Footwall degradation styles and associated sedimentary facies distribution in SE Crete: Insights into tilt-block extensional basins on continental margins

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Abstract

Depositional facies resulting from footwall degradation in extensional basins of SE Crete are studied based on detailed geological maps, regional transects, lithological columns and outcrop photos. During an extensional episode affecting Crete in the late Miocene-early Pliocene, depocentres trending N20oE and N70oE were filled with fan deltas, submarine mass-wasting deposits, turbidites and fine-grained hemipelagites sourced from both nearby and distal sediment sources. Deposition of proximal continental and shallow-marine units, and relatively deep (marine) turbidites and mass-transport deposits, occurred within a complex mosaic of tectonically controlled depocentres. The new geological maps and transects in this work reveal that depositional facies in SE Crete were controlled by: a) their relative proximity to active faults and uplifting footwall blocks, b) the relative position (depth and relative height above sea level) of hanging-wall basins, and c) the nature of the basement units eroded from adjacent footwall blocks. Distal sediment sources supplied background siliciclastic sediment ('hemipelagites'), which differ markedly from strata sourced from local footwalls. In parallel, mass-transport of sediment was ubiquitous on tectonically active slopes, and so was the presence of coarse-grained sediment with sizes varying from large blocks >50 m-wide to heterolithic mass-transport deposits and silty-sandy turbidites. We expect similar tectono-

sedimentary settings to have predominated in tectonically active Miocene basins of the eastern Mediterranean, in which hydrocarbon exploration is occurring at present, and on rifted continental margins across the world.

Keywords: Extensional basins; Eastern Mediterranean Sea; Miocene; Messinian evaporites; footwall degradation; depositional facies.

1. Introduction

Extensional (or syn-rift) basins are often filled by continental and shallow-marine deposits in their initial stages, later forming marine depocentres as crustal stretching leads to fully rifted continental margins (Mohriak and LeRoy, 2013; Ellis and Stoker, 2014; Leleu et al., 2016). Yet, their depositional histories are still poorly documented in the literature, chiefly because syn-rift strata on continental margins are frequently buried under thick post-rift successions. Extensional basins also record complex (and markedly variable) evolutions depending on their position(s) relative to the future axes of continental breakup (Nirrengarten et al., 2017; Alves and Cunha, 2018). A first characteristic known to induce complexity in extensional systems is that proximal parts of future continental margins become important sources of sediment to more distal rift axes, particularly as the former are exhumed and become the shoulder areas of the latter during the last stages of rifting and continental breakup (Braun and Beaumont, 1989; Huismans and Beaumont, 2011; Hartz et al., 2017). Second, resulting continental-slope basins are predominantly filled by mass-wasting strata, including disrupted channel-fill and turbidite deposits (so-called olistrostromes) whose development and distribution are markedly controlled by the subsidence histories of discrete depocentres and adjacent highs (Alves et al., 2009, Alves and Cunha, 2018). This characteristic often results in the deposition of 'passive margin' olistrostromes containing both intraformational and exotic blocks (Ogata et al., 2012; Festa et al., 2012, 2016), which are usually poorly imaged on seismic data (Liu et al., 2016; Riedel et al., 2016). Third, the depositional architecture of syn-rift basins is also controlled by the nature of basement units, producing variable regoliths that are eroded at variable rates (and at different times) during crustal stretching (Blaich et al., 2011; Gerginon et al., 2014). This latter caveat is all the most important when considering that borehole data of syn-rift footwall degradation complexes are seldom documented in the literature.

In extensional basins, footwall degradation occurs not only on exposed (subaerial) tilt-blocks (Densmore et al., 2004, 2009), but also over submarine footwall blocks affected by strong currents and slope instability (Micallef and Mountjoy, 2011). Alternatively, thick salt and carbonate units may accumulate in closed, confined seas generated during continental breakup as documented, for instance, in SE Brazil and West Africa (Beglinger et al., 2012), or in the Central Atlantic Ocean (Tari and Jabour, 2013). Dominated either by evaporite, carbonate or siliciclastic deposition, hyperextended blocks close to the loci of continental breakup record enhanced faulting, footwall degradation and erosion (Alves et al., 2009; Jeanniot et al., 2016; Alves and Cunha, 2018).

As the few examples of marine syn-rift strata documented in the literature have focused on continental margins drilled by the Deep-Sea (DSDP), Ocean Drilling (ODP) and International Ocean Drilling (IODP) programmes, or used geophysical data of insufficient quality beyond a certain depth (e.g., Wilson et al., 2001; Tucholke and Sibuet, 2007), there is a pressing need in academia and industry for new outcrop analogues of extensional basins revealing structures and stratigraphic sequences of similar scales to those imaged on state-of-the-art seismic data. Southeast Crete is one such analogue region, and records the deposition of late Miocene strata sourced from nearby footwall blocks, continental shelves and distal slopes under significant late Miocene extension (Fortuin, 1978; Peters, 1985; Postma and Drinia, 1993; ten Veen and Postma, 1999; Alves et al., 2007; Alves and Lourenço, 2010) (Fig. 1).

A new set of depositional facies maps for SE Crete is presented here based on a reassessment of stratigraphic formations interpreted in Fortuin et al. (1977), Postma and Drinia (1993) and ten Veen and Postma (1999). We reassessed the significance of distal marine strata outcropping on coastal areas of SE Crete to understand the degree of stratigraphic overlap (i.e., lateral variations in facies) between distal marine successions and more proximal strata in extensional basins (Fig. 1). In order to achieve this goal, we grouped the regional tectono-stratigraphic units defined by Postma (1990) and Postma and Drinia (1993) into genetic units, and analysed them in the context of a rifting, fault-dominated, South Aegean region during the late Miocene. This study has implications for the interpretation of: a) pre-evaporite successions in the Eastern Mediterranean Sea, and b) syn-rift successions on deep-water continental margins.

2. Materials and methods

This work presents new geological maps, regional transects, lithological logs and outcrop photos from SE Crete. It documents the basin expansion in the investigated area, where a series of hanging-wall basins and adjacent footwall blocks are exposed (Figs. 1c, 2). The approach followed in this study was to reassess morphological and sedimentological features related to (syn-rift) footwall degradation as recorded by upper Miocene strata(Figs. 2a, 2b). In addition, we conducted a re-mapping of the Fothia Formation (Fortuin, 1974) in the region east of the city of Ierapetra. The sediments of Fothia Formation were re-interpreted as a lateral equivalent of strata spanning the entire late Miocene in the Ierapetra Graben and surrounding paleoslopes (Fig. 2b).

Our geological data were acquired using army maps at a 1:50,000 scale (Hellenic Mapping and Cadastral Organization) as reference maps. Relative ages for the interpreted stratigraphic formations are based on Fortuin (1977, 1978); Meulenkamp (1979), Peters (1985), Postma and Drinia (1993), Postma et al. (1993), Van Hinsbergen and Meulenkamp (2006) and Zachariasse et al. (2008). Most of these ages derive from detailed micropaleontological analyses of foraminiferal assemblages collected in the Ierapetra Graben (e.g., Fortuin, 1977; Fortuin and Peters, 1984; Peters, 1985; Zachariasse et al., 2008).

3. Geological Setting

3.1 Late Cenozoic convergence and extension in the Eastern Mediterranean

The Eastern Mediterranean Sea, in which Crete is located, was first generated by the segmentation of the Pangean supercontinent (Koukouvelas and Doutsos, 1990; Burg et al., 1996; Koukouvelas and Aydin, 2002), and was deformed during the late Mesozoic-Cenozoic due to convergence between the African, Eurasian and Arabic tectonic plates (Thomson et al., 1999; Romer et al., 2008) (Fig. 1a). The closure of the Neotethys Ocean produced E-W structures in the Aegean region, which accreted with a microcontinent (Apulia) to generate the Hellenic Arc and associated tectonic nappes in the late Cretaceous-Paleogene (Stampfli, 2000). These nappes form the basement units of Greece and surrounding islands (Kissel and Laj, 1988; Pearce et al., 2012; Sachpazi et al., 2016) (Fig. 1b).

The Hellenic Nappes comprise the dominant basement sequences of Crete, and two main units are usually recognised in them; a pre-Neogene unit and a Neogene unit, the latter of which includes strata accumulated in supradetachment basins (van Hinsbergen et al., 2006) (Figs. 1b, 2a). Thus, Crete comprises a nappe of non-metamorphic rocks (Upper Sequence) over which Neogene strata were deposited, and a metamorphic unit named the Lower Sequence (van Hinsbergen et al., 2006; Kokinou et al., 2012) (Fig. 1b, 2a). Separating the Lower and Upper Sequences are several extensional detachments of Oligocene-Miocene age that outcrop in parts of Crete (Figs. 1b, 2a). These extensional detachments have exhumed the Lower Sequence over footwall blocks to form extensional klippens on Crete, and several islands and offshore structural highs of the Aegean Sea.

Extensional detachments are chiefly located at the base of the Upper Sequence, i.e., close to the contact with Cycladic Blueschists, granites and metamorphic basement rocks (Fig. 2a).

At present, the Aegean Sea records 90o convergence west of central Greece, with a change towards an oblique configuration south of Crete (Papazachos et al., 2000; Bohnhoff et al., 2005; Shaw and Jackson, 2010). This obliquity in the convergence vectors is responsible for important transtension south of Crete, and has triggered a long period of extensional collapse since the Middle Miocene (Fassoulas et al., 1994; Ring et al., 2001; Papanikolaou and Vassilakis, 2010) (Fig. 1a). Importantly, sidescan sonar and high-resolution seismic data show, at present, a similar tectono-stratigraphic setting to the late Miocene. Similar depositional facies to those exposed in the Ierapetra Graben predominate along the modern continental slope of South Crete (Alves et al., 2007; Kokinou et al., 2012).

3.1.1 Lower Sequence

The Lower Sequence includes a thick succession of phyllites, quartzites (Phyllite-Quartzite Unit) and ‘parauthochtonous’ rocks in the Plattenkalk Series, a hard carbonate-rich series forming the core of Crete’s mountains (Creutzburg et al., 1977; Thomson et al., 1999; Papanikolaou and Vassilakis, 2010). Data in Thomson et al. (1999) indicate that the High Pressure-Low Temperature (HP-LT) rocks of Crete were subducted between 36 and 29 Ma (latest Eocene-early Oligocene), heated to peak temperatures in excess of 350°C, and then rapidly cooled to below 290°C prior to 19 Ma (Burdigalian). These same HP-LT rocks were at temperatures below 60°C at ~ 15 Ma (Langhian). The Plattenkalk Series should have undergone the same sequence of events in an even shorter time period, i.e., as short as 10 Ma (Thomson et al., 1999). Thus, depths of <10 km and temperatures <300oC predominated after 19 Ma (Burdigalian) in what were, prior to their exhumation, HP-LT units buried at depths of 30-40 km (Thomson et al., 1999).

3.1.2 Upper Sequence and overlying supradetachment basins

The Upper Sequence on Crete comprises non-metamorphic rocks and younger sediments (Ring et al., 2001). In SE Crete, non-metamorphic Upper Cretaceous–Eocene rocks are part of the highly faulted Tripolitza unit (Zambetakis-Lekas et al., 1998; Ring et al., 2001). Above these limestones were deposited Neogene strata in supradetachment (extensional) basins (Ring et al., 2001) (Fig. 2b). According to Meulenkamp et al. (1994), Langhian strata in the Mithi Formation (at the base of the Miocene sequence in SE Crete) represent deposition in a fluvial peneplain and, therefore, can be used as a marker of tectonic movements (subsidence and uplift) on the island.

3.2. Facies associations in supradetachment basins

Meulenkamp et al. (1979) divided the Neogene (supradetachment) units of Crete into six stratigraphic groups; Prina, Tefeli, Vrisses, Hellenikon, Finikia, and Agia Galini (Alves et al., 2007, their Fig. 2). Stratigraphically, these groups are observed below thin, undifferentiated Quaternary strata. Locally in the Ierapetra Graben, Postma and Drinia (1993) subdivided the six stratigraphic groups of Meulenkamp et al. (1979) in facies associations. These facies associations reflect proximal (continental) to distal (marine) environments:

a) Facies associations A to C (Fa A-C) comprise deep-water delta and slope systems forming the most part of the Kalamavka and Makrilia Formations (Figs. 2b, 3d, 4). Fa A comprises channel-fill pebble to cobble conglomerates that are up to 2–3 m thick and massively bedded. They are included in bioturbated laminated sand and mud intervals. Fa A is generally sandier and more stratified than the conglomerates embedded in Fa B–C (Figs. 3d, 4). Facies associations B and C comprise finer-grained material, mostly representing turbidite deposits, with distinct amounts of coarse-grained material. In contrast to Fa B, the finer-grained Fa C shows rare sandstone intervals and is essentially composed of blue-grey fossiliferous marls with abundant Zoophycos ichnofacies. Much of the coarse-grained material in these deep-water systems suggests a slope environment where seafloor instability was common and tectonic oversteepening prevailed. Postma and Drinia (1993) present evidence for submarine slope channels incising into delta slopes, and transferring small lobe deposits in the form of thin turbidites sandstone sub-units with sheet-like geometries. According to the latter authors, such a character indicates a lateral shift in point sources of sediment.

b) Facies association 1, or Fa1, comprises alluvial systems and mass-flow deposits that alternate with conglomerate beds deposited by cohesive debris flows, sensu Lowe (1982). This facies association is chiefly represented by the Males Formation, but is also visible in parts of the Fothia Formation on the eastern shoulder of the Ierapetra Graben (Figs. 1c, 2b, 3a). Stream-flow deposits can be documented at Kalamavka and also east of Ierapetra (Fig. 1c). Current directions are predominantly to the south and southwest (Alves and Lourenço, 2010) (Fig. 5).

c) Facies associations 2 to 4 (Fa 2-4) comprise delta and prodelta units. They were deposited by a shallow-water delta system around Ierapetra and later disrupted on tectonically active slopes to form the Prina Series (Postma and Drinia, 1993) (Figs. 2b, 3b, 3c). Typical lithologies in Fa 2-4 are ungraded and graded pebbly sandstone beds, fine to coarse-grained sandstone sheets, and thin-bedded sandstones and marls. Burrows are common in Fa 2-4 and include Skolithos, Chondrites and Thalassinoides ispp. Boulder conglomerates comprise structureless lobe-shaped beds that are up to 2 m thick. Intervals with sand and silt in Fa 2-4 were affected by wave action and likely triggered by stream floods and hyperpycnal flows during periods of extreme water discharge.

In addition to facies associations of Postma and Drinia (1993), Postma et al. (1993) and ten Veen and Postma (1999) interpreted five post-mid Miocene tectonic sequences on Crete (Table 1). We acknowledge the latter tectonic sequences in this work, but we divide the strata observed in the field into specific genetic units as we found strata on coastal outcrops to be less time-specific than considered by Postma et al. (1993) and ten Veen and Postma (1999). Hence, the focus is given in this work to depositional facies, not tectonic sequences, as seemingly synchronous strata present distinct depositional facies along SE Crete, as also suggested by Fortuin (1977, 1978) (see regional correlation panel in Fig. 2b, Table 1).

4. Results

4.1 Key structures and lithologies at outcrop

The new maps and corresponding transects in this paper reveal three distinct zones in SE Crete (Figs. 6-8). The three zones follow, and are separated by, faults striking WNW (N70o E to N90oE) and NE-SW (N20oE to N40oE).

Zone 1 stretches from Arvi to Gra-Ligia (Fig. 6). Here, a series of N70oE to N90oE faults bound a late Serravalian-early Pliocene continental slope exhumed in the Quaternary to expose a series of marine units (Fig. 4, Table 1). Zone 1 comprises autochthonous carbonate fans and boulder conglomerates interbedded with slope turbidites (Figs. 6, 9). Turbidites and individual mass-transport deposits are more abundant on coastal outcrops, reflecting a distal slope succession with prominent gully and channel-fill deposits. Sand-mud ratios in this area are relatively high as channels were capable of transferring coarse-grained material from hinterland sources (Figs. 6, 9, 10).

Inland, towards the village of Anatoli, there is a gradual increase in the volume of carbonate megabreccias and fan-delta deposits (Fig. 7). In addition, most of the Males Formation is disrupted and fragmented in discrete blocks. Boulder conglomerate units of Fa 2–4 predominate in proximal regions of Zone 1 (to the north), whereas Fa A to C are common on the coast, where a relatively deeper late Miocene-Pliocene depocentre was located (Figs. 7-12).

Zone 2 corresponds to the Ierapetra Graben, which is bounded by the Anatoli anticline (and associated paleoslope) to the northwest, and to the east by the southwards prolongation of the Ierapetra Fault to the south; the Ierapetra Cape Horst (Fig. 7). This horst is blanketed by a large, faulted mass-transport complex (Fothia Formation) that spans most of the late Miocene (Fig. 7). To the west of the Ierapetra Cape Horst, the Ierapetra Graben was filled by a minimum of 1400 m of sediments in the late Miocene-early Pliocene (Fortuin, 1977).

The Ierapetra Graben is bounded to the north by a series of faults marking the Makrilia Fault Zone sensu Postma and Drinia (1993). Zone 2 is dominated by distal marine facies (Fa A to C), deposited within the main basin depocentre in the SE Crete, the Ierapetra Graben (Figs. 7, 13, 14). The two shoulders of this graben record important mass-wasting with large scale megabreccia blocks dominating the successions deposited there (Figs. 13, 14). In these two shoulder areas, boulder-conglomerate and megabreccia blocks overlie continental to shallow-marine siliciclastic units of the Males Formation (Figs. 2b, 14). This setting is well documented on the western shoulder of the Ierapetra Graben, whereas a combination of fault scarps and displaced megabreccia blocks is observed towards the east at Fothia (Fig. 13). The same region documents the intersection of ENE-WSW and NNE-SSW faults and comprises large slide blocks embedded in marine (Makrilia Formation equivalent) siliciclastic sediments (Fig. 11).

Zone 3 includes the region east of Ierapetra, from Ferma to Makri Gialos, and includes the southern prolongation of a sedimentary basin named as Sitia Basin by ten Veen and Postma (1999) (Fig. 8). In this region, a series of tilt-blocks and associated half-graben basins (generally trending N70oE to N90oE) are filled with continental/alluvial to deep-marine strata, as shown later in this paper. Zone 3 comprises alluvial fan deltas vertically stacked in between ‘background’ shelf sandstones and mudstones with a characteristic yellow to white colour (Figs. 15, 16). In places, strata in alluvial cones and fan deltas dip towards the North due to local rotation of tilted blocks (Fig. 17a). South of the area of tilt-block rotation is observed a marked change in facies towards Fa A to C, which predominate in coastal outcrops (Fig. 17b). Structural deformation at some of these coastal outcrops is clearly associated with local extensional faults, tilt-block rotation, and with prominent (slope) instability of marine successions of Fa A to C (Fig. 17b, 17c).

4.2 Genetic units associated with footwall degradation

In this work, we reassess the facies associations documented in Postma and Drinia (1993) in larger genetic units that are specifically associated with footwall degradation, and correlate to seismically resolvable units on geophysical data.

4.2.1 Fan deltas

Description: Fan deltas (Fa1) are observed in the northernmost parts of Zones 1 and 3 as the most proximal deposits in SE Crete (Figs. 6-8). Fan deltas are chiefly observed on the paleoslopes bordering the Ierapetra Graben, where they comprise autochthonous megabreccia fans and rotated slabs tens to hundreds of metres thick (Fig. 14). In Zone 3, fan deltas are fed from distinct basement units, and include polymictic breccias and conglomerates. These fan deltas are stacked vertically on top of rotated hanging-wall blocks (Figs. 18, 19). Clasts in these polymictic breccias were derived from Tripolitza and flysch units that outcrop in nearby mountains. In addition, dispersed clasts of higher-grade metamorphic rocks include marbles and ophiolites sourced from rocks below the Cretan detachment (i.e., Lower Sequence) (Fig. 3d).

One such example is observed east of Kalamavka village, where alluvial systems of facies association 1 (Fa1) are abundant within the Males Formation (Figs. 2b, 3c). A second example is recorded at Agios Ioannis (Fig. 19). Here, limestone rich fan deltas breccia–conglomerates were deposited above shallow marine strata equivalent to the shallower part of Kalamavka Formation (Fig. 2b). Isolated disrupted sediment blocks that are not part of the Prina series rest above (or are partly embedded within) marine clays, marls, and sands belonging to facies associations similar to those in the Kalamavka Formation (Fig. 2b, 19).

Breccia–conglomerate fans are mainly documented in Zone 3, where stacked successions of fan deposits occur over rotated half-grabens (Figs. 8, 17). Here, breccia–conglomerates show a predominance of carbonate clasts derived from Tripolitza and Plattenkalk basement units, but also mixed with higher grade metamorphic clasts derived from the Flysch unit and from units below the Cretan detachment.

Interpretation: Fan deltas in SE Crete are dominated by mass-flow deposits, with conglomerate beds originating from cohesive debris flows, sensu Lowe (1982), whereas stream-flow deposits are observed around the village of Kalamavka (Fig. 7). Current directions in these latter alluvial systems are predominantly to the S and SE as revealed by cross-bedding geometries, imbricated clasts and lateral facies variations within the Males Formation (Figs. 2b, 5).

Vertical stacking of fan deltas was an important process in proximal parts of Zone 3, with E-W half-graben basins becoming the location of significant breccia-conglomerate deposition (Figs. 14, 18). Fan deltas were fed by alluvial fans, are smaller than the deltas of contemporary rivers, and are characterised by large variations in morphology, geometry and facies (Postma, 1990). Therefore, the prominent structural style in this type of deposits is one controlled by active normal faults that dissect the slope, oversteepening and fracturing the basement to develop footwall degradation products. This is particular the case for Zone 3, whereas fan deltas in Zone 1 contain less angular breccia-conglomerates, which indicate relatively longer sediment transport.

4.2 Mass-transport deposits and oversteepened (slumped) strata

Description: Mass-transport deposits (Fa2-4 and A-C) are abundant in Zones 1 and 3, and often occur together with large 5–100 m-wide blocks in distal parts of fan deltas in Fa 2-4 (Figs. 3a, 19). These blocks were separated from fan deltas during late Miocene tectonics and were mostly transported downslope over a ductile substrate (see Alves and Lourenço, 2010). Towards the easternmost part of Zone 1, large blocks give rise to discrete mass-transport deposits and slabs, most of which remobilised carbonate and sandy intervals in lower-slope stratigraphic successions. Thus, there is an overall tendency for slumped strata and discrete (but relatively thin) mass-transport deposits to occur at coastal outcrops in Zone 1, with sporadic blocks being observed here (Fig. 6). In turn, the more proximal parts of the paleoslope in Zone 1 reveal the presence of large slide blocks that are buttressed against slope strata of Makrilia and Ammoudhares facies (Figs. 3a, 6).

An example of the importance of mass-transport to the development of palaeoslopes in Zone 3 is shown west of Makri Gialos where slumps occur over a wide area (Fig. 8). Here, intraformational slumps can form thick successions of disrupted strata that not only contain ‘background’ siliciclastic material, but also slumped channel-fill deposits, limestone and sandstone blocks disrupted on a tectonically active slope (Fig. 19).

Interpretation: These deposits are typical of a slope environment where rivers and streams are capable of bypassing the narrow continental shelf to form submarine channels on the slope. Most channel-fill sediments show some degree of tectonic oversteepening and later collapse on marine slopes (Figs. 8, 19). The Ammoudhares Formation caps these channel-fill strata and comprises marls and bioclastic limestones reflecting a relative shallowing of the region during the Messinian (Fig. 2b).

Large slumped masses of calcarenites and turbidites devoid of slide blocks are indicative of slope oversteepening on local paleoslopes. This character is commonly observed within the Makrilia and Ammoudhares formations, with slumped strata being scattered on coastal outcrops that extend from the village of Ammoudhares to Arvi, both in Zone 1 (see Fig. 10 as example). In these areas, slumping occurred in intervals with sandy interbedded channel-fill deposits and (finer-grained) hemipelagites. Slumping can be local (affecting a few metres of strata) to involving large slabs 50-100 m in length. In Zone 3, the mud-rich matrix in boulder conglomerates suggests deposition from cohesive debris flows, in a setting dominated by slope instability and block movement over a ductile, oversteepened slope. Reservoir potential is relatively poor in these gravitational units as sands composing discrete clasts have been cemented prior to mass-wasting. Carbonate blocks also have a clayey matrix that derives from deposition in proximal alluvial fans prior to their disruption on the continental slope (Alves and Lourenço, 2010).

4.3 Undisturbed (background) hemipelagites

Description: Background hemipelagites and distal submarine fan deposits are particularly observed in the Myrtos area, in the Ierapetra Graben, and at Cape Ierapetra (Figs. 6-8, 16). They comprise loosely consolidated silty sands and clays interbedded with channel-fill deposits comprising a > 1000 m-thick succession at Makrilia, and approximately 500 m-thick at Myrtos (Fig. 8). Turbidite deposits are mostly fine-grained at the limit between Zones 2 and 3 (Fig. 7). Distal submarine fan deposits are not observed in Zone 3, around Makri Gialos. Instead, a series of shelval deposits with important carbonate contribution is recorded by the deposition of sand-silty successions with coarser channel and submarine-fan deposits (Fig. 8).

Interpretation: The relative scarcity of sand in Zone 2 indicates that the area was relatively far from local sediment sources. These sediments are, towards the east in Zone 3, increasingly interbedded with channel-fill breccias and conglomerates representing episodes of channel erosion derived from footwall blocks to the north.

Slope turbidites are abundant in Zone 1, in proximal parts of Zone 2, but occur only at coastal outcrops in Zone 3 (Fig. 8). Background sediment comprises silt and clay with variable amounts of dispersed sand - often resting on south-facing monoclines (Figs. 17, 18). In Zone 1, strata in the Makrilia and Ammoudhares formations are deformed ahead of a large recumbent fold, and show remobilised channel overbank sands and silts in coastal outcrops (Alves and Lourenço, 2010, their Fig. 14). Fracturing and injection of sandy layers associated with this frontal fold denotes a ductile regime occurring typically a few metres below the paleoseafloor.

4.4 Gully- and channel-fill deposits

Description: Gully and channel-fill deposits are ubiquitous at coastal outcrops of Zones 1 and 3, and in several locations around the village of Makrilia (Zone 2) (Fig. 7). This type of deposit comprises polymictic breccias and conglomerates that were chiefly sourced from basement units. Grain size varies from well sorted coarse- to medium-sands, to polymictic gravel and conglomerate channel-fill deposits (Fig. 17). Limestone clasts and boulders are prominent in most coarse-grained deposits.

Gully and channel-fill deposits are also exposed in Zone 3 around Agios Ioannis, occupying similar space as modern subaerial gorges (Fig. 18). This indicates a structural control on the position and distribution of channels, gullies and gorges in the SE Crete. In Zone 1, channel-fill deposits are part of the oversteepened slopes element.

Channel-fill deposits in Zone 2 are observed around the village of Makrilia, where they incise background silts and clays. Their origin is marine, and they reflect episodic erosion of the Makrilia paleohigh, which was providing most of the feeding material to the north in the form of fan deltas and prodelta deposits, some of which resembling breccia-conglomerates in the Prina Group (Figs. 2b, 3a, Table 1).

Zone 3 records the incision of channels and gullies in specific areas of the late Miocene paleoslope, and likely involved an underlying fault-related structural control. Between Agios Ioannis-Sinokapsala, channel-fill deposits are composed of coarse sand and gravel showing massive bedding (Figs. 18, 19). They are intercalated with shelval deposits into which they were incising, and with intervals containing blocks and megabreccias. In this same Zone 3, breccia–conglomerates are markedly coarse, involving the deposition of boulders and large blocks in the fan deltas themselves (Fig. 19). Fan delta sediment becomes relatively finer (but still comprising breccia-conglomerates) in the southernmost tips of fan deltas, suggesting they were deposited in subsiding half-grabens roughly oriented E-W (Fig. 8).

Interpretation: The interpreted depositional systems reflect the incision of channels during relative lowstands (or episodes of footwall uplift), with NE-SW faults leading to the formation of relays between developed N70oE-N90oE faults. These faults and relay zones provided preferential pathways for transport and deposition of products of footwall degradation in the form of streams, channels and fan deltas developed on the paleoshelf, whereas continuous fault strands fed large slide blocks and megabreccias towards evolving depocentres. Such a character indicates that turbidite and mass-transport deposition were occurring at the same time and where complementary.

In Zones 1 and 2, channel-fill deposits alternate with sandstones and conglomerates in main basin depocentres, and with coarsening-upwards massive/parallel-laminated red marls and clays. Finning-upwards turbidites are related to deposition on a fault-bounded slope. Sequences Ta, Tbe/Tbde and Tbcde of Bouma (1962) compose the bulk of the sandy deposits, but proximal Ta sequences predominate in the coarser levels. Polymictic conglomerates and sands relate to submarine canyon deposits. Massive marls, siltstones/sandstones and massive mudstones comprise, respectively, lower-slope Td and Tet turbidites and distal Tet/Teh turbidites/hemipelagic fall-out.

Late Miocene-early Pliocene tectonics (i.e., prior to onset of uplift on Crete) is thus expressed by the deposition of coarse-grained gully- and channel-fill units in the Makrilia and Ammoudhares formations (Table 1). In a region extending from Tertsa to Arvi, marine channel-fill deposits alternate with gravel fills that hint at more proximal, subaerial sources (Figs. 6, 19). We interpret these latter channels as reflecting Quaternary tectonic uplift on Crete and, as such, they likely reflect the erosion of renewed sediment sources. Most of these channel-fill deposits show a clear fining-upwards trend in individual beds, which are stacked in discrete (>30) cycles of sand and silt (Figs. 6, 10). Not every channel incises background slope deposits, with some seemingly emplaced in slope depressions. In this case, overbank deposits show continuity towards the axis of channel-fill strata, pinching-out gradually away from the same channel axes.

6. Discussion

6.1 Local controls of basement lithology on footwall-degradation products

A first question deriving from this study is why there is a significant presence of siliciclastic deposits in the Ierapetra Basin and coastal outcrops of SE Crete when basement units of the whole region are predominantly composed of carbonate rocks. One way to explain this discrepancy is by considering the Ierapetra Basin and adjacent slope depocentres as part of a tectonically active, collapsing Aegean microplate, whose morphology was distinct from the present day's (Meleunkamp et al., 1994; ten Veen et al., 1999; Ring et al., 2001). In other words, the presence of Miocene landmasses and erodible structural blocks close to the island of Crete explains, in the study area, the large volume of siliciclastic units not related to eroded basement units.

It is widely known that a consequence of enhanced footwall degradation, either in continental or marine extensional basins, is a relatively increase in the frequency (and thickness) of coarse-grained material deposited adjacently to active structures (Gawthorpe and Leeder, 2000; Leeder et al., 2002). In extensional basins dominated by siliciclastic depositional systems, the nature and grain size of sediment are closely controlled by the nature of eroded 'basement' rocks (Leeder et al., 2002). Basement rocks that are intrinsically brittle and fine-grained are more likely to produce clays, silts and minor volumes of sand. Basement units dominated by granites and crystalline metamorphic rocks will preferentially produce conglomerates, gravels and sands as predominant lithologies (Knudsen, 2001; Lundmark et al., 2014). When capped by carbonates, subaerial karsts can develop in exposed footwalls (Scheibner et al., 2003; Bosence, 2005; Tomás et al., 2010), whereas large mass-wasting complexes often accompany the degradation of carbonate platforms to increase the extent of reservoir units in immediate hanging-wall basins (Wilson et al., 2000; Bosence, 2005). Farther offshore, carbonate platforms give rise to deep-marine shales and finer-grained material (e.g., Loucks and Ruppel, 2006).

A second, but not less important, question concerns the reservoir potential of fan deltas, which are clearly poorly graded and immature in their nature. Fan deltas in SE Crete occur on hanging-wall depocentres that were formed very close to basement highs, a character implying very little transport of sediment from immediate footwalls and fault scarps. In most of the area around Agios

Ioannis (Zone 3), the fan deltas comprise low porosity immature breccia-conglomerates, occurring together with channellised bodies comprised of coarse sand and gravel. We interpret the breccia-conglomerates as being directly derived from footwall scarps, whereas the channellised bodies were fed by rivers and ephemeral streams capable of bypassing the fan deltas to input sediment in distal slope depocentres (Figs. 14-19). In comparison, Zone 1 fan deltas at NW of Ierapetra are much thinner, smaller in area and widespread laterally. They are also more mature in terms of the clasts they contain, presenting conglomerates, gravel, sand and silt. This difference between fan deltas in Zones 1 and 3 demonstrates a contrast in the lithology of basement units being eroded and relative degree of uplift (i.e., fault activity) experienced by the eroded footwall blocks. Zone 1 fan deltas were deposited on an immediate hanging-wall depocentres to the Ierapetra and Makrilia Faults and, as such, represent a depositional setting of important sediment progradation from structural highs in Zone 2 (Fig. 7). In contrast, Zone 3 fan deltas reflect important activity of N70oE faults and the deposition of coarse-grained sediment in adjacent half-grabens (Fig. 8). In this area, footwall blocks comprise Tripolitza and Plattenkalk limestones that were degraded and eroded to form very immature fan deltas. We therefore postulate that the late Miocene-early Pliocene depositional facies in SE Crete are structurally controlled, with terraced sets of half-grabens controlling the type and thickness of sediment accumulated (Fig. 20).

6.2. Genetic units associated with continental slope basins: comparing SE Crete with drilled deep-water continental margins

Figure 20 presents a schematic illustration (and corresponding lithological logs) across Zones 1 and 2 to illustrate the distribution of late Miocene-early Pliocene strata in SE Crete. In the study area, we observe a tripartite distribution of sediment, with proximal, intermediate and distal depocentres recording different facies associations. The very proximal depocentres formed at this time in subsiding half-graben are filled with alluvial fans and fluvial deposits, which were affected by important erosion and incision by Pliocene-Holocene streams formed due to tectonic uplift and fault reactivation (Fig. 20). These proximal depocentres give rise to an intermediate area with transitional and shallow-marine strata, effectively recording the late Miocene paleo-continental shelf. This shelf was similar to the present-day's, being narrow and abruptly changing into a fault-bounded continental slope towards the south. Slope deposits thus occur in a third set of half-graben basins in the form of prograding sets of strata dominated by significant mass-wasting deposits (Fig. 20). In such a setting, mass-wasting resulted from a combination of tectonic oversteepening of the paleo-continental slope, high to very-high sedimentation rates during hyperpycnal and turbidite flows, and control of sediment transport through submarine channels and gullies (Fig. 20).

Hence, the final question posed in this discussion is if deep-water margins across the world can record similar depositional patterns to SE Crete. In the Antalya Basin of south Turkey, Miocene compression deposited coarse grained fan deltas and fluvial deposits that appear to continue south into contiguous offshore Miocene depocentres (Hall et al., 2014). Large, regional thrusts associated with counter-clockwise rotation of the western side of the Isparta Angle (south Turkey) resulted in the erosion of basement units to generate facies associations that are similar to those on Crete (e.g., upper Karpuzçay Formation and overlying Aksuçay and Köprüçay conglomerates; Çiner et al., 2008). Cyprus records a similar late Miocene of siliciclastic influx into the region occurring in response to the generation of a mosaic of carbonate platforms and interconnecting seaways in the eastern Mediterranean region. This mosaic of basins was formed regardless if the predominant tectonic regime was extensional, compressional or strike-slip (Eaton and Robertson, 1993; Robertson, 2000; Schildgen et al., 2012). In the Aegean part of western Turkey, extension forces predominated from the Middle Miocene, as on the island of Crete, leading to the coeval deposition of footwall-degradation products in multiple E-W to WSW-ENE tectonic troughs (Angelier et al., 1981; Seyitoğlu and Scott, 1991; Genç et al., 2001; Ocakoğlu et al., 2005).

In west Iberia, DSDP and ODP wells have drilled thick syn-rift siliciclastic units where the bulk of the continental slope is carbonate in nature, with early-Mid Jurassic units comprising >3000 m of carbonates in places (Boillot et al., 1987). On seismic data from west Iberia, syn-rift turbidites alternate with mass wasting deposits that are, themselves, coarse grained and siliciclastic. The break-up sequence is much finer grained, but mass transport deposits are still abundant within a setting of forced regression on the continental shelf (Alves and Cunha, 2018). Offshore Newfoundland, west Iberia and west Africa, the advanced rifting stages preceding continental break-up denote the influx of siliciclastic material onto the future continental slope (Soares et al., 2012; Beglinger et al., 2012). Sediment maturity in these regions depends, in theory, on transporting distances from source areas and on the nature of basement units eroded on the margin, apart from base level.

In summary, more than 1400 m of siliciclastic sediments deposited in the Ierapetra Graben during late Miocene implies very high sedimentation rates in a setting recording the input of sediment from large hinterland areas located in the Aegean Sea. The relative position of hinterland regions at that time likely relate to a narrower Aegean in the late Miocene-early Pliocene, i.e., parts of continental Greece and Turkey coasts were relatively close to Crete, with much larger numbers of structural highs, islands and erodible footwalls in the Aegean Sea. We favour a tectono-sedimentary setting in which extensional collapse in the Aegean Sea predominated during the late Cenozoic, with subsequent formation of multiple sub-basins in around Crete. In a second stage, tectonic uplift of the island during the Quaternary isolated the Cretan Trough from the extensional basins to the south of the island (Alves et al., 2007; Kokinou et al., 2009).

7. Conclusions

Depositional styles of the sedimentary facies patterns of late Cenozoic strata in SE Crete are displaying great variability both in the form of lithological composition and spatial distribution. This characteristic of strata accumulated in the Ierapetra Graben, and exposed in numerous coastal outcrops, is mostly a result of intense tectonic activity. A complex pattern of relatively uplifted and subsiding blocks was produced in such extensional setting. The main results of this study can be summarised as follows:

1. The highly faulted, brittle Tripolitza limestone unit fed a series of fan deltas, marine mass wasting deposits and turbidites to late Cenozoic extensional basins on SE Crete. A series of basins trending N20oE to N70oE-90o were filled by continental and transitional siliciclastic and carbonate units (fan deltas) in proximal areas, whereas a complex fault bounded series of continental slope basins were predominantly filled by turbidites and hemipelagic units.

2. Depositional facies in SE Crete were controlled by the relative depth of eroded footwall blocks, the lithology and degree of structural disturbance of basement units, and paleo relief at the time of deposition. Active normal faulting contributed for frequent oversteepening (and slumping) of strata on the paleocontinental slopes bordering Crete. Rapid tectonic uplift and base level variations led to the incision of submarine channels in specific parts of the paleoslope.

3. Mass wasting was ubiquitous in such a tectonically driven environment and, as a result, coarse grained sediment varying in size from large blocks >50 m wide to silty-sandy calcarenites are frequently observed in outcrop.

4. In the study area, genetic units with potential to form good quality reservoirs comprise: a) gully and channel fill conglomerates and sandstones, and b) sand rich open slope turbidites and proximal fan deltas. The relative porosity and sorting of sediment in these two genetic units show great variability depending on their distance to main sediment source areas. These sediment source areas are controlled by active faulting exposing basement units and older sediment to erosion.

5. In such a setting, open slope turbidites (when sand rich), represent the genetic unit with the greatest potential to comprise volumetrically important reservoirs. Their geneses, distribution patterns and relative ages are still to be understood, and need to be further correlated with other Neogene basins on Crete, and within the wider context of late Miocene regional tectonics and overriding regional sea level variations in the Mediterranean Basin. In addition, SE Crete provides an important analogue to marine extensional basins on rifted continental margins that should be compared and contrasted with other parts of the world in terms of reservoir character and potential.

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Figures

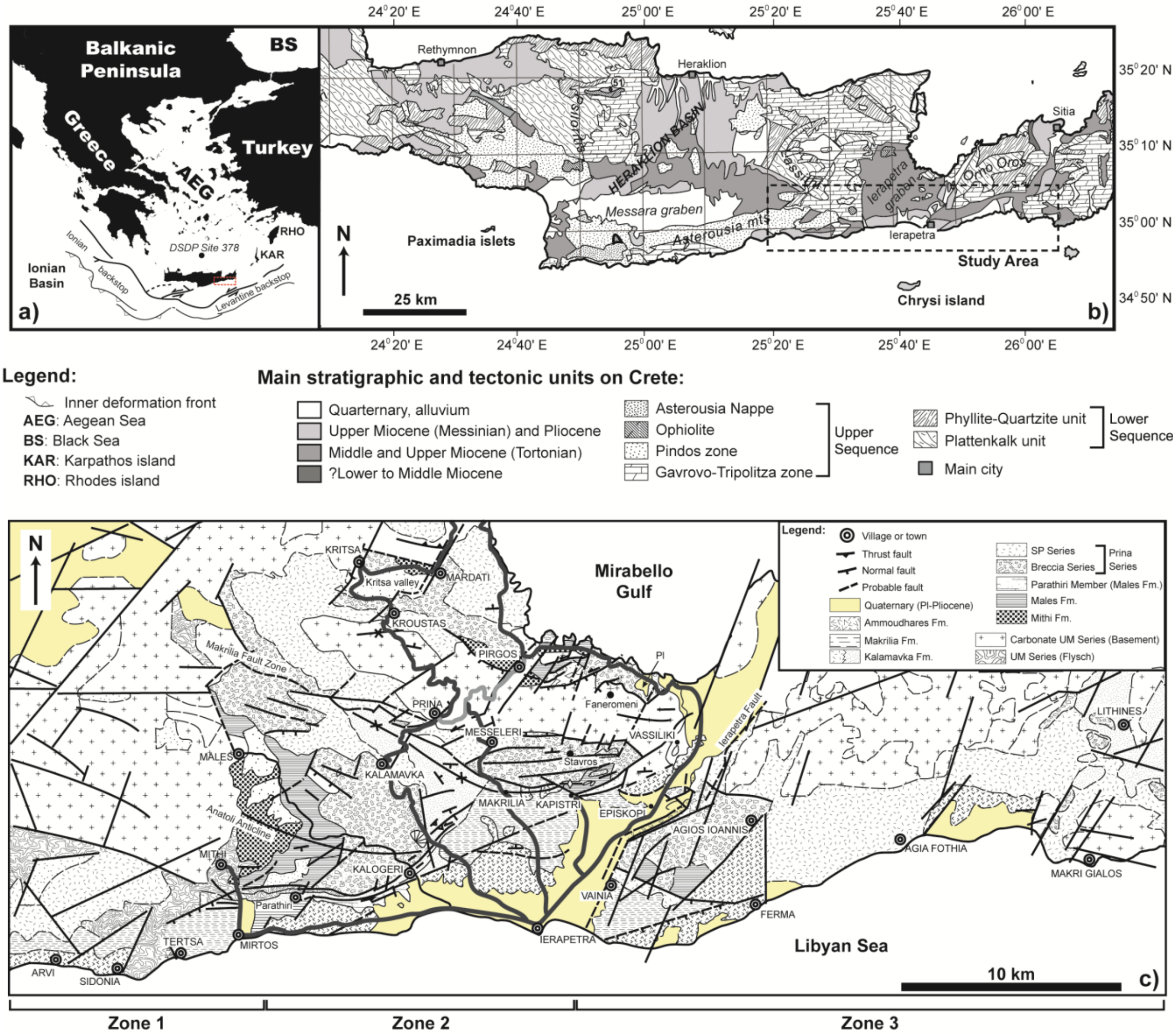

Figure 1

Fig. 1. Regional geological map of the southern Cretan margin highlighting: (a) the relative location of Crete in relation to the Aegean Sea, Greek and Turkish landmasses; (b) the regional geology of Crete and of the study area (modified from Postma et al., 1993). (c) Geological map of the study area in SE Crete.

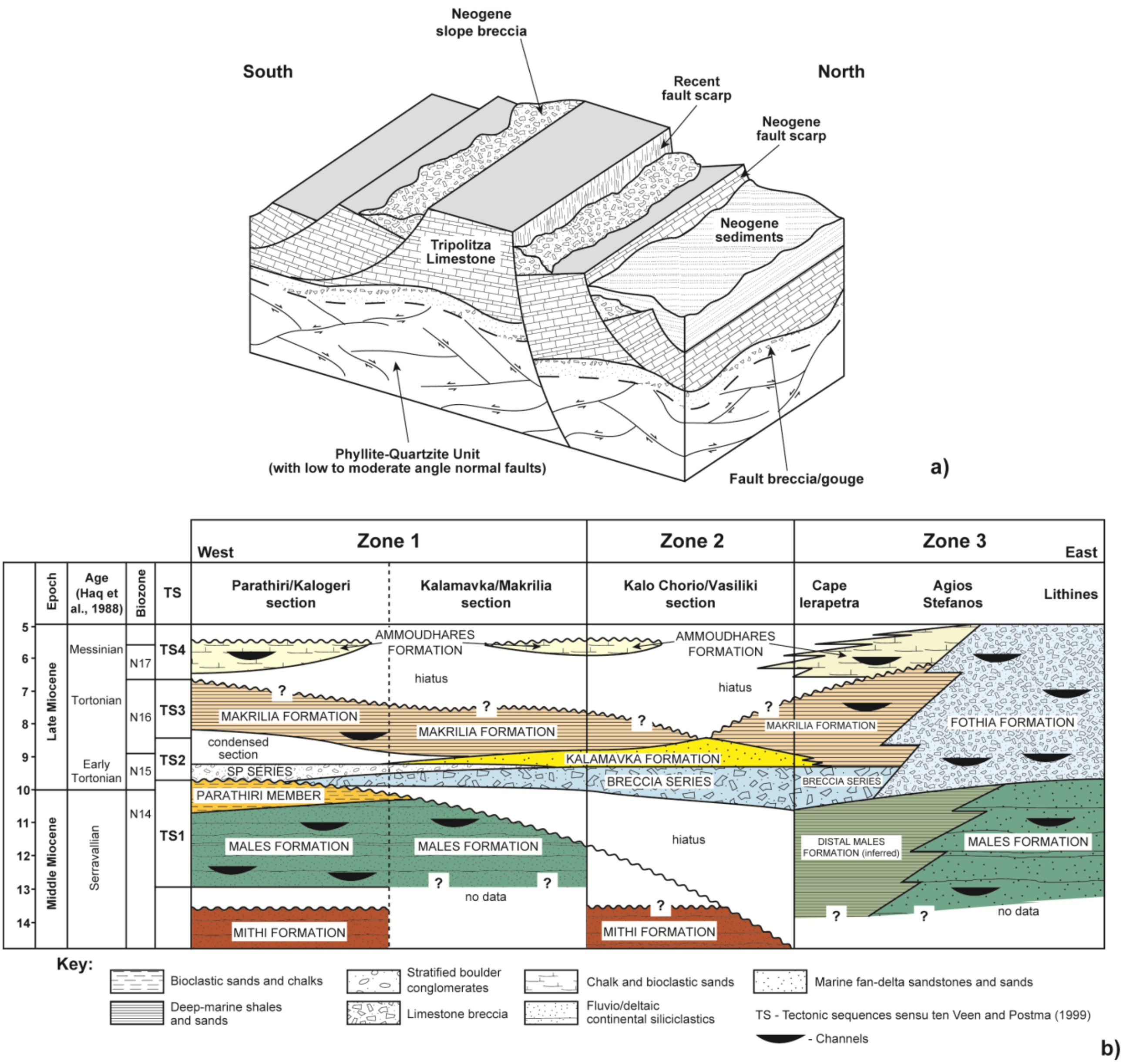

Figure 2

Fig. 2. Schematic diagrams illustrating the tectono-sedimentary evolution of Crete in the late Cenozoic. (a) Three-dimensional sketch summarising the extensional character of the studied area in Crete. Modified from Thomson et al., 1998; Kokinou et al., 2012. (b) Principal lithological units in the Ierapetra region and southern Crete. Lithological units in Zones 1 and 2 units, based on Postma and Drinia (1993), are compared in this figure with their counterparts to the East of Ierapetra (Zone 3) and with the Tectonic Sequences of Ten Veen and Postma (1999), which are described in this paper.

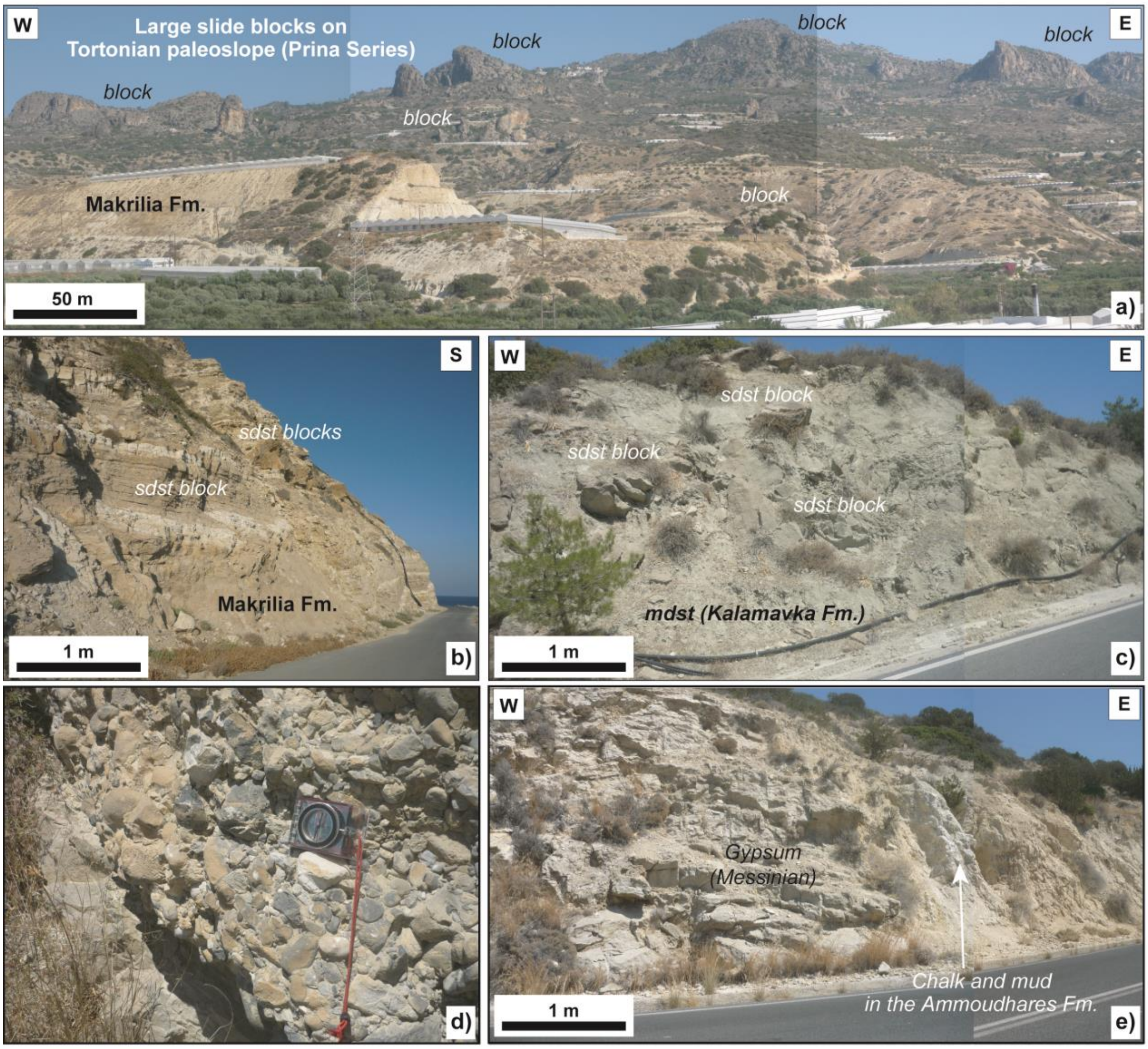

Figure 3

Fig. 3. Outcrop examples of facies associations as defined by Postma and Drinia (1993). (a) Fa 2-4; allochthonous slide blocks in Zone 2, over the paleoslope bordering the Ierapetra Graben to the northeast (Anatoli-Kalamavka region; Figures 1c and 5). (b) Fa A; example of channel-fill deposits in Zone 2, which are sandier and less erosive than in Zone 1, Location 50 in Figure 5. (c) Fa 1, strata belonging to the Males Formation in slope strata (unit t in Figure 5) outcropping around Anatoli (location 23, Fig. 5). (d) Fa 2-4, detail of boulder-conglomerate facies in proximal parts of the paleoslope in Zone 2 (unit pr in Figure 5). (e) Messinian evaporites, not included in Postma and Drinia (1993) facies associations and comprising mostly blocky and cavernous salt, outcropping close to Ammoudhares at location 48, Figure 5.

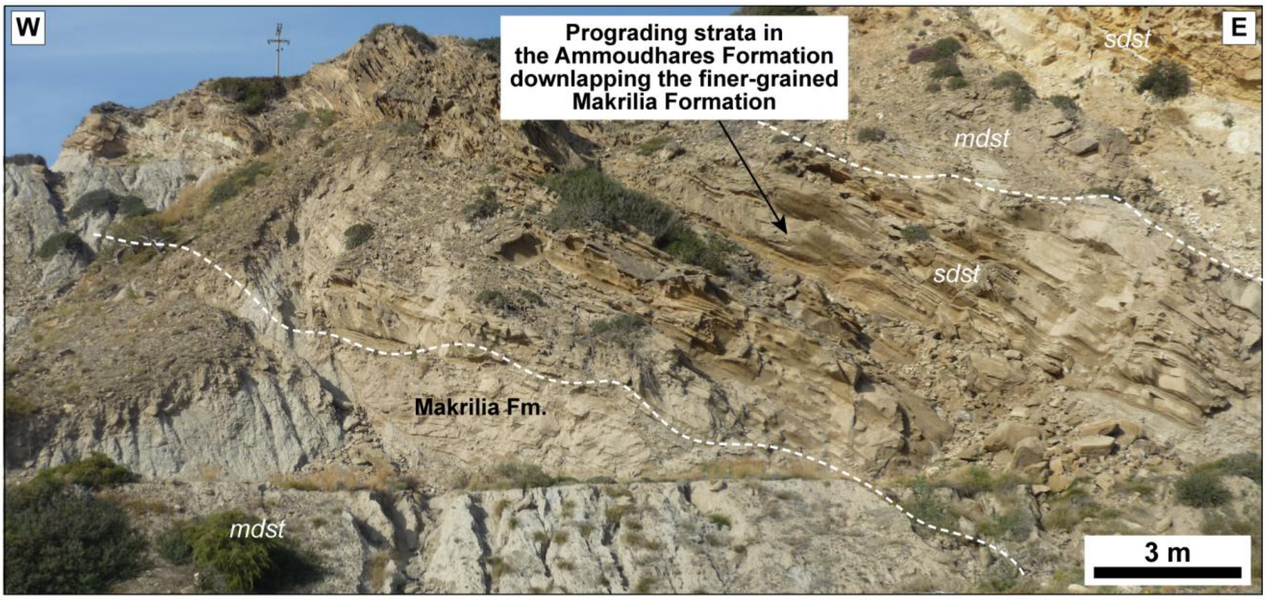

Figure 4 -

Fig. 4. Detail of facies associations A to C as observed at coastal outcrops. The photo shows interbedded with slope turbidites in the upper part of the Makrilia Formation at Sidonia, Zone 1. Location 73, Figure 4.

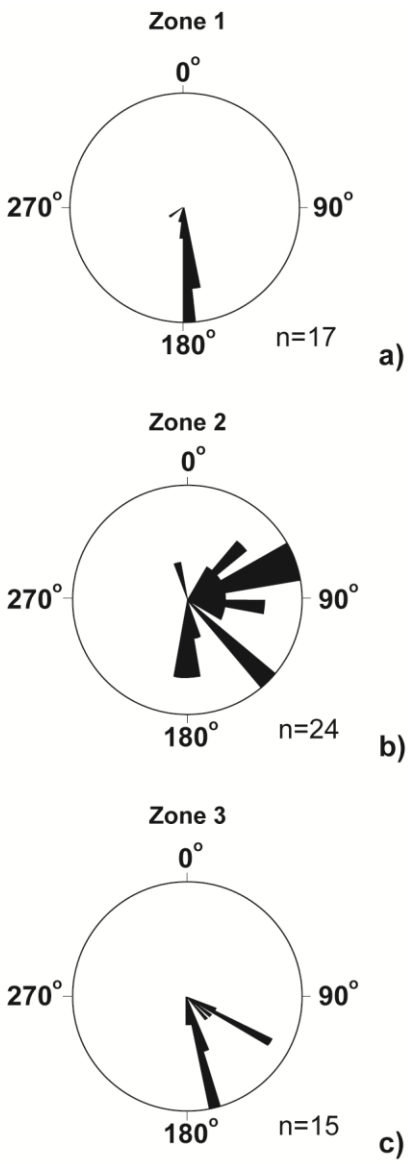

Figure 5

Fig. 5. Paleocurrent indicators acquired in: (a) Zone 1, (b) Zone 2, and (c) Zone 3.

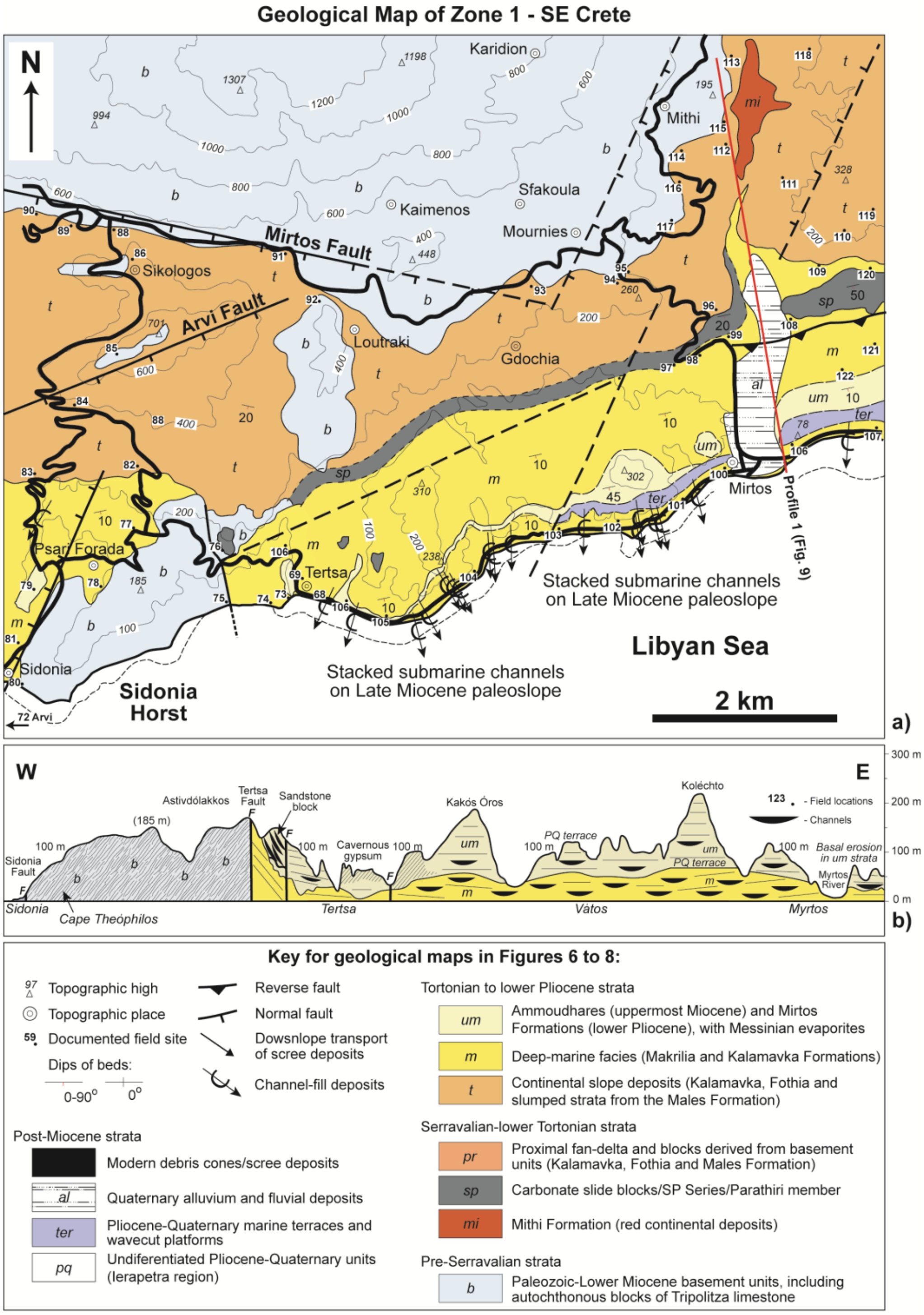

Figure 6

Fig. 6. (a) Geological map of Zone 1, located between the village of Myrtos and Sidonia/Arvi, and (b) regional transect along coastal outcrops in Zone 1. The figure also shows the key for the geological maps in Figures 6 to 8. The location of lithological profile 1 in Figure 9 is also highlighted in the geological map in a).

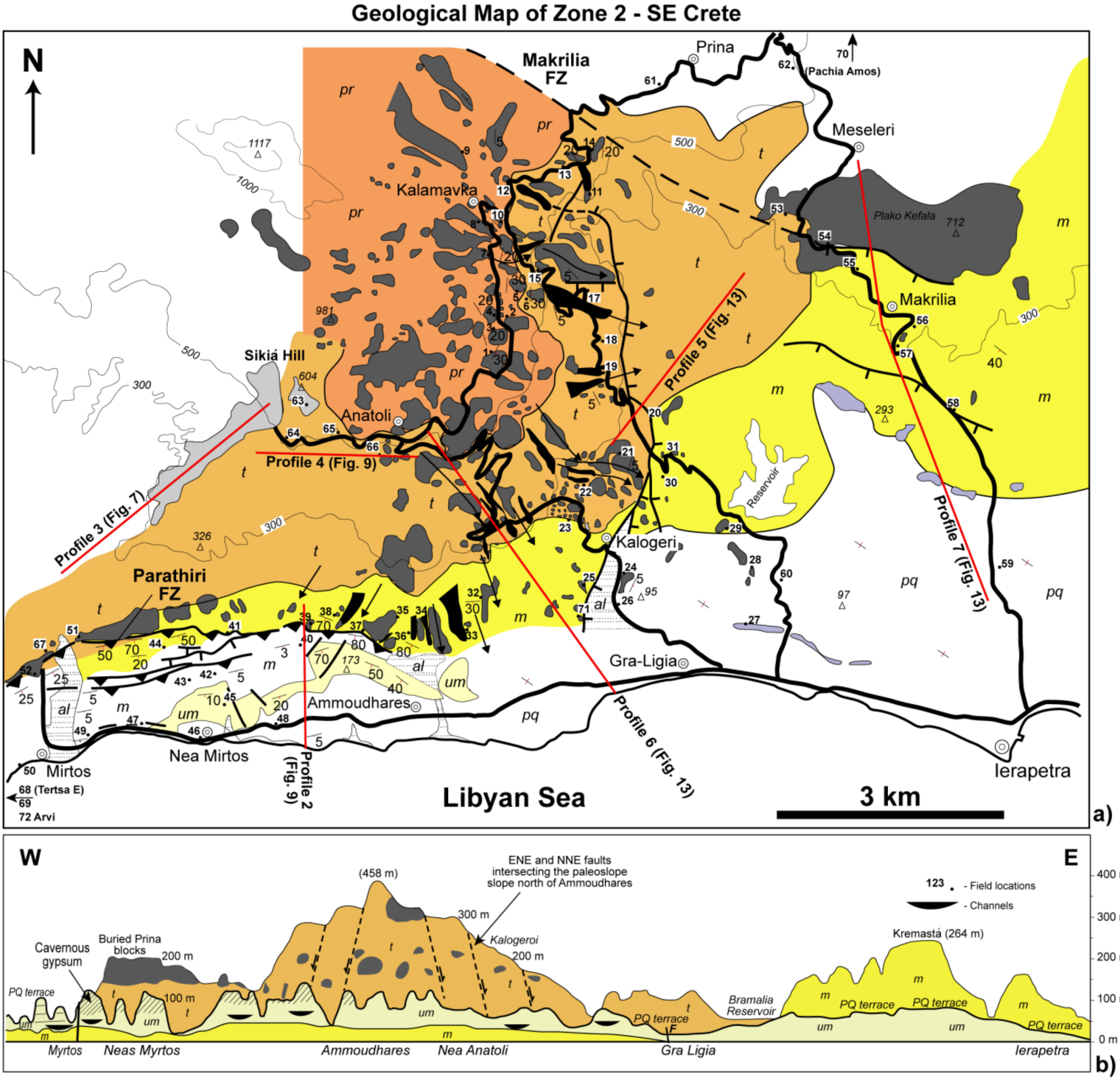

Figure 7

Fig. 7. (a) Geological map of Zone 2, located in the southern and central parts of the Ierapetra Graben and paleoslopes to the northwest and north. (b) Regional transect along coastal outcrops in Zone 2. The locations of lithological profiles 2 to 7, shown in Figures 9 and 13, are also highlighted in the geological map in a). Key given in Figure 6.

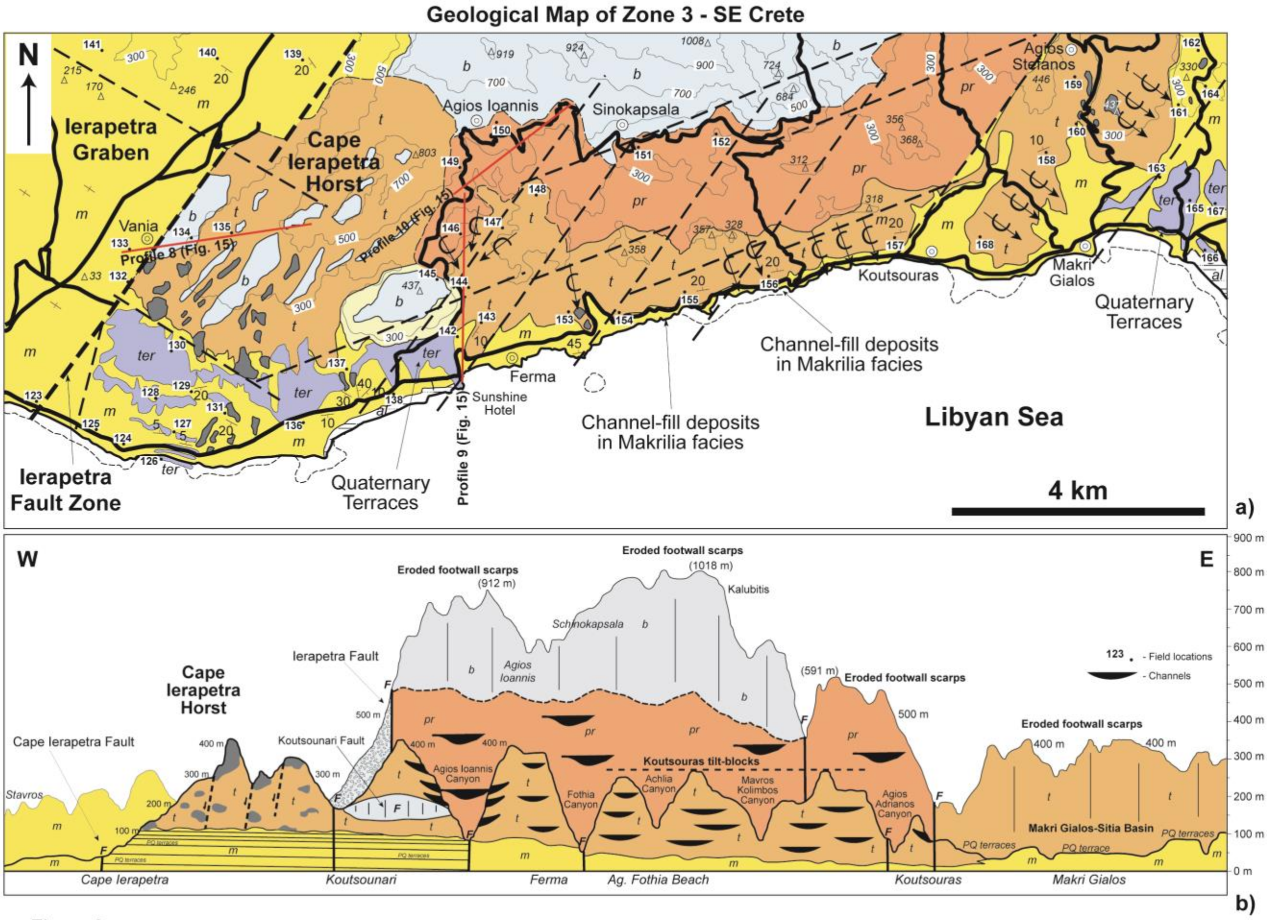

Figure 8

Fig. 8. (a) Geological map of Zone 3, located to the east of the Ierapetra Graben. (b) Regional transect along coastal outcrops in Zone 3. The locations of lithological profiles 8 to 10 in Figure 13 are shown in the geological map in a). Key given in Figure 6.

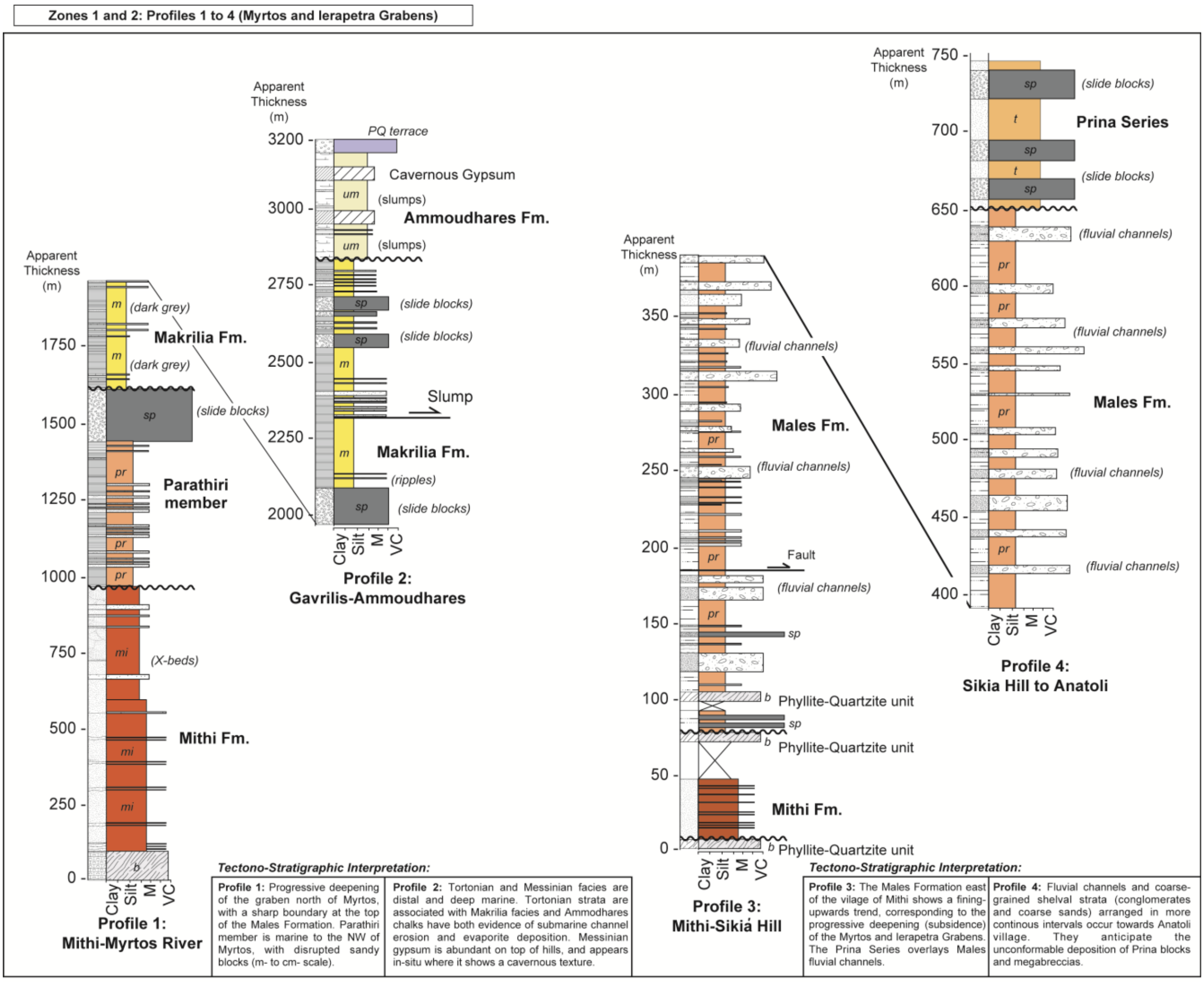

Figure 9

Fig. 9. Lithological profiles 1 to 3 across Zone 1, as shown on the map in Figure 6.

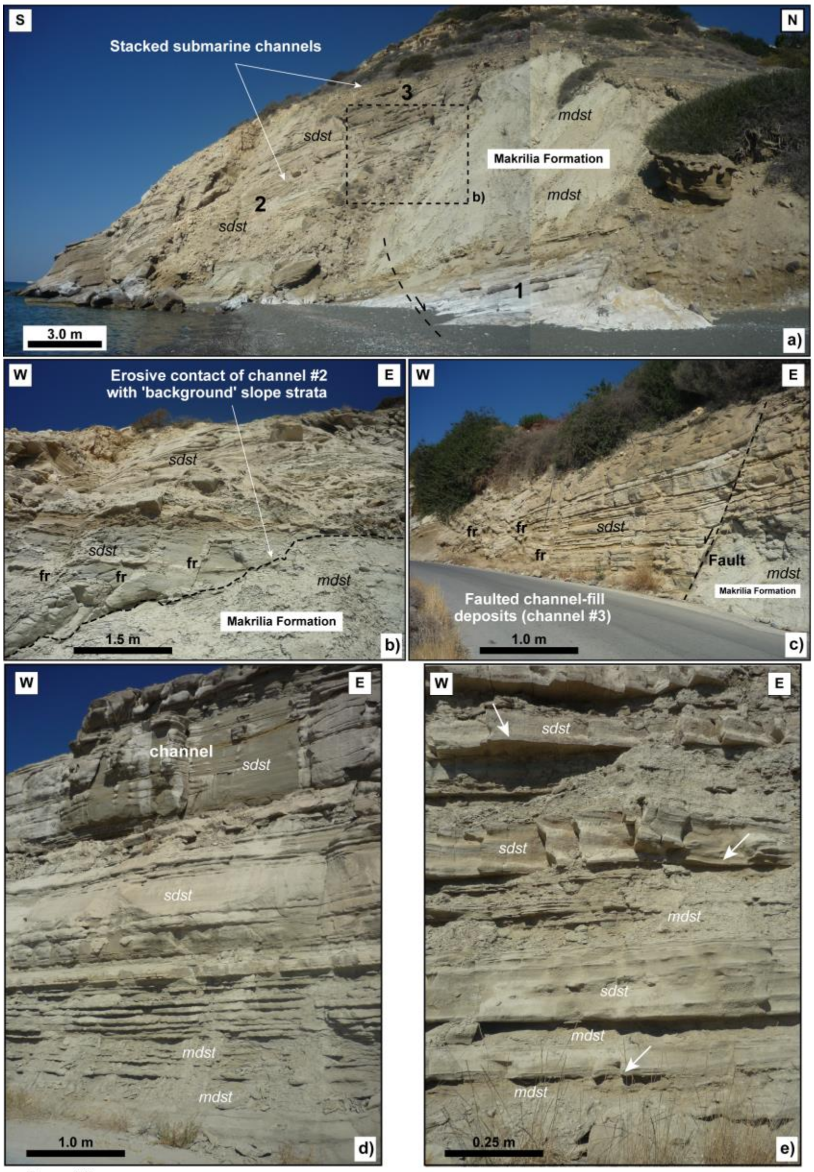

Figure 10

Fig. 10. Field photographs highlighting the depositional facies, tectonic sequences and stratigraphic formations of the study area. (a) Stacked submarine channels in Sidonia (location 80, Fig. 6), within uppermost Makrilia Formation strata. (b) Detail of the erosive contact between one of the channel-fill deposits at Sidonia (channel #2, location 80) and mudstones in the Makrilia Formation. (c) The top of the Makrilia Formation is marked at Sidonia by wider channel-fill deposits, and sandy overbank strata. (d) Example of turbidite sands and mudstones in the Makrilia Formation in location 103, west of Myrtos (see Fig. 6). (e) Example in location 102 of submarine fan deposits, with minor sequences of and larger amounts of mudstone when compared with channel-fill deposits. sdst-sandstone; mdst-mudstone.

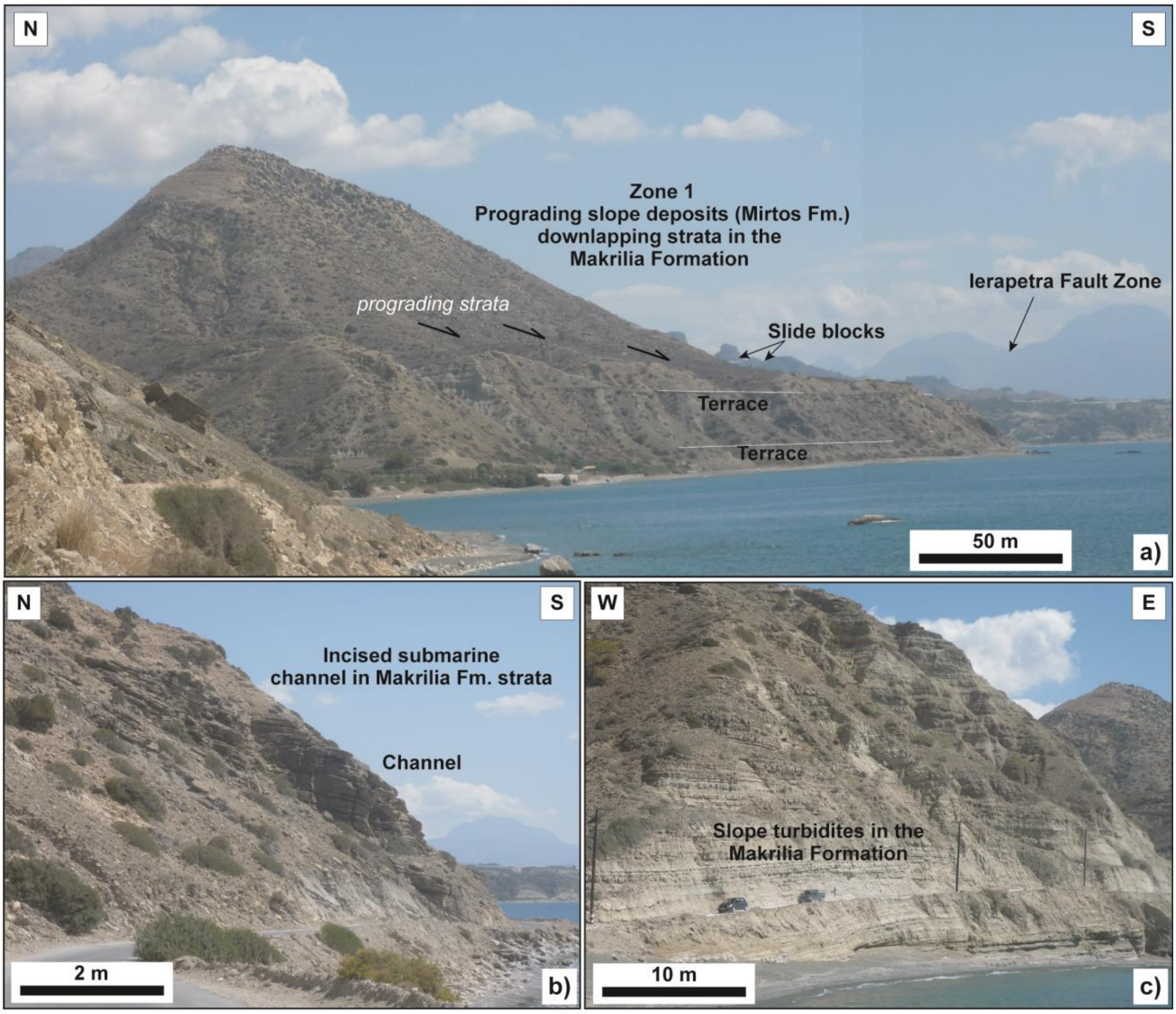

Figure 11

Fig. 11. (a) Sub-horizontal Makrilia strata are downlapped by early Pliocene strata in the Myrtos Formation (Table 1), Location 101 in Figure 6. (b) Detail of submarine channel-fill deposits in Tertsa, Zone 1, location 106 (Fig. 6). (c) Detail of slope and submarine-fan strata deposited on the late Miocene paleoslope in Zone 1 (location 102, Fig. 6).

Figure 12

Fig. 12. Section showing (a) slumped continental-slope turbidites part of the uppermost Makrilia and Ammoudhares Formations, Arvi, and (b) interpretation of strata displacement (location 72, Fig. 5).

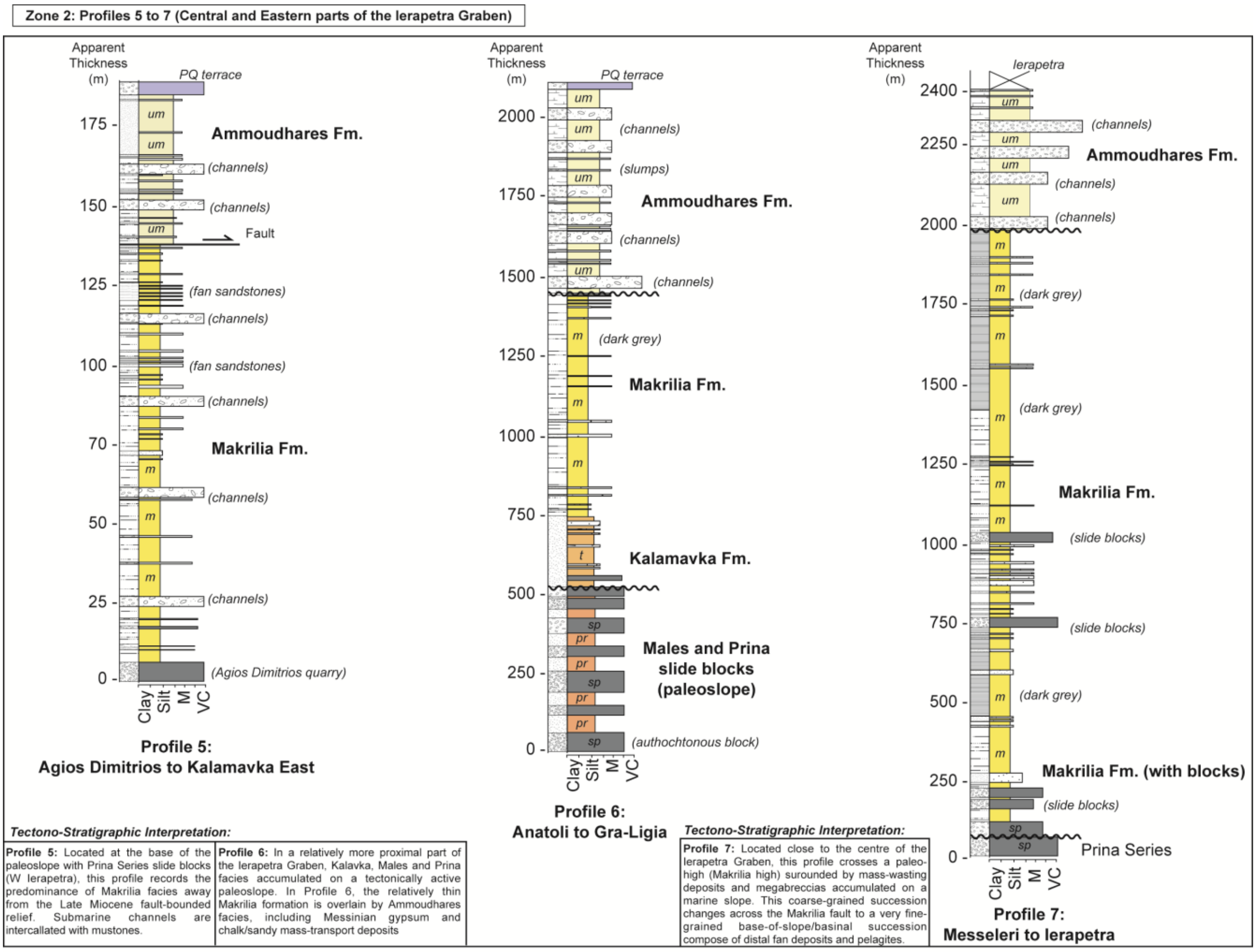

Figure 13

Fig. 13. Lithological profiles 5 to 7 across Zone 2, as shown on the map in Figure 7

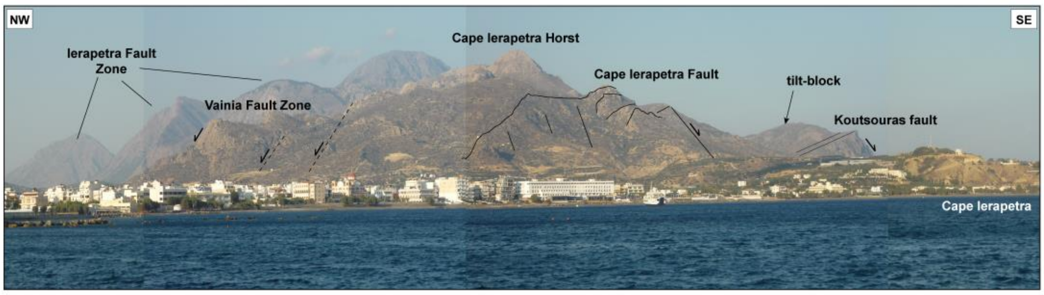

Figure 14

Fig. 14. Panoramic view of the Cape Ierapetra Horst and associated fault zones from Ierapetra, SE Crete. The photo mosaic shows the Fothia Formation at the zone of intersection of faults trending N20oE and N70oE.

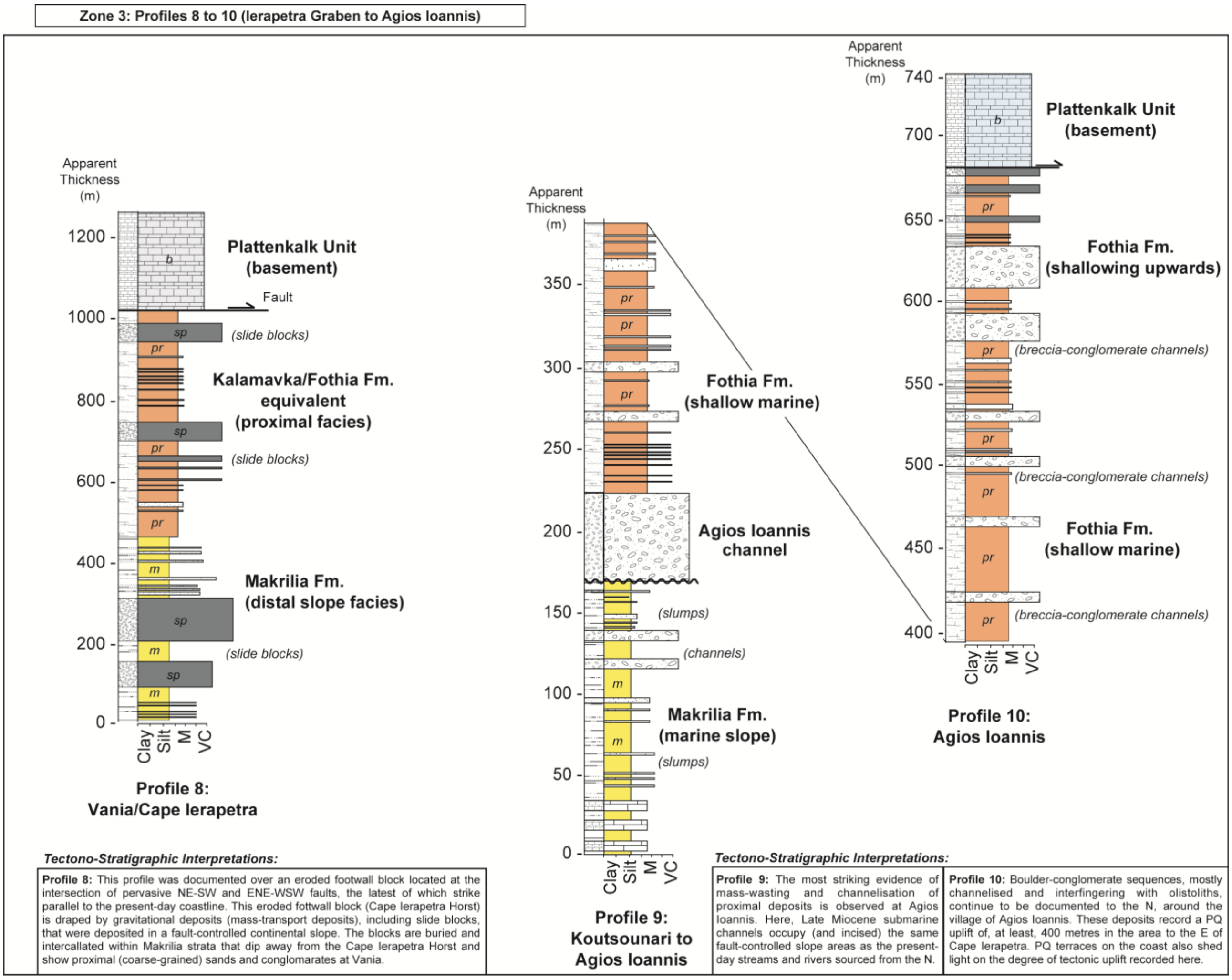

Figure 15

Fig. 15. Lithological profiles 8 to 10 across Zone 3, as shown on the map in Figure 8.

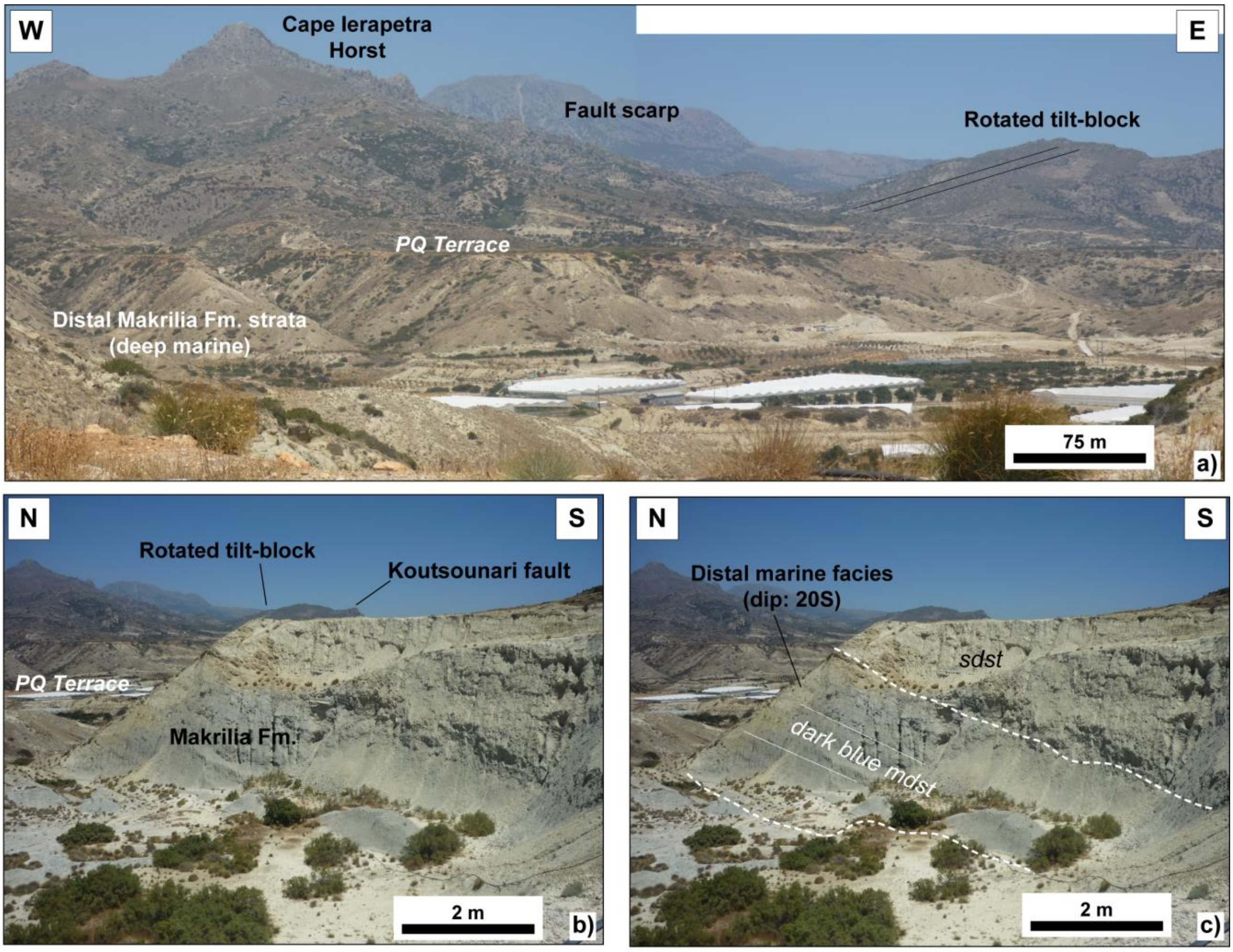

Figure 16 -

Fig. 16. (a) View of strata at Cape Ierapetra, where Makrilia Formation sediments predominates together with uplifted Pliocene-Quaternary terraces and rotated tilt-blocks (location 128, Fig. 8). (b) Example of distal Makrilia Formation facies here composed of dark-blue shales and minor sand intervals. Location 129, Figure 8. (c) Interpretation of lithologies, inferred boundaries and strata dips in the same outcrop location in b). sdst-sandstone; mdst-mudstone.

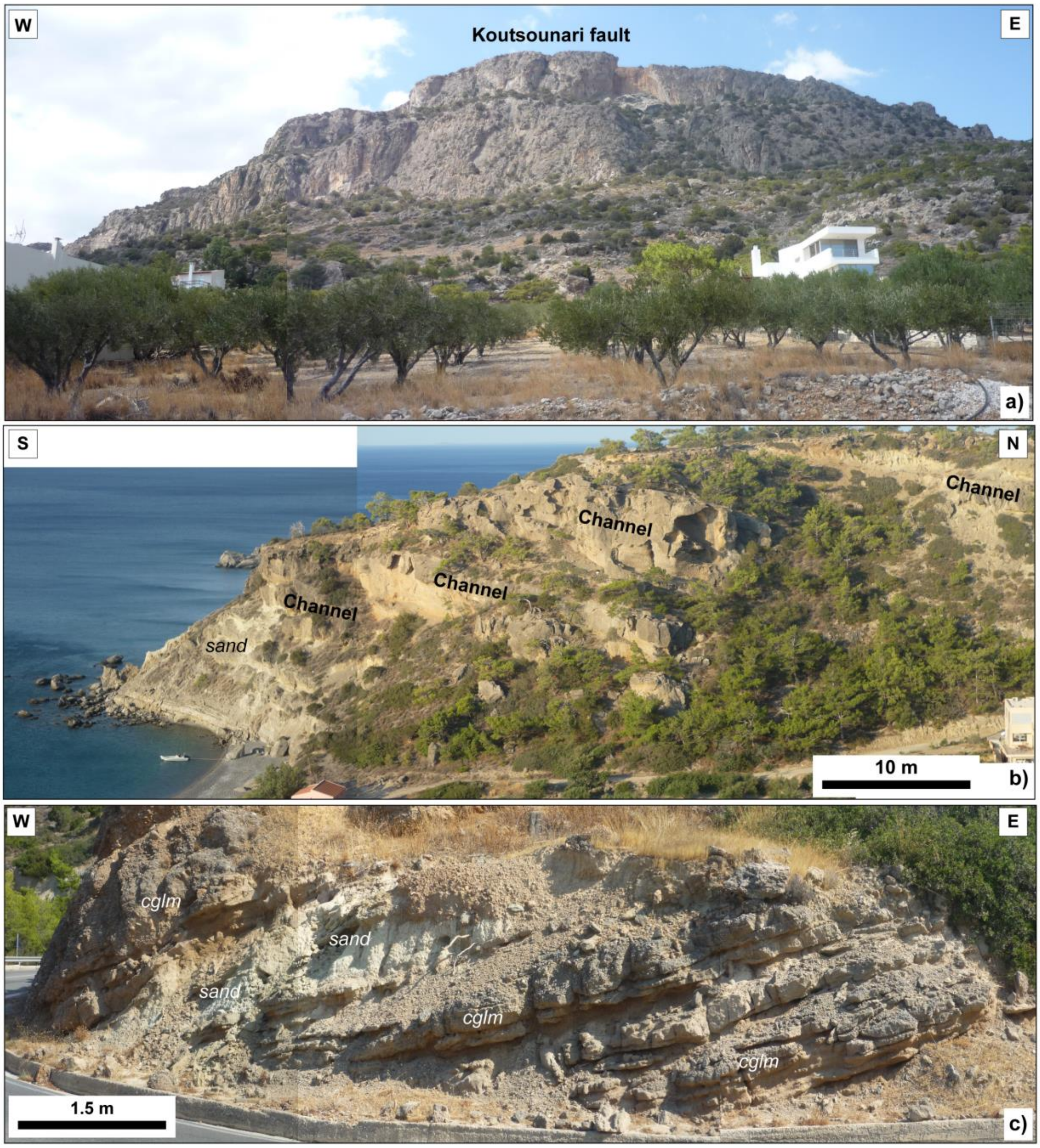

Figure 17

Fig. 17. (a) Panoramic view of the Koutsounari fault in Zone 3, and associated fan delta deposits accumulated on its toe. Location 138, Figure 6. (b) Continental fan-delta deposits give way to channel-fill deposits and distal fan-delta (pro-delta?) deposits on coastal outcrops. Location 153, Figure 8. (c) Example of channel-fill deposits at location 154 (Fig. 8) composed of poorly consolidated conglomerates interbedded in marine sands and muds.

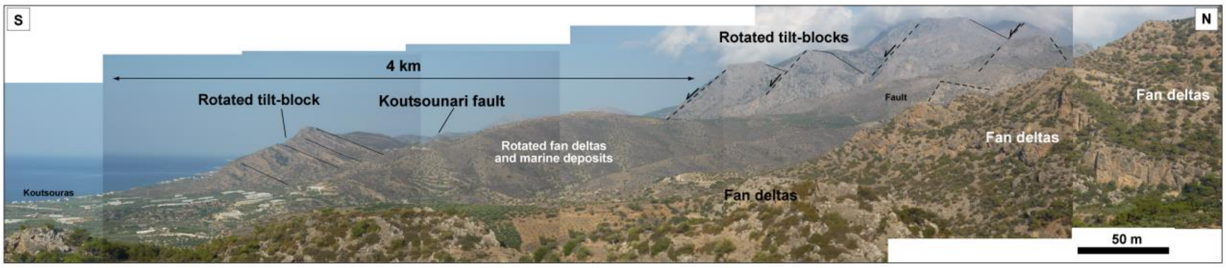

Figure 19

Fig. 18. a) Panoramic view from the eastern part of Zone 3, from Agios Stefanos (location 158, Fig. 8). The photomosaic highlights the geometry of E-W half-grabens where proximal deposits (fan deltas and shallow marine strata) change abruptly into more distal marine facies along the present-day coastline.

Figure 19

Fig. 19. Detail of channel-fill units at Agios Ioannis, location 146 in Zone 3 (Fig. 8), sourced from the Cape Ierapetra Horst and footwall blocks to the north.

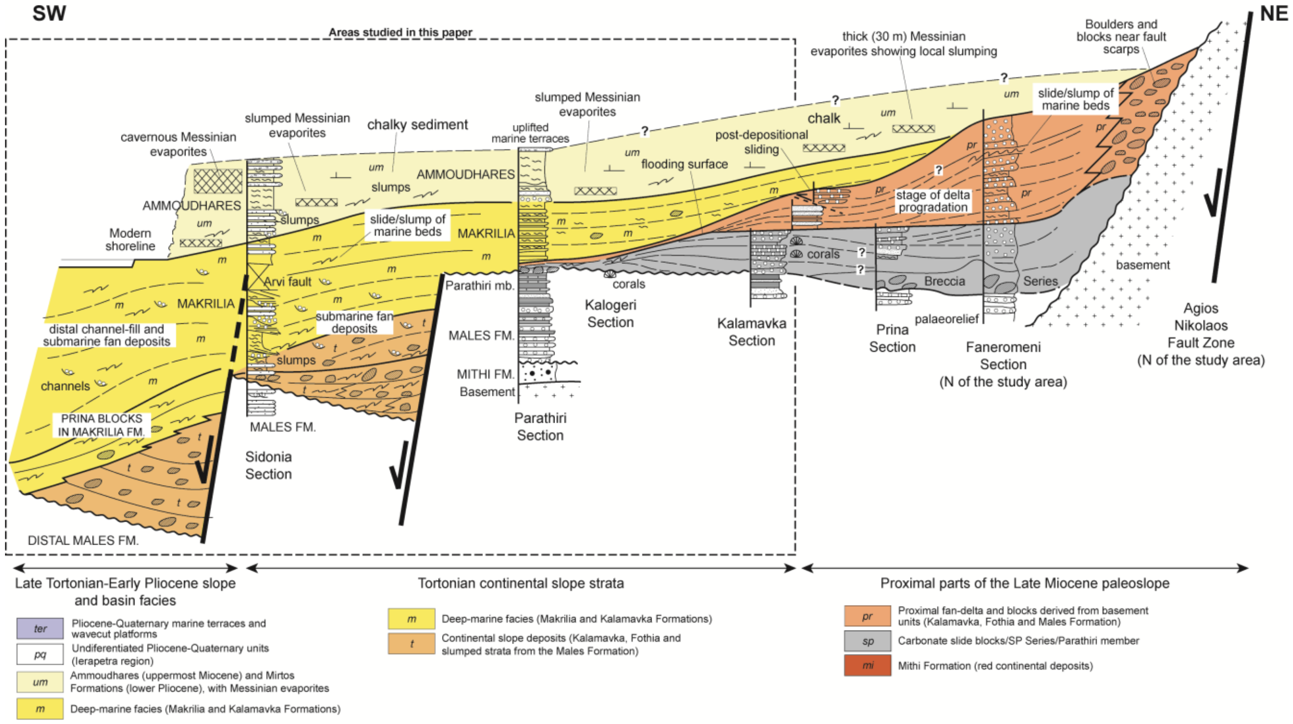

Figure 20

Fig. 20. Architecture of fault-bounded basins deposited SE Crete during the late Serravallian–Messinian, from NE to SW across Zones 1 and 3.

Tectono-Sedimentary Unit (TS)	Age	Regional Stratigraphic Units	Sedimentological character and local tectonic evolution (ten Veen and Postma, 1999)
TS5	Late Messinian to Recent	Mirtos Formation and undifferentiated Quaternary terraces/alluvial fans	Shallow marine, estuarine, coastal, and deltaic deposits. Gradual deepening is recorded towards the top of the unit. No conspicuous faulting controlling basin fill.
TS4	Late Tortonian-Messinaian mostly moderately sloping	Uppermost Makrilia and Ammoudhares Formations	Bioclastic chalks and debrites interrupted by turbidites, calcarenites and marls. White, rich in sponge needles and evaporites.
TS3	Middle Tortonian	Makrilia and Upper Kalamavka Formations	Subsidence in N-S seaways with uplift of basin shoulders (and older strata). Stacked channel fill deposits and distal turbidites and shales.
TS2	Early Tortonian	Prina Series and lower Kalamavka Formation	Sudden influx of large masses of Tripolitza limestone breccias and blocks. Distal turbidites in starved basins recording very high subsidence rates
TS1	Late Serravalian	Parathiri Member	Shallow marine, estuarine, coastal, and deltaic deposits. Gradual deepening is recorded towards the top of the unit. No conspicuous faulting controlling basin fill.

Table 1. Summary table correlating the Late Miocene tectono-sedimentary (TS) units on Crete with formal stratigraphic units and their lithological character. Tectono-sedimentary units are from ten Veen and Postma (1993). Formation and member names are based on Fortuin (1977).