

PROGRADING CLASTIC FANS AND TRANSITION FROM A FLUVIATILE TO A MARINE ENVIRONMENT IN NEOGENE DEPOSITS OF EASTERN CRETE

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ABSTRACT

In Neogene deposits of the eastern Sitia district (eastern Crete), a lateral succession from fluvatile to marine deposits has been reconstructed. Paleocurrent analysis indicates mainly southwest-directed sediment transport. The reddish deposits in the east (Kastri Formation) display braided-river characteristics. The fluviomarine deposits in the central part of the area (Toplou Formation), lie laterally of the braided-river deposits eastward. The fluviomarine deposits include thick conglomerate sheets, which display giant foresetting in sets between 5 and 30 m. high. This giant foresetting probably reflects the depositional slopes of large fans built by the discharging river below sea level. The submarine nature of deposition is confirmed by *Ostrea* between or on the pebbles. In the extreme southwestern part of the area marine marls occur (Akhkladia Formation) with clastic intercalations, which bear evidence of mass transport, and which probably have been derived from the discharging river courses northeastward. Uniserial *Uvigerina* and *Globorotalia* in these marine marls point to a Late Miocene age of these deposits and hence of the fluviomarine and the fluvatile sediments.

INTRODUCTION

The island of Crete, situated in the southern Egean Sea, is dominated by several preneogene mountain ranges of very rugged morphology, connected with the alpine period of folding. In front of these massifs a hilly lowland is found, mainly consisting of relatively little disturbed Neogene strata.

The greater part of the Neogene deposits, which together cover about 25% of the island, and which display a considerable variety in lithology and depositional environment, occurs along the north-coast.

In 1961/1962 an extensive investigation of the Cretan Neogene was started as part of stratigraphical and micropaleontological research carried out under the direction of Prof. C.W. Drooger, Utrecht. So far only the results of the investigations in the western part of the island have been published, (Freudenthal, 1969; Meulenkamp, 1969).

In this paper Neogene deposits from the eastern part of the island, the Sitia district, will be dealt with. Stratigraphical fieldwork was carried out by Gradstein in 1966, 1967, and 1969, the last year with the assistance of Van Gelder. The latter paid special attention to the sedimentary features.

PREVIOUS WORK

The only information concerning the Neogene of the area described here is given in sheet 23 of the Geological map of Greece (1954). On this map three units are recognized. The Miocene is represented by (1) a "coral limestone" overlain by (2) an "offlap, compact conglomerate with lenticular intercalations of sand and marl with *Ostrea crassissima*". Judging from their extension on the map these two units would correspond to deposits of the Toplou and Kastri Formations described in this paper. Our Akhkladia Formation and part of the westernmost Toplou deposits have been indicated on the Geolo-

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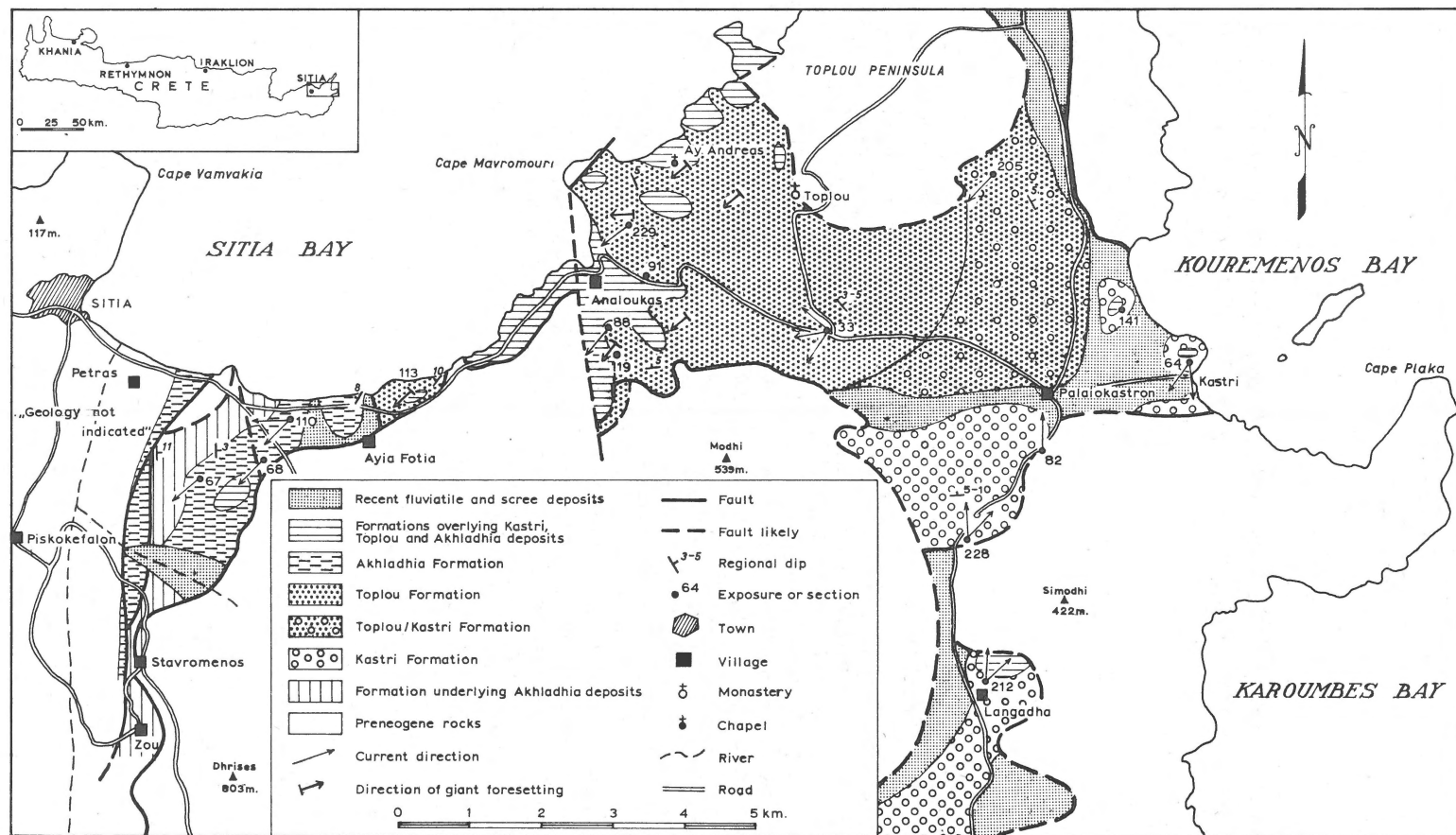


Fig. 1

Geological Map of the region between Petras and Kastri, eastern Sitia district, Crete. Special attention has been paid to the distribution of the Neogene Kastri, Toplou, and Akhladhia Formations, which reflects probably a lateral succession from fluvatile to marine deposits.

gical Map of Greece as (3) "not further subdivided marine Pliocene (marl, clay, sandstone, and conglomerate)".

STRATIGRAPHIC AND TECTONIC FRAMEWORK

The Neogene deposits considered here, are situated between Kastri in the east and Petras in the west (see fig. 1). They belong to several formations, three of which will be dealt with. In the east near Palaio-kastron, the Kastri Formation occurs, which merges westward in the Toplou Formation. The deposits of these formations probably have been formed in a fluvial to fluvio-marine environment. The marine deposits of the Akhladia Formation, in the west near Petras, are supposed to occur on a comparable stratigraphic level. The distribution of these units is shown on the Geological Map of fig. 1. In fig. 2 the lithological successions are represented from seven localities in the area. The mean direction of tectonic dip in the whole area is $3-5^\circ$ to the northeast. Faults are rare, folds are absent.

It should be noted that both the Kastri and the Akhladia Formations are found also outside the area covered by our Geological Map. For an extensive report on these occurrences and on the complete stratigraphy of the Neogene deposits in the entire Sitia district the reader is referred to a forthcoming paper in preparation by Gradstein.

KASTRI FORMATION

Red-coloured silts and violet clays, alternating with poorly sorted conglomerates constitute the Kastri Formation. The Formation is named after the Kastri hill, situated on the Kouremenos Bay (fig. 1). It is found in the eastern part of the area and reaches a thickness of some 40-100 m. (exp. 64, 82, 141, 212, and 228; see figs. 1 and 2). The type section is formed by exp. 64, which is situated in the lower and middle part of the Kastri hill (photo no. 1). The formation overlies preneogene rocks; the contact is visible in exp. 82.

The silts and clays generally occur in 1-2 dm. thick beds, which are mainly massive and locally show some parallel lamination, convolutions, and load-casting. Tiny plant remains and small structures

caused by burrowing animals or plant roots are common. In some clay beds lignitic laminae have been found. Some silt beds in the lower part of the type section contain scattered pebbles, less than 0.5 cm. in diameter, together with small conglomerate lenses composed of slightly larger pebbles.

Poorly sorted, coarse-grained conglomerates are intercalated in the red silts and clays especially in the higher part of the formation. Pebbles are closely packed, mean pebble diameter is less than 10 cm., maximum diameter is 30-50 cm. Bed thickness may be up to 5 m.; most beds appear to be channel fills with a concave, strongly erosive base and a rather flat top (photo no. 1).

Some conglomerate beds in the type section (exp. 64) show indistinct horizontal stratification, low-angular large-scale cross-stratification probably due to channel infilling, and vague imbrication of the pebbles. The direction of numerous channel axis and the imbrication indicate current directions to the south and southwest.

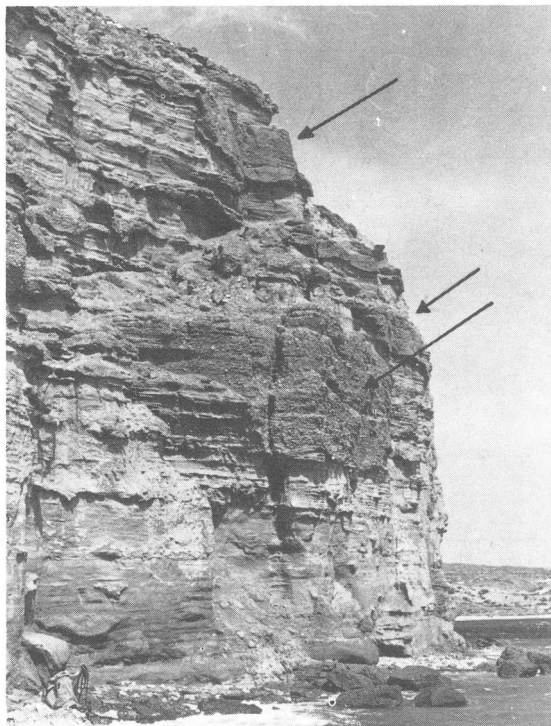


Photo 1

Silts and clays, alternating with poorly sorted, coarse conglomerates displaying channelling. Arrows indicate channel fills. Type section of the Kastri Formation (exp. 64) in the Kastri hill, east of Palaiokastron.

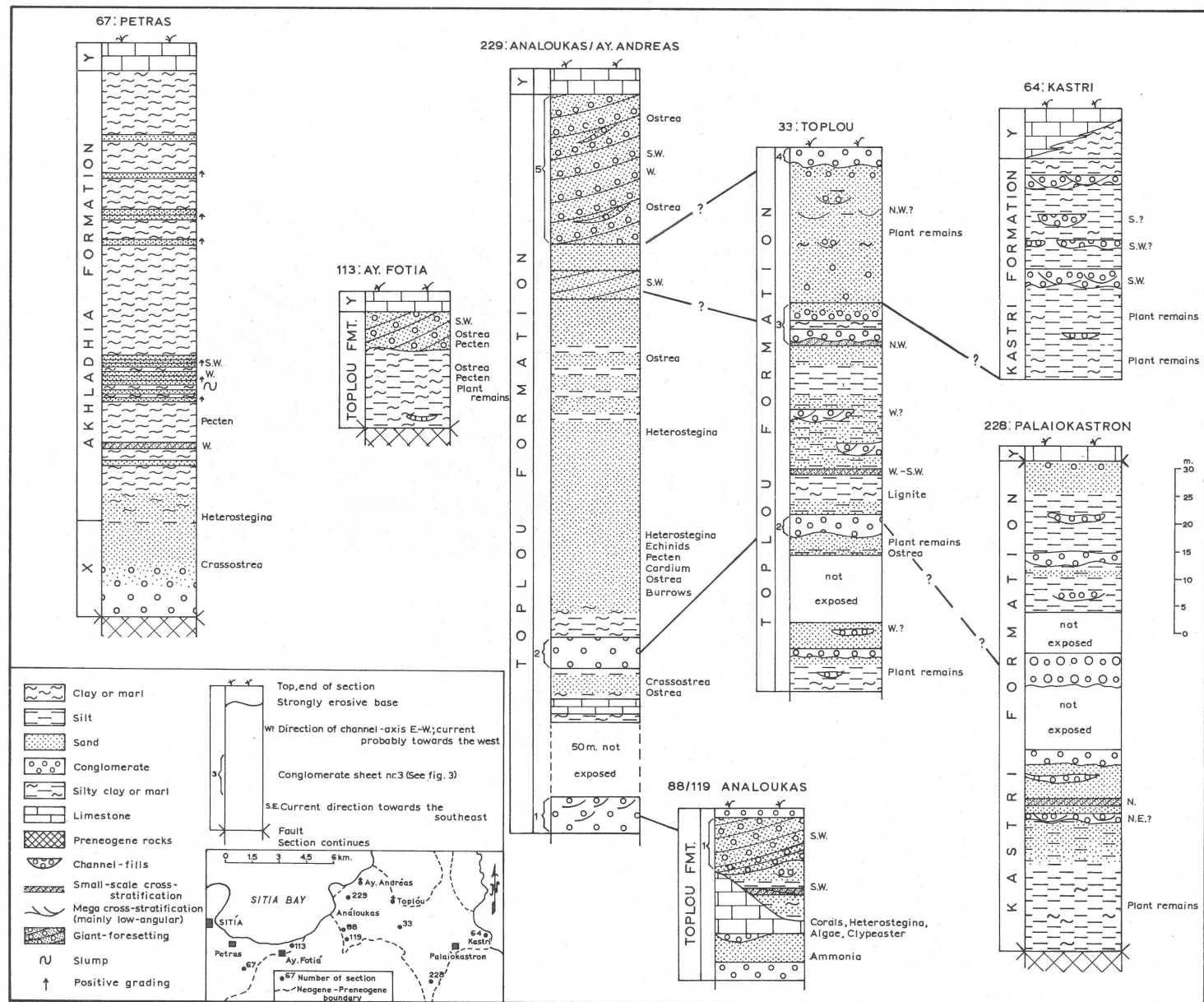


Fig. 2

Stratigraphic sections in Akhladia, Toplou, and Kastri deposits of the eastern Sitia district, Crete. For the location of the sections see the inset map and fig. 1. The basal, clastic deposits of section 67 (indicated with an x), and the uppermost calcareous deposits at the top of sections 64, 67, 228, and 229 (indicated with an y) are not discussed in this paper.

In the lower part of section 228, southwest of Palaiokastron, several up to 20 cm. thick, well-sorted grey sand beds show pronounced small-scale cross-stratification in tabular sets indicating a north-and-northeastward-directed sediment transport. It is noteworthy, that in the nearby thick Kastri deposits, south of the present Simodhi Massif, evidence was found of current directions again to the north (exp. 212 near Langhada; see fig. 1).

DISCUSSION

One of the characteristics of the Kastri Formation is the absence of fossils, except for the tiny plant remains. This fact combined with the completely clastic character of the sediments, the irregular alternation of very coarse and very fine-grained deposits, and the deep erosive channeling seem to be indicative of a continental (fluvial) environment. No fining-upward sequences of the meandering-river type were found. The relatively continuous gravel beds may have been laid down by a braided-river system. The source area(s) of the sediment probably was very close, as can be inferred from the poor sorting and the often poor rounding of the pebbles. The fine fractions must have been deposited from suspension, perhaps on a kind of floodplain intersected by a channel system. The massive silt beds with scattered small pebbles may have been deposited by occasional mud-flows. Another explanation for this phenomenon could be that a thin layer of small pebbles has been deposited on unconsolidated silts, after which individual pebbles sank into the silt.

TOPLOU FORMATION

The Toplou Formation consists of silts, sands, and conglomerates; locally clay beds and limestones occur. It is named after the monastery of Toplou, northwest of the village of Palaiokastron. The formation occurs between Palaiokastron and Aya Fotia (exp. 33, 88, 91, 113, 119, and 229; see figs. 1 and 2). It overlies preneogene rocks; the contact is exposed near exp. 119 and near Toplou. Maximal thickness is reached near Analoukas (about 200 m). The type section is formed by exp. 33 situated south of Toplou, along the road Sitia-Palaiokastron. In the eastern Toplou deposits plant remains are the only

fossils; the western Toplou deposits, near Analoukas and Aya Fotia are more fossiliferous, including *Heterostegina*, *Ostrea* and corals.

The transition of the Kastri Formation into the Toplou Formation westward, is apparently a gradual one. In the poorly exposed area in between (fig. 1) no evidence was found of faults; the pronounced reddish color of the Kastri silts and clays gradually disappears westward and sandy intercalations become more common. Toplou conglomerates are generally less coarse and better stratified than Kastri conglomerates.

Typical for the Toplou Formation are the thick conglomerate sheets numbered 1, 2, 3, 4, and 5 which occur at different stratigraphic levels and which can be traced over up to 6 km. Their extension has been plotted in the contour map of fig. 3.

Sheet nr. 1 occurs in the basal part of the formation exposed in the Analoukas area (exp. 88, 91, 119, and 229). In exp. 88 it overlies a thick coral reef limestone. Laterally of the reef limestone, thin organo-clastic deposits are overlain by 10-15 m. parallel-laminated silts and sands, showing climbing ripples and graded beds; also symmetrical (wave) ripples occur. Current direction for the climbing ripples was to the southwest. The transition to the overlying conglomerate sheet no. 1 is well exposed in exp. 119. The sheet has locally an erosive base; as a whole it shows a coarsening upwards and it is generally well

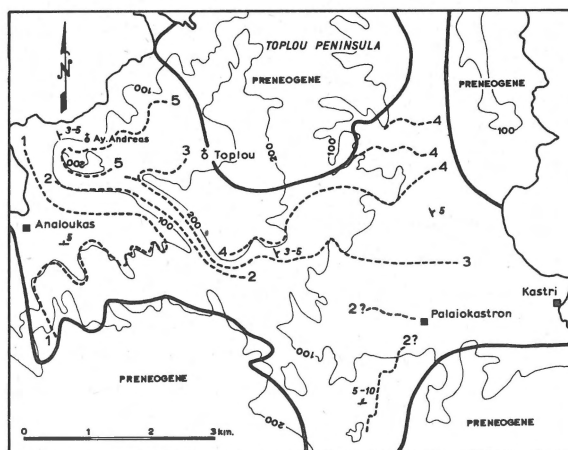


Fig. 3

Contour map of the conglomerate sheets in the Toplou and Kastri Formations, eastern Sitia district, Crete. The sheet numbers (1-5) correspond to the numbers in the stratigraphic sections of fig. 2.



Photo 2

Conglomerate sheet no. 1 at the top of section 88 (Toplou Formation) near Analoukas, showing giant foresetting. Set height is about 10 m.; dip of the individual beds is $15-18^\circ$ to the southwest. (Not to be confused with the zig-zag path halfway up the hill).

sorted. The fine fraction consists of multicolored silt and sand. The coarser beds contain pebbles up to 15 cm. in diameter; they show frequent channeling. In the southern part of the Analoukas valley (exp. 88, 119) the sheet shows giant foresetting (photo no. 2). Set height is about 10 m.; the beds in dip $15-18^\circ$ to the southwest with a slightly down-curved base. The foresetting could be traced over at least 1 km. in the direction of dip. The top is cut off rather straight by a course 1-3 m. thick, poorly sorted conglomerate, showing almost no stratification.

Conglomerate sheet no. 2 can be traced from the type section (exp. 33) to exp. 229, 3 km. west of it. In exp. 33 it overlies erosively yellow, silty sand with plant remains and very rare *Ostrea*. This sand coarsens upwards. Above the sheet in this section lignitic clays and silts occur. In exp. 229 the conglomerate is much finer grained and better stratified than in exp. 33, and there it is intercalated between clays with numerous *Crassostrea*, which may indicate a brackish environment, and thick bioturbated *Heterostegina* sands of (shallow) marine origin.

Conglomerate sheet no. 3 can be traced for nearly

6 km. East of the road from Palaiokastron to the north; it seems to dip below the surface, but extrapolated further eastward it would be present below the outcrops of the Kastri Formation in the type area. In the type section of the Toplou Formation this conglomerate is divided into two by a clayey interval. The lower part is very coarse and truncates small-scale cross-stratified sands. The upper part gradually passes into parallel-laminated sands. The pebble diameter in sheet no. 2 as well as in sheet no. 3 is less than 15 cm. Near Analoukas (exp. 229) sheet no. 3 perhaps corresponds to well-sorted, parallel-laminated sands with symmetrical ripples and *Ostrea*. Especially near Ayos Andreas, 2 km. northeast of section 229, well-developed giant foresetting is present in these sands. Set-height is more than 10 m., the laminae dip $10-15^\circ$ to the west.

Conglomerate sheet no. 4 extends from exp. 205 in the northeastern part of the area, where it is poorly sorted and of chaotic structure, to the Toplou type section. In this section it is finer grained than in exp. 205 and rather well stratified. According to its stratigraphic position it may correspond with the thick sheet no. 5 near the top of exp. 229, north of Analoukas.

Conglomerate sheet no. 5 reaches a thickness of 20-30 m.; it is restricted to the Analoukas area and forms the upper part of the Toplou Formation in section 229, (fig. 2). The conglomerate is well stratified and well sorted. Pebbles are less than 5 cm. in diameter, well-rounded, and occur in layers interbedded in coarse grey-brown to red-brown sand. Peculiar are the numerous *Ostrea* valves sticking to many pebbles. The conglomerate shows giant foresetting; height of the giant set is up to 30 m., dip of the individual beds is about 16° to the west. Near Toplou the dip is directed to the southwest. The individual beds which construct the giant set occasionally display channel-fill structures.

One more example of giant foresetting occurs outside the Analoukas region, 3 km. to the west, in an isolated conglomerate sheet in exp. 113 (fig. 2 and photo no. 3). This sheet abruptly overlies about 20 m. of rather massive silty marl containing wood fragments, *Pecten*, and *Ostrea*. Between the pebbles fragments of these pelecypod genera were found. Set height of the giant foresetting is 3-4 m., dip of the beds is $20-25^\circ$ to the southwest.

Except for the directions of sediment transport in the Toplou Formation mentioned above, more indica-



Photo 3
Giant foresetting in the conglomerate sheet of section 113 (Toplou Formation) near Aya Fotia. The sheet overlies silty marls with *Pecten* and *Ostrea*. Set height is 3-4 m, dip of the individual beds is 20-25° to the southwest. Between the pebbles *Pecten* and *Ostrea* fragments occur.

tions for current directions are present. In exp. 205 in the eastern corner of the area pebble imbrications indicate current directions to the southwest. Pebble imbrications, current-ripple cross-bedding, and channel-axis orientation in the sediments in exp. 33, occurring between the conglomerate sheets, point to northwest-, west-, and southwest-directed sediment transport (fig. 1).

DISCUSSION

The transitional Toplou/Kastri deposits and the adjoining Toplou sediments near the type-section seem to have been deposited by a braided-river system, carrying much silt. Evidence for a braided-river environment is inferred from the absence of fining-upwards sequences, the predominance of horizontal to low-angular stratification and the widespread extent of the thick conglomerate sheets. These sheets must have been formed in a wide flat area, e.g. a floodplain, during periods of abundant supply of water. Sediment transport took place in western directions.

An essentially fluvio-marine environment is found in the western distribution area of the Toplou Formation, as can be inferred from the alternation of conglomerate sheets with thick marine deposits of shallow water character. The current directions mainly point to a northeastern source area, but it is likely that part of the Toplou sediments has been supplied

from the east and southeast, via the fluvial regime of the Kastri Formation.

In our opinion the giant foresetting reflects the successive depositional slopes of large cones or fans built up by fluvial distributaries, discharging their bed load below sea level (see also p. 391). A submarine mode of deposition is likely for several reasons. First, the initiation of such huge sets requires a water depth of at least set height. Secondly in sheet no. 5 deposition below sea level is likely because of the numerous *Ostrea* sticking to many pebbles. Similar evidence is given by the pelecypod fragments in the isolated conglomerate outcrop of exp. 113. Thirdly the conglomerates alternate with shallow marine deposits.

AKHLADIA FORMATION

Between Aya Fotia and Petras, 4-5 km west of the Toplou deposits near Analoukas, up to 85 m of rather massive, blue-grey marls are exposed (exp. 67, 88, 110) with scattered molluscs (mainly *Pecten*), and a rich foraminiferal fauna. These marls constitute the Akhladia Formation, named after the village of Akhladia in the western Sitia district (Gradslein, in prep.). The type section is situated near this village. The deposits underlying and overlying the formation in section 67 (fig. 2) are not discussed here. Intercalated in the Akhladia marls near Petras are numerous greyish silt laminae and beige to red-brown, fine-grained sand beds (photo no. 4). These sand beds

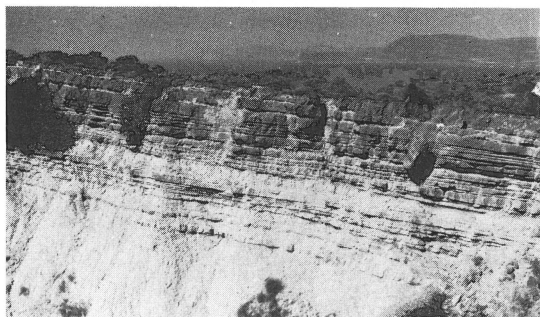


Photo 4

Marine marls of the Akhladia Formation in exp. 67 near Petras, with numerous thin-bedded sand intercalations showing an upward increase in number and thickness of the beds.

are 1-30 cm thick and contain at their base rare *Heterostegina* or *Ammonia*. The beds are mainly concentrated in two intervals (exp. 67, fig. 2); they are flat-bedded and have slightly erosive lower boundaries. They show positive grading, sometimes groove casts (exp. 67), and small-scale cross-stratification in tabular sets (exp. 110). The sequence shown in photo no. 4 represents the stratigraphically lower one of the two intervals mentioned above; it displays an upward increase in number and thickness of the sandstones. In exp. 68, 1 km east of exp. 67, this interval shows considerable scour-and-fill structures and slumping.

DISCUSSION

The Akhladia deposits near Petras were obviously deposited in a marine environment. The numerous clastic intercalations bear features of mass-transport, e.g. the pronounced positive grading and slump structures. The rare fossils at the base of some beds seem to be allochthonous. If we plot the current directions as deduced from groove casts and small-scale foresetting it is evident that the source area of the sands must have been situated in the northeast (fig. 2)

STRATIGRAPHIC CORRELATIONS

As pointed out above it is likely that there is a lateral transition from the Kastri in the Toplou Formation, based on field evidence. No direct evi-

dence could be derived in the field for the relative stratigraphic position of the Toplou and the Akhladia Formations. This seems to be due to numerous (mainly small) faults in the transitional area and the resulting lack of coherent outcrops. However, several indications provide a clue for the relation between both formations. It has been mentioned that the source area of the sand beds in the Akhladia marls near Petras must have been situated in the northeast. Taking into account the fluviomarine facies of the Toplou deposits in the Analoukas area, 5-6 km to the northeast, and the main current direction there going to the southwest, it seems reasonable to suppose that the Toplou and Akhladia deposits occur on a comparable stratigraphic level. It seems well possible that the discharging river courses, which were present in the Analoukas area, provided the clastics of the Akhladia Formation near Petras. It is noteworthy that the bluish Toplou silts in exp. 113 between Analoukas and Petras strongly resemble the Akhladia marls.

AGE

The only sediments to which a relative age could be assigned are the marine Akhladia marls of section 67 near Petras. Several samples of these marls were studied for their content of *Globorotalia* and uniserial *Uvigerina*. Since the morphological studies of Bizon (1967) concerning the Tertiary planktonics of Greece and the biometrical study of Meulenkamp (1969) on lineages in uniserial *Uvigerina* in the Neogene of Crete and Italy, rather detailed and valuable zonations are present regarding the Neogene sediments encountered in Crete.

In the lower part of section 67 *Uvigerina selliana* Meulenkamp ($\bar{S}_2 = 78$, $\bar{A} = 1.08 \pm 0.14$; $n = 62$) was found abundantly, which species is characteristic of the Early to Middle Tortonian (Late Miocene). The upper part of the formation in section 67 is rich in *Globorotalia menardii* (d'Orbigny), especially the var. *miocenica* Palmer, together with *Globorotalia scitula* (Brady), particularly the var. *ventriosa* Ogniben. According to Bizon, *Globorotalia menardii miocenica* is typical for the youngest part of the Miocene.

As discussed before, a lateral relationship seems likely between the Akhladia deposits and the Toplou Formation. This leads to the conclusion that the Toplou Formation and the Kastri Formation which

lies lateral to it, and in which no datable fossils were observed, are also of Late Miocene age.

THE GIANT FORESETTING

Although we only made a superficial study of the giant foresetting as compared to the detailed observations of Collinson (1968) on the enormous foresetting in the Kinderscout Grit (Namurian) of Northern England, we believe this to be a more or less similar phenomenon. Collinson described foresetting in a coarse pebbly sandstone with a maximal inclination of 27° in sets 4-40 m high, up to 1 km wide and 2 km long. The foresetting is explained by the seaward advance of fluvial clastics in "deltaic sedimentation units". This corresponds with our opinion concerning the origin of the Toplou foresetting.

Collinson assumes "a high rate of bed load supply combined with the prior existence of a body of standing water or a sudden deepening". The sudden deepening is proposed by this author in the case where the deltaic sedimentation units directly overlies fluvial sandstones.

In our case obviously a body of standing water was present as can be inferred from the indications for submarine deposition (p. 389). Large amounts of bed-load material have been supplied by the braided-river system. A problem is the continuity of the giant-foresetted beds. In sheet no. 1 the foresets can be seen to keep the same dip and set height over a distance of about 1 km. This might be explained by assuming a progradation of the fan, concomitant with a relative subsidence of the marine basin of about the same rate as the rate of deposition on the fan.

Collinson postulated the existence of a (giant) vortex in front of his "deltaic sedimentation units" to explain the complex pattern of "intrasets-cross-

bedding". In our case no evidence of a similar pattern could be found, although a more detailed investigation may yield more data. The small channel-fills in our giant-foresets may easily have been brought about by bottom currents flowing down the foreset slope.

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