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The Prina Complex in eastern Crete and its relationship to possible Miocene strike-slip tectonics

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Abstract—The basal Neogene formations in the Ierapetra region, eastern Crete, are strongly influenced by a Late Serravallian tectonic phase which resulted in the breakup of pre-existing palaeogeographic patterns. Important vertical movements caused the southward emplacement of Neogene sediments, together with parts of the underlying pre-Neogene nappe pile. The resulting chaotic association of exotic blocks and sediments, known as the Prina Complex, has the properties of a sedimentary mélange. It can be traced for more than 15 km from north to south.

In the north a relatively coherent accumulation of large slide masses overlies deformed Neogene coarse clastics and pre-Neogene rocks. Distally it comprises a poorly stratified sequence of breccias and intermixed finer grained sediments, which locally contains olistostromes and debris-flows and interfingers to the south with submarine fan deposits. The intricate relation of faulting and gravity sliding in a rapidly subsiding basin can be explained by generation in a strike-slip setting. It is suggested that the Ierapetra basin and its offshore extension, the South Cretan trough, were initiated by sinistral movements along a NE-SW oriented fault zone. Implications of this model for the geodynamic evolution of the south Aegean area are discussed.

INTRODUCTION AND REGIONAL SETTING

THE ISLAND of Crete forms the southernmost part of the Hellenic Arc (Fig. 1). Plate tectonic models of the convergence between the African and Eurasian lithospheric plates imply for the Hellenic Arc a convergent boundary in the Ionian Sea, west of the Greek mainland, and a transform boundary in the southeastern Aegean area (McKenzie 1978, Le Pichon & Angelier 1979). According to these models the loci of sinistral strike-slip movements are aligned along the two major SW–NE oriented trenches of the south Hellenic Arc, the Pliny and Strabo trenches. The overall structure of these trenches is extremely complex (see Mascle *et al.* 1982a).

The Ierapetra region is located in eastern Crete, where the island is at its narrowest (Fig. 1). The stratigraphy and sedimentary history of the Neogene deposits in this part of the island were studied by Fortuin (1977, 1978). The most prominent feature of the present-day morphology of the Ierapetra region is a central NE–SW oriented depression. The very pronounced fault scarp forming the eastern margin, the so-called Ierapetra fault, has a considerable submarine extension, both to the north and south (Nesteroff *et al.* 1977). Contrary to what is shown on many tectonic maps of the south Aegean area, the western boundary of the depression is not a series of active normal faults.

Recent marine geological research in the south Hellenic Arc (Leité & Mascle 1982) indicates that the Ierapetra region forms the onshore continuation of the South Cretan trough, a branch of the Hellenic Trench (Fig. 1). Consequently, detailed information on the evolution of the Ierapetra region will directly contribute towards understanding of the adjoining offshore areas. The South Cretan trough is located in the region where subduction along the Hellenic Trench passes into the inferred transform motion along the Pliny and Strabo trenches. Normal faults, delimiting horst and graben structures, are the prevalent type of current deformation in the South Cretan trough (Huson 1982). Leité & Mascle (1982) demonstrated a pre-Upper Miocene origin of this basin, a result corresponding with the data for the Ierapetra region.

The objective of this paper is to draw attention to the intricate relation of faulting and gravity sliding, developed along the margin of the rapidly subsiding Ierapetra basin during a Late Serravallian phase of crustal movements. The Prina Complex, a chaotic sediment association, reflects the important changes that took place during this palaeogeographic revolution.

STRATIGRAPHICAL OUTLINE

The sedimentary history and palaeogeography of the Cretan Neogene is one of frequently changing land–sea distribution because of the complex interaction between fault blocks delimiting the different sedimentary basins (Drooger & Meulenkamp 1973, Meulenkamp 1979). Apart from the rapid vertical and lateral facies changes

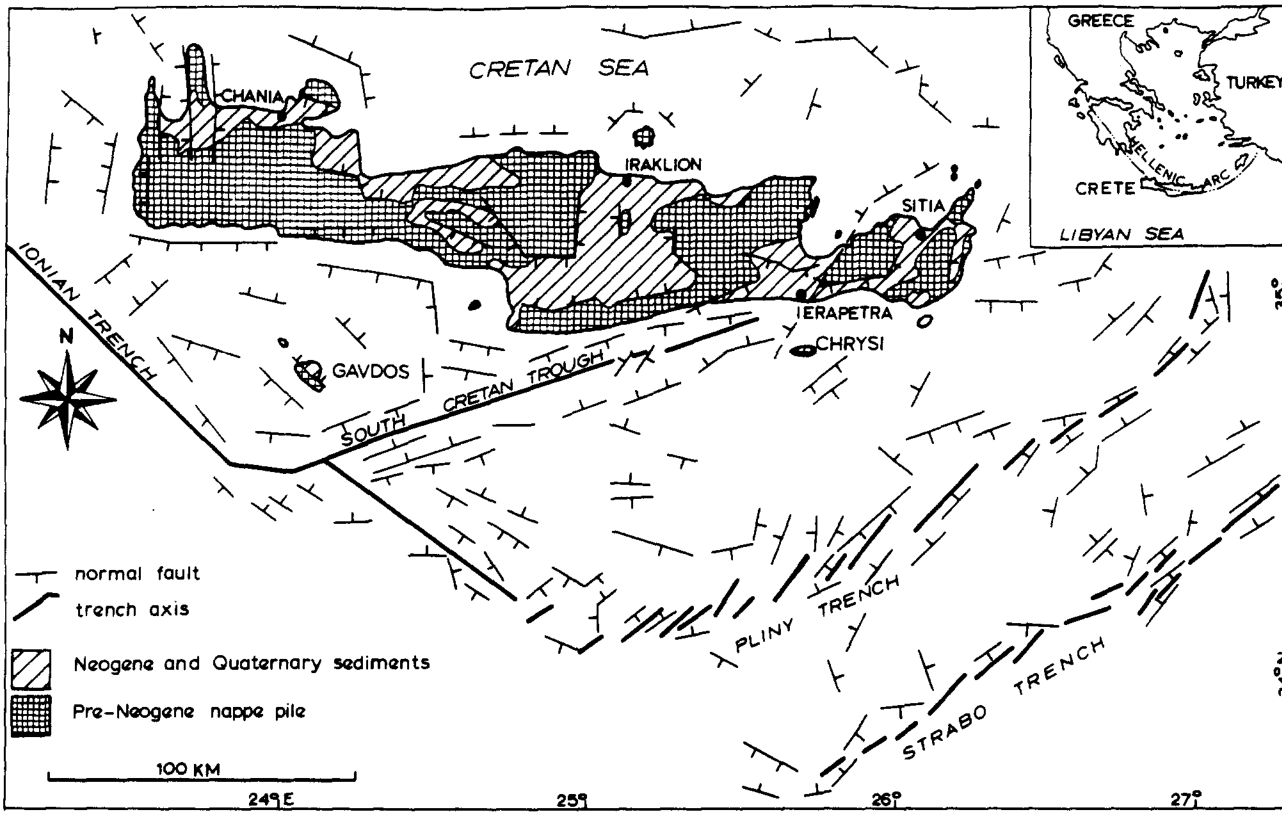

Fig. 1. Geological sketch map of the south Hellenic Arc and location of the Ierapetra region. The offshore fault pattern has been compiled after Angelier *et al.* (1982) and Mascle *et al.* (1982b).

due to various episodes of block faulting, the Messinian salinity crisis and its related drop of the Mediterranean sea level further complicated the overall stratigraphic picture. In response to the dynamic crustal behaviour, most of the Neogene sediments are of detrital origin: breccias and conglomerates dominate in the continental to shallow marine basal units, whereas marls, including turbidites in the deeper basins, characterize the marine deposits. In eastern Crete limestones were mainly formed during the Late Tortonian–Messinian timespan.

The formation of the Prina Complex is related to the fragmentation and partial submergence of a pre-existing continental borderland known as the South Aegean landmass (Meulenkamp 1971 (see Table 1). Before this event the region formed part of a large east to west-flowing fluvial drainage system in which conglomerates, sandstones and clays were laid down (Males Formation) on top of older coarse clastic alluvial fan deposits (Mithi Formation). The fluvial sedimentation ceased in the Late Serravallian when the area became gradually submerged. Fossiliferous, shallow marine marls characterize the top of the Males Formation (Parathiri Member).

During the breakup stage an approximately N–S oriented, fault bounded submarine trough was established. During its development sediments accumulated rapidly: large slide masses, dominated by exotic blocks and coarse clastics, came from the uplifted parts in the north (Prina Complex). Upwards and to the south they interfinger with southward thinning submarine fan deposits (Kalamavka Formation, see Table 1).

Subsequently, in response to progressive subsidence, a turbidite basin was formed and extended over the southern parts of the Ierapetra region. It was filled by sediments derived from relatively distant source regions in the west (Makrilia Formation). The Kalamavka sediments, which show north to south palaeocurrent directions, are partly interfingered with the Makrilia turbidites. Planktonic foraminifera, occurring in marls just below and above the Prina Complex, indicate a Late Serravallian age. Thus, during a relatively short time interval, the palaeocurrent directions changed through 180 degrees.

East of the Ierapetra fault the lithostratigraphic succession is different. The Fothia Formation, which is developed only in this area (Table 1), contains large-scale gravity slides in the proximity of the fault and is genetically related to the Prina Complex. Correlation of the sedimentary history on either side of the fault is an important tool in understanding the tectonic evolution of the region, as will be pointed out later.

PRE-NEOGENE ROCKS AND THEIR RELATION WITH THE NEOGENE CLASTICS

In eastern Crete the pre-Neogene rocks form five major tectonic units, an 'autochthonous' basal unit and a pile of four nappes with strongly contrasting lithological and structural characteristics. The final phase of nappe emplacement took place during the Eocene–?Early Miocene timespan (e.g. Bonneau 1982).

Table 1. Lithostratigraphic scheme of the pre-Messinian Neogene formations in the Ierapetra region showing their relation to fundamental changes in environmental and tectonic conditions.

FORMATIONS (maximum thickness indicated)		AGE	DEPOSITIONAL ENVIRONMENT	REGIONAL TECTONIC SETTING
	MAKRILIA FORMATION (450 m)	TORTONIAN	Marls and turbidite sands, deposited in relatively deep basin. West to east transport.	Continued subsidence along normal faults; marine basins established throughout Crete.
FOTHIA FORMATION (500 m) East of Ierapetra Fault	KALAMAVKA FORMATION (350 m)	LATE SERRAVALLIAN	Submarine fan sediments (marls, calcareous sandstones, conglomeratic channel-fills), deposited on top of and interfingering to the south with the Prina Complex. N - S directed paleocurrents.	Rapid N - S channelling of clastics to subsiding fault blocks.
FOTHIA FORMATION (500 m) East of Ierapetra Fault	PRINA COMPLEX (500 m)	LATE SERRAVALLIAN	Break-up stage: uplift of basement in the north, resulting in local N - S overthrusting and associated gravity gliding of the sedimentary cover.	Fragmentation of the South Aegean landmass; strike-slip movements along the Ierapetra fault.
FOTHIA FORMATION (500 m) East of Ierapetra Fault (upper part)	MALES FORMATION (350 m)	LATE SERRAVALLIAN (upper part); ?	Gradual marine incursions at top. Mature fluvial drainage system (conglomerates, sandstones, marly clays). Sediment transport from east to west.	Gradual subsidence. Position at southern margin of a then existing South Aegean landmass.
	MITHI FORMATION (150 m)	?	Alluvial fan deposits: breccias, conglomerates and lignitic clays.	First evidence of the accumulation of erosion products derived from newly (?) established South Aegean landmass.

Table 2. Lithology and lateral development of the elements constituting the Prina Complex. The letters in the two right-hand columns refer to the position of the various lithologies in Fig. 3.

STRUCTURAL LEVEL	LITHOLOGICAL ELEMENTS	SEQUENTIAL ASPECTS	
		PROXIMAL (north)	DISTAL (south)
UPPER	Marly sediments at the top. Stratified coarse clastics, including marly or sandy strata.	Marine boulderconglomerates with sandy intervals, overlain by fossiliferous marls (F).	Olistostrome, at base of the Kalamavka Formation (H). Stratified breccias, representing sheetflood deposits (locally overlain by oyster beds and/or coral bioherms) (G).
MIDDLE	Compact breccias and breccioconglomerates, predominantly composed of Tripolitza limestone fragments. Mass-flow deposits, often occurring as rafts, up to 250 m in diameter. Well-stratified, laterally discontinuous sediments, originating from the Males Formation. Exotic blocks of Tripolitza limestone, mostly bounded by shear planes.	Thick succession of poorly stratified breccioconglomerates, at base associated with Tripolitza limestones (D).	Mass-flow deposit, associated with exotic blocks of Tripolitza limestone and overlying locally deformed Males Formation (E).
LOWER	Crushed and brecciated Tripolitza limestones. Strongly deformed Neogene, derived from Mithi and Males formations, forming matrix between pre-Neogene competent bodies. Blocks and laterally discontinuous masses of granodiorites, coarse crystalline marbles and flysch-type sediments, all originating from UM - unit.	Tripolitza limestones and Neogene breccias form coherent thrust mass in the north (A), passing southward into chaotic association (B).	Normal superposition of basal Neogene formations, unconformably overlying UM - unit (C).

The Plattenkalk Series is considered to represent the parautochthonous basement of the nappe pile and consists mainly of carbonates with chert nodules. The rocks were metamorphosed under HP/LT conditions (Seidel *et al.* 1982) and have a less complex deformational history than the overlying nappes (Richter & Kopp 1983, Hall & Audley-Charles 1983). The heavily deformed Phyllite–Quartzite unit (PQ-unit), the lowermost nappe, is highly heterogeneous and comprises Permo-Triassic sediments and volcanics plus slices of metamorphic rocks with Hercynian radiometric ages (Seidel 1978). All rocks have undergone Early Miocene HP/LT metamorphism (Seidel *et al.* 1982). The Plattenkalk Series and the PQ-unit are widely exposed east of the Ierapetra fault.

Above the PQ-unit follows the non-metamorphic Tripolitza Series which consists predominantly of dark coloured, shallow water carbonates of Mesozoic age and siliciclastic turbidites of Eocene age. Bedding is generally indistinct in the limestones. The Tripolitza Series, in turn, is overlain by the Pindos Series in which grey and white limestones and radiolarites dominate. The top of the Pindos sequence is formed by turbidites and 'blocky flysch" (Hall *et al.* in press). The Pindos Series is often missing in the nappe pile of eastern Crete.

The uppermost nappe (abbreviated to UM-unit in this paper) has various names in literature such as Asteroussia nappe (Bonneau 1972), Serpentinite–Amphibolite association (Creutzburg & Seidel 1975) or Volcanic Sedimentary Complex (Wachendorf *et al.* 1980). It contains Late Cretaceous HT-metamorphics and intrusives which are genetically unrelated to Jurassic serpentinized ultramafics which form the higher parts of this tectonic mélange (Seidel *et al.* 1981, Reinecke *et al.* 1982).

The pebble composition of the basal Neogene formations, which are deposited unconformably on the basement rocks, shows a close relationship with the lithologies of the pre-Neogene nappe units. From old to young the Neogene in the Ierapetra region reflects the progressive erosion and denudation of the nappe pile. The basal clastics (Mithi Formation) consist almost exclusively of components derived from the UM-unit. The age of the Mithi Formation is not known; locally intercalated lignitic clays do not allow any age determination (Benda pers. comm.).

The conglomerates of the overlying Males Formation are characterized by large amounts of erosion products from the Pindos nappe. In sharp contrast, debris from the Tripolitza nappe prevails in the Prina Complex. Structurally higher in the complex, clasts derived from the lower pre-Neogene units, the PQ-unit and the Plattenkalk Series, also become frequent.

East of the Ierapetra fault no debris from the UM-unit is found. The Fothia Formation is widespread here and its coarse clastics were derived from pre-Neogene units below the UM-unit.

THE PRINA COMPLEX

General

The Prina Complex is a heterogeneous sediment association, built up of several lithologies which accumulated on top of, or were intermixed with, the underlying Mithi and Males Formations and pre-Neogene rocks. We interpret the Prina Complex as a sedimentary mélange. In the last section of this paper the origin of the complex will be discussed. Because all elements of the complex have been displaced, for consistency, the incorporated Mithi and Males sediments should also be included in the Prina Complex. This concept modifies the original definition of Fortuin (1977) who mapped these occurrences separately. In addition to the data on the geological map of Fortuin (1977) some new outcrops of the Prina Complex have been found, e.g. in the Kritsa valley in the NW part of the region. The distribution of the complex in its wider sense has been indicated in Fig. 2.

The lithologies which built up the Prina Complex are listed in Table 2. They are grouped in three structural levels, representing an idealized vertical sequence. Boundaries between the levels are not sharply delineated and the relative proportions of the different rock types vary considerably within a given level.

Due to uplift and extension of Crete along numerous normal faults since the Late Miocene (Angelier 1978, Mercier *et al.* 1979), reconstruction of the original geometry of the Prina Complex is hampered. Furthermore, the lateral discontinuity of many of the constituent rocks makes correlation over large distances hazardous. Fortunately the N–S development of the complex can be studied along a line from the Katharo valley to the village of Anatoli (Fig. 2). In the north the complex almost directly overlies the UM-unit, whereas 8 km to the south it lies above some 500 m of Neogene sediments. Observations along the north side of the Katharo and Kritsa valleys indicate that in this area Tripolitza limestones and flysch are thrust on rocks of the UM-unit and its thin Neogene cover, including the lower parts of the Prina Complex. The estimated minimum displacement along the thrust is several hundred metres. Figure 3 gives a schematic reconstruction of the complex, not taking into account the effects of later deformation.

In general, the thickness of the complex decreases from north to south, i.e. in the inferred direction of mass transport. The maximum thickness is about 500 m, as reconstructed for the central parts of the region. In contrast, the Prina Complex cannot be distinguished in the basal Neogene of the south coast areas. Instead, an olistostrome, up to 35 m thick, is found at the base of the contemporaneous Kalamavka Formation (Fig. 3). The lithology of the olistostrome elements is identical to sediments and exotic blocks in the Prina Complex. Slump folds indicate mass transport in a SSW direction. We interpret the olistostrome to represent the most distally developed part of the complex (Table 2).

Lithologies in the complex

For detailed descriptions concerning the lithologies the reader is referred to Fortuin (1977). The most important aspects are summarized and discussed here, together with additional new observations.

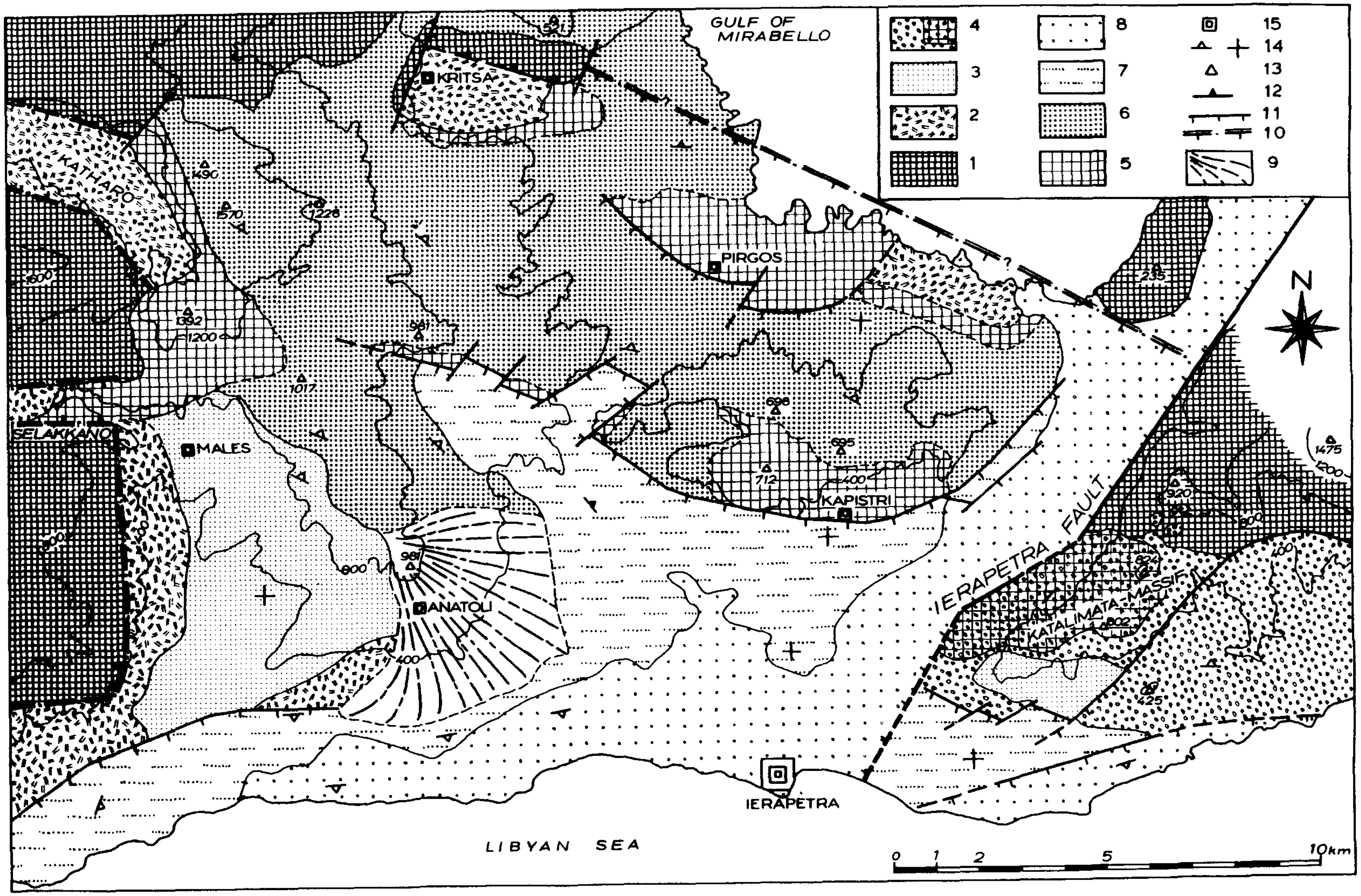

Fig. 2. Simplified geological map of the Ierapetra region (after Fortuin 1977). (1) Tripolitza Series; (2) UM-unit; (3) Mithi and Males Formations; (4) Fothia Formation, including allochthonous Katalimata-deposits (cross-hatched); (5) Prina Complex, lower structural level; (6) Prina Complex, middle and upper structural levels; (7) Kalamavka and Makrilia Formations; (8) post-Tortonian sediments; (9) Prina Complex affected by Quaternary landsliding; (10) initial Miocene normal fault zones; (11) younger Neogene and Quaternary normal faults; (12) thrust fault; (13) mountain top, height in metres; (14) bedding; (15) village or town.

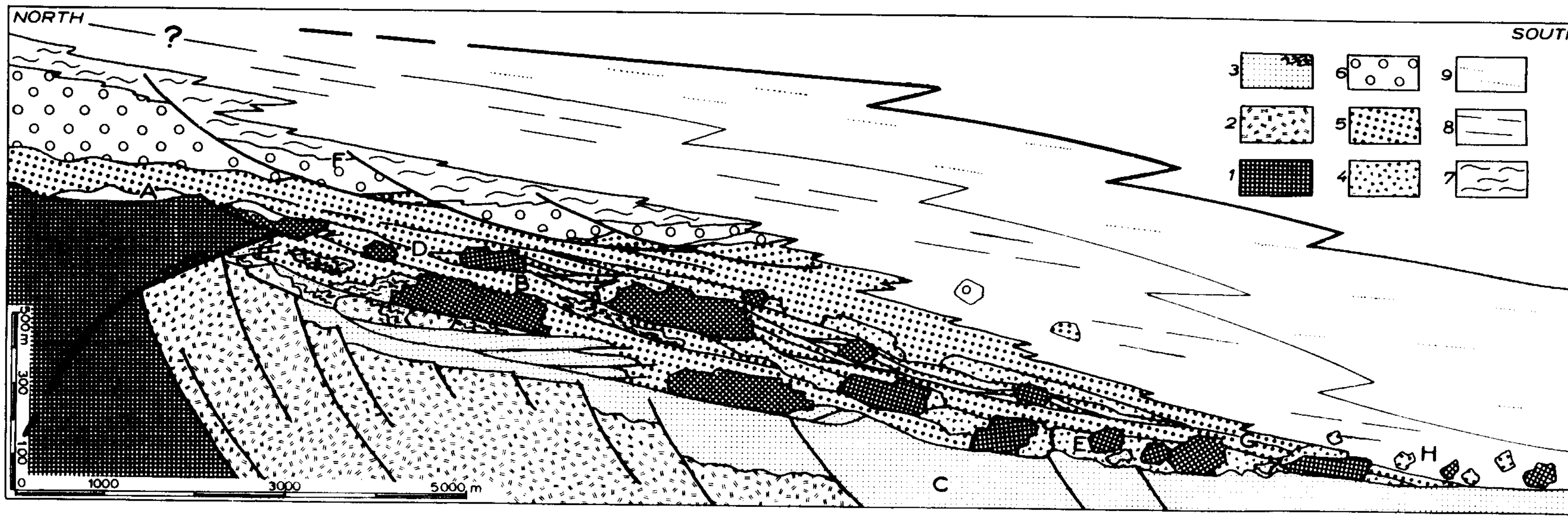

Fig. 3. Hypothetical N–S cross-section through the Ierapetra region at the end of the Tortonian, showing the geometry of the Prina Complex and its relation to pre-Neogene and Neogene rock units. Letters refer to Table 2. (1) Tripolitza Series; (2) UM-unit; (3) Mithi and Males Formations, deformed when incorporated in the Prina Complex; (4) debris-cones and debris-flows; (5) clastic deposits of the Prina Complex; (6) marine boulder conglomerates; (7) marly sediments; (8) Kalamavka Formation; (9) Makrilia Formation.

(A) *Exotic blocks and associated debris.* Most of the elements belonging to this category are Mesozoic limestones of the Tripolitza Series. In addition, marbles and other rock types from the UM-unit have been found. Incorporated blocks of Tripolitza limestone (Fig. 4a) are tabular to roughly equidimensional in shape. They can measure up to 1 km in length and be up to 200 m thick. These dimensions may be slightly overestimated because many of the blocks show intensive cataclasis and can hardly be distinguished from their unstratified and monomict sedimentary cover (debris-cones). Aggregates of limestone blocks, tectonic breccias and debris-cones are common. At least some of the sedimentary cover must have been formed prior to the emplacement of the blocks. On the other hand the field data suggest that part of the stratified breccia deposits in the higher and more distal parts of the complex were supplied by these blocks.

Most of the features of brittle deformation in the limestones are the result of tectonic transport during the emplacement of the Tripolitza nappe in Eocene–?Early Miocene time. However, comparison of the blocks with similar rocks in the nappe pile indicates that the penetrative microfracturing in the exotics is probably the result of faulting related to the formation of the Prina Complex. The brittle character of the limestones must have considerably facilitated detachment from the Tripolitza Series along the fault bounded basin margin.

Elements derived from the UM-unit are confined to the base of the complex. These exotics are only exposed at localities where also the Mithi and Males Formations are incorporated, e.g. the Katharo valley and in the area of Kapistri and Pirgos (Fig. 2). The largest blocks are at least 200 m in diameter and several tens of metres thick. Granodiorites, crystalline marbles, weathered ultramafics and flysch-type sediments have been found, usually mixed with sheared Neogene clastics.

(B) *Matrix lithologies.* The presence of allochthonous sediments of the Mithi Formation is restricted to the lower level of the complex; Males lithologies also occur in the middle level (Table 2). Due to their relatively soft character they act as a matrix between the exotic competent bodies. The sediments are highly disturbed and laterally discontinuous, showing variable dips to the north with fairly constant E–W strikes. In conglomerates exposed in northern outcrops sheared and crushed pebbles are abundant (see next section). Although clayey intervals are common in undisturbed sections of the Males Formation, the Males strata incorporated in the complex often lack these intervals, a feature suggesting that these incompetent beds easily developed into shear and gliding planes. Another striking characteristic of the emplaced Males sediments is the presence of breccia intercalations, composed of poorly sorted Tripolitza limestone debris. These have not been encountered in undisturbed sections of the Males Formation (excluding the uppermost few metres). We interpret these breccias as related to the onset of tectonic activity and suggest that they represent the rapid deposition of erosion products, transported only a short distance from the newly uplifted areas in the north, in peripheral parts of the Males floodplain. These sediments were later emplaced southwards, to form part of the Prina Complex.

(C) *Mass-flow deposits.* Unstratified, coarse clastic sediments form the lower parts of the Prina Complex in places where it is distally developed, such as in the area SE of the village of Males. Here an impressive mass-flow is exposed which is up to 20 m thick. The base is an irregular erosion surface and the underlying strata of the Males Formation are contorted. Mud lumps, reworked from the top of the latter unit and occasionally fossiliferous, are intercalated (Fig. 4b). In general the sediments consist of angular fragments of Tripolitza limestone, ranging in size from centimetres up to more than a metre, lying unsorted in a calcareous matrix. The mass-flow is covered by well stratified, finer grained breccias which exhibit properties of sheetflood deposits.

The chaotic character of the deposits, their immature components and the incorporation of underlying strata point to rapid deposition from catastrophic debris-flows. Similar mass-flows are found in the area just north of Kapistri as massive, isolated blocks below more coherent clastic sediments which form the top of the succession. Their distribution and lateral discontinuity clearly indicate post-depositional sliding due to repeated relief instability during the formation of the complex.

(D) *Stratified breccias and breccio-conglomerates.* These sediments are up to 200 m thick and have characteristics suggesting rapid accumulation of debris in coastal plains, either as sheetfloods or in ephemeral channels. Locally intercalated fine sediments may include brackish water faunas, thus witnessing repeated submergence of the depositional area. Distal breccia successions, as exposed W and S of Kalamavka, are locally overlain by *Ostrea* beds and small coral bioherms. These strata, in turn, are succeeded by the Kalamavka Formation.

Very recently Kopp & Richter (1983) introduced a new lithological unit, the Topolia Formation, comprising limestone breccias occurring in western Crete, which resemble the Prina breccias. The authors discussed a possible correlation with the Prina Complex (as earlier suggested by Meulenkamp 1979) and concluded that these units are not equivalent. We agree that fundamental differences in pebble composition and stratigraphical setting exist.

(E) *Marine boulder conglomerates.* In the region south of the Gulf of Mirabello the most significant Prina deposits are made up of boulder conglomerates. The total thickness of these sediments is difficult to determine because post-depositional gravity sliding has played an important role in this area. The estimated thickness is 300 m.

In their marine aspect and abundance of components derived from the Plattenkalk Series the boulder conglomerates differ from the bulk of stratified Prina clastics. The boulders are well rounded and embedded in a sandy–gravelly matrix (Fig. 4c). Sandy intervals, occasionally 50 m thick, are intercalated and contain channel-fills of boulder conglomerates. These sands are very well sorted and almost devoid of sedimentary structures. Bioturbation is frequent. This association of coarser and finer grained strata was probably deposited in a very proximal submarine fan which developed in front of an active coastal hinge zone where subaqueous mass-flows were triggered time and again.

In their distributional area the boulder conglomerates form the highest part of the complex. At the top they pass into marls in the area of Pirgos, or into deposits of the Kalamavka Formation.

Deformation in the complex

The genesis of the Prina Complex is closely related to active deformation along the southern boundary of the South Aegean landmass. Deformational structures, such as shear planes and tectonized conglomerates, are numerous in the basal parts of the complex. In the stratigraphically higher and more distal parts ample evidence exists for syn- and post-depositional relief instability and deformation is usually expressed as low-angle normal faults and large-scale gravitational sliding. Soft-sediment deformation is widespread at this level and invariably points to sediment transport towards the south.

In the northern parts of the Ierapetra region, subhorizontal to weakly N-dipping shear planes are present, along which Prina breccias and pre-Neogene rocks are overlying deformed clastic sediments of the Mithi and Males Formations (Fig. 3). The shear planes dip north probably due to the well-documented northward tilt of the island during the Quaternary (Fortuin 1977, Flemming 1978, Angelier 1979). Thus, the initial dip of the faults may have been subhorizontal. The amount of displacement, the superposition of the elements and small-scale deformation structures vary considerably along the different shear planes, as can be demonstrated by comparing data from a few localities. For instance, at the eastern margin of the Katharo valley, folded pre-Neogene flysch is truncated by a chaotic gliding mass of Tripolitza limestones, Prina breccias and Males sediments, showing imbrication. The minimum displacement is at least 500 m. The spatial relationships between the different lithologies in the gliding mass is well illustrated around Pirgos, where various pre-Neogene rock types overlie imbricated Neogene sediments. Here the horizontal displacement along the shear planes must be 2 km or more. The base of the Pirgos section is formed by N–NE dipping conglomerates and sandstones of the Males Formation, followed by a few metres of sheared sediments of the same formation which, in turn, are overlain by clastics of the older Mithi Formation along a major shear plane (Fig. 5). Locally this inversion is repeated several times. Upwards this mass of imbricated sediments is truncated by another shear plane above which huge masses of pre-Neogene rocks occur as laterally discontinuous blocks, separated by small strike-slip faults with subhorizontal slickensides. The pre-Neogene exotics are overlain by folded and sheared Males lithologies, some limestone blocks and minor quantities of flysch. The top of the section consists of massive Prina breccias. The contact at the base of the breccias is not exposed but, in the absence of a stratigraphic transition, is interpreted as an important gliding plane.

Further eastward, sheared contacts between Tripolitza limestones and underlying, relatively undisturbed Males conglomerates are well exposed in three aligned peninsulas along the Gulf of Mirabello. Slickensides are numerous and all point to emplacement towards the south. The limestones are interpreted as giant blocks in an extensive gliding mass.

Components of the Mithi and Males conglomerates are often strongly deformed in the vicinity of shear planes and unambiguously demonstrate the importance of tectonic stresses during the formation of the Prina Complex. Limestone pebbles have been vulnerable to deformation and exhibit numerous cracks (Fig. 6a). Frequently, rotation along the fractures has occurred, resulting in peculiarly shaped pebbles (Fig. 7a). In addition, pressure-solution is a widespread phenomenon in these rocks. This can be concluded from the pitted surface of pebbles and from the sutured contacts between components in lithified conglomerate (Fig. 8a). In stratigraphic levels where clays are present in the sediments, deformed pebbles are rare and deformation is restricted to shearing along incompetent layers.

From the Gulf of Mirabello to the south, in the direction of the village of Kapistri, a thick sequence of boulder conglomerates with sandy intervals is present. We assume the occurrence of large-scale gravity slides in this area to account for its thickness. Due to paucity of good exposures it has been impossible to test this hypothesis, but deformation in the sediments is obvious, since a distinct fracture-pattern was found in structurally deeper levels of the stacked sequence (Fig. 6b). The extent and exact origin of the fracture-pattern is not yet clear; its geometry shows similarities with deformation structures known as Riedel shears (see e.g. Tchalenko 1970). If this comparison is correct, the Riedel shear zones are probably related to the emplacement of the boulder conglomerates. The fractures dip about 45° SW, correlating with a NE–SW slip direction of the gravity masses.

STRATIGRAPHIC TRENDS EAST OF THE IERAPETRA FAULT

To determine the time of onset and character of movements along the Ierapetra fault and to study their influence on the palaeogeographic evolution of the

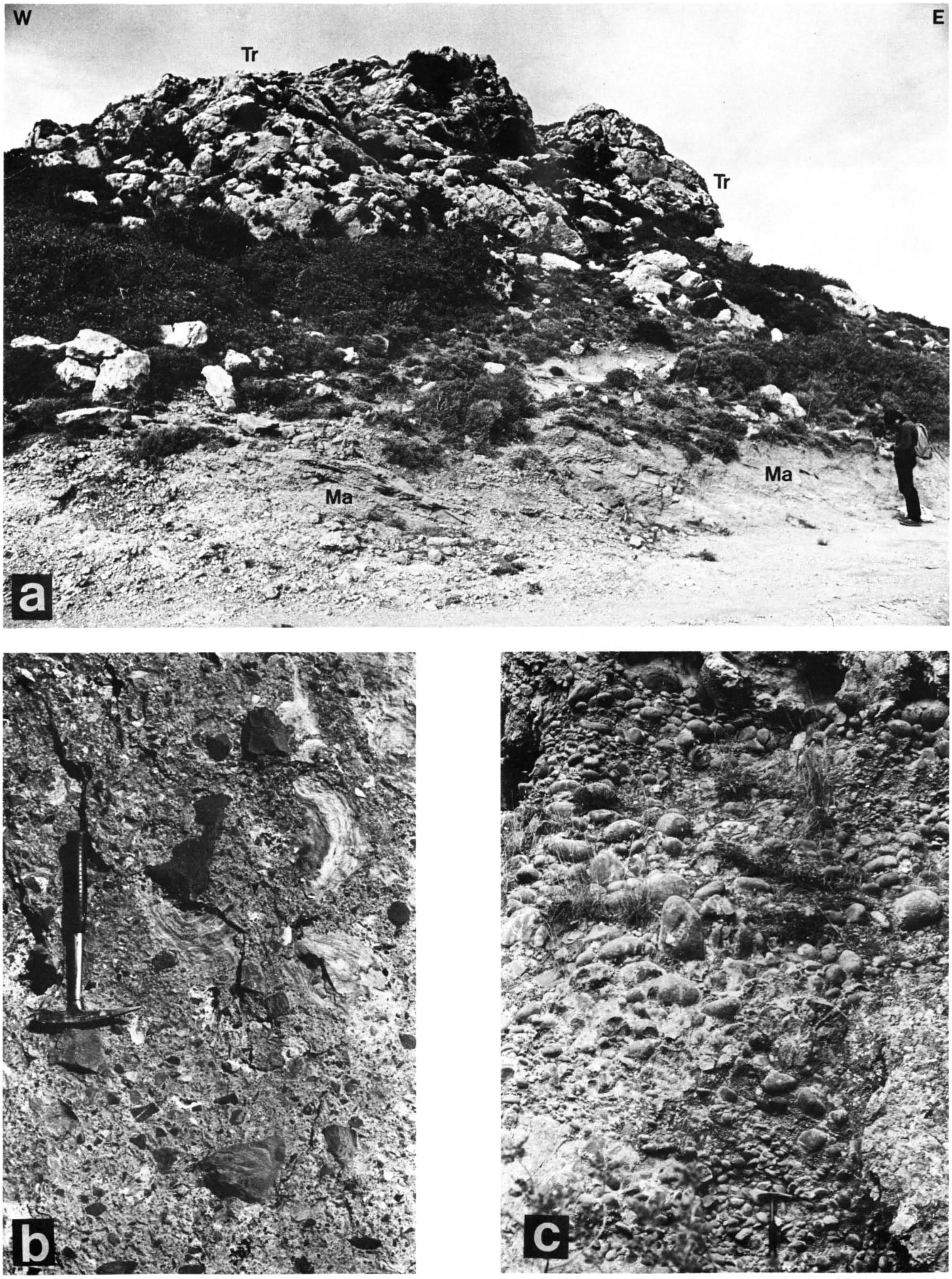

Fig. 4. (a) Exotic block of Tripolitza limestone (Tr) overlying allochthonous, north dipping conglomerates and sandstones of the Males Formation (Ma) in the area of Kapistri. This relatively small block measures 30 × 30 × 20 m. (b) Debris-flow breccia, containing mud lumps reworked from the underlying Males Formation. Photo of distal portion of Prina Complex, 2 km east of Males. (c) Detail of succession of marine boulder conglomerates which form the bulk of the structurally higher part of the Prina Complex south of the Gulf of Mirabello. Hammer indicates scale.

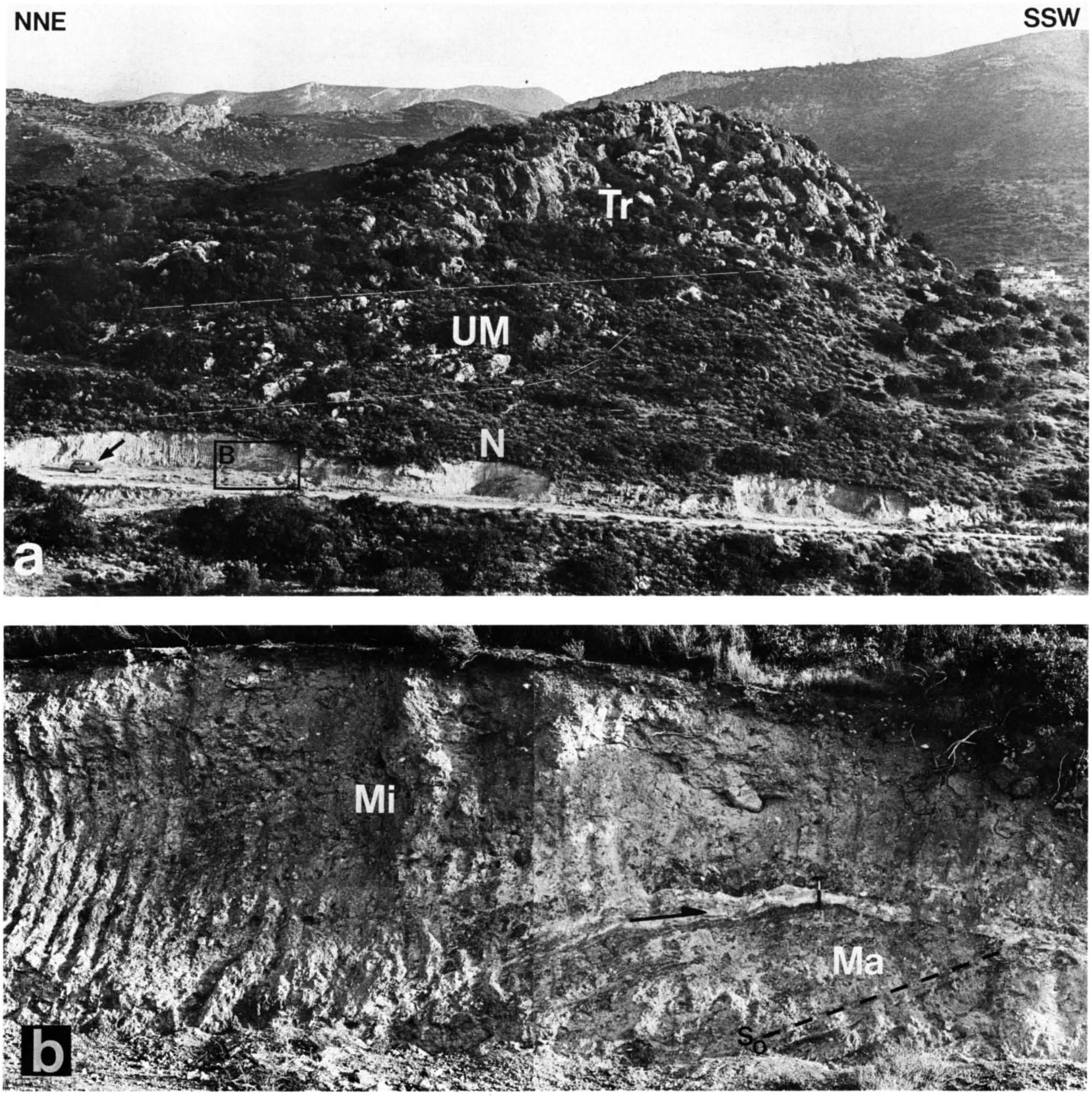

Fig. 5. Structures in the lower structural level of the Prina Complex (Pirgos area). (a) Giant block of Tripolitza limestone (Tr) and coarse crystalline marbles of the UM-unit (UM) overlie deformed Neogene sediments (N) along major shear planes. Inset shows location of (b). Car indicates scale (arrow). (b) NNE-dipping coarse clastic deposits of the Males Formation (Ma), truncated along a shear plane by conglomerates of the Mithi Formation (Mi).

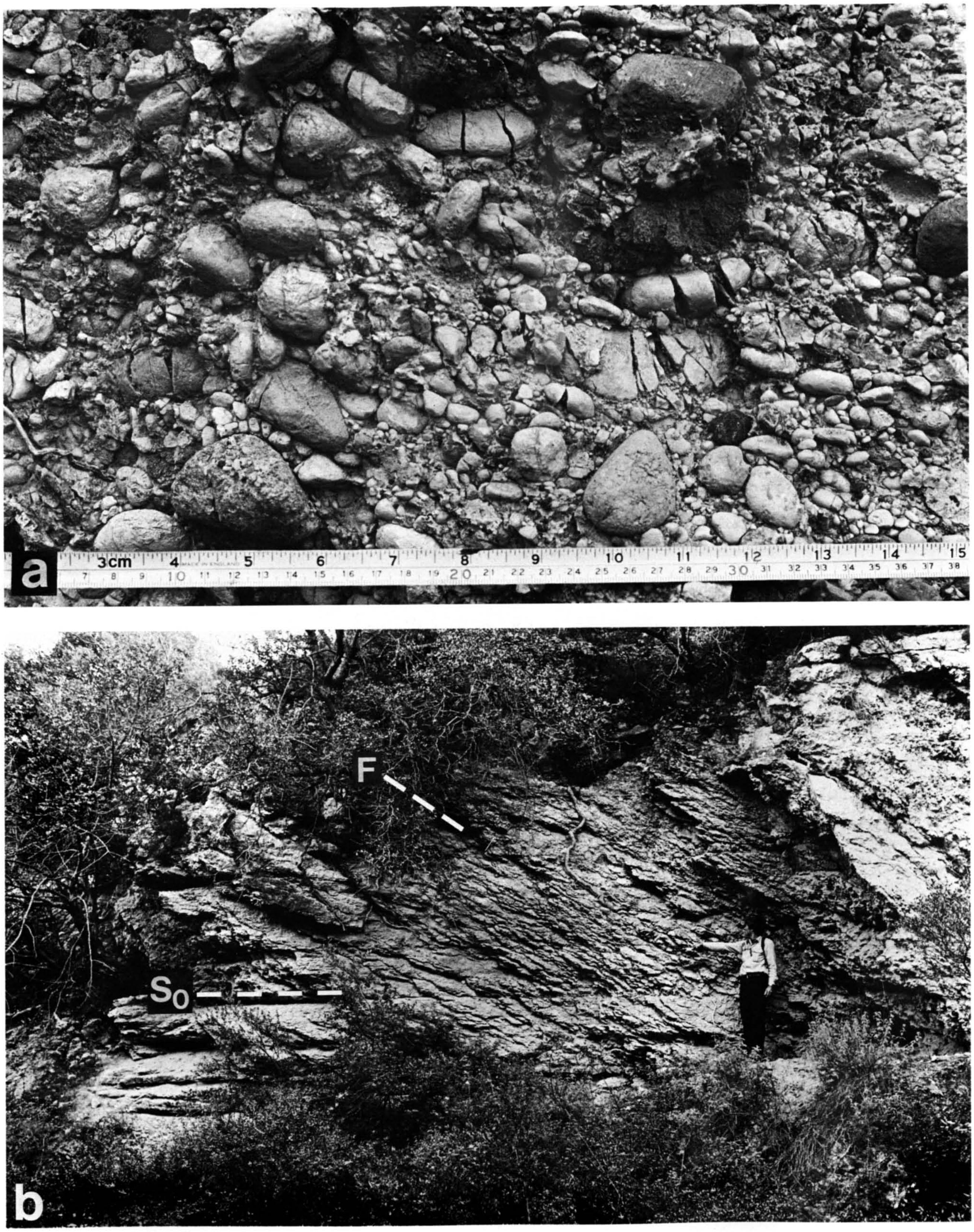

Fig. 6. Tectonic deformation structures in the Prina Complex. (a) Tectonized conglomerates of the Males Formation along the base of the Prina Complex in the Kritsa valley. Pebbles are cracked and usually disintegrate upon weathering. (b) SW-dipping fracture pattern (F) developed in a sandy interval near the base of a large-scale gravity slide of boulder conglomerates (south of the Gulf of Mirabello). The fractures are interpreted as Riedel shears.

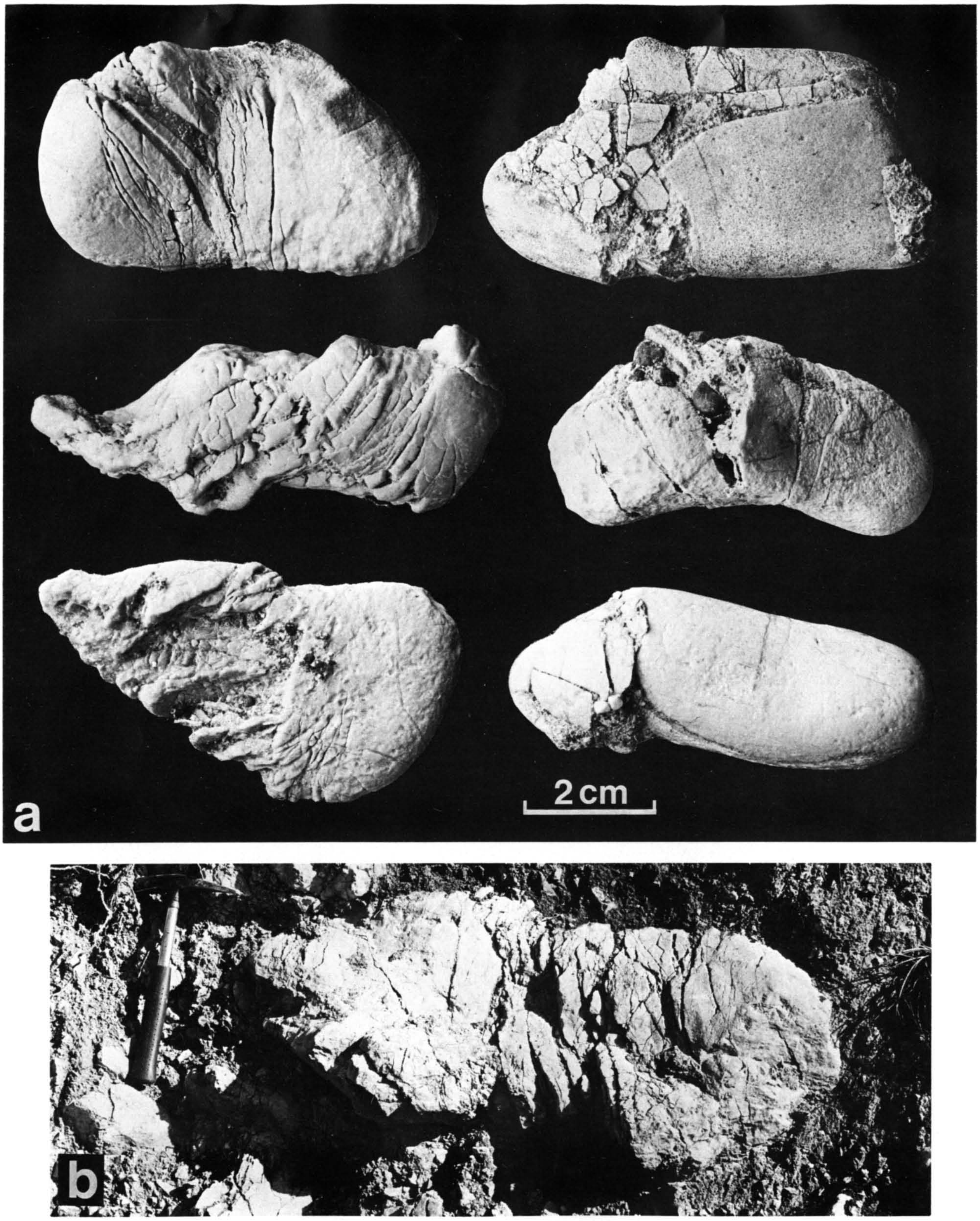

Fig. 7. (a) Inhomogeneously deformed limestone pebbles originating from conglomerates of the Males Formation in the lower level of the Prina Complex. Pebbles on the left show closely spaced fractures along which rotation of the different segments has occurred. Examples on the right are less intensively deformed. (b) Deformed limestone boulder of the Fothia Formation at the base of the allochthonous Katalimata-deposits (eastern end of Katalimata-massif).

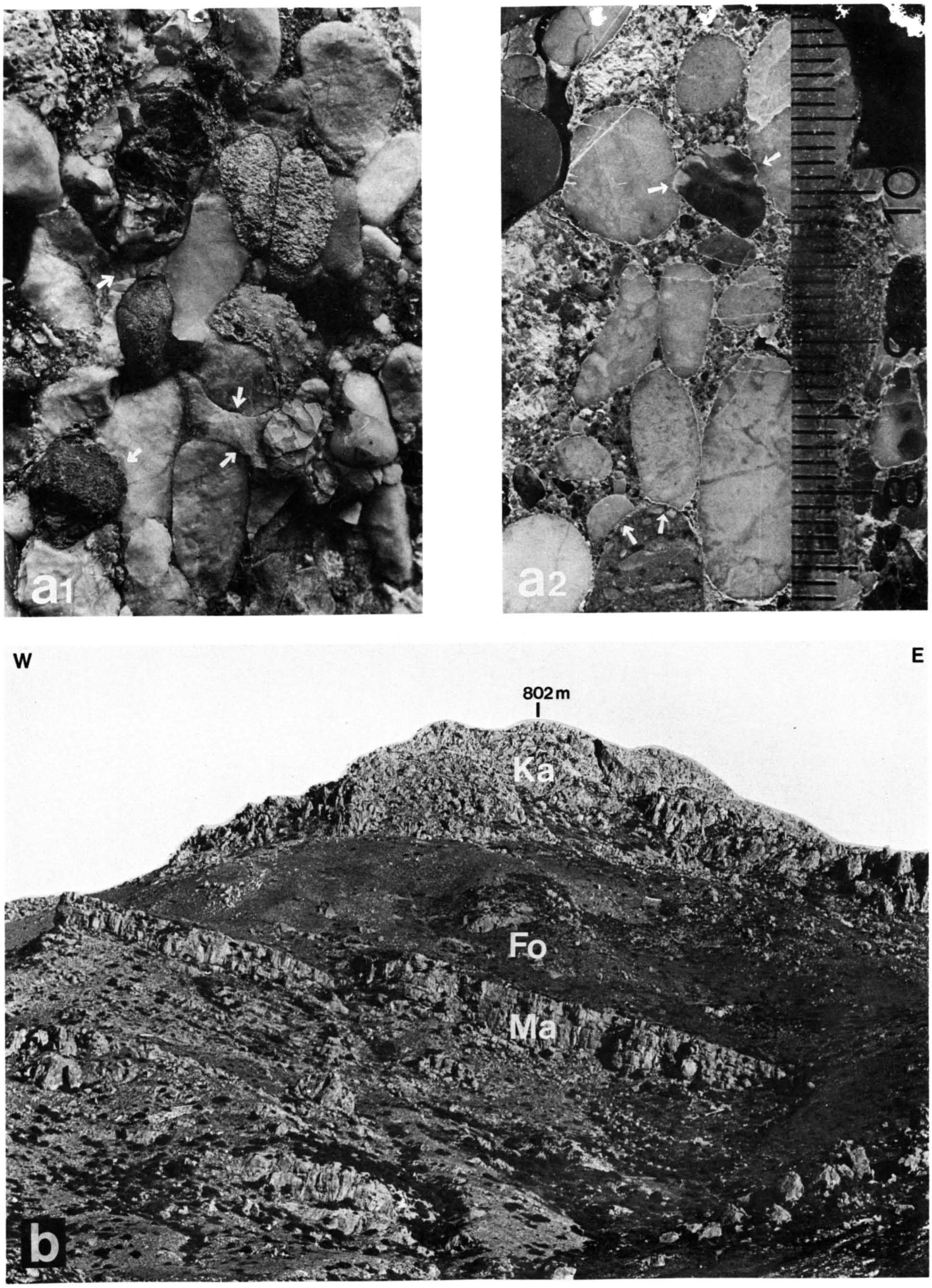

Fig. 8. (a) Effects of pressure-solution in lithified Males conglomerates (Kritsa valley). Scale in cm.; a1, weathered surface, showing strongly dissolved limestone components with concave outlines along contacts with competent pebbles (chert etc.); a2, polished surface, illustrating sutured contacts between pebbles (arrows). (b) View on the southern slope of the Katalimata-massif, east of the Ierapetra fault, showing succession of Males conglomerates (Ma) overlain by 200 m of coarse clastics of the Fothia Formation (Fo) and capped by the allochthonous Katalimata-deposits (Ka).

region, it is necessary to correlate the Neogene successions on either side of the fault. There are some fundamental differences in lithostratigraphic development.

Firstly, the Mithi Formation is not developed east of the fault. The oldest Neogene sediments belong to the Males Formation. Palaeocurrent directions in the Males Formation are consistent with those west of the fault, i.e. to the west. Secondly, the fluvial Males clastics do not grade into marine marls at the top. Instead, the upper part of the Males Formation is characterized by sudden influxes of Tripolitza limestone debris and a rapid transition to the Fothia Formation. The Fothia Formation is a coarse clastic unit (up to 500 m thick), mainly consisting of irregularly stratified polymict conglomerates. Throughout the sequence the prevailing palaeocurrent directions are to the southwest. The components are derived from the Plattenkalk Series, the PQ-unit and the Tripolitza Series, which are exposed further to the north. The formation does not indicate sequential erosion of the nappe pile. The basal terrigeneous clastics were accumulated in a piedmont area. Upwards and westwards the number and thickness of finer grained beds increases, suggesting a gradual shift towards a coastal plain environment. The Fothia Formation is overlain by marine sediments of the Makrilia Formation (Table 1).

In the Katalimata area, just east of the Ierapetra fault (Fig. 2), the basal 200 m of conglomerates of the Fothia Formation are truncated by a chaotic association of exotic blocks which displays many of the mass-transport features of the Prina Complex. Slickensides at the base of some of the blocks indicate that they slid to the southwest. Due to its coherent character and lateral extent, more than 4 km in the direction of transport, this unit has the appearance of a thrust mass (Fig. 8b). The allochthonous mass is over 200 m thick and contains blocks of Tripolitza limestone (up to several hundreds of metres in length) plus minor elements of the Plattenkalk Series and PQ-unit, all embedded in a sheared fine grained matrix.

A few kilometres north of the Katalimata-massif, the same chaotic deposits are found, this time directly on top of distinctly tectonized pre-Neogene rocks and remnants of Males and Fothia sediments (Fig. 7b). This area therefore strikingly resembles the situation reported in this paper from the northern parts of the Ierapetra depression (Pirgos section). Further to the east, 5 km away from the fault, 80 m of poorly stratified debris-flow deposits, including blocks of more than 10 m diameter, are intercalated in the Fothia Formation and represent a distal development of the Katalimata-deposits.

DISCUSSION

The position of the UM-unit in the Selakkano, Katharo and Kritsa valleys proves the existence of early WNW-ESE trending graben structures which became (partially) filled with Neogene sediments (Peters 1982). The normal faults were subsequently covered by the Prina Complex, as exemplified by the spatial distribution of pre-Neogene and Neogene rocks at the southeastern end of the Katharo valley (Fig. 2).

During deposition of the Males Formation sedimentation was uniform over large areas all over southeastern Crete. The palaeocurrent directions invariably indicate sediment transport parallel to the orientation of the WNW–ESE older grabens. Vertical movements may have been limited because the monotypical component association of these mature sediments points to derivation from only one level in the nappe pile.

Comparison of the lithostratigraphic data from both sides of the present Ierapetra fault shows that, due to renewed tectonic activity in the region, an important palaeogeographical division took place in the Late Serravallian. West of the fault, relative subsidence led to a transgression and resulted in the deposition of marine marls on top of Males conglomerates. However, the area east of the fault was uplifted and the nappe pile deeply eroded, leading to the deposition of a thick sequence of coarse clastics on the Males Formation. Subsequently, normal sedimentation was interrupted by a major period of gravity sliding, forming the Prina Complex west of the fault and the Katalimata deposits east of it.

To the west, the WNW–ESE oriented fault zones were reactivated. The presence of both normal and thrust faults in this area indicates a close relation in space and time of extensional and compressional zones. Strong uplift of basement fault-blocks in the north occurred along the WNW–ESE faults and huge masses of Tripolitza limestone, which characterize the lower level of the Prina Complex, moved as rotational slides from the upwarped basin margin. During their basinward transport these exotics eroded rocks of the UM-unit and basal Neogene sediments in the relatively down-thrown segments of the fault zone, forming a chaotic mixture. Generous supply of the blocks indicates rapid upwarping of the Tripolitza Series. The presence of marine boulder conglomerates in the upper level of the complex, many components of which have been derived from the Plattenkalk Series, proves that in the final stage of events the deepest levels of the pre-Neogene nappe pile were being eroded along the northern basin margin. This implies considerable vertical movements. Strong subsidence is also indicated by the contemporaneous submarine fan deposits of the Kalamavka Formation (Fortuin 1978).

The distribution of incorporated Males sediments, lateral discontinuity of the sedimentary sequences, and structures in the complex clearly show that large parts of the complex slid several times *en masse*, leading to its chaotic character. Shear in the deeper levels of the complex is indicated by well-defined deformation structures, such as intensively deformed pebbles. In the upper part, deformation is less pronounced and mainly expressed as normal faults and soft-sediment deformation. The configuration of the marine boulder conglomerates is compatible with low-angle listric normal faults

(Fig. 3), as argued by Jackson *et al.* (1982) and Wernicke & Burchfiel (1982).

The observed thrust faults in the NW-part of the Ierapetra region point to local shortening, related to the genesis of the Prina Complex. Because of its limited extent and the fact that no regional Late Serravallian thrusting has been reported from the south Aegean area (Angelier 1979), we consider it to be a local phenomenon, typifying the Ierapetra region. Local shortening in an otherwise extensional setting can be the result of strike-slip movements. As suggested by Mitchell & Reading (1978) and Reading (1980), zones of shortening and extension may accompany lateral crustal displacements, with the possibility of local thrusting, rapid vertical movements and basinward-thinning facies units. This pattern is similar to that found in the Ierapetra region. If we adopt the concept of wrench tectonics and interpret the Ierapetra region as part of a NE–SW oriented strike-slip zone that was initiated in the Late Serravallian and was bounded in the east by the present Ierapetra fault, it could account for:

(1) The stratigraphic anomalies between the basal Neogene successions east and west of the fault. As shown earlier, the area east of the fault was uplifted and eroded while marine marls were deposited further west. As regards the palaeocurrent directions within the Fothia Formation, which are directed westwards towards the Ierapetra fault, and the total absence of Fothia clastics in the western marine deposits, it is concluded that the sedimentary environments were initially well separated and that strike-slip movements are necessary to produce the present configuration.

(2) Simultaneous development of both extensional and compressional tectonics within the fault zone. Areas of divergence and convergence in strike-slip zones are the result of curvature of the faults. Divergence leads to subsidence and is well exemplified in the Ierapetra region by the rapid formation of a marine basin whose geometry is compatible with the orientation of the strike-slip zone. On the other hand, convergence causes local thrusting and strong uplift of fault-blocks. Synchronous erosion and (subaqueous) mass-gravity processes lead to formation of thick clastic facies units with local provenance of the components and restricted lateral extent, which characterize the Prina Complex.

(3) The lateral discontinuity of the mass-transport features in the Fothia Formation east of the fault (Katalimata deposits).

(4) The relatively strong disturbance of all Neogene deposits in the area compared to other Neogene basins on Crete. We interpret this to be the consequence of a wide zone of intensively faulted pre-Neogene and lower Neogene rocks which, during the younger phase of normal faulting, was rejuvenated and split up into numerous fault-blocks.

Interpretation of the Prina Complex

The chaotic character of the Prina Complex makes the term 'sedimentary mélange' an appropriate qualification. The complex is in many aspects similar to the Casanova Complex in the Apennines (Italy), a sedimentary mélange studied by Naylor (1982). But, besides the soft-sediment deformation described by that author, we have clear evidence for tectonic deformation in the lower level of the complex. The distinction between tectonic and sedimentary processes is difficult to make in certain parts of the complex, thus emphasizing the importance of using the term 'mélange' as a descriptive field term and not as a genetic classification (see discussions by Naylor (1982) and Özkaya (1982)). In addition, it is interesting to note that our environmental setting is very different from the one postulated by Naylor (1982) for the Casanova Complex, which originated at a distal passive continental margin, approximately at the junction between oceanic and continental crust.

The Prina Complex did not result from one catastrophic event but is related to rapidly changing tectonic conditions in a strike-slip zone, associated southward sliding of pre-Neogene exotics and Neogene sediments, and continuous readjustment of the depositional environment in the basin. The complex illustrates instability along an incipient basin margin. The gliding masses may have been triggered by high seismic activity which is a characteristic feature of modern strike-slip zones.

Regional significance

The pattern of thrusting in a NNE–SSW direction, as observed in the NW-part of the region, can be expected in a sinistral, NE–SW oriented strike-slip setting (see Harding 1974). Unfortunately, the sense of movement cannot be determined by lateral matching of displaced palaeogeographies across the fault zone because, due to extensive younger faulting and erosion, the present distribution of Miocene sediments does not directly reflect the palaeodepositional surface. Consequently, we now discard the suggestion of Fortuin (1978) that dextral movements took place along the fault zone because this idea was based on correlating the northern limit of exposures of the Males Formation.

A NE–SW orientation of the strike-slip vector would conform to the orientation of the South Cretan trough and thus fit into the picture of kinematics of the south Aegean area. If sinistral wrenching indeed controlled the Miocene structure of the Ierapetra region and the South Cretan trough, this would considerably strengthen the theory of Le Pichon & Angelier (1979) that the geometry of subduction in the south Hellenic Arc has not changed significantly since its initiation in Late Serravallian times. However, the active Ionian continental margin in the northwest sector of the Hellenic Arc was formed later, in the Lower Pliocene (Sorel *et al.* 1976, Mercier 1981, Laj *et al.* 1982). Thus the present subduction system is not older than approximately 13 Ma, with most of the motion occurring since the uppermost Miocene (Huchon *et al.* 1982).

Because there are no indications of post-Miocene lateral displacements in the Ierapetra region and the

South Cretan trough, strike-slip movements must have ceased in a later stage. A similar tectonic development of a Late Serravallian–Early Tortonian sinistral strike-slip zone, followed by normal faulting has been reported from the southern Peloponnese by Lallemant *et al.* (1983).

Recent normal faulting in the Ierapetra region is related to the current regional stress pattern which leads to NW–SE extension (Mercier *et al.* 1974, Angelier *et al.* 1982). The area east of the fault was rapidly uplifted during the Quaternary, leading to the formation of marine terraces along the south coast (Angelier & Gigout 1974, Angelier *et al.* 1976). The South Cretan trough is also characterized by normal faulting (Leité 1980, Leité & Mascle 1982) and although there is a dense cover of seismic profiling in this area, no evidence has been found for strike-slip faults (Huson 1982).

The reported change in structural style may be related to an eastward progression of the inferred transform movements. The possibility of eastward progression of strike-slip movements in the eastern portion of the Hellenic Trench, which consists of a double system of SW–NE oriented trenches, has been suggested by Jongsma (1977) and Mascle *et al.* (1982b). Huchon *et al.* (1982) have pointed out that this tendency is linked to the kinematics of subduction. Seismic investigations (Leité & Mascle 1982) and Sea-Beam morphological studies of the Pliny and Strabo trenches (Le Pichon *et al.* 1979a, Lybéris *et al.* 1980, Huchon *et al.* 1982) demonstrate the presence of en échelon patterns of small troughs, which indeed suggest sinistral strike-slip movements (Fig. 1).

We postulate that the Ierapetra basin and the South Cretan trough were initiated in the Late Serravallian as a strike-slip zone and became subject to extensional deformation when the transform motions shifted eastward. Their Miocene evolution may represent an early phase of crustal dynamics related to the formation of the Hellenic Trench and the onset of subduction of Mediterranean lithosphere.

To conclude, we would like to suggest that, as an alternative interpretation, the thrusting reported from the southwest part of the Rhodes basin (Jongsma & Mascle 1981, Mascle *et al.* 1982a) may be an expression of an initial stage of transform movements (transpression) in the eastern part of the Strabo trench. The scale of the observed deformation structures is much larger than the arc-directed thrusts reported further west in the outer slope of the Hellenic Trench (Le Pichon *et al.* 1979b) and we feel that the processes involved are clearly different.

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