contourite drift construction (Faugères *et al.* 1993) along the eastern and southern margins of the rising Troodos terrane, as well as with moat areas that experienced higher velocity bottom currents and more marked erosion.

(3) Deposition occurred on a carbonate slope-apron system in the closing Tethys seaway. The depositional setting and likelihood of bottom currents both independently support our case for contourites.

The contourite facies are very easy to overlook in the field. Firm identification necessitates a combination of evidence gained from further laboratory work and literature review, as presented in this paper. There is a clear need for type examples of fossil contourites exposed in ancient series on land, that are well documented and readily accessible for examination by geologists and oceanographers. We provisionally propose the adoption of these Oligocene examples from Cyprus, especially the sections at Lymbia and Petra Tou Romiou, as the first of a series of type samples to be established worldwide. At the same time, we recognize that further work is required on these examples as well as on comparable Oligocene successions elsewhere in the Tethyan region.

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