Stratigraphic architecture, sedimentology and structure of the Vouraikos Gilbert-type fan Delta, Gulf of Corinth, Greece

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ABSTRACT

In the Aegion to Kalavrita region of the Gulf of Corinth, Greece, Plio-Pleistocene syn-rift stratigraphy comprises a fluvial-dominated lower group and an upper group dominated by Gilbert-type deltas separated by an erosive unconformity. The lower group records substantial accumulation (1.3 km) of fluvial sediment across a broad area of fault controlled grabens and half grabens, which was terminated by a marine transgression. The upper group records a great increase in accommodation space, the migration of the depocentre to the north and an increase in sediment supply. It is dominated by large gravel-rich systems that were sourced in the footwalls of active normal faults. The Vouraikos Delta is an exceptionally well-exposed Gilbert-type fan delta complex, which is > 800 m thick, with a surface area of 32 km^2. It lies in the hangingwall of the Pirgaki-Mamoussia (PM) Fault and has been exhumed in the footwall of the Eastern Helike Fault (EHF). Preliminary palynological results from topset and pro-delta fine grained facies and from lower group strata indicate that the Vouraikos Delta began some time before 1.1 Ma and was terminated soon after 0.7 Ma. These preliminary Early to Middle Pleistocene age estimates are coherent with published models of the uplift history on the EHF. Sedimentation rates are thus estimated between 1.3 to 2 mm yr^{-1}. While the earliest delta infilled an incised palaeovalley, accommodation space was primarily tectonically controlled, first by an extensional forced fold and later by a system of major normal faults (PM Fault and its splays). Several families of syn-sedimentary and late normal faults cut the delta. A listric growth fault controlled a large rollover anticline in the lowest stratigraphic package. The delta prograded (to the NNW) into water that reached depths of 200-

600 m. Topset limestones associated with coastal conglomerate facies indicate that the delta built into a water body that was wholly or periodically marine. Internally, the Vouraikos Delta comprises five stratigraphic packages each characterized by a distinctive organization of topsets, foresets, bottomsets and pro-delta facies and bounded by major stratigraphic surfaces. These packages are tentatively correlated with regressive glacio-eustatic interglacial periods. The trajectory of the offlap break in the centre of the Vouraikos reflects early progradation-dominated behaviour followed by increasingly aggradational behaviour.

Keywords: Early to Middle Pleistocene, Vouraikos Gilbert-type Delta, Corinth rift, Greece, normal faults.

INTRODUCTION

Along the southern shore of the Gulf of Corinth (Fig. 1) high relief outcrops expose some of the finest examples of ancient Gilbert-type deltas in an active extensional tectonic setting. Despite published research on several of this suite of deltas, there is little information on complete systems and some confusion about the relationships between several of the deltas. These conglomerate-rich Gilbert-type delta bodies are unusually large, varying in radius from 3 to 8 km (Fig. 1) and are up to 900 m thick. They have been uplifted to altitudes of over 800 m and are deeply incised by north-flowing rivers. While absolute and relative ages are as yet poorly constrained, various delta bodies have been attributed ages of between Pliocene and Holocene (Collier 1990; Dart *et al*., 1994; Ori, 1989; Ori *et al*., 1991; Poulimenos *et al*., 1993). Recent provisional age estimates from palynofloras for the Vouraikos Delta give an Early Pleistocene age (Malartre *et al*., 2004). Currently, major deltas of the same type are building out into the western Gulf, as modern rivers cannibalize their antecedent deltas (Fig. 1). The purpose of this paper is to present a detailed analysis of the Vouraikos Delta, one of the largest and best exposed of the giant Gilbert-type deltas of Corinth.

The Vouraikos Delta lies in the hangingwall of the Pirgaki-Mamoussi (PM) Fault (Figs 1-3) and has been uplifted and incised in the footwall of the Eastern Helike (or East Eliki) Fault. Three river valleys, the Keranitis, Vouraikos and Ladopotamos provide exceptional natural sections 3 to 4 km apart and with over 700 m of incision. These sections allow us to present a detailed sedimentological and structural study of a substantially complete delta system. Additionally, the syn-rift stratigraphy and internal structure of the whole PM Fault block is described so that delta development can be placed in the context of rift evolution. The vertical and lateral stacking pattern of the delta (its internal architecture) is interpreted in terms of sequence stratigraphy and creation of accommodation space in order to distinguish tectonic and eustatic controls.

Detailed analyses of major cliff sections using photographic panoramas form the backbone of this work. These sections were tied together by detailed field mapping at various scales integrating GPS technology, which forms the basis of ongoing 3D database construction using GIS and gOcad. The stratigraphical architecture was established for each cliff, and key units and surfaces were correlated between cliffs. Facies associations for each stratigraphical unit were identified and detailed sedimentological analysis was carried out by logging at a scale of 1:25. Preliminary analysis of ^{13}C and ^{18}O isotopes was undertaken to characterize the chemical signature of critical stratigraphical horizons, and sampling for palynological analysis was carried out in order to biostratigraphically date the succession.

GROSS STRUCTURAL SETTING: THE GULF OF CORINTH

The Gulf of Corinth is an active rift that initiated sometime in the last 5 Ma (Doutsos & Piper, 1990; Collier & Dart 1991) in the upper plate of the Hellenic subduction zone (Fig. 1, inset). The rift is superimposed on the NNW-SSE trending Hellenide orogenic belt (Oligocene-Miocene) and is oriented N105°. It is 120 km long, some 0.5 km wide in the west and is ca. 30 km at its widest point in the east. The basin has a maximum water depth of 900 m in the east and shallows westward to the Straits of Rion where water depth is only 62 m. WNW-ESE oriented north-dipping normal faults lie somewhat oblique and en echelon to the present southern coastline (Fig. 1). Active south-dipping faults, flanking the northern limit of the present graben have recently been reported offshore (McNeill *et al*., 2005). Seismic activity is concentrated at the western end of the basin where geodetic measurements indicate a N-S extension rate of 1.2 cm yr^{-1} (Briole *et al*., 2000). On the south shore older syn-rift sediments have been uplifted and deeply incised over an area stretching south from the coast for 25-30 km (Fig. 1). Current uplift rates are estimated to be 1 to 1.5 mm yr^{-1} (McNeill & Collier, 2004; De Martini *et al*., 2004). This unusual situation has generated superb vertical sections through the older syn-rift succession while active rifting takes place offshore.

LOCAL STRUCTURAL SETTING

In the Aegion-Kalavrita region (Fig. 1) major, north-dipping normal faults, with a mean trend of 110° and dipping 55°N define five principal fault blocks that are between 3 and 5 km wide (Goldsworthy & Jackson, 2001; Bourlange *et al*., 2005).

From south to north these blocks are delimited by the Kalavrita, Kerpini, Doumena, PM and Helike faults (Fig. 2). Each block preserves a succession of coarse alluvial syn-rift sediments, generally tilted south with thicknesses up to 1.3 km. The Pirgaki-Mamoussi (PM) Fault block preserves a more complex syn-rift succession, comprising heterogeneous alluvial (and other) clastic rocks overlain by conglomeratic Gilbert-type fan delta sequences.

In the study area the PM Fault block is 5 km wide, and is bounded to the south by two fault segments - the Pirgaki Fault to the west and Mamoussia Fault to the east, which are hard-linked by a breached relay ramp in the Keranitis River Valley (trending N070°, Figs 1 and 3). This oblique ramp probably extends northward along the Keranitis Valley. The PM Fault (specifically the Mamoussia Fault) accommodated at least 1.5 km of vertical displacement. East of the Vouraikos Gorge, the east-west trending Kastillia Fault and the Katafugion Fault branch from the ESE-WNW trending PM Fault (Fig. 3) and formed important bounding faults to the Vouraikos Delta for part of its history. Further south the PM Fault separates the older syn-rift succession from pre-rift carbonates in its footwall (Fig. 3).

Pre-rift strata comprise Mesozoic carbonates, radiolarites and clastic turbidites ('flysch') that record multiphase deformation at low metamorphic grades related to the westward emplacement of Hellenic nappes during the Oligo-Miocene (Doutsos *et al*., 1993). These pre-rift strata are the source rocks for the Gilbert-type delta gravels. In the PM block pre-rift carbonates are exposed in the Selinous River Valley and just to the east of the Ladopotamos River in the immediate footwall of the Eastern Helike Fault (Fig. 1). The lower syn-rift succession has a marked northward dip of up to 30°, while the top of the syn-rift succession (i.e. the uppermost conglomeratic units *above* the Gilbert delta succession) shows a shallow (< 5°) tilt to the south.

REGIONAL SYN-RIFT STRATIGRAPHY

Published stratigraphical schemes

Two general schemes have been applied in this region (Ori, 1989; Doutsos & Piper, 1990); both differ significantly from that described here (Fig. 4). In the region around the Ilias and Evrostini deltas (Fig. 1), Ori (1989) reports a syn-rift stratigraphy that consists of a 1-3 km thick lower succession of alluvial plain-lacustrine-alluvial fan sediments (organized in a transgressive-regressive cycle), unconformably overlain by Gilbert-type fan deltas (but see Doutsos *et al*., 1990). Doutsos & Piper (1990), working in an area to the southeast of that of Ori (1989, fig. 1), also describe a two-unit stratigraphy comprising a lower unit of lacustrine and fluvial sands and silts of Middle to Late Pliocene age, and an upper unit of Quaternary conglomerates, the older part of which has been dated as 'Calabrian' (Lower Pleistocene; Doutsos & Piper, 1990, p. 815 and references therein). These conglomerates are of aerially contrasting facies, being (1) terrestrial where they overlie basement rocks at the southern margin of the basin, and (2) of Gilbert-type delta facies towards the north, where they are interbedded with marine, lacustrine and brackish 'marls' of locally Middle Pleistocene age.

More recently, Ghisetti & Vezzani (2005) present a synthetic stratigraphic column for the study area, which they call the Aegion Basin, and another for the Derveni-Corinth Basin further east. The Aegion Basin column corresponds very generally with our observations; however, we have not observed major clino-stratified conglomerates at the stratigraphic level they call 'Mid Rift' (equivalent to our lower group). In the Evrostini-Akrata area (Fig. 1), Rohais *et al*. (in press) recognize three stratigraphic groups, which are a lower alluvial-lacustrine group, a middle group of Gilbert-type deltas and an upper group of recent small deltas and terrace deposits.

At present there is a consensus that the onshore syn-rift stratigraphy comprises two main stratigraphical groups. The lower group of alluvial-lacustrine(?)-marine(?) clastics appears to vary rapidly in facies and thickness from west to east, so that attempts to generalize its component units across the south coast have led to some confusion. Detailed biostratigraphical dating is necessary to achieve good lateral correlation. A major unconformity probably separates the lower and upper groups, although all authors do not accept this. The upper group is dominated by the giant Gilbert-type fan deltas that are developed principally between Aegion and Xylokastron (Fig. 1). Equivalent stratigraphical levels to the east (and west?) appear to comprise thinner, smaller deltas and thick fine-grained marine clastics (e.g. Doutsos & Piper, 1990). A relatively small volume of young Gilbert-type fan deltas, fluvial deposits and terrace deposits locally unconformably overlie the main rift succession along the coastal strip, recording the late phase of surface uplift.

Stratigraphical age and dating

There is a lack of precise biostratigraphical dating of the various sedimentary successions in the Gulf of Corinth rift. This is mainly due to the dominance of conglomerates and sandstones in which biostratigraphical markers are poorly preserved. The oldest age published is Lower Pliocene (Zanclean, 5.32-3.58 Ma, Papanicolaou *et al*., 2000) from syn-rift coal-bearing rocks in the Kalavrita Basin (to the south of Vouraikos Delta), although details of the dating method are not specified. Andesites that represent the initiation of the Corinth Basin, in the east of the rift system, are dated as 4 Ma (Collier & Dart, 1991).

Along the south-eastern coast of the Gulf, brackish, lacustrine and fluvial siliciclastic sediment are dated as Middle to Late Pliocene to Quaternary (Kontopoulos & Doutsos, 1985; Frydas, 1987; Fernandez-Gonzalez *et al.* 1994 and references therein). Thick Quaternary conglomerates (Gilbert-type deltas) overlie this lower series and in their lower levels contain mammalian fossils that have been dated as Calabrian (1.77-0.95 Ma) by (Symeonidis *et al*., 1987). Intercalated marl levels within conglomerates have given some calcareous nannofossils of Middle to Late Pleistocene age (Poulimenos *et al*., 1993; Zelilidis & Kontopoulos, 1996). Gilbert-deltas in the Xylokastron-Aegion area are capped by marine terraces that have been assigned ages from the top of Middle Pleistocene to Late Pleistocene (Keraudren & Sorel, 1987; Collier *et al*., 1992; Dia *et al*., 1997). Late Pleistocene to Holocene coral-algal reefal facies rocks are well developed within the eastern Gulf of Corinth (Kershaw *et al*., 2005; Portman *et al*., 2005).

SYN-RIFT STRATIGRAPHY IN THE PM BLOCK

General

The syn-rift succession of the study area (Fig. 3) is here divided into two informal stratigraphical groups (Fig. 4). The *lower group* comprises two units: the Ladopotamos and Katafugion formations. The lowest syn-rift succession within the PM block is best exposed in the Ladopotamos Valley, represented by the dominantly coarse-grained clastic Ladopotamos Formation, which dips and youngs towards the NW to NNW (Fig. 3). The Ladopotamos Formation comprises at least 300 m of reddish conglomerates, sandstones and siltstones (Fig. 4) unconformably overlying Mesozoic carbonate (basement) rocks (Fig. 1). An inlier of sandstones and conglomerates, previously regarded as part of the Keranitis Delta (Dart *et al*., 1994, fig. 3a, b; Ori *et al*., 1991, fig. 2 'topset beds') crops out in the Keranitis valley (Fig. 3) is considered to be part of the Ladopotamos Formation. The Katafugion Formation (ca. 40 m thick, Fig. 5) comprises a fine white calcareous unit (ca. 20-25 m thick) overlain by a package of fine-gravel clastics (ca. 18 m thick). This is followed by poorly exposed siltstones and mudstones (included in the Derveni unit). The Katafugion Formation is observed below the SE part of the Vouraikos Delta to the south of the Kastillia Fault (Fig. 3). To the north of this fault the fine-grained pro-delta facies of the upper group directly overlie the Ladopotamos Formation. We suggest that the unconformity at the base of the upper group has eroded down through the Katafugion Formation to the north of the Kastillia Fault. To the south of the fault the unconformity is located within the Derveni unit.

To the south of the PM Fault (Figs 1 and 2), markedly contrasting syn-rift successions can be traced for up to 15-20 km. Here, conglomerates (locally up to small boulder grade) with minor sandstones (and red siltstones) are organized in tilted fault blocks, locally reaching thicknesses of 1.3 km. Although precise dating is not yet available, we provisionally correlate this conglomerate succession with the lower group of the PM block.

The *upper group* comprises a relatively thin succession of (often beige-coloured) siltstones and rarer mudstones (< 50 m) (included in the Derveni unit; Fig. 4) overlain by a series of individual conglomeratic bodies (Gilbert-type fan deltas) that reach thicknesses of over 800 m. These are represented in the study area by the Vouraikos Delta, but also includes the immediately flanking (western) Keranitis and (eastern) Plaka (or Platanos) deltas (Fig. 1). The top of the Vouraikos Delta succession is unconformably overlain by a thin (10-15 m) conglomerate unit, which is capped by recent red soils on the Asomati Plateau (Figs 3 and 4). Along the range front of the Eastern Helike Fault the upper group is incised and unconformably overlain by uplifted small Gilbert-type deltas (Fig. 3).

Lower group: Ladopotamos Formation

The Ladopotamos Formation consists of interbedded conglomerate/pebbly sandstone-bodies and (minor) red siltstone/sandstone intervals. Typical conglomerate/pebbly sandstone bodies are ca. 2 m thick flat- and sharp-based, horizontally-bedded or more rarely cross-bedded sheets, or erosively based multi-storey bodies composed of similar sheets. Observed cross-stratification indicates north- and north-east-quadrant palaeoflows. Textures of the pebbly sandstone sheets are clast-supported, though rich in a matrix mixture of granules, sand and very small pebbles. Component clasts are extraformational, with rare instances of intraformational siltstone (pebbles and cobbles) lining basal erosive surfaces. Coarse-grained conglomerate-sandstone bodies (5-7 m thick) observed near the top of the formation are markedly heterolithic, containing beds of medium-coarse grained red sandstone, pebbly sandstone and small pebble to small cobble conglomerates. These show concordant channel-form structures, which incise into fine-grained red bed sequences, steep channel margins and meso- and macro-scale inclined strata-sets (terminology of Bridge, 1993) with opposed dip-directions. Interbedded fine-grained sequences with the conglomerate-sandstone bodies are orange or red sandstones, small pebble conglomerates, small pebble-rich sandstones and blocky and faintly laminated red (dusky red) siltstones/mudstones. The latter contain occasional isolated small calcareous nodules and black charcoalified wood fragments of ca. 0.75 cm size.

Interpretation. The Ladopotamos Formation is considered to be fluvial in origin, with coarse-grained probably braided river conglomerate-sandstone bodies and relatively fine-grained overbank (floodplain) siltstones and interbedded sand and gravel sheets. No lacustrine facies have been observed, as are reported further east in this fault block (see Ori, 1989; Dart *et al*., 1994). Moreover, the basin-wide 'fanglomerate' unit reported by Ori (1989) beneath the Gilbert-type delta sediment-bodies of the region does not occur our study area.

Lower group: Katafugion Formation

The Katafugion Formation begins with a distinctive white-weathering flat- and parallel-laminated shelly siltstone/marly limestone (Fig. 5). Its basal contact, though not well exposed, is apparently conformable. Fresh exposures of the white-weathering facies reveal a rhythmical alternation of pale to white competent fossiliferous beds up to 10 to 12 cm in thickness and olive green-coloured laminated silty to fine sandy beds that are ca. 5 to 6 cm thick. The calcareous facies (typically a fine-grained, massive to faintly laminated bioclastic calcsiltite) contains distributed broken bivalve and gastropod shell material. Intact but disarticulated bivalves are concentrated on bedding planes. Much of the broken and intact bivalve material appears to be from a single genus, of small (< 1 cm) members of the sub-order Pterioida. Intact small gastropods are as yet unidentified. In thin section, finer grained facies are finely laminated mudstones to wackestones with a high component of clay, seams of dark, fine-grained organic material and abundant calcitic microspar. Larger bioclasts include entire and broken ostracods, whereas smaller bioclasts include relatively abundant diatoms and possible coccoliths. A palynological study from the upper part of the carbonate member yielded dinoflagellate cysts. Apart from planar-horizontal lamination, these facies lack structures. Conformably interbedded in the fine-grained marly limestone facies at one interval is a bedset of 0.7-0.8 m thick small pebble conglomerate beds. Up section within the fine calcareous unit, the horizontal lamination dies out giving way to a massive texture that is accompanied by the appearance of occasional small pebbles.

A preliminary stable isotope analysis of shell and rock matrix from the calcareous facies was undertaken (at the CRPG, Nancy, F. Palhol, pers. comm.). Results for $\delta^{13}C$ were 1.71 and 1.8 for shell and rock material respectively, and for $\delta^{18}O$ PDB, -3.69 and -3.64‰ respectively, the determinations being consistent for the differing materials. The values for $\delta^{13}C$ are typical for a large lake or the sea with open circulation. However, the extremely negative values for $\delta^{18}O$ suggest a water body of high salinity (typical values for the eastern Mediterranean are between -0.1 and +1.0‰).

Overlying the fine calcareous unit (although an exposure gap intervenes) is a distinctive moderately sorted, well-stratified ca. 18 m thick unit of interbedded sandy-pebbly conglomerates, coarse to very-coarse (and granule-rich) sandstones and pebbly sandstones (Fig. 5) organized in beds of 30-50 cm thickness. The conglomerates are matrix-rich, and show matrix-support of the maximum clast size population. Gravel stringers that are one to three clasts thick are composed dominantly of pebbles with occasional small cobbles. The planar stratification has a (24°) depositional dip to the NW with respect to the underlying calcareous unit (Fig. 5). Lineations defined by grain alignment (and possible obstacle shadows) on bedding planes show a near down-dip orientation. Although not well exposed, the top of the conglomerate unit is apparently extremely abrupt and sharp (?non-erosional) where very fine grained lithologies replace the gravel. The poorly exposed overlying succession (?70-100 m) comprises laminated, poorly consolidated yellow to red-weathering siltstones, with possible very thin fine-very fine sandstones.

Interpretation. The transitional succession of the lower group, from fluvial channel and oxidized floodplain environments (Ladopotamos Formation) to a mixed fine-grained clastic-carbonate system capped by well-stratified fine gravel and finally much finer-grained sediments (Katafugion Formation) is thought to indicate a marine transgression. The Katafugion Formation is interpreted as representing a protected subtidal (dominantly carbonate) lagoon in a microtidal regime (e.g. Anthony *et al*., 1996), as no peritidal or obvious marsh facies were found. The restricted diversity of the mollusc-ostracod fauna plus the evidence of marine microfossils, allied to the preliminary geochemical data, suggests a saline coastal lagoon. The rare interbedded pebble gravel sheets within the lagoonal facies are likely to be storm-generated washovers or due to storm-generated flow through the barrier into the lagoon. The overlying conglomerates and sandstones suggest a high wave energy shoreface-barrier beach system (Nemec & Steel, 1984), probably at a ravinement surface This is interpreted as part of a shoreface-shoreline retreat during transgression leaving a seaward-dipping strata-set (Reinson, 1984). The termination of the coarse facies is thought to have occurred at a flooding surface and the overlying fine-grained possibly offshore marine clastics locally contain thin-bedded turbidites.

The upper group

The upper group (Fig. 4) is characterized by Gilbert-type fan delta conglomerates and their laterally equivalent facies. The Vouraikos Delta is one of the largest of these uplifted deltas, covering a (preserved) surface area of ca. 32 km^2 (Fig. 3). It is at least 800 m thick in its central region but thins considerably to the east and west (Figs 4 and 6). The delta comprises conglomerate-dominated packages of topsets, foresets and bottomsets that are grouped together as a single mapping unit (Fig. 3; Vouraikos fan delta Conglomerates). These are underlain by a unit (< 50 m thick) of siltstones and fine sandstones with 'floating' gravel clasts) that are interpreted as proximal pro-delta facies. At several localities on the western and eastern borders of the delta conglomeratic bottomsets are observed to pass laterally and asymptotically into these pro-delta facies. The pro-delta facies are distinguished as the Derveni unit (Fig. 3). The top of the Vouraikos Delta is characterized by two south-dipping plateaux (the Asomati to the west and the Kastillia to the east) at altitudes of between 750 and 820 m (Fig. 3). These plateaux are displaced by late secondary normal faults, and capped by red soil deposits (Fig. 4). The detailed internal stratigraphy and sedimentology of the Vouraikos Delta are described below.

Basal contact of the upper group

The base of the Vouraikos Conglomerates can be traced on the eastern and western flanks of the delta. As the underlying pro-delta unit is consistently 20-50 m thick we assume that the base of the upper group is sub-parallel to the base of the Vouraikos Conglomerates. In the Keranitis Valley the western base of the Vouraikos Conglomerates dips 8° N and rises southward to 600 m altitude. At the south-east edge of the delta in the Ladopotamos Valley this contact is also at 500 m altitude and locally dips 15° west (Fig. 7). However, the base of the delta is not exposed in the

Vouraikos Gorge in the centre of the delta body, despite incision down to 120 m elevation.

The transverse change in elevation of the basal contact of the Vouraikos Conglomerates and, by implication, of the upper group (Fig. 7) is here interpreted as due to incision and infill of a palaeovalley some 7-8 km wide by the Vouraikos Delta. No transverse faults that could explain the lateral change in elevation of these contacts were detected. The general cuspate base of the delta implies a relief of at least 300 m for this valley incised into the lower group. This cuspate form, however, may have been enhanced by (a) differential subsidence below the thicker central delta succession and (b) by progradation of foresets across older bottomsets thus progressively raising the delta base basinward and laterally. The palaeovalley model implies that a major regression-transgression event occurred at the boundary between the lower and upper stratigraphic groups.

In the eastern delta block (Kastillia Plateau) in the footwall block of the Kastillia Fault (Fig. 5) the character of the basal contact is different. Approximately 100 m up-section from the Katufugion Formation are conglomerates and sandstones of foreset/bottomset facies associations of the Vouraikos Delta. The thickness of the upper group (Vouraikos Conglomerates) in the footwall block of the Kastillia Fault is only ca. 200 m, whereas in the hangingwall the Vouraikos conglomerates are much thicker (> 800 m; Fig. 2b). This fault is therefore interpreted as a sealed growth fault, since there is no evidence for its surface trace. The implication of this relationship is that the Vouraikos Delta conglomerates in the footwall of the Kastillia Fault are some of the youngest sediments of the system, despite overlying the Katafugion Formation (Fig. 6). Furthermore, although a definite downlapping surface has not been identified, the structural observation that the approximately flat-lying Gilbert-type delta succession (from sub-horizontal topsets) structurally overlies a panel of north-dipping lower group sediments strongly suggests an angular unconformity between these respective successions.

BIOSTRATIGRAPHY

Pollen content was used to date selected samples of fine-grained rocks from the lower and upper groups. The presence or absence of certain thermophilous plants that became successively extinct in this area during the last 2 Myr was used for this purpose. The chronological succession of their disappearance is relatively well known at latitude 36°-39°N in the eastern Mediterranean region based on several reference pollen successions covering the time-interval under consideration. These sections are at Crotone [Vrica Santa (Combourieu-Nebout and Vergnaud Grazzini, 1991), Santa Lucia (Joannin *et al*., submitted)], Citadel of Zakynthos (Subally *et al*., 1999), Monte San Giorgio at Caltagirone (Dubois, 2001), Tsampika in the Rhodos Island (Cornée *et al*., in press; Joannin, 2003), Peloponnese localities [Megalopolis (Okuda *et al*., 2002), Phlious (Urban & Fuchs, 2005), the Argive Plain (Jahns, 1993)] and Oeniades (Gulf of Corinth) (Fouache *et al*., 2005).

A preliminary analysis has been performed on nine samples in which pollen grains are the most abundant. Their stratigraphical positions are indicated in Fig. 4. The pollen flora is represented by 58 taxa, which are generally at the genus level for the trees and the family level for the herbs. From an ecological point of view, these taxa belong to various groups: (1) subtropical trees (Taxodiaceae, *Cathaya*), (2) warm-temperate trees (deciduous *Quercus*, *Carpinus*, *Acer*, *Ulmus*, *Zelkova*, *Castanea*, *Taxus*, *Populus*, *Salix*, *Liquidambar*, *Fraxinus*, *Ligustrum*, *Betula*, *Alnus*, *Corylus*, *Tamarix*, Cupressaceae, *Carya*), (3) Mediterranean xerophytes (evergreen *Quercus*, *Pistacia*, *Olea*, *Phillyrea*, *Cistus*, *Vitis*), (4) cool-temperate (i.e. altitudinal) trees (*Cedrus*, *Tsuga*, *Abies*, *Picea*), (5) herbs and shrubs (Poaceae, Asteraceae Asteroideae, *Centaurea*, *Artemisia*, Asteraceae Cichorioideae, Brassicaceae, *Scabiosa*, *Knautia*, *Polygonum*, *Geranium*, *Mercurialis*, *Hippophae rhamnoides*, *Convolvulus*, *Catalpa*, *Jasminum*, *Ambrosia*, Fabaceae, Cyperaceae, Caryophyllaceae, *Plantago*, Ranunculaceae, Ericaceae, *Potamogeton*, *Ephedra*, Amaranthaceae-Chenopodiaceae), (6) *Pinus* and Rosaceae, which are non-significant elements because they can be related to many different biotopes, (7) *Tricolporopollenites sibiricum,* which has an artificial species name partly based on the pollen morphology because the corresponding plant is unknown. The prevalence of tree pollen grains vs. those of herbs indicates that all the samples represent interglacial phases. Some samples yielded very scarce dinoflagellate cysts (C05-11, C02-1, C05-29), indicative of marine influence. The presence or absence of certain thermophilous plants allow the samples to be divides into two broad age groups.

(a) Early Pleistocene: Five samples (C02-4, C02-7, C02-6, C05-29, C05-4) showed a significant percentage of thermophilous tree pollen, such as Taxodiaceae (in sample C02-4 only), *Cathaya* (in samples C02-4 and C02-7 only which also include a non identified pollen, the so-called *Tricolporopollenites sibiricum*), *Tsuga*, *Cedrus*, *Carya*, *Liquidambar*, and *Zelkova* (Table 1). Taxodiaceae and *Cathaya* simultaneously disappeared from the area at about 1.1 Ma whereas *Carya* and *Tsuga* persisted up to about 0.9 Ma. The extinction of *Cedrus* occurred later (ca. 0.7 Ma), and is still present in South Turkey and Lebanon. *Liquidambar* and *Zelkova* became rare and disappeared very recently (during the Last Glacial); they are still present in some refuge territories in Turkey. Stratigraphically, two of these samples come from the lower group, C05-29 from the Katafugion Formation and C05-4 from the alluvial succession in the footwall of the PM Fault (Kalavrita conglomerates). The three other samples, two of which contain the oldest assemblages, are from the upper group, specifically in the fine-grained beds below the western edge of the Vouraikos Delta (pro-delta facies). These pro-delta beds are estimated to belong to the SP3 package in the Vouraikos Delta (see below). These five samples are grouped into an age bracket of Early Pleistocene (1.8-0.78 Ma, Gradstein *et al*., 2004). No distinction can be made between the lower group samples and those from the lower parts of the upper group. Hence the basal unconformity of the upper group is not detectable.

(b) Middle Pleistocene: Four samples (C02-3, C05-11, C02-1, C05-20) do not contain these thermophilous plants, except some rare pollen grains of *Cedrus* (samples C02-3 and C05-11) and *Carya* (C02-3) (Table 1). In addition, they show increased percentages of *Olea* and sometimes the presence of *Vitis* (Table 1), two Mediterranean elements that developed during the Middle Pleistocene. Two samples come from within the delta itself: C05-11 comes from the upper topsets of SP1 in the centre of the delta and C02-1 comes from the western topsets of SP3. Two samples come from SP5 beds at the top of the delta (C02-3 and C05-20). These samples may be somewhat younger that those of the previous group and may belong to the Middle Pleistocene (i.e. after 0.78 Ma).

Although preliminary, these results indicate that the Vouraikos Delta was built mainly during the Early Pleistocene beginning sometime before 1.1 Ma and probably during the beginning of the Middle Pleistocene (up to somen time after 0.6 Ma). These data indicate that the unconformity at the base of the upper group does not represent a major time gap.

VOURAIKOS DELTA SEDIMENTOLOGY

Previous work

Very little detailed stratigraphical or sedimentological research has been published on the Vouraikos Delta. Ori *et al*. (1991, fig. 2) regard the Keranitis and Vouraikos deltas (Fig. 2) as a single system. They indicate that the sediments of the Vouraikos Delta (sensu stricto – as used in our definition) are composed of variously alternating sequences of topsets and foresets (their fig. 12) and the uppermost internal stratigraphical units to be 'foreset beds' (their fig. 2). Poulimenos *et al*. (1993) and Zelilidis & Kontopoulos (1996, fig. 1b and fig. 2a C-C’) regard the western part of the

Vouraikos Delta (our definition) to be the eastern fan delta system in their 'Egio Sub-basin'. They consider the delta to lack ‘toesets’ (bottomsets), describing it as a ‘trapezoidal’ delta on the basis of its longitudinal cross-section, and attribute this form to deposition in a "protected" or narrow basin. Dart *et al*. (1994), did not report specifically on the sediments of the Vouraikos Delta system, but they show the Vouraikos as a separate system from the Keranitis, as did Malartre *et al*. (2004).

Facies and facies associations

Facies associations in Gilbert-type delta systems can be defined to a first-order by their position (and attitude) in the tripartite structural division of these deltas: sub-horizontal topsets, angle of repose foresets and low-angle (< 10°) bottomsets. The range of facies associations defined (see also Malartre *et al*., 2004) further includes the markedly finer grained (sub-horizontal) pro-delta and the relatively thin shoreline/coastal heterolithic types. The distinction between bottomset and pro-delta environments differs from that of several other studies. Several of these gross divisions contain distinctive sub-associations, which are elaborated below.

Alluvial topset facies association

This consists of (1) a heterolithic sub-association of sandstone, conglomerate and siltstone red-bed facies, and (2) a volumetrically- and areally-dominant conglomerate-rich sub-association. Both have been observed to comprise only depositionally horizontal architectures (cf. Dart *et al*., 1994, p. 549), and tend to occur in sequences of tens of metres thickness, although the conglomerate-rich association is consistently more thickly developed, and often reaches hundreds of metres of preserved thickness. Mean palaeoflow was towards the N-NNE.

Heterolithic sub-association. This consists of interbedded small pebble-small cobble conglomerates, pebbly sandstones, red or brown sandstones and reddened siltstones (Fig. 8). The small pebble conglomerate facies are commonly horizontally-stratified in sheet-like or lenticular beds, with erosive bases showing longitudinal scours. Coarser conglomerates (small cobble grade) tend to be massive, or locally cross-stratified. Normal grading has been observed in some ca. 1 m thick beds. Sub-spherical carbonate nodules have been observed in red-brown siltstone facies, overlain by weakly undular-laminated carbonate (calcrete) in fine sandstone (forming a > 0.7 m thick bedset). The heterolithic sub-association is similar to 'topset facies association 2' of Dart *et al*. (1994), except that examples of their association 2 are traceable for distances up to 1 km across the fan delta top.

Conglomeratic sub-association. This is principally composed of matrix-rich (coarse sand to small pebbles) clast-supported conglomerates with modal grain sizes of medium pebble to small cobble grade. The modal grain populations are poorly sorted, and maximum particle size is small boulder grade. Clasts are well rounded to rounded and shapes variable. Fabrics are dominantly unordered, with *a*(t)*b*(i) imbrication being subordinate. Palaeoflow data from imbrication indicated north-quadrant vectors. Bed thicknesses of the typical conglomerates range from 1 to 5 m. Finer grained conglomerate facies (e.g., small pebble conglomerates) can have bed thicknesses of < 0.5 m. Bases of coarse facies are generally prominent irregular-erosive surfaces lacking obvious large-scale relief, but with variably developed small-scale (ca. 0.1 m) longitudinal scours. Stratification within beds is very poorly developed, with a predominance of massive (structureless) to crudely horizontally-stratified beds. Stratification is enhanced occasionally by very thin (often reddened) sandstones. Large-scale cross stratified conglomerates occur rarely, and have been observed only as solitary sets, ranging from 1.5 to 4 m in thickness. Cryptic and very low-angle planar (cross) stratification has been occasionally observed, with surfaces having (N-quadrant) dip-directions similar to associated clast imbrication palaeocurrent indicators. Grading profiles in beds are not well developed and, although a detailed study has not been carried out, there is no obvious correlation between bed thickness and maximum particle size.

This sub-association is frequently organized in cyclical sequences, metres to tens of metres thick. Topset cycles are developed from prominent basal erosional surfaces, followed by massive, crudely-bedded conglomerates and capped by thinner-bedded conglomerates with development of reddened sandstones (e.g. Fig. 9). Thus, there is a tendency towards fining- and thinning-upwards cycles. Other cycles between prominent basal surfaces are neutral in terms of grain size and bed thickness.

Interpretation. The texture (particularly *a*(t)*b*(i) imbrication, clast-support and poor sorting) and bed geometry of the conglomerates (and subordinate sandstones) comprising the conglomeratic topset association are consistent with turbulent water (stream) flows (Nemec & Steel, 1984). Sheet-like geometries and lack of channel forms suggest either deposition in wide, shallow low-sinuosity gravel rivers that occupied the sub-aerial fan delta top or as unconfined high magnitude sheet floods (e.g. Young *et al*., 2000). Occasionally preserved downstream-dipping low-angle inclined surfaces imply low-relief (?longitudinal) bars, on which gravel may have been accreted as diffuse gravel (bed load) sheets (Hein & Walker, 1977; Bridge, 2003); however, the preserved facies lack an openwork texture and well developed grading profile typical of lower-stage plane beds (Bridge, 2003; see also Nemec & Postma, 1993).

The stacked thinning- and fining-upwards topset cycles may be a reflection of declining accommodation modulated by high frequency fluctuations in relative sea level, where thinner bedded units correspond to progradational episodes and basal thick-bedded topsets aggradational episodes. The heterolithic sub-association is interstratified with the gravel-dominated topset sequences, and is thought to represent sub-aerial, non-channelized (floodplain) environments on the delta top.

Shoreline-shallow marine topset facies association

This lithologically and structurally diverse facies association occurs in grossly sub-horizontal units and is therefore a 'topset' association. It is referred to as shoreline-shallow marine based on evidence of distinctive textures, stratification and faunal/ichnofaunal content. It comprises four main sub-associations, detailed below.

Very well sorted and stratified clinoform conglomerates (SFA1). Examples of this sub-association occur interstratified with texturally-contrasting alluvial topsets (Fig. 9), in association with limestones (SFA3 below; Fig. 10c) and have also been observed to overlie the accretionary toplap association (SFA2, see below). This sub-association is exemplified by two detailed examples.

A well exposed 7-8 m thick sequence from the Vouraikos Gorge (location B, Fig. 3) consists of three inclined stratasets (A-C, Fig. 9). The basal unit is heterolithic, with ca. 5 cm thick, inclined, very well sorted small pebble to granule conglomerates interbedded with laminated red, yellow and beige fine sandstones and siltstones. There are frequent downward-tapering burrows into the tops of the fine facies from the overlying fine gravels/sandstones. Unit B coarsens-upwards, commencing with sub-horizontally stratified, very well sorted granule to small pebble conglomerates (bed thicknesses 4-6 cm), which are clast-supported and normally-graded. The upper two-thirds of Unit B contains evenly-spaced 'stringers' of large pebbles to small cobbles. Unit C is finer grained, composed of interbedded, very well stratified small pebble conglomerates (9 to 38 cm in thickness) and red, medium to coarse sandstones (5-8 cm sheets) that contain granule to small pebble laminae. The sandy facies contain a moderate frequency of sub-horizontal, tube-like burrows.

The second example of SFA1 (location C, Fig. 3) shows, in adjacent sections (Fig. 10b), diverse facies comprising metre-scale sequences of (1) well imbricated, normally-graded small pebble conglomerates, very well sorted parallel-laminated granule conglomerates, massive angular-shaped small-medium pebble conglomerates (Fig. 10d), (2) steeply-dipping (22°) openwork small to large pebble conglomerates, parallel-laminated coarse sandstone to granule conglomerates and massive bimodal conglomerates (Fig. 10d) and (3) bioturbated siltstones, coarse sandstones and poorly sorted small pebble conglomerates (Fig. 10e). Section (1) occurs above an exceptionally sharp-planar surface overlying a prominent limestone bed (SFA3, below) and comprises a package of sediment that has restored low-angle strata (5-10°), but was probably an overall sub-horizontal unit. Two conglomerate beds within this section contain calcite-cemented and limestone-encrusted bed tops (Fig. 10c). Observed clast imbrication indicated consistent north-quadrant palaeoflow.

Interpretation. SFA1 is considered to have been deposited subaqueously. The tightly-packed conglomerate textures, stratified granule conglomerates and very coarse sandstones and seaward-dipping imbrication suggest moderate to high wave-energy conditions, and the lack of wave ripples in gravel sediments suggest shallow depth conditions prevailed. The variable ichnofauna, thin carbonates, consistently-directed clinoforms, occasional cross-bedding with distinctive openwork textures again suggest wave-influenced and wave-reworked gravels in a shallow marine shoreface-lower beachface setting (e.g. Nemec & Steel, 1984; Dabrio & Polo, 1988; Dabrio, 1990; Massari & Parea, 1990; Hart & Plint, 1995).

Accretionary toplap conglomerates/sandstones (SFA2). A suite of moderately distinctive facies is associated with accretionary toplap contacts where, rather than a single erosive contact between Gilbert foresets and flat-lying topsets, a series of areally-restricted local contacts are arranged en-echelon, sometimes climbing upwards in the progradation direction (see Dart *et al*., 1994, figs 7 and 8). Sequences arranged about accretionary toplap contacts (equivalent to the "transition zone" of Colella, 1988; Gawthorpe & Colella, 1990) are ca. 5 m thick or less and are characterized by showing moderately improved fabric development and stratification compared to alluvial topset conglomerates. The principal conglomerates' grain size varies typically from medium pebble to large cobble and large cobble to small boulder sizes. Sorting is generally poor, with matrix-rich facies showing matrix- and local clast-support systems. Weak *a*(t)*b*(i) clast imbrication is recorded (with north-quadrant palaeoflows), but massive-unordered fabrics are the norm. Facies with matrices of coarse sand-granules to very small pebbles and outsize clasts are recorded, with variants being small to medium pebble conglomerates with small boulder outsize clasts. Stratification is characteristically enhanced in conglomerates of SFA2, being defined by either thin (5-10 cm thick) fine-grained conglomerates, equally thin medium-coarse (reddened) normally-graded sandstones or simply thin stratification in homogeneous gravelly sediments. Thicker interbedded sandstones within the accretionary toplap structure have been observed in inaccessible cliff sections, occupying the lower topset-upper foreset position. Apparently texturally-distinct topset beds that overlie erosive toplap contacts have also been observed, but not directly examined. These are apparently massive and moderately to well sorted, tabular beds up to several metres thick.

Interpretation. The structural position of this sub-association alone suggests a contrasting emplacement process to alluvial topsets. The interpreted location is suggested as a shallow sub-aqueous environment, which was affected by periodic flood-generated fluvial inputs of gravel (and sand) and reworking by moderate wave energy, equivalent to the 1 km wide shallow-marine topset of the modern Vouraikos Delta (Dart *et al*., 1994, p. 549). The textural and stratification character of SFA2 contrasts with that of SFA1 where wave and current reworking of the sediment was considerably stronger. This may have been suppressed in SFA2 due to the dominance of fluvial supply during episodes of progradation-vertical accretion of the delta system. Occasionally observed distinct (single) beds erosionally overlying toplap contacts, which are apparently structureless and show closely-packed textures, may represent wave-reworked gravels in a shoreline environment (see Colella, 1988).

Limestones (SFA3). Two limestone units were found in the Vouraikos Delta in this study, the Marathia and Mamoussia limestones (Figs 3, 6 and 10c). The Marathia Limestone is a bioclastic arenitic grainstone (Fig. 11a) to rudstone. It is massive to crudely horizontally stratified with a sandy texture in its lower part, and a 'rubbly' 45 cm thick top (Fig. 10c). The limestone contains low-spire gastropods, fragmentary large, thick-shelled pecten bivalves, fragmentary small bivalves, ?tubiform bryozoa encrusting/cementing clasts, ostracods, foramineras, echinoid spines, ?rhodophytic algae and other bryozoans (Fig. 11a).

The Marathia Limestone is associated with SFA1 sediments with low-angle (7-10°) primary depositional dips (Fig. 10b, c). This limestone abruptly overlies a massive, pebble to cobble conglomerate, and is terminated by the exceptionally sharp, planar basal surface of a small pebble conglomerate of SFA1 (Fig. 10c). The thickness of the limestone decreases southwards from 2.2 m to > 1.4 m over a distance of 30 m, where the bed terminates in a low-relief (1.4 m) palaeocliff with a steep east-west striking orientation (091/86°). Near the base of the palaeocliff there is a talus-like deposit with a northward-dipping inclined-curved fabric oriented 074/54°. However, the wall rocks of the palaeocliff have the same flat-lying bedding orientation of the main limestone, and are mixed clastic-carbonate lithologies, in which sands and granule to pebbles are organized in typically 5 to 30 cm thick beds with white fine calcareous matrices.

The Mamoussia Limestone is located in the extreme south-west of the Vouraikos Delta in the western part of the Mamoussia cliff (location D, Fig. 3). This is a thin bed < 2 m thick, stratigraphically located between the locally lowest Gilbert set and overlying topsets (Fig. 6). In thin section the limestone is seen to be very rich in fragmentary and complete algae (Fig. 11b). The lithology and texture is an arenitic bioclastic packestone to grainstone, containing probable peloids and extraformational clasts. Algal bioclasts have micritized envelopes. This facies with its concentration of particular organisms most closely resembles standard microfacies type 12 of Wilson (1975) and Flügel (1982).

Interpretation. The Marathia Limestone facies represents high-energy, shallow-water open marine carbonate deposition on a flooded sector of the Vouraikos Delta top isolated from clastic input, following transgression. Similar facies from a Pliocene Gilbert-type delta setting have been described by Mortimer *et al*. (2005), where carbonate units represented marine transgression of the delta top. The Marathia palaeocliff and the contrasting mixed clastic and carbonate facies, suggests an earlier phase of episodic carbonate-clastic deposition followed by erosion and a later phase of sustained carbonate deposition lacking significant clastic input and having developed after minor fluctuations in relative sea level on the flooded delta top. The Mamoussia Limestone microfacies typifies wave affected shelf edges (Tucker & Wright, 1990, table 1.1), which is analogous to the structural position of the unit at the seaward edge of the submerged delta topset. Carbonate sediments containing algal remains are reported in analogous shallow subaqueous (topset) settings, in (non-Gilbert) gravelly fan deltas (Ethridge & Wescott, 1984) and Gilbert-type deltas (Postma *et al*., 1988; Young *et al*., 2002, their facies 2b, c).

Laminated shelly siltstones and sandstones (SFA4). This rare sub-association consists of units up to 8 m thick of (1) laminated fine sandstone-siltstones with a uniform grain size profile and (2) laminated white-pale grey siltstone (to mudstone), which contain distributed fragmentary shelly fossils, as well as monospecific bivalve assemblages. Units may be sharply-based conformably overlying stratified pebble-cobble conglomerates. This fine facies is interbedded with rare < 10-12 cm thick parallel-sided pebble conglomerates and pebbly sandstones, or interstratified with one clast-thick layers of small pebbles.

Interpretation. This sub-association is considered to represent shallow water back-barrier/lagoonal fines. The fine-grained laminated, weakly calcareous character plus the restricted diversity fauna point to a protected sub-aqueous environment at the margin of the flooded topset region of the delta. Small pebble clasts layers and pebbly sands are interpreted as with storm washover sediments across coastal barriers or spits.

Gilbert-type delta foreset facies association

This facies association represents the largest volume of the Vouraikos fan Delta. A compilation of large-scale (Gilbert) foreset orientations from the whole delta (Fig. 6) indicates a mean direction of progradation toward the NNW (345°, Fig. 12). The dispersion of the data suggests a convex (linguoid)-shaped sediment body. Dip values for foresets shown by the polar plot (Fig. 12; 10-35°) indicate a typical range for gravel-dominant Gilbert deltas (Nemec, 1990). It comprises well-bedded sequences of metre-scale pebble-cobble grade conglomerates, thinner bedded sand matrix-rich very small to small pebble conglomerates, as well as coarse and pebbly sandstones. Notable are matrix-free openwork clast-supported pebble-cobble conglomerates (typically 10-20 cm in thickness), in units parallel to other facies. Stratification also includes types that are discordant, very low-angle planar strata and convex-up cross-stratification in single sets. Foreset stratification tends to be uniform and the texture homogeneous; sub-parallel, cross-cutting surfaces such as those described by Dart *et al*. (1994) or large-scale syn-sedimentary deformation features for the Keranitis Delta (described by Ori *et al*., 1991) have not been observed. However, examples of interbedded fine-grained foreset intervals include mutually cross-cutting channel-form conglomerates < 2 m thick with 10 to 15 m wide transverse sections, interbedded with and eroding into red and brown laminated sandstones and red siltstones-mudstones. The shallow channel conglomerates are moderately to poorly sorted pebble to small cobble size with a sand matrix. Channel form bases are marked by scour structures in the form of occasional large-scale (10-15 cm thick), isolated flute marks. The channel form axes are oblique but dominantly down-dip of the foresets; interbedded associated fine-grained facies have been observed to contain small-scale down-dip verging soft sediment folds. Cliff-scale exposures of complete sets reveal very gently concave foresets, with clear reduction in dip as the bottomsets are approached.

Interpretation. Large-scale foresets represent bedload and mass-flow emplacement of gravel and sand into a standing water body (cf. Prior & Bornhold, 1990; Postma, 1990; Falk & Dorsey, 1998). The set thickness of the association indicates palaeowater depths in the range of 300-700 m. Clast-supported openwork foreset conglomerates were interpreted by Dart *et al*. (1994) as the tops of individual flow units, whereas the massive to crudely bedded, matrix-rich beds were considered as grain flows.

Bottomset facies association

This association is composed of thinly interbedded plane-laminated and rippled sandstones and conglomerates (Fig. 13a). Erosion surfaces and/or scours are common. In some places, soft sediment deformation occurs with small-scale slump folds and/or dewatering structures (Fig. 13b). They represent the base of Gilbert foresets where low-angle slopes dip at values typically 5-10°.

Pro-delta facies association

This is an important facies association as it represents distal environments to the Gilbert-type delta, affected by basinal processes as well as sediment input from the delta. It is dominated by thinly bedded, beige and grey-green coloured, massive to finely parallel-laminated siltstones and silty sandstones with sharp bases (Fig. 13d), thin pebble conglomerates and laminated siltstones. Floating gravel clasts commonly occur in the fine (sand and silt) facies (Fig. 13c). This association is spatially related to the Gilbert-type delta bottomsets, and the two can be frequently mapped together in the field (Fig. 13e). Pro-delta and bottomsets share individual facies types (such as fine sandstones). Depositional dips are lower than those of bottomsets, and are generally undetectable.

Interpretation. These deposits can be interpreted as the products of processes ranging from suspension fallout deposits to turbidity current deposits that are *largely* beyond influence of gravel input. They represent the deepest facies of all the associations observed in the Vouraikos fan Delta system. This facies association is genetically related to the fan delta foreset-bottomset structure of the system, and results from emplacement of major increments of clastic sediment following periodic fluvial flood events. The pro-delta of Type A feeder Gilbert-type fan deltas are affected by foreset-derived mass flows and density currents, as well as hemipelagic sedimentation (Postma, 1990; see also "basin plain" deposits of Hwang & Chough, 2000).

VOURAIKOS DELTA ARCHITECTURE

Within the Vouraikos Delta we have defined five internal stratigraphic packages numbered SP1 to SP5 (Fig. 4). A stratigraphic package is here defined as a distinct succession limited by prominent bounding surfaces. A stratigraphic package can comprise (a) packages of topsets (representing palaeohorizontal) and (b) very large-scale foresets (at angles of repose of ca. 20-35°) and/or (c) multiple sets of topsets and foresets. Comparatively thin, but locally distinctive, bottomset, thin pro-delta and shallow-water coastal facies associations are occasionally found within the thicker stacked packages. There is considerable lateral variation in individual stratigraphic packages (see Fig. 6), related to (a) thickness variations, (b) transitions of topsets into foresets and (c) other variations due to intra-deltaic growth faults. Detailed correlation is further complicated by changes in structural elevation due to second-order extension faults, such as the Derveni Fault (Fig. 3). While bounding surfaces are clearly distinguishable in the proximal (topset) part of the delta, they can be lost distally, in particular within thick foreset sequences.

Despite this, good stratigraphic coherence is displayed, particularly in the southern and western parts of the delta. We present principally an analysis of the western half of the delta (Asomati block) along two major NNE-SSW cross-sections (Fig. 14), three east-west profiles in the Asomati block (south, centre and north). The eastern part of the delta (Kastillia block) is represented in less detail in the regional cross section in Fig. 2b and in one natural east-west profile on the north-east side of the Kastillia block (Fig. 3).

Centre of delta - the Vouraikos Gorge

The Vouraikos Gorge, with a relief of > 700 m, provides the most complete section through the centre of the Vouraikos Delta. For convenience, the section along the western side of the gorge is divided into four sectors demarcated by major faults and labelled A to D (Fig. 14a). The base of the delta is not exposed anywhere along this section.

The lowest stratigraphic package SP1 is found only in the centre of the delta (sectors A, B and C in Fig. 14a). It comprises a single set of major foresets at least 200 m thick (base not seen) overlain by 200-250 m of topsets that together describe a gentle rollover anticline dissected by secondary north-dipping normal faults. At the southern extremity of the fold, in the immediate hangingwall of the PM Fault, topsets have been rotated to dip 30° S and foresets have become horizontal (Figs 14a and 15). Fold amplitude decreases upward indicating that fold activity died out during deposition of SP3. A simple 'chevron' construction (Verrall, 1981) suggests that the controlling listric fault soled out about 100 m below the present erosion level (not shown on Fig. 14a). At the southern end of the section, tilted foresets lie within 20 m of the PM Fault and there is no evidence of extreme basin-margin proximal facies in the southernmost SP1 packages. This implies that the topsets equivalent to these foresets must have lain further south. The PM Fault, hitherto regarded as the basin-bounding fault for the whole Vouraikos Delta, is therefore here interpreted as a post-SP1 fault. The southern topsets of SP1 were thus uplifted and eroded in the footwall of the PM Fault. On this section line the listric fault that generated the rollover anticline was cut out by the later PM Fault, however we identify the Kastillia Fault in the eastern delta block is probably it lateral equivalent.

Across sector B, SP1 foresets curve from horizontal to dip north, while SP1 topsets become sub-horizontal. These topsets are predominantly alluvial in character although a ca. 12 m thick sequence of shallow-marine conglomeratic and sandy sediments occurs near the top (SFA1, Fig. 9). On the southern limb of the rollover anticline an angular unconformity of 12° marks the boundary between SP1 and SP3 (UC1 on Figs 14a and 16). This unconformity disappears northward as the rollover anticline dies out. Toward the south UC1 can be continued as the erosive boundary between SP1 and SP2.

In the immediate hangingwall block of the Derveni Fault (panel C, Fig. 14a), the top of SP1 is downthrown ca. 300 m so that only the uppermost topsets are exposed. These south tilted alluvial conglomerates are incised by an erosional scour with a (minimum) relief of 50 m (Fig. 17c, d) and oriented N-S. This surface is correlated with the UC1 unconformity to the south and is overlain by a set of shallowly NW dipping SP3 foresets.

SP2 is an aerially restricted ca. 200-220 m thick package of north-dipping foresets that lies between SP1 and SP3 in sector A (Figs 6, 7 and 14a, described below). It is found nowhere else in the delta. NW dipping foresets of SP3 abruptly overlie SP2 foresets and locally preserve fine pro-delta facies at the SP2-SP3 contact.

SP3 is a 200 m thick alluvial topset sequence showing a weakening rollover geometry up-section in sector B (Fig. 14a). These thickly-bedded conglomeratic topsets are laterally equivalent to major NW-dipping foreset packages that are visible on the Mamoussia cliff and western profile (Fig. 14b).

Above UC1 in sector C of the central profile, the SP3 foresets (Fig. 14a) are cut by weakly curved faults, which have back-rotated the foresets to sub-horizontal attitudes in places. The overlying SP3 alluvial conglomerate topsets thicken southward toward the Derveni Fault indicating that it was active during their deposition.

In sectors B and C (Fig. 14a) SP3 is abruptly terminated by a sharp, apparently horizontal bedding surface that forms the base to a finer-grained, and well-bedded, sequence of conglomerates and sandstones defined as SP4 that includes alluvial topsets and small Gilbert-type delta packages of 10-20 m thickness all building out to the NW (Fig. 17a, b). SP4 thickens northward across panel B from 170 m to 200 m (top exposed). The unit also thickens abruptly across the Derveni Fault to form the upper 300 m of panel C (top eroded), implying syn-SP4 activity on this fault.

Panel D (Fig. 14a) is demarcated to the south by a weakly listric, poorly exposed, growth fault of unknown displacement. The panel is dominated by a set of large foresets dipping shallowly toward the NW and having a minimum thickness of ca. 400 m. Above, at least two smaller sets occur as well as at one horizon of conglomeratic topsets of unverified environment. As correlation across the fault is unclear we assign all these strata to SP3/4. The Eastern Helike Fault abruptly terminates the delta to the north.

At the top of the cliff in sector B (Fig. 14a) a prominent, thin (5-10 m) south-dipping conglomerate unit (SP5) gives a wedge-shaped aspect to SP4.

Western limit of delta - Keranitis Valley

This N-S cliff section (Fig. 14b, shown as a mirror image for ease of comparison) forms the eastern side of the Keranitis River valley. The profile affords a near complete section of the western limit of the Vouraikos Delta, comprising a relatively simple architecture of upper topsets, a continuous foreset succession with thin (20-50 m) underlying pro-delta sediments (Malartre *et al*., 2004, fig. 2). The architecture of this section is markedly different from the central Vouraikos Gorge section, which lies just 3 km to the east. The basal (diachronous) ‘enveloping surface’ of the delta conglomerates dips markedly (8°) to the north; this is a (largely) primary dip. As the topsets dip gently south, the delta body thickens northward. Bottomsets and foresets build toward the W and WNW (i.e. obliquely out of the plane of the section; Fig. 6). North-dipping sediments of the Ladopotamos Formation are exposed below the delta in the southern Keranitis Valley. Correlation of stratigraphic packages from the Vouraikos Gorge identifies the lowest stratigraphical level of the delta at the southern end of this section as SP3 foresets and topsets (compare with Fig. 16a, b). We estimate that somewhere to the north of Derveni Village SP3 foresets pass up into SP4 foresets, however, it is not possible to pinpoint this transition. Thus the SP3 and SP4 topsets observed in the Vouraikos Gorge (Fig. 14a) have passed distally (toward the NW-WNW) to foresets on this profile. Thin SP3 topsets are only observed at the southern end of the western section where they include the Mamoussia algal limestone facies (SFA3, Figs 6 and 11b). Horizontal topsets above the main succession of foresets are assigned to SP4 because they contain small Gilbert-type deltas of 5-10 m height interspersed with alluvial topset sequences. This package can also be traced around to the central profile along the cliffs in the immediate footwall of the Derveni Fault (see Fig. 17a, b). Therefore the major toplap surface on this section is the SP3-SP4 boundary. SP5 is not visible on this section line. The marked contrast in geometry and stratigraphy between this section and that in Fig. 14a is because this section represents the younger western fringe of the delta, which has overspilled the edge of the palaeovalley.

The minimum displacement on the PM Fault is considerably less on this profile than in the centre of the delta (Fig. 14a), implying that fault displacement decreases rapidly westward. The section is cut by three secondary extension faults, the Asomati, Derveni and Marathia faults. The Derveni Fault downthrows the toplap contact by ca. 200 m to the north. Late displacement on the Derveni Fault has tilted topsets of the hangingwall block to 3° south. Between the Derveni Fault and the Helike Fault the delta conglomerates are highly fractured but comprise principally west-dipping SP4 foresets of > 400 m height (see below).

The stratigraphic architecture of the western end of the Vouraikos Delta is quite distinct from that of the nearby eastern part of the Keranitis Delta (see Dart *et al*., 1994, fig. 6). The bases of these deltas are separated by ca. 400 m of altitude, while the tops are at the same level (detailed by Malartre *et al*., 2004). This implies that they developed as independent delta systems separated by a transverse fault in the Keranitis Valley (Fig. 3).

SW proximal corner of delta - WSW-ENE Mamoussia section

This indented east-west cliff extends from the Vouraikos Gorge westward to just north of the village of Mamoussia (here referred to as the Mamoussia Pass, Figs 7 and 18b), a distance of ca. 2 km, and links the proximal parts of the two sections described above. An oblique view of this cliff is shown in Fig. 18a. The cliff forms a gross depositional strike section in terms of the Vouraikos Delta as a whole, but for several of the constituent stratigraphical units it forms a dip and oblique section with respect to foreset building directions. The Avriyiolaka Fault, striking E-W, obliquely cuts the indented cliff and downthrows to the north by 30-40 m with displacement dying out rapidly to the west (fault not seen on western section, Fig. 14b). Four stratigraphical packages, SP2 to SP5 can be traced between the central and western cross sections. No cross faults (i.e. striking around N-S) are detected in this cliff, however the base of the delta clearly rises from below 120 m in the Vouraikos Gorge westward to an altitude of 600 m at Mamoussia Pass (Fig. 18b). At the same time the delta edifice thins from over 800 m to less than 200 m westward. We interpret these observations to mean that the delta gradually infilled a palaeovalley of around 500 m depth as represented in Fig. 18b. A similar configuration is observed on the eastern side of the delta between the Vouraikos Gorge and the Ladopotamos Valley.

SP2 is the smallest delta package being 1.7 km wide and around 200-220 m thick (Fig. 18). It is limited to the SW sector of the delta and comprises principally conglomeratic foresets although its lowest, most easterly exposures include bottomset facies. The true base to the set is not exposed but it must erosionally overlie SP1. In the lowest part foresets and bottomsets build towards 041° however the package is dominated by foresets with a mean building direction toward 357°. Foreset and bottomset inclinations suggest that little or no rotation has occurred. SP2 can be followed westward to within 1 km of the Mamoussia pass. In its most westerly exposure it is overlain by bottomset and pro-delta facies of SP3. This delta package must terminate westward because, at the same elevation 2 km further west in the

Keranitis Valley, north dipping sandstones and conglomerates of the Ladopotamos Formation crop out.

The SP3 package can be traced across the entire length of the cliff (Fig. 18a). It is dominated by a major set (ca. 180 m thick) of foresets with a true NW building direction. This set and its erosional toplap contact are downthrown to the north by the extensional Avriyiolaka Fault. SP3 foresets pass eastward to flat-lying topset facies associations, which correlate with SP3 alluvial topsets in the Vouraikos Gorge section (Figs 14b and 18b).

In the footwall of the Avriyiolaka Fault, fine-grained bottomset to pro-delta facies are exposed at around 500 m, marking the base of the SP3 delta. This contact gradually rises westward in elevation to 600 m at Mamoussia Pass. SP3 correspondingly thins rapidly to the west where it comprises markedly curved-asymptotic foresets some 4-50 m high, passing into bottomsets and pro-delta beds (Fig. 18a).

The upper part of SP3 (Fig. 18a) is a flat-lying sequence of horizontally stratified conglomerates of alluvial aspect. The facies are best seen in the mid-central part of the main cliff (hangingwall of the Avriyiolaka Fault), where they sharply truncate the underlying foresets. The package can be divided into three units by prominent sharp conformable bedding surfaces (Fig. 18a). The upper surface to the whole package is a very sharp, planar trace.

The uppermost major package in the profile, SP4, is finer grained than those units below, and contains facies showing well developed fine-scale stratification, heterolithic character, with (finer-grained) conglomerates, pebbly sandstone and sandstones. Overall it is horizontally stratified, but contains several levels comprising large-scale cross-stratification with consistent apparent inclinations to the west, which are interpreted as small-scale Gilbert-type deltas. The approximate thickness of these sets is 5-20 m. The gross horizontal stratification is conformable with the underlying SP3 topsets. The unit is terminated by a notably continuous conglomerate bed at the top of the cliff (SP5), which dips to the south. SP4 is 60-70 m thick in the Mamoussia cliff (Fig. 18a) indicating that it thins westward from 170 m at the southern end of the Vouraikos Gorge (Figs 14a and 18b).

SP5 is a ca. 8-10 m thick grossly flat-bedded unit, comprising a variable sequence of facies that include matrix-rich, poorly sorted pebble- to cobble-grade massive conglomerates and matrix-poor, moderately sorted inclined- and flat-stratified conglomerates. Cross-bedded conglomerates occur, with sets up to 2 m thick and moderate to low-angle planar foresets. Finer-grained facies include interbedded reddish mudstones (8-10 cm bed thickness) and 12-15 cm thick bioturbated fine sandstones (with bedding parallel burrows). Highly indurated very coarse sandstone-granule facies contain sparry calcite cements and ostracod and algal bioclasts.

Northern exposures of the delta: east and west frontal profiles

The Vouraikos Delta has been cut and exhumed in the footwall of the East Helike Fault to form a range front 7 km long and 700-800 m in height. At the NW corner of the Asomati Plateau the youngest delta foresets belonging to SP4 are well exposed in an east-west cliff in the footwall of the secondary Marathia Fault (Fig. 19a). These frontal foresets are at least 350 m high (being cut by the Marathia Fault) and dip predominantly 23-30° to the WNW and west. The overlying fluvial topsets at the NW tip of the plateau dip 10-20° S-SW (Fig. 14b). The topset-foreset transition shows that the delta front prograded toward the west. Small Gilbert delta packages are seen to build out toward the west within the SP4 topset complex.

Similarly, the youngest north-eastern frontal part of the delta is visible on the E-W range front of the Kastillia Plateau (Fig. 19b). Here two major packages of foresets are visible; a lower north-building package below Faghia, some 250 m high, and a larger upper package of consistently NE-dipping foresets that are at least 600 m in height. This vast (unfaulted) foreset package forms the whole NE and eastern side of the Vouraikos Delta. These foresets are probably the equivalent of SP4. Thin topsets of both packages dip shallowly south on the top of the Kastillia Plateau.

At the mouth of the Vouraikos Gorge on the western side of this section a thick sequence of south-dipping fluvial sediments occurs in front of and below the delta foresets. It is not yet clear if these strata belong to the Ladopotamos Formation and thus truly underlie the delta, or if they are younger deposits deposited along the range front during late exhumation of the delta. These deposits are incised into and overlain by the youngest Gilbert-type deltas whose tops form depositional terraces dipping gently toward the NE (Fig. 19b). These young deltas have themselves been uplifted in the footwall of the Eastern Helike Fault. Their foresets are up to 30 m high and dip predominantly to the NE (Fig. 19b).

EVOLUTION OF THE VOURAIKOS DELTA

The data presented above are used to reconstruct of the depositional history and character of the Vouraikos Delta and to identify the factors that controlled its evolution. Accommodation space was created principally by the PM normal fault system with displacement distributed on different branches at each stage of basin history (Fig. 20).

Delta deposition (800 m minimum) is estimated to have occurred during the early to mid Pleistocene from before 1.1 Ma to after 700 ka (600 to 400 ka) implying a high sedimentation rate of between 1.3 to 2 mm yr^{-1}. The delta built northward in a radial fan fault controlled basin. The carbonate facies (in SP3 and SP4) and the isotope study (Katafugion Formation) described above indicate that this basin was wholly or periodically marine. High-resolution studies on Late Pleistocene deposits in the Gulf of Corinth indicate that the salinity of the basin fluctuated between marine and fresh water, controlled by eustatic sea level variations (Perissoratis *et al*., 2000; Kershaw & Guo, 2003). In addition, biostratigraphic studies on Lower and Middle Pleistocene sediments record brackish, lacustrine and marine fauna (Frydas, 1989, 1991; Fernandez-Gonzalez *et al.* 1994).

Reconstruction of the western half of the delta is divided into five stages equivalent to the five stratigraphic packages SP1-5 described above. These are represented in scaled maps and in longitudinal and cross sections (Figs 20 and 21). The cross sections represent only the western half of the delta where the PM Fault consistently formed the basin bounding fault. It is not currently possible to define the duration of each of these stages due to lack of precise dating.

Early Rifting (lower group and unconformity at base of upper group)

During the early phase of rifting (pre-1.1 Ma) the fluvial and alluvial successions of the lower group (Kalavrita conglomerates and the Ladopotamos Formation) were deposited in a series of half graben controlled mainly by north-dipping faults spaced at between 4 and 5 km and with displacements of up to 1.5 km (Ghisetti and Vezzani 2004, 2005; Bourlange *et al*., 2005). The PM Fault was not active at this stage. Preliminary palaeocurrent data indicate that the main source areas lay to the south and west. Towards the end of this period a base level rise is recorded by deposition of the Katafugion Formation.

In the early Pleistocene a major change occurred in the tectonic and depositional dynamics of the Corinth region. The main depocentre shifted northward and became narrower and the southern area (Kalavrita to Mamoussia) became uplifted. Sediment supply increased as major rivers began to transport large volumes of coarse sediment from the southern area to newly established Gilbert-type deltas. The establishment of new Gilbert-type delta systems requires high sediment supply and the creation of significant accommodation space below base level requiring the activity on new normal faults. The northward dip of the Ladopotamos Formation indicates that a tectonic tilting took place before the major normal fault broke surface. This tilting is interpreted as due to forced folding above the upward propagating PM Fault. The early delta (SP1) was therefore deposited above an active northward tilting ramp in a manner similar to that described by Young *et al.* (2000) in the Gulf of Suez and as shown in the numerical models of Gawthorpe & Hardy (2002) and Ritchie *et al*. (2004a, b). Moreover, the concave erosive base of the Vouraikos Delta requires that the early delta (SP1) infilled a pre-existing palaeovalley of some 300 m relief. As this feature requires a major erosional (incision) event before initiation of delta deposition we infer a relative sea level fall before the major relative sea level rise.

The dramatic change in basin development between the lower and upper groups occurred sometime in the middle of the Early Pleistocene (before 1.1 Ma). The well-established change in Quaternary climate regime occurred between 0.9 and 0.6 Ma (Williams *et al*., 1988), that is during deposition of the Vouraikos Delta. Therefore, tectonic forces must have been principally responsible for this change in basin regime.

Stage 1 of delta deposition (SP1)

The oldest delta package (SP1) was deposited in a palaeovalley incised into a gently north-dipping ramp (Figs 20a, 21a, e and f). The SP1 delta had an estimated radius of less than 2 km. Foresets, up to 200 m high, prograded across the ramp. These foresets are overlain by alluvial topsets at an 'accretionary' toplap contact, suggesting regression and aggradation. Considerable aggradation then took place until thin coastal facies (Fig. 9) record marine transgression across the top of the delta. Transgressive sediments over 12 m thick were deposited until terminated erosively by a return to alluvial facies SP1 topsets. The topsets thicken southward to over 200 m across a syn-sedimentary rollover anticline generated above a listric fault that soled into a shallow decollement (Fig. 21f). This fault seems to have cut through an already well-established delta and was perhaps generated by gravitational instability on the basinward dipping ramp. Significant progradation and aggradation occurred implying rapid creation of accommodation space.

Stage 2 of delta deposition (SP2)

The top of SP1 is marked by the erosional unconformity UC1 implying a relative fall in sea level, which we correlate with the incision into the front of the SP1 delta (Figs 14a and 17c, d). The following SP2 package of foresets (no topsets preserved), over 200 m high, unconformably overlies the most southerly topsets of SP1 in the SW corner of the delta. In our map reconstruction these foresets represent the frontal part of a small northward-building delta of radius 1 km (Fig. 20c), most of which is now eroded. The delta front therefore stepped southward at the beginning of stage 2 requiring a significant relative rise in sea level. We suggest that the SP2 delta infilled the remaining bathymetry of the palaeovalley on the W side of the SP2 delta (Fig. 20b). It is possible that the same phenomenon occurred in the east of the delta. While the SP1 topsets are tilted, the SP2 foresets do not appear to be significantly tilted implying that the Kastillia Fault and its rollover anticline were not active during deposition of SP2.

Stage 3 of delta deposition (SP3)

A significant unconformity separates SP2 from SP3 and pro-delta and bottomset facies associations of SP3 are seen directly above SP2 foresets south of the Avriyiolaka Fault (Fig. 18). North of the Avriyiolaka Fault, SP3 was deposited directly on SP1 topsets. SP3 topsets in the centre of the delta (Fig. 14a) pass westward into SP3 foresets that record progradation (foresets reach heights of over 300 m) toward the NW and WNW during a relative sea level (RSL) highstand (Figs 18 and 14b). The succeeding SP3 topsets on the Mamoussia cliff (Fig. 18) indicate aggradation following erosional planation of the foresets probably accompanied by regression. The topsets are dominantly alluvial, although the Mamoussia Limestone may indicate a marine incursion across the (distal) delta top. The delta rapidly grew in E-W width to over 7 km and it significantly overspilled the palaeovalley (Fig. 21c). Its N-S width, however, remained limited at just under 4 km. The significant increase in accommodation space at the SP2 to SP3 boundary may be explained by the emergence of the controlling normal fault. To the east of the Vouraikos Gorge displacement was distributed on two fault strands, principally on the Kastillia Fault to the north and probably on the PM Fault to the south (Fig. 20b). The Kastillia Fault formed the major bounding fault to the eastern half of the delta during Stage 3.

Stage 4 of delta deposition (SP4)

The SP4 sequence is conformable on SP3. It is however markedly different in character, with a finer average grain size, finer bedding and small scale *Gilbert-type delta*s interspersed with alluvial topsets (Fig. 17c-d). The change occurs across a key planar surface traceable over most of the western part of the delta (Figs 14, 16 and 18), which is interpreted as a major transgressive flooding surface across the previously sub-aerial delta. The small delta packages record regular high frequency relative sea level variations right across the delta top, implying that it was regularly flooded, in marked contrast to the earlier alluvial-dominated topsets. These small delta-top foresets built out until they spilled over the delta front into the large frontal foresets. These frontal foresets can be over 600 m high indicating a very deep basin (Fig. 19). The N-S width of the SP4 delta is estimated to have been at least 4.5 km (but cut by the Eastern Helike Fault), while its E-W width was over 8 km (Fig. 20d). The topsets are at least 300 m thick in the hangingwall of the Derveni Fault and are 200m thick in its footwall implying that this fault was active during deposition of SP4 (Fig. 14a). At the SE side of the delta the Kastillia Fault was sealed by 100 m high SP4 deltas that built N and NE across its footwall from the Katafugion Fault (Figs 3 and 20d). It is possible that secondary point sources were active in the eastern part of the delta during this stage. (Figs 20d and 21d, h)

Stage 5 of delta deposition (SP5)

Before the deposition of SP5, the Vouraikos Delta was effectively terminated during an episode when it was tilted north by 5-7° and eroded, due probably to a fault-related mechanism. This is exemplified by the SP4 sequence having a wedge-shape, thinning southward below SP5 (Figs 14a and 16). SP5 is itself tilted gently south, compatible with later extensional fault block uplift and rotation. SP5 comprises a distinctive marine-influenced (shallow-marine), dominantly conglomeratic sequence. This conglomerate is the last deposit of the Vouraikos Delta, and its planar sheet-like form represents the final approximate position of sea level prior to uplift. Following delta uplift (see below) thick red soils developed above SP5, which now cover the Asomati and other plateaux.

Uplift of the Vouraikos Delta

Sometime in the MIddle Pleistocene the Vouraikos Delta began to be exhumed in the footwall of the newly initiated Eastern Helike Fault (EHF). During exhumation the delta was cut and tilted by a number of secondary normal faults. The EHF is still active today and its displacement history continues to be intensively studied (Koukouvelas *et al*., 2001, 2005; Pavlides *et al*., 2003; McNeill & Collier, 2004; Leeder *et al*., 2003; De Martini *et al*., 2004; McNeill *et al*., 2005). The range front preserves a series of erosional and depositional marine terraces (see Fig. 19), which have been used to model footwall uplift rates (assuming a constant uplift rate) giving estimates of between 1 and 1.5 mm yr^{-1} (e.g. McNeill & Collier, 2004; De Martini *et al*., 2004 and references therein). Assuming that the present day plateau top (at *ca.* 800 m) is close to the original delta top, these rates would imply that uplift of the delta (and thus activity on the EHF) began some time between 530 and 800 ka. The biostratigraphic dates presented in this paper bracketing the age of the Vouraikos Delta from before 1.1 Ma to sometime after 700 ka, are largely compatible with this exhumation history.

DISCUSSION

The symmetry of the gross building directions of its foresets suggests that the Vouraikos Delta had a fixed point sediment supply from the footwall throughout its history (Type A feeder system of Postma, 1990, 1995). The approximate location of the input point, coincident with the present day Vouraikos River, coincides with the intersection of the PM, the Katafugion and Kastillia faults, suggesting some structural control.

Although the Vouraikos was a footwall-derived delta, it has a preserved proximal profile more akin to a hangingwall delta (see e.g., Ritchie *et al*., 2004a, b), probably due to a ramp-related steepening. This steepening during SP1, above the propagating footwall fault, may have achieved rapid deepening to give the high initial bathymetry modelled as being essential for the development of deltas of this architectural style (Ulicny *et al*., 2002).

The curved structure of the foresets, and the development of prominent bottomset and pro-delta facies associations does not support the view of Zelilidis & Kontopoulos (1996) that the Vouraikos had a simple trapezoidal dip profile, nor that it built into a laterally restricted basin. The most distal facies of the delta do not suggest this, and it is more likely that downthrow on the Eastern Helike Fault disguises a considerable part of the distal delta. Early aggradational foresets are not notably preserved, except for one case. However, frequent transitions to interstratified thick sequences of topsets record significant regressive events and aggradational episodes. Transgressions of the sub-aerial delta also occurred, with limestones indicating the delta built into a marine basin, and associated shoreline gravels indicating significant basinal wave energy. The marine carbonates indicate that the Corinth rift Basin would have been affected by Pleistocene orbitally-controlled glacio-eustatic sea level cycles.

The overall form of the Vouraikos contrasts strongly with that of the flanking Keranitis Delta, in that the latter comprises a major proximal reach composed entirely of topset facies, with relatively limited foreset progradation (e.g. Ori *et al*., 1991, fig. 9). We regard the Vouraikos and Keranitis as separate delta systems (cf. Ori *et al*., 1991) of similar age that are separated by a cross-fault in the Keranitis Valley. Correlation with events recorded in the foresets of the Keranitis Delta is not straightforward; the multiple depositional sequences defined by Dart *et al*. (1994) are not characteristic of the Vouraikos. However, the large relief incision surface above Sequence 2 of Dart *et al*. (1994, fig. 6) is of similar scale to the surface identified here at the base of SP3 (UC1). Possible linkage of major surfaces would suggest basin-wide changes in RSL. Sedimentation rates derived for the Keranitis Delta (1.5 mm yr^{-1}) by Dart *et al*. (1994) are similar to our estimates based on consideration of the dating and sediment thickness. Finally, an interesting contrast between the deltas occurs in the degree to which syn- and post-depositional extensional faulting affected their development. The proximal rollover anticline affecting the Vouraikos, and the suite of planar and listric syn-sedimentary faults observed, have no apparent counterparts in the Keranitis. The Keranitis also lacks the post-delta planar normal faults that disrupt the Vouraikos at a number of scales. This is probably because the Vouraikos Delta lies in the immediate footwall of the Eastern Helike Fault while the Keranitis lies further south.

Based on the biostratigraphic dating we estimate that the delta was deposited within a period of ca. 0.4 to 0.6 Myr between >1.1 Ma and 0.6-0.7 Ma. This age estimate implies that the whole Vouraikos Delta represents a third-order highstand systems tract (*sensu* Vail *et al*., 1991). The five stratigraphic packages SP1 to SP5 therefore represent mainly fourth-order highstand system tracts. Each sedimentary cycle essentially comprises the regressive phase (progradation) with the vertical succession from pro-delta fines to bottomsets to foresets and finally to topsets (i.e. “normal” regression sensu Posamentier *et al*., 1992).

The development of each stratigraphic package is related to an interglacial period, which is consistent with the interglacial character of the palynological assemblages. If preserved, the lowstand deltas related to glacial periods may be situated to the north below the present gulf. Each stratigraphic package comprises stacked fifth-order transgressive-regressive cycles, which are rarely detected in SP1 to SP3. However, in SP4 these fifth-order cycles are clearly recorded by the stacked small Gilbert deltas on the delta top.

Within the time period 1.1 to 0.6 Ma the oxygen isotope ^{18}O stages are MIS31 to MIS16. Potentially four or five major positive excursions may be recognized that could be correlated with the four stratigraphic packages SP1 to SP4. This suggests that the stratigraphic packages were primarily controlled by eustasy superimposed on a high subsidence rate, in turn controlled by the PM Fault.

The bulk of this compact delta is made up of SP1, SP3 and SP4. While SP1 records significant progradation (>2 km) coupled with strong aggradation (200 m) across the early ramp (Fig. 21e, f), SP3 and SP4 each record limited frontal progradation (<1 km) of thick foresets coupled with strong aggradation (200-300 m) of topsets. This implies that rates of both sediment supply (S) and creation of accommodation space (A) were very high during deposition of SP3 and SP4 and that the ratio of S/A was about 1. The cyclic flooding of the delta top during SP4 implies that S/A had decreased either because sediment supply was waning or because creation of accommodation space was increasing.

CONCLUSIONS

(1) The syn-rift stratigraphy in the Kalavrita to Aegion region of the southern Corinth rift shows a two-phase rifting history. The coarse alluvial succession of the lower group (up to 1.3 km thick) was deposited in a series of 4-5 km wide tilted blocks. This early rift phase ended with a marine transgression, preserved in the north. An erosional unconformity marks the base of the upper group, which records a great increase in accommodation space, the migration of the depocentre to the north and an increase in sediment supply. The upper group is characterized by Gilbert-type fan deltas.

(2) The Vouraikos Delta is one of several giant fault controlled Gilbert-type fan deltas that built into the Corinth rift during the Early to Middle Pleistocene in response to a major change in basin dynamics. We argue that this change in basin dynamics in the

Early Pleistocene was not related to climate change but was probably due to a change in large-scale regional tectonics (Fig. 1, inset).

(3) A limited number of palynological dates indicate that the Vouraikos Delta was initiated sometime in the middle of the Early Pleistocene and terminated in the Middle Pleistocene sometime after 0.7 Ma. These preliminary age estimates are coherent with published models of the uplift history on the Eastern Helike Fault. Sedimentation rates are thus estimated between 1.3 to 2 mm yr^{-1}.

(4) The early Vouraikos Delta (SP1) was constructed on a basin-dipping ramp generated by an extensional forced-fold. Internally, it was affected by a listric normal fault and its rollover anticline. Later, the Vouraikos Delta was primarily controlled by displacement on the emergent PM Fault and its splays to the east (the Kastillia and Katafugion faults). Smaller planar and curved normal faults affected the delta throughout its history and also during exhumation of the delta in the footwall of the Eastern Helike Fault.

(5) The internal architecture of the conglomeratic delta records both tectonic and eustatic controls. Five stratigraphic packages are separated by major surfaces. SP1, SP3 and SP4, which make up the bulk of the delta, are each characterized by thick topsets and thick foresets, and limited bottomset and pro-delta facies. The stratigraphic packages are tentatively correlated with regressive glacio-eustatic interglacial periods. This model requires that the glacio-eustatic signal was superimposed on a relatively constant creation of accommodation space by normal faulting (by the PM Fault system). While this eustatic interpretation seems quite plausible we cannot eliminate the possibility that the stratigraphic packages and their bounding surfaces may have been generated wholly or partly by pulses of high and low slip-rate on the PM Fault.

(6) Topset limestones associated with coastal conglomerate facies indicate that the Vouraikos Gilbert-type Delta built mainly into a marine water body. Gravel-rich sediment prograded (to the NNW) into water that reached depths of 200-600 m.

(7) The N-S radius of the 800 m thick fan delta increased only slowly (2 to 3.5 to 4.5 km) through time. The trajectory of the offlap break in a section through the centre of the Vouraikos Delta (Figs 14a and 21) reflects early progradation-dominated behaviour (SP1), followed by increasingly aggradational behaviour during SP3 and SP4.

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Figure captions

Fig. 1. Map of the southern coast of the Gulf of Corinth showing the distribution of pre-rift and syn-rift sequences. Three generations of syn-rift Gilbert-type deltas are distinguished. The principal normal faults are shown, with dip-direction and throw indicated by small ticks. The progradation directions of the principal Lower-Mid Gilbert-type fan deltas are shown by large arrows. The location of the cross sections of Fig. 2 are shown. This map is based on Ghisetti & Vezzani (2004, 2005), Rohais *et al*. (in press) and authors' own work. Inset: Tectonic map of the Aegean region showing the Corinth rift and the location of the study area. NAF (S) is the southern branch of the North Anatolian Fault.

Fig. 2. Structural cross-sections through the central south coast of the Corinth Rift. (a) SSW-NNE cross-section from the Kalavrita Fault to the coast passing through the

western Vouraikos Delta. (b) SSW-NNE cross-section from the Doumena Fault block to the coast passing through the eastern Vouraikos Delta. (c) Equal area stereoplot of poles to fault planes cutting the PM Fault block only (data and contours), showing a dominance of north-dipping planes with an average plane of 098/62N.

Fig. 3. Detailed geological map of the Vouraikos Delta in the PM Fault block based on new mapping by the authors, revised from fig. 1 of Malartre *et al*. (2004). A is the location of heterolithic fluvial topsets (Fig. 8), B is the location of outcrops of shoreline-shallow marine topset association (Fig. 9), C is the location of the Marathia Limestone (Fig. 11a) and D is the location of the Mamoussia Limestone (Fig. 11b). AF is the Avriyiolaka Fault.

Fig. 4. Composite stratigraphical scheme for the syn-rift depositional sequence in the PM Fault block between the Keranitis and Ladopotamos rivers. Note that due to poor exposure, the fine grained offshore marine facies at the top of the Lower group and the fine grained pro-delta facies at the base of the upper group are here provisionally treated as a single mappable unit, the Derveni unit. The postulated erosive contact between the lower and upper groups lies within this unit. Pro-delta facies are equivalent to the SP1 to SP4 stratigraphic packages.

Fig. 5. Simplified graphic log of the limestone-clastic succession of the Katafugion Formation. MPS is maximum particle size.

Fig. 6. Sketch map of the Vouraikos Delta showing simplified stratigraphies and foreset dip directions. Key for Gilbert delta foreset dip-directions - green SP1, blue SP2, red SP3 and 4, white SP4 (south of Kastillia Fault).

Fig. 7. Vertical ENE-WSW transverse section of the Vouraikos Delta orthogonal to its progradation direction (Fig. 6), located in the hangingwall of the Kastillia and PM faults, showing incision of the delta into the Lower group succession. No vertical exaggeration.

Fig. 8. Graphic log of a short section through the relatively fine-grained (heterolithic) alluvial topset facies association located on the SW margin of the Vouraikos Delta at 675 m altitude (location A, Fig. 3), containing interbedded sandstone, conglomerate and siltstone red bed facies. Road section to Asomati Plateau at co-ordinates N38°09'55.7"/E022°08'46.0".

Fig. 9. Graphic log of well-stratified and sorted conglomerates and sandstones (SFA1) of the coastal-shallow marine facies association organized in a west-dipping clinoform, and overlying flat-bedded and cross-stratified alluvial topset conglomerates (location B, Fig. 3).

Fig. 10. (a) Line drawing of a valley side exposure (location C, Fig. 5) of facies association SFA1 and SFA3 that is structurally divisible into three units A, B and C based on differences in dip of strata. Unit C thought to downlap unit B that comprises shoreline-shallow marine topset sub-facies associations (1 and 3). (b) Minor cliff exposure transverse to (a) showing Unit C to comprise topset and foreset facies associations, and subtle downlapping contact onto Unit B. Also shown are graphic logs of (c) sub-associations SFA 1 and 3, (d) SFA1 and (e) a relatively poorly sorted sequence of SFA1.

Fig. 11. (a) Photomicrograph of bioclastic grainstone carbonate facies at N38°11'02.3"/E022°10'28.1" (Marathia Limestone). (b) Photomicrograph of algal packestone-grainstone facies from transitional section between foresets and topset facies association, at the SW extremity of the Mamoussia cliff section (location D, Fig. 3, Mamoussia Limestone). Field of view in both cases is 5 mm, taken plane-polarized light, with gypsum plate in (b). Each photomicrograph measures 5mm across.

Fig. 12. Combined rose diagram and equal area polar dip-direction plot of the Vouraikos Delta foresets. Vector mean of foresets is 345° (n = 103). Rose diagram class interval is 3°.

Fig. 13. Field photographs of bottomset and pro-delta facies associations of the Vouraikos Delta. (a) Bottomset conglomerates and sandstones from SW base of delta (Keranitis Valley); (b) slump folds showing basinward asymmetry from SW base of delta (Keranitis Valley); (c) conglomeratic bottomsets wedging downward into fine grained pro-delta facies eastern base of delta (Ladopotamos Valley); (d) floating pebble in pro-delta siltstones and fine sandstones (Ladopotamos Valley).

Fig. 14. Detailed NNW-SSE cross section of (a) the western side of the Vouraikos Gorge, representing the centre of the delta and (b) east side of the Keranitis Valley, representing the western limit of the Vouraikos Delta. Circles indicate palynologically-dated sample horizons (Table 1). AF is the Avriyiolaka Fault.

Fig. 15. (a) and (b) View west of tilted fault blocks in SP1 at the southern end of the Vouraikos Gorge (located on Fig. 14a). (c) Line drawing of a cliff section at 90° to (a) viewed toward the north, showing foresets, toplap contact and overlying low-angle clinoforms. X is the common point to the two views.

Fig. 16. Panoramas of the southern end of the Asomati Plateau and the Vouraikos Gorge. The star is a common point to the two views. (a) View westward of the southern margin of the Asomati Plateau. Relief on the section is 700 m. (b) Interpretation of (a) showing the organization of stratigraphic packages SP1 to SP4 in the immediate hangingwall of the PM Fault. AF is the Avriyiolaka Fault. UC1 is the unconformity between SP1 and SP3. TS, topsets; BS, bottomset to pro-delta facies; FS, foresets. SP3 foresets dip to NW. (c) Oblique view toward the WSW across the Vouraikos Gorge of the Asomati Plateau (sectors A and B of Fig. 14a). Relief in the gorge is over 700 m. (d) Interpretation of (c) showing stratigraphic packages, faults and the rollover anticline in SP1. The small secondary faults cutting SP3 are not represented in Fig.14a. The heavy grey line in SP1 topsets is the coastal facies level (Fig.10).

Fig. 17. (a) Photograph and (b) line drawing of major Incision surface into SP1 topsets in the central Vouraikos Gorge (panel C, Fig.14a). The incision is overlain by north dipping foresets of SP3. (c) Photograph and (d) line drawing of a 110°-trending cliff in the immediate footwall of the Derveni Fault in the centre of the Asomati Plateau showing stacked Gilbert-type deltas of SP4 building out to the NW. PD are bottomset to pro-delta facies at the base of individual Gilbert-type deltas.

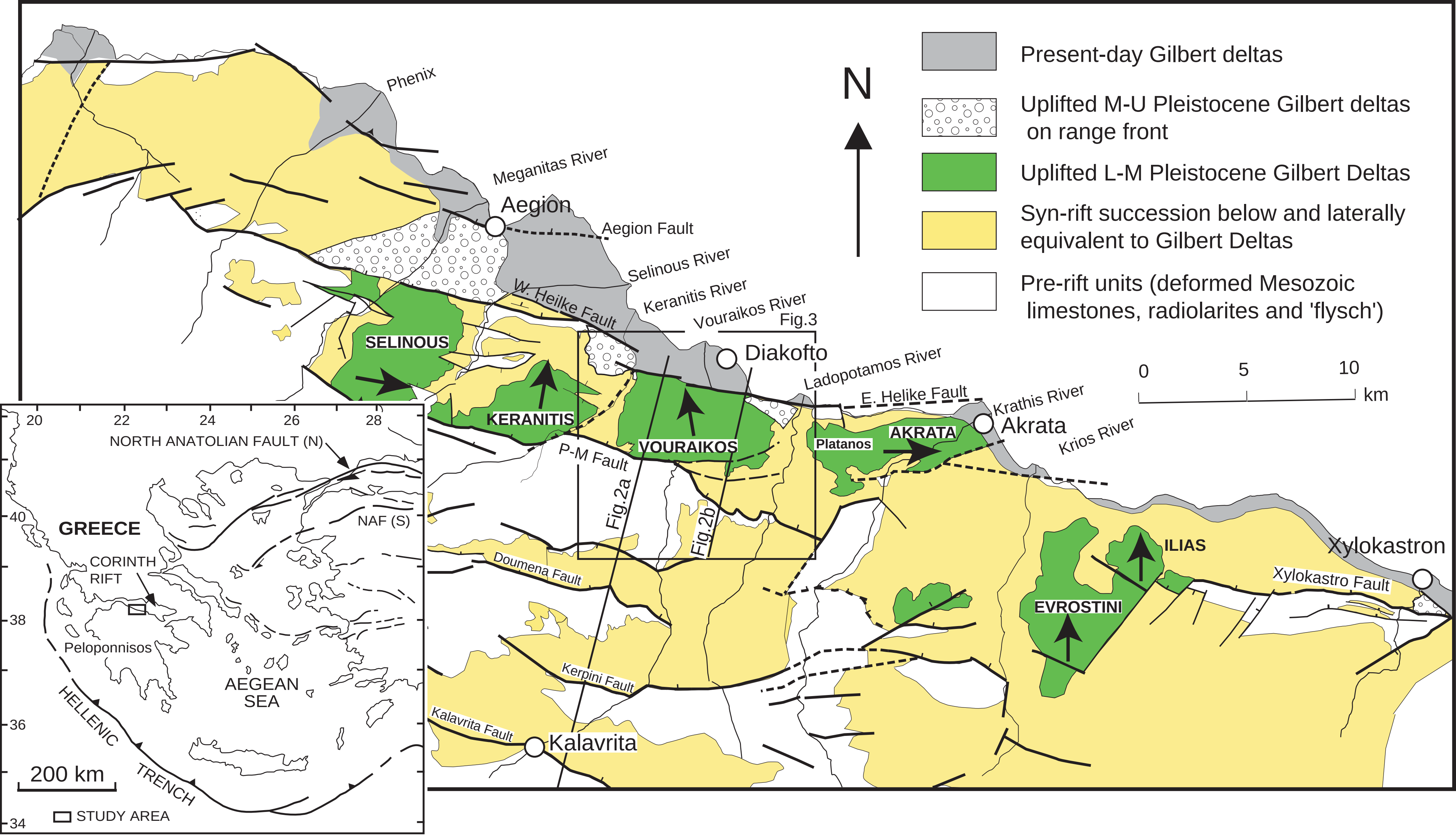
Fig. 18. Field sketch of the east-west Mamoussia Cliff section representing the SW side of the Vouraikos Delta viewed from Mamoussia village. (b) Correlation and geometry of stratigraphic packages within the proximal Vouraikos Delta from the Vouraikos Gorge (Fig. 14a) to the Keranitis Valley. The complex trace of the Avriyiolaka Fault is due to the indented cliff morphology.

Fig. 19. Line drawing of the (a) NW range front and (b) NE range front of the Vouraikos Delta in the immediate footwall of the Eastern Helike Fault. Younger Gilbert deltas, deposited on the range front during its exhumation, are shown in light grey. The largest of these (*ca.* 100 m high) lies in the hangingwall of the Marathia Fault on the NW range front and contains WSW dipping foresets. Depositional terraces on the NE range front dip 8°NE and are shown in heavy black lines with the letter T or in dark grey when dipping north.

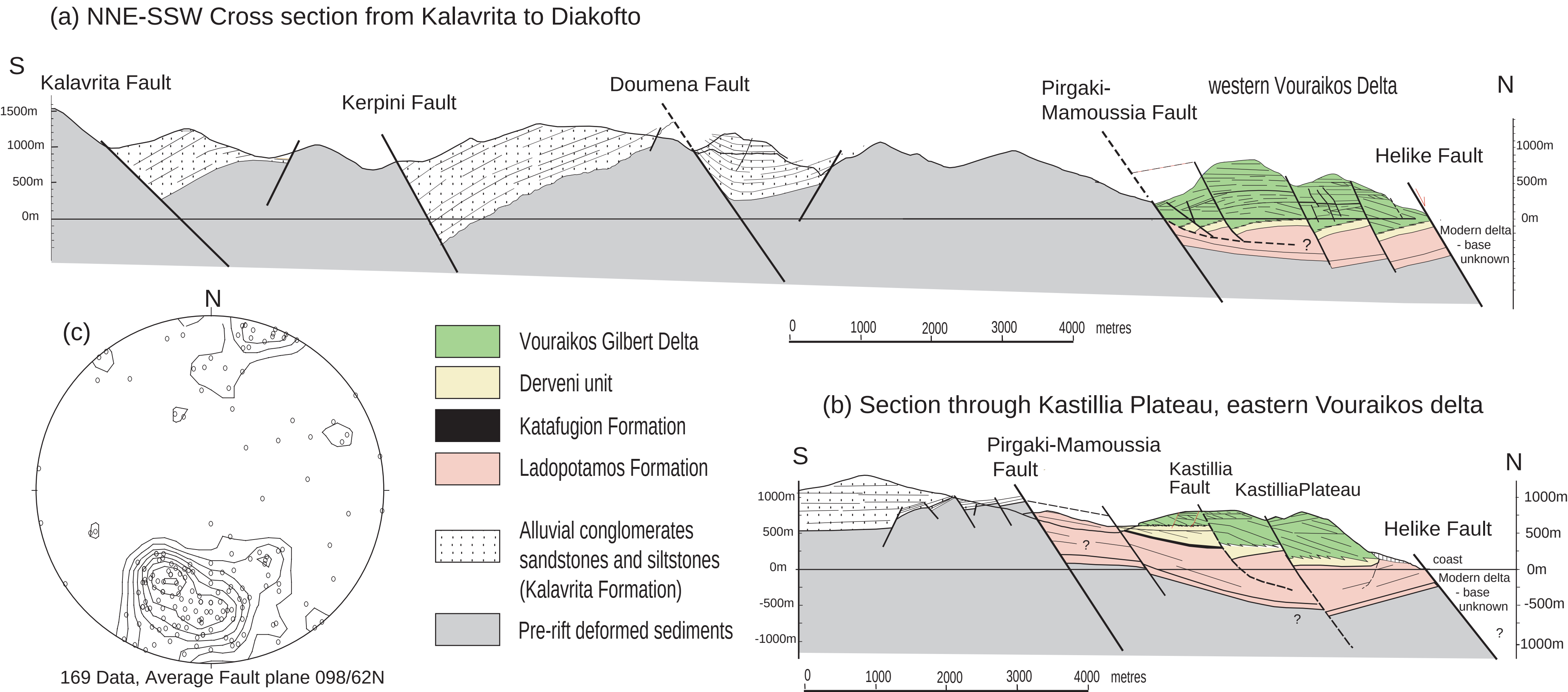
Fig. 20. Map view models for the four main stages in the evolution of the Vouraikos Delta corresponding to SP1 to SP4.

Fig. 21. Proximal longitudinal (a to d) and cross sections through the centre of the Vouraikos Delta (e to h) representing the four stages in delta evolution corresponding to SP1 to SP4, using a vertical exaggeration of two. SP1 is represented in two cross sections while there is no cross section for SP2 as this small delta is hardly seen on the central cross section (Fig. 14a). The offlap break is shown as a blue dashed line. The upward propagating Pirgaki-Mamoussia Fault (PMF) is shown in (e) and (f) and the upward propagating Helike Fault (HF) in (h).

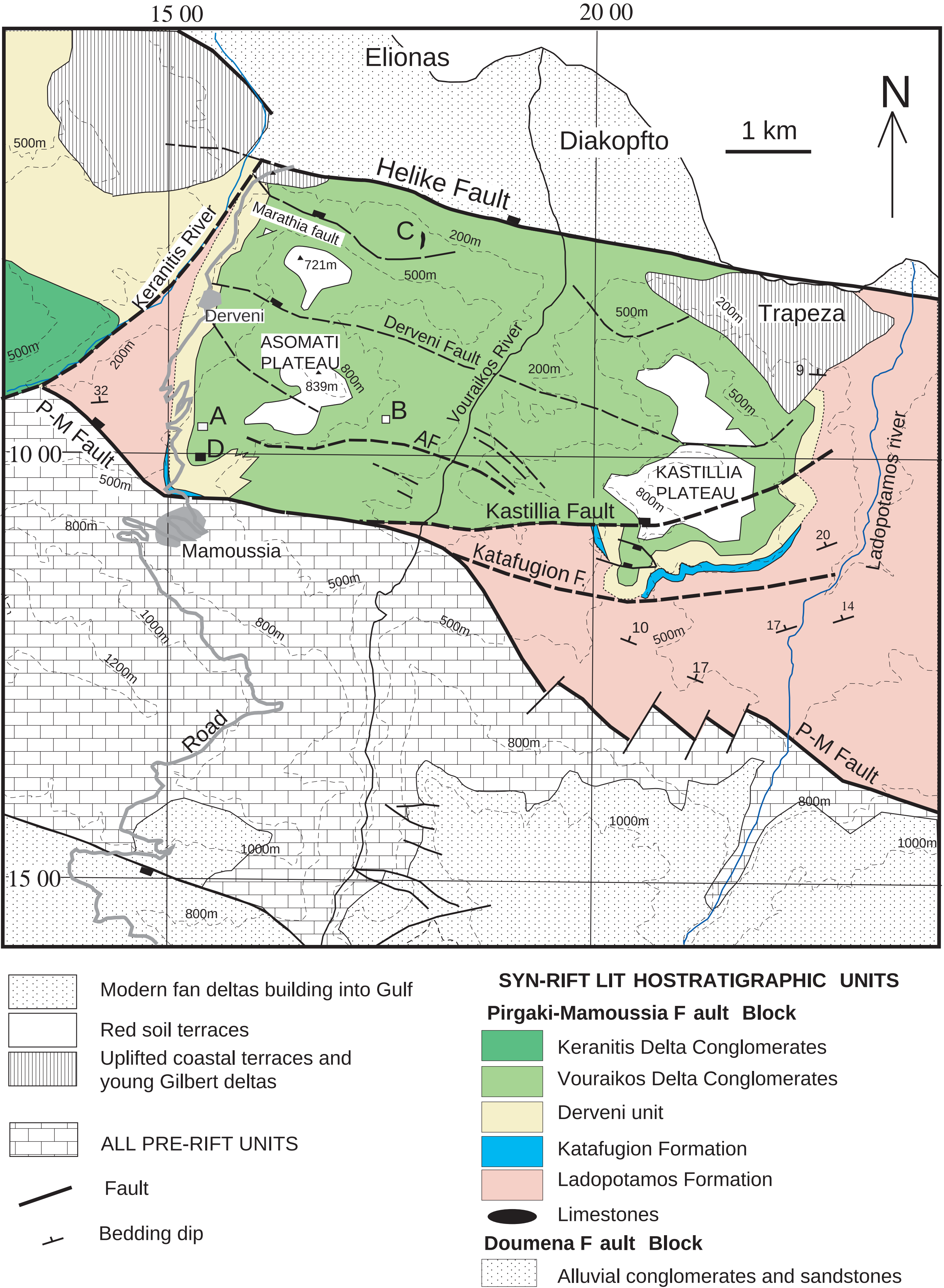
Table 1. Nine samples (from lower and upper groups) were analysed for pollen content. The presence/absence of the most significant thermophilous plants used for dating in the Pleistocene of the eastern Mediterranean are shown here. Percentages are of the total number of pollen grains counted in each sample (between 150 and 300 grains per sample). See text for further details and interpretation. Most samples are located on Figs 4 and 14.



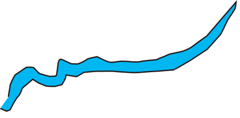
Present-day Gilbert deltas
Uplifted M-U Pleistocene Gilbert deltas on range front
Uplifted L-M Pleistocene Gilbert Deltas
Syn-rift succession below and laterally equivalent to Gilbert Deltas
Pre-rift units (deformed Mesozoic limestones, radiolarites and 'flysch')
N
0 5 10 km
Phenix
Meganitas River
Aegion
Aegion Fault
Selinous River
Keranitis River
Vouraikos River
Fig.3
W. Heilke Fault
Diakofto
Ladopotamos River
E. Helike Fault
Krathis River
Akrata
Krios River
SELINOUS
KERANITIS
VOURAIKOS
Platanos
AKRATA
P-M Fault
Fig.2a
Fig.2b
ILIAS
EVROSTINI
Xylokastron
Xylokastro Fault
Doumena Fault
Kerpini Fault
Kalavrita Fault
Kalavrita
20 22 24 26 28
NORTH ANATOLIAN FAULT (N)
NAF (S)
GREECE
CORINTH RIFT
Peloponnisos
AEGEAN SEA
HELLENIC TRENCH
200 km
STUDY AREA
40 38 36 34

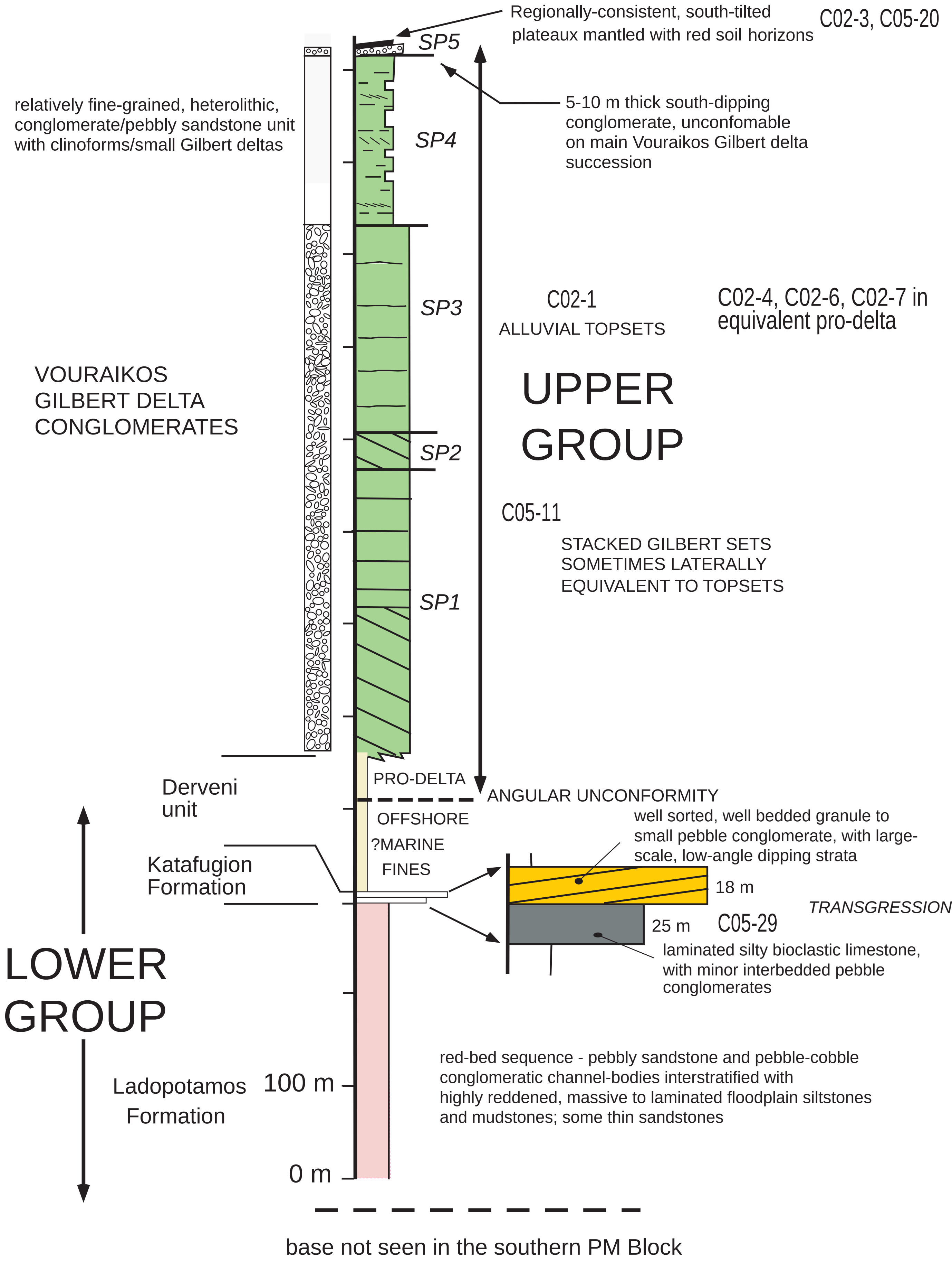


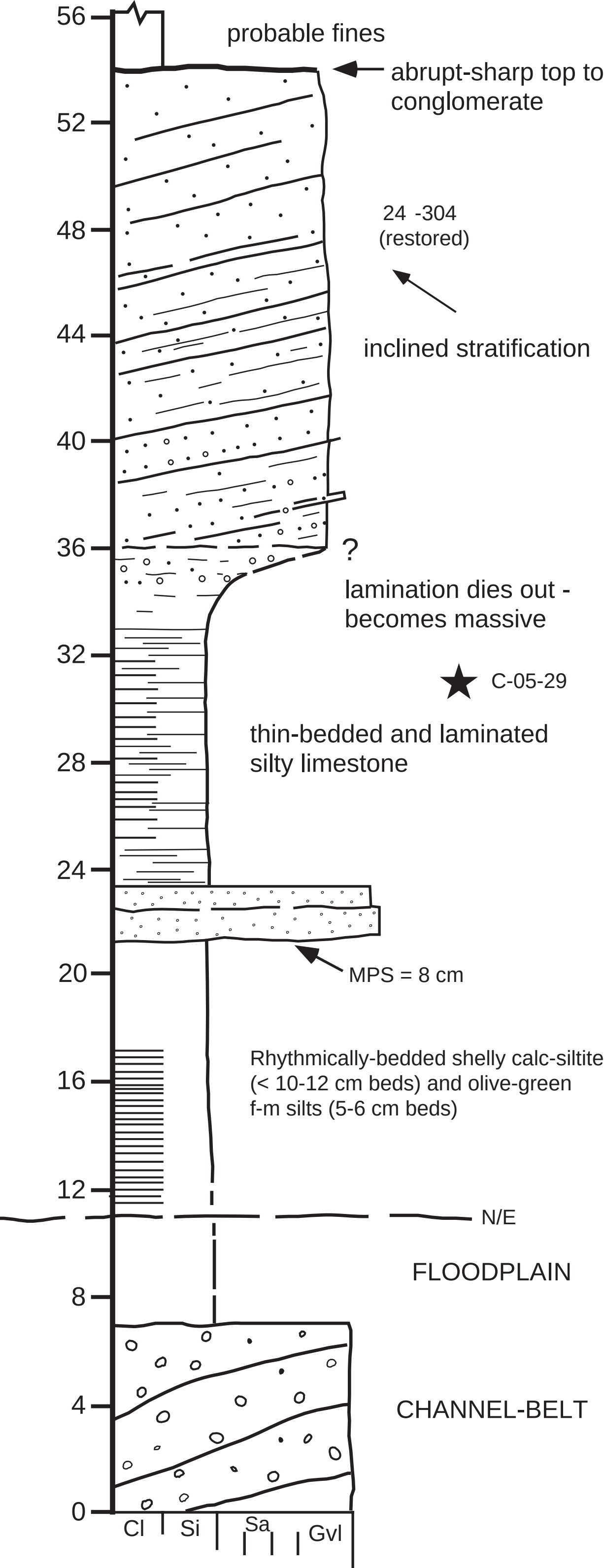
(a) NNE-SSW Cross section from Kalavrita to Diakofto
S
Kalavrita Fault
Kerpini Fault
Doumena Fault
Pirgaki-
Mamoussia Fault
western Vouraikos Delta
N
Helike Fault
1500m
1000m
500m
0m
Modern delta
- base
unknown
?
0
1000
2000
3000
4000
metres
(c)
N
169 Data, Average Fault plane 098/62N
Vouraikos Gilbert Delta
Derveni unit
Katafugion Formation
Ladopotamos Formation
Alluvial conglomerates
sandstones and siltstones
(Kalavrita Formation)
Pre-rift deformed sediments
(b) Section through Kastillia Plateau, eastern Vouraikos delta
S
Pirgaki-Mamoussia
Fault
Kastillia
Fault
KastilliaPlateau
N
Helike Fault
coast
Modern delta
- base
unknown
1000m
500m
0m
-500m
-1000m
?

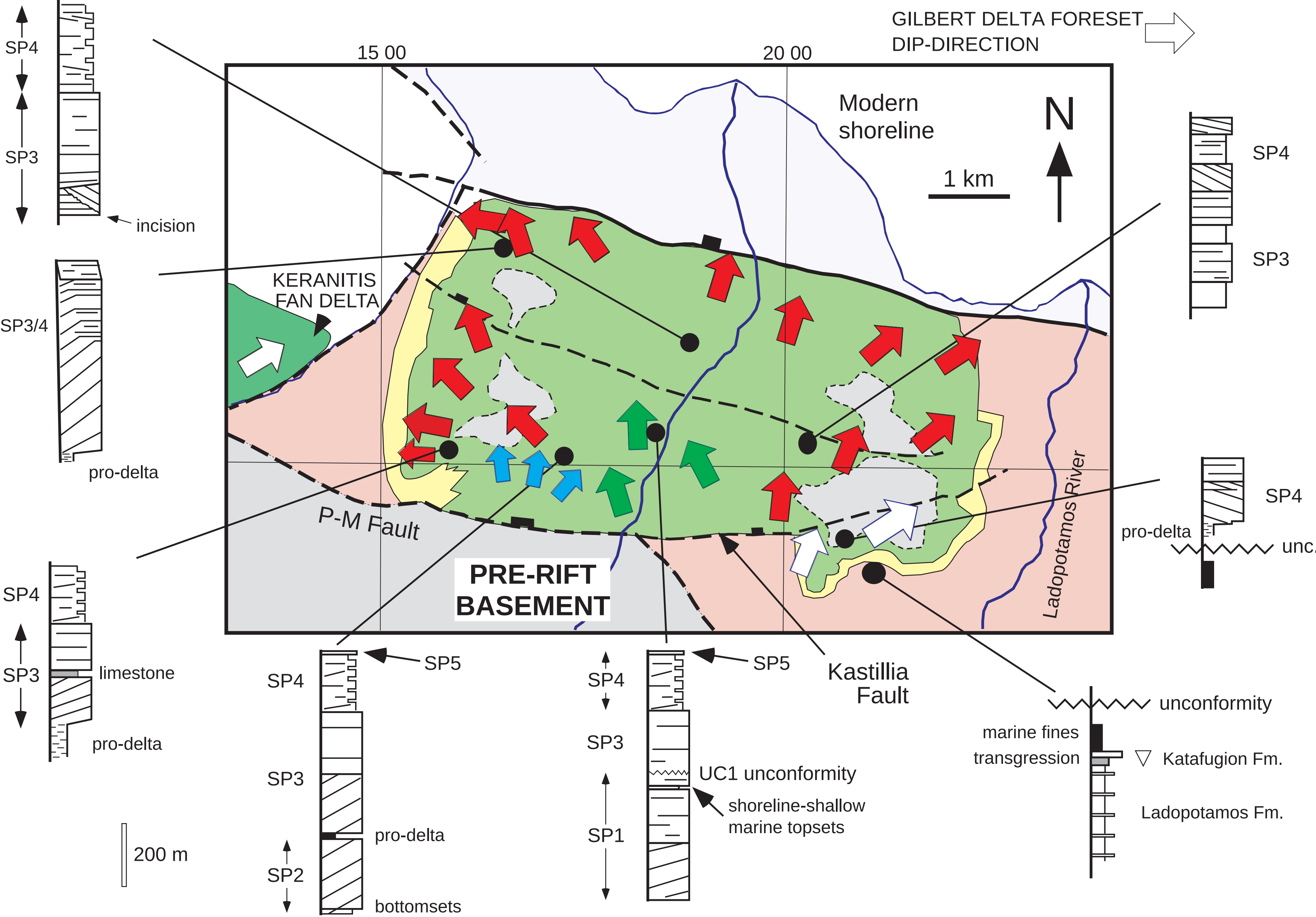


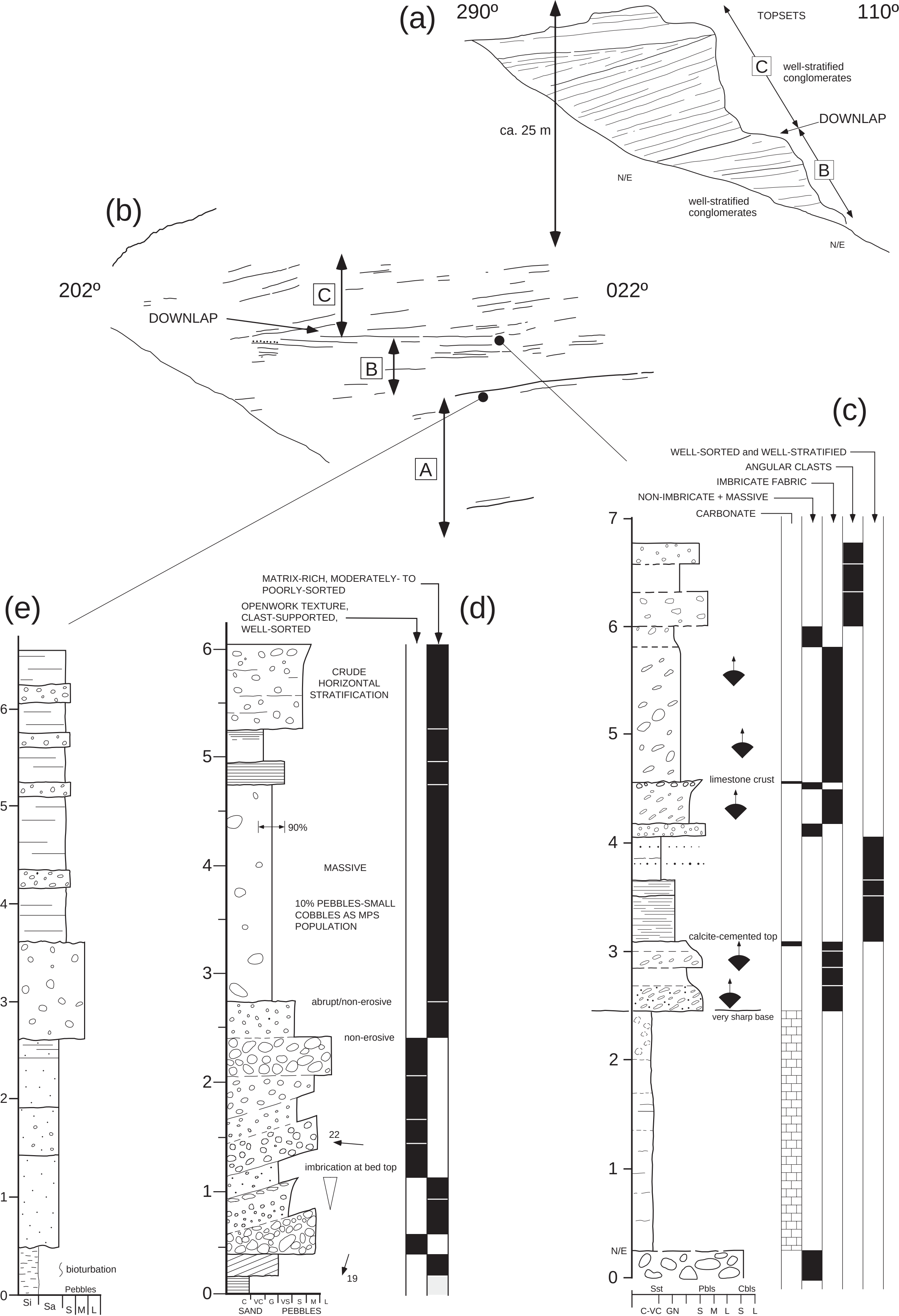
15 00
20 00
Elionas
Diakopfto
1 km
N
Helike Fault
Keranitis River
Marathia fault
C
721m
Derveni
ASOMATI
PLATEAU
839m
Derveni Fault
Vouraikos River
Trapeza
A
B
D
AF
KASTILLIA
PLATEAU
Kastillia Fault
Katafugion F.
P-M Fault
Mamoussia
Road
Ladopotamos river
10 00
15 00
500m
200m
800m
1000m
1200m
32
9
20
14
17
10
Modern fan deltas building into Gulf
Red soil terraces
Uplifted coastal terraces and young Gilbert deltas
ALL PRE-RIFT UNITS
Fault
Bedding dip
SYN-RIFT LIT HOSTRATIGRAPHIC UNITS
Pirgaki-Mamoussia F ault Block
Keranitis Delta Conglomerates
Vouraikos Delta Conglomerates
Derveni unit
Katafugion Formation
Ladopotamos Formation
Limestones
Doumena F ault Block
Alluvial conglomerates and sandstones



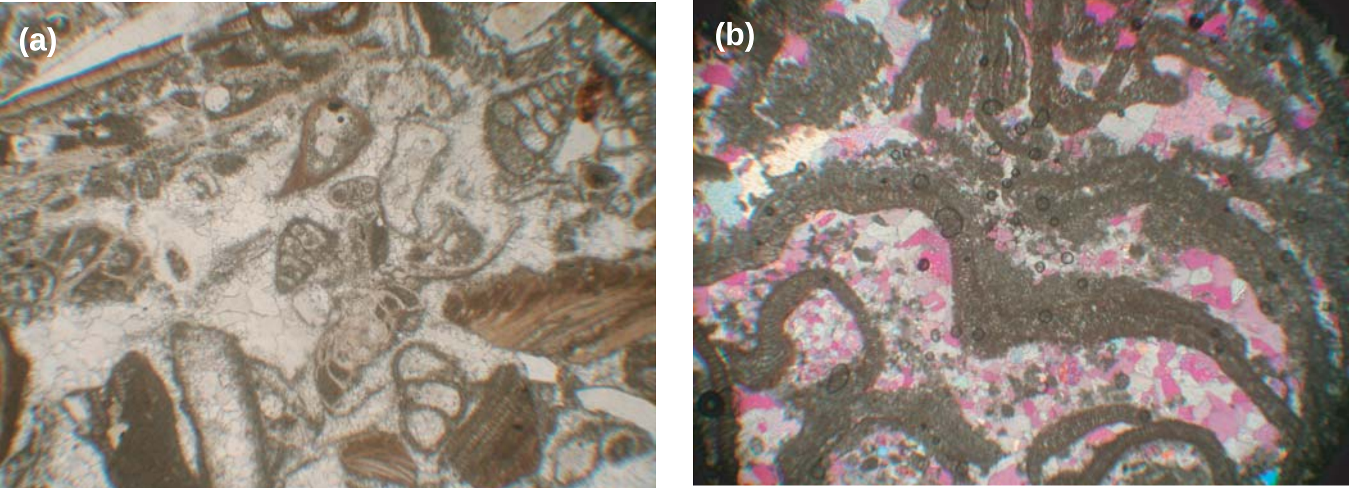

Regionally-consistent, south-tilted plateaux mantled with red soil horizons
C02-3, C05-20
SP5
relatively fine-grained, heterolithic, conglomerate/pebbly sandstone unit with clinoforms/small Gilbert deltas
SP4
5-10 m thick south-dipping conglomerate, unconfomable on main Vouraikos Gilbert delta succession
SP3
C02-1
ALLUVIAL TOPSETS
C02-4, C02-6, C02-7 in equivalent pro-delta
VOURAIKOS GILBERT DELTA CONGLOMERATES
UPPER GROUP
SP2
C05-11
STACKED GILBERT SETS SOMETIMES LATERALLY EQUIVALENT TO TOPSETS
SP1
PRO-DELTA
Derveni unit
ANGULAR UNCONFORMITY
OFFSHORE ?MARINE FINES
well sorted, well bedded granule to small pebble conglomerate, with large-scale, low-angle dipping strata
Katafugion Formation
18 m
TRANSGRESSION
25 m
C05-29
laminated silty bioclastic limestone, with minor interbedded pebble conglomerates
LOWER GROUP
Ladopotamos Formation
100 m
red-bed sequence - pebbly sandstone and pebble-cobble conglomeratic channel-bodies interstratified with highly reddened, massive to laminated floodplain siltstones and mudstones; some thin sandstones
0 m
base not seen in the southern PM Block

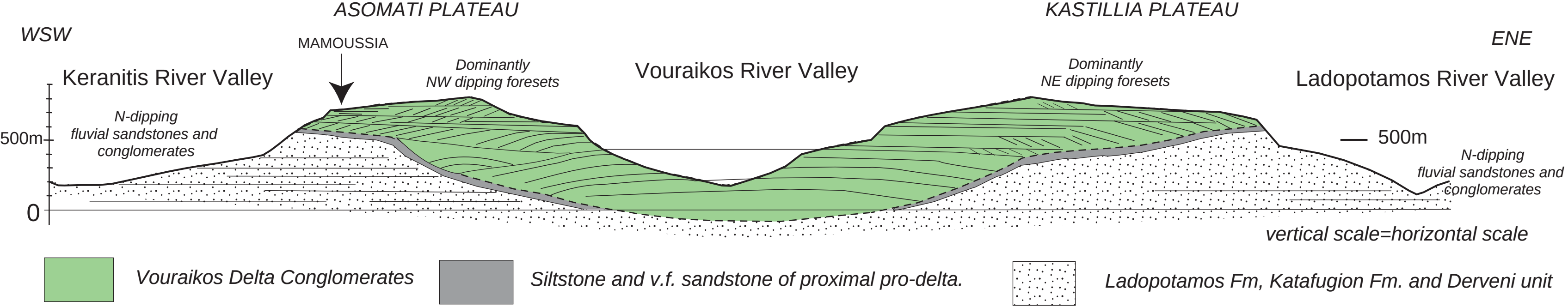

56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
probable fines
abrupt-sharp top to conglomerate
24 -304
(restored)
inclined stratification
?
lamination dies out - becomes massive
C-05-29
thin-bedded and laminated silty limestone
MPS = 8 cm
Rhythmically-bedded shelly calc-siltite (< 10-12 cm beds) and olive-green f-m silts (5-6 cm beds)
N/E
FLOODPLAIN
CHANNEL-BELT
Cl
Si
Sa
Gvl


GILBERT DELTA FORESET
DIP-DIRECTION
15 00
20 00
Modern
shoreline
N
1 km
KERANITIS
FAN DELTA
P-M Fault
PRE-RIFT
BASEMENT
Ladopotamos River
Kastillia
Fault
SP4
SP3
incision
SP3/4
pro-delta
SP4
SP3
limestone
pro-delta
200 m
SP5
SP4
SP3
pro-delta
SP2
bottomsets
SP5
SP4
SP3
UC1 unconformity
shoreline-shallow
marine topsets
SP1
SP4
SP3
SP4
pro-delta
unc.
unconformity
marine fines
transgression
Katafugion Fm.
Ladopotamos Fm.

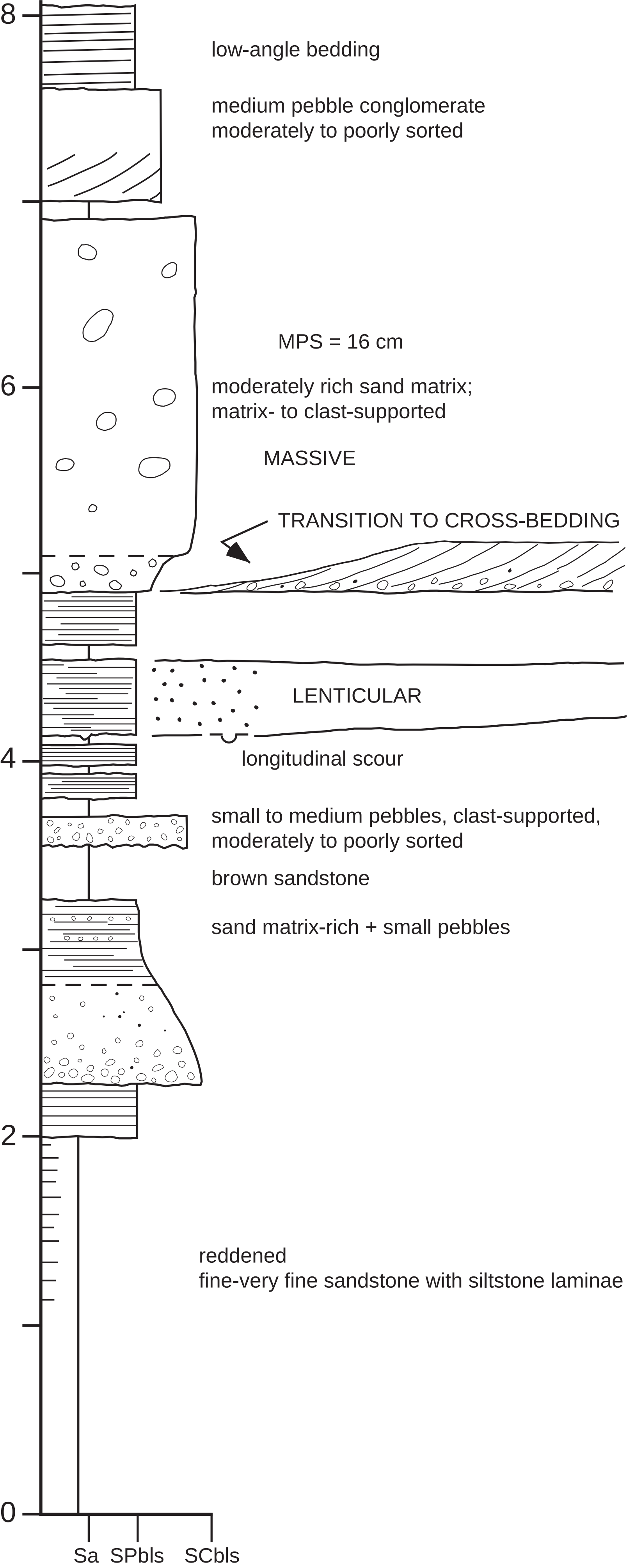


(a)
290º
110º
TOPSETS
C
well-stratified conglomerates
DOWNLAP
B
ca. 25 m
N/E
well-stratified conglomerates
N/E
(b)
202º
022º
C
DOWNLAP
B
A
(c)
WELL-SORTED and WELL-STRATIFIED
ANGULAR CLASTS
IMBRICATE FABRIC
NON-IMBRICATE + MASSIVE
CARBONATE
limestone crust
calcite-cemented top
very sharp base
N/E
Sst
Pbls
Cbls
C-VC GN S M L S L
(d)
MATRIX-RICH, MODERATELY- TO POORLY-SORTED
OPENWORK TEXTURE, CLAST-SUPPORTED, WELL-SORTED
CRUDE HORIZONTAL STRATIFICATION
90%
MASSIVE
10% PEBBLES-SMALL COBBLES AS MPS POPULATION
abrupt/non-erosive
non-erosive
22
imbrication at bed top
19
C VC G VS S M L
SAND PEBBLES
(e)
bioturbation
Pebbles
Si Sa S M L

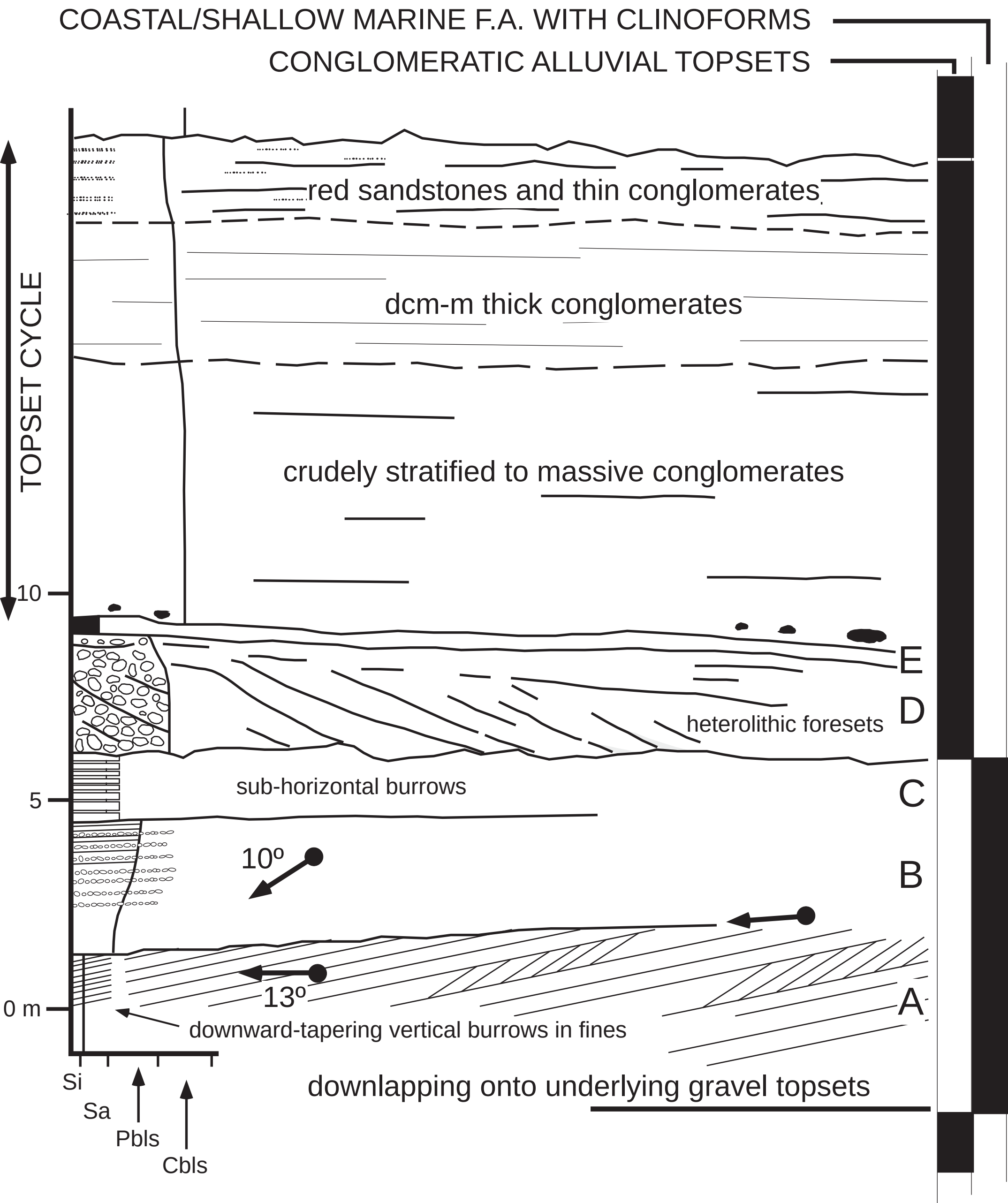

(a)
(b)



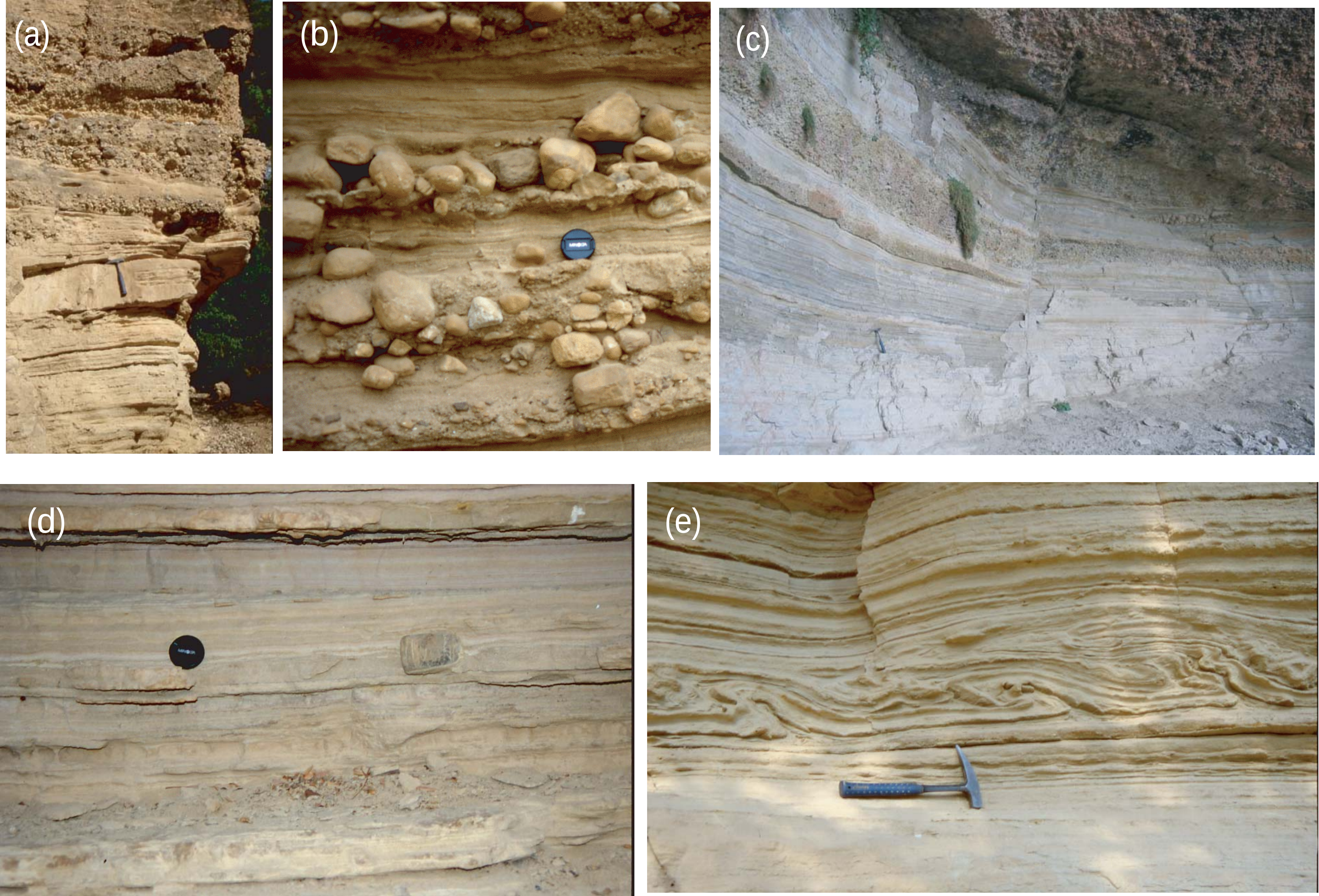
ASOMATI PLATEAU
KASTILLIA PLATEAU
WSW
ENE
MAMOUSSIA
Dominantly
NW dipping foresets
Vouraikos River Valley
Dominantly
NE dipping foresets
Keranitis River Valley
Ladopotamos River Valley
N-dipping
fluvial sandstones and
conglomerates
500m
500m
N-dipping
fluvial sandstones and
conglomerates
0
vertical scale=horizontal scale
Vouraikos Delta Conglomerates
Siltstone and v.f. sandstone of proximal pro-delta.
Ladopotamos Fm, Katafugion Fm. and Derveni unit

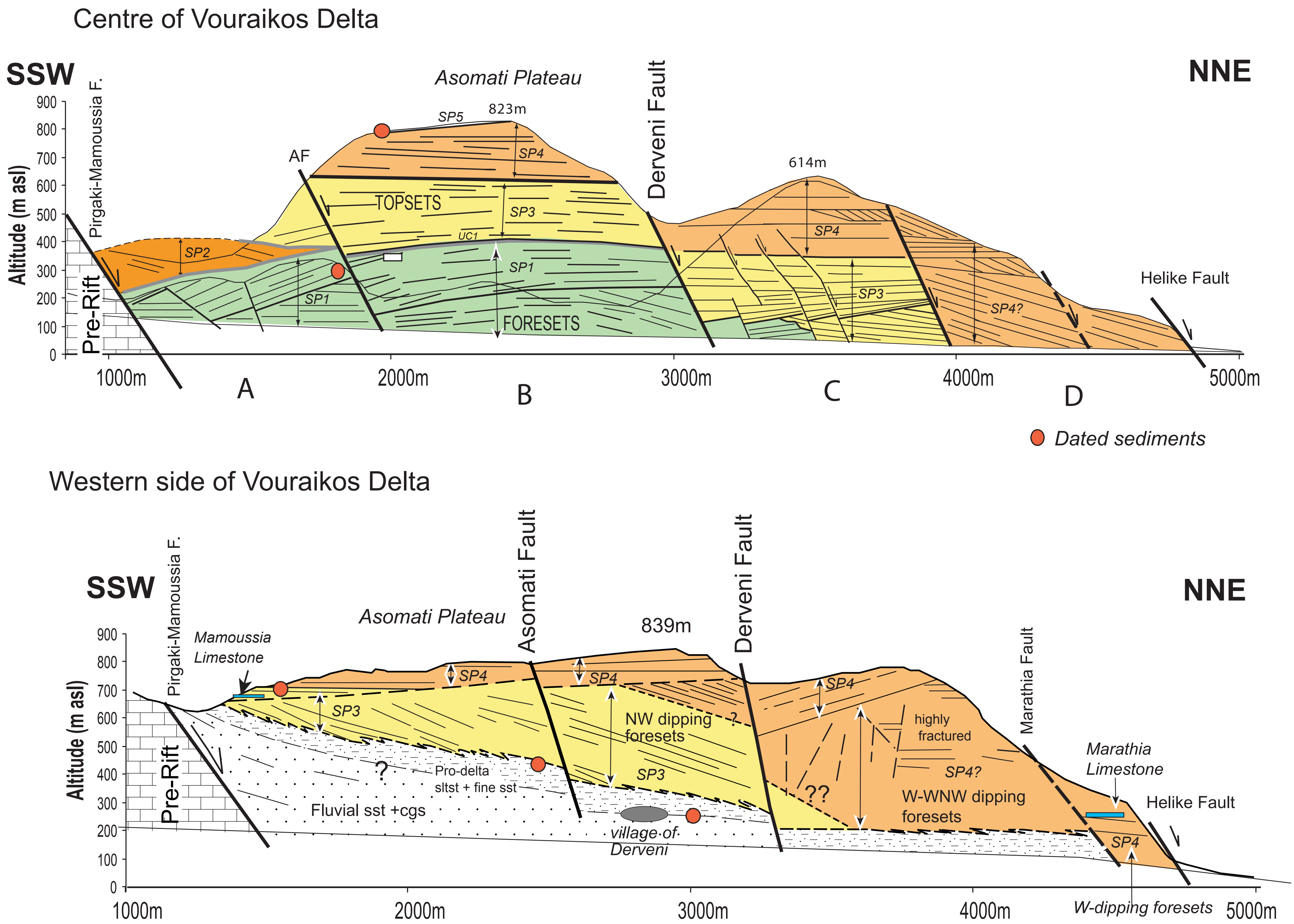


8
low-angle bedding
medium pebble conglomerate
moderately to poorly sorted
MPS = 16 cm
6
moderately rich sand matrix;
matrix- to clast-supported
MASSIVE
TRANSITION TO CROSS-BEDDING
LENTICULAR
4
longitudinal scour
small to medium pebbles, clast-supported,
moderately to poorly sorted
brown sandstone
sand matrix-rich + small pebbles
2
reddened
fine-very fine sandstone with siltstone laminae
0
Sa
SPbls
SCbls

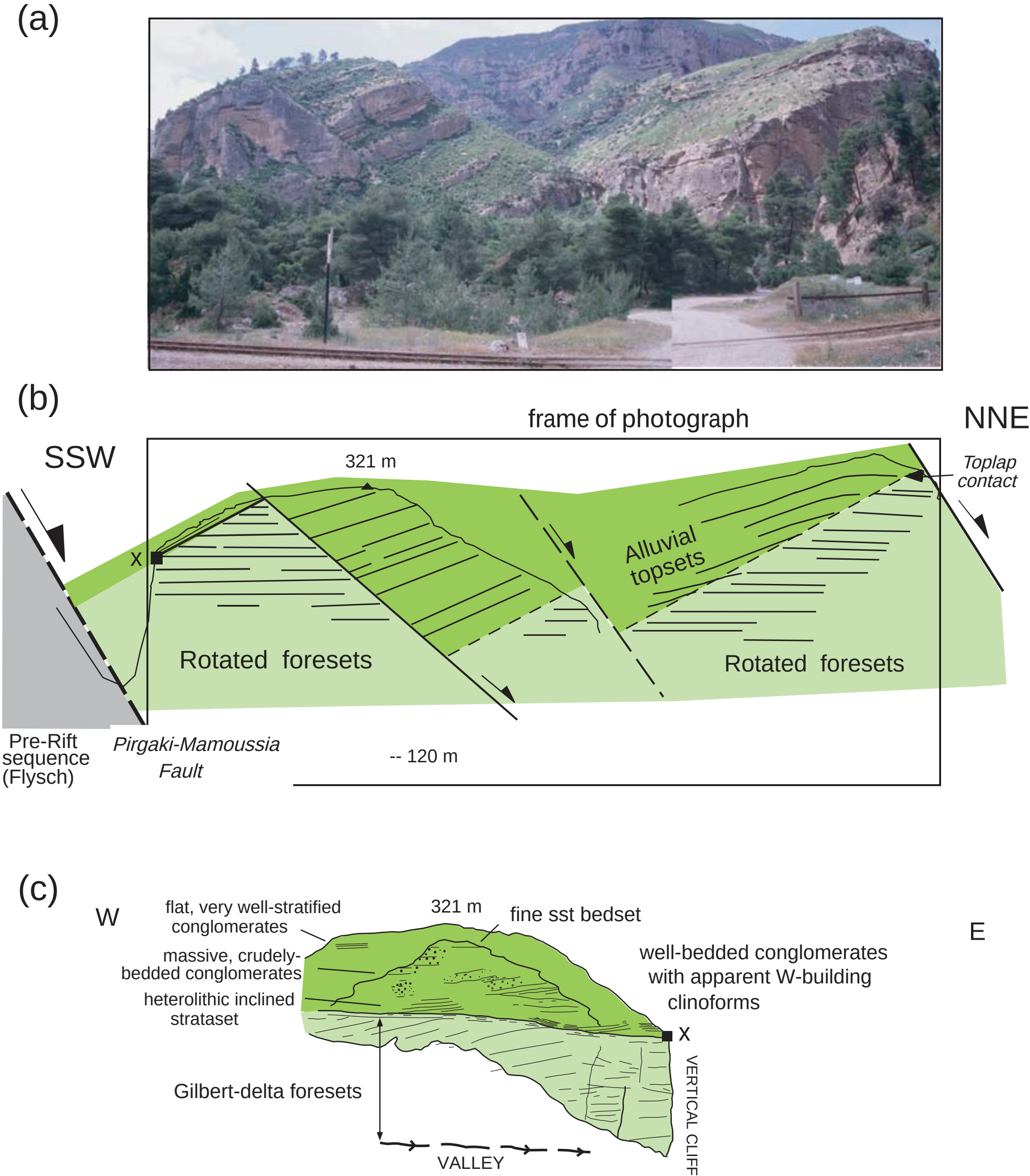


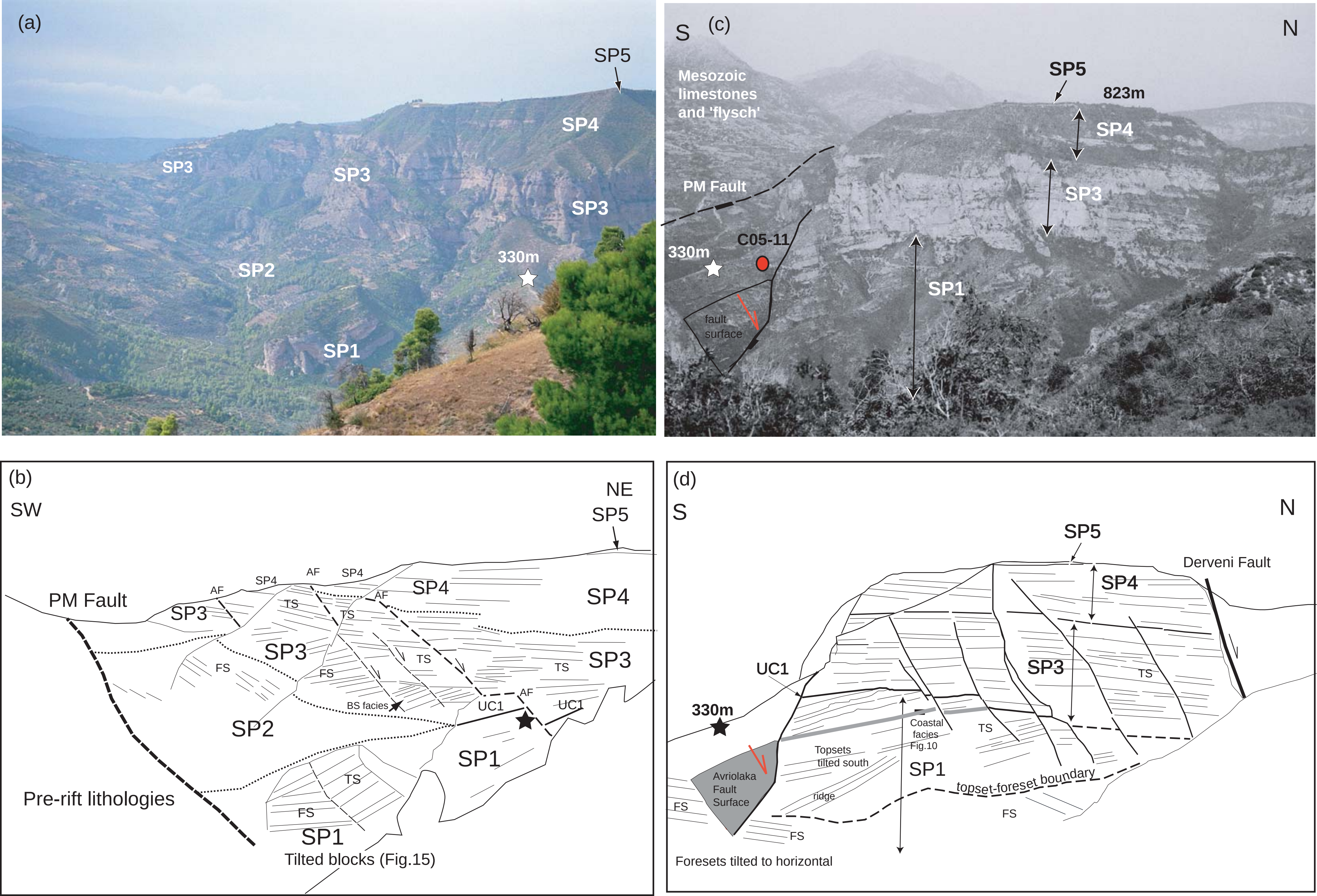
COASTAL/SHALLOW MARINE F.A. WITH CLINOFORMS
CONGLOMERATIC ALLUVIAL TOPSETS
TOPSET CYCLE
red sandstones and thin conglomerates
dcm-m thick conglomerates
crudely stratified to massive conglomerates
10
E
D
heterolithic foresets
5
sub-horizontal burrows
C
10º
B
13º
0 m
A
downward-tapering vertical burrows in fines
Si
Sa
Pbls
Cbls
downlapping onto underlying gravel topsets

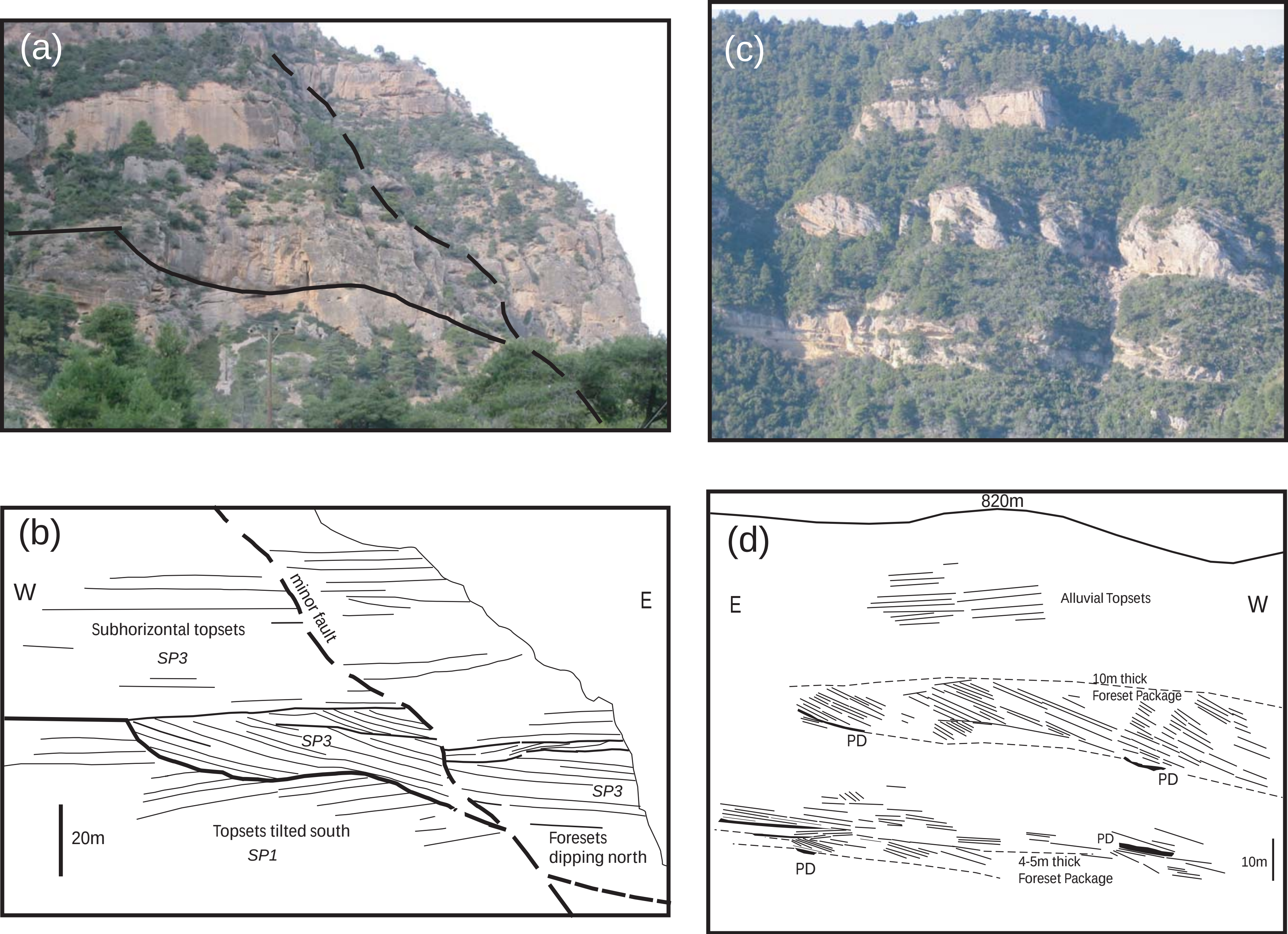

(a)
(b)
(c)
(d)
(e)

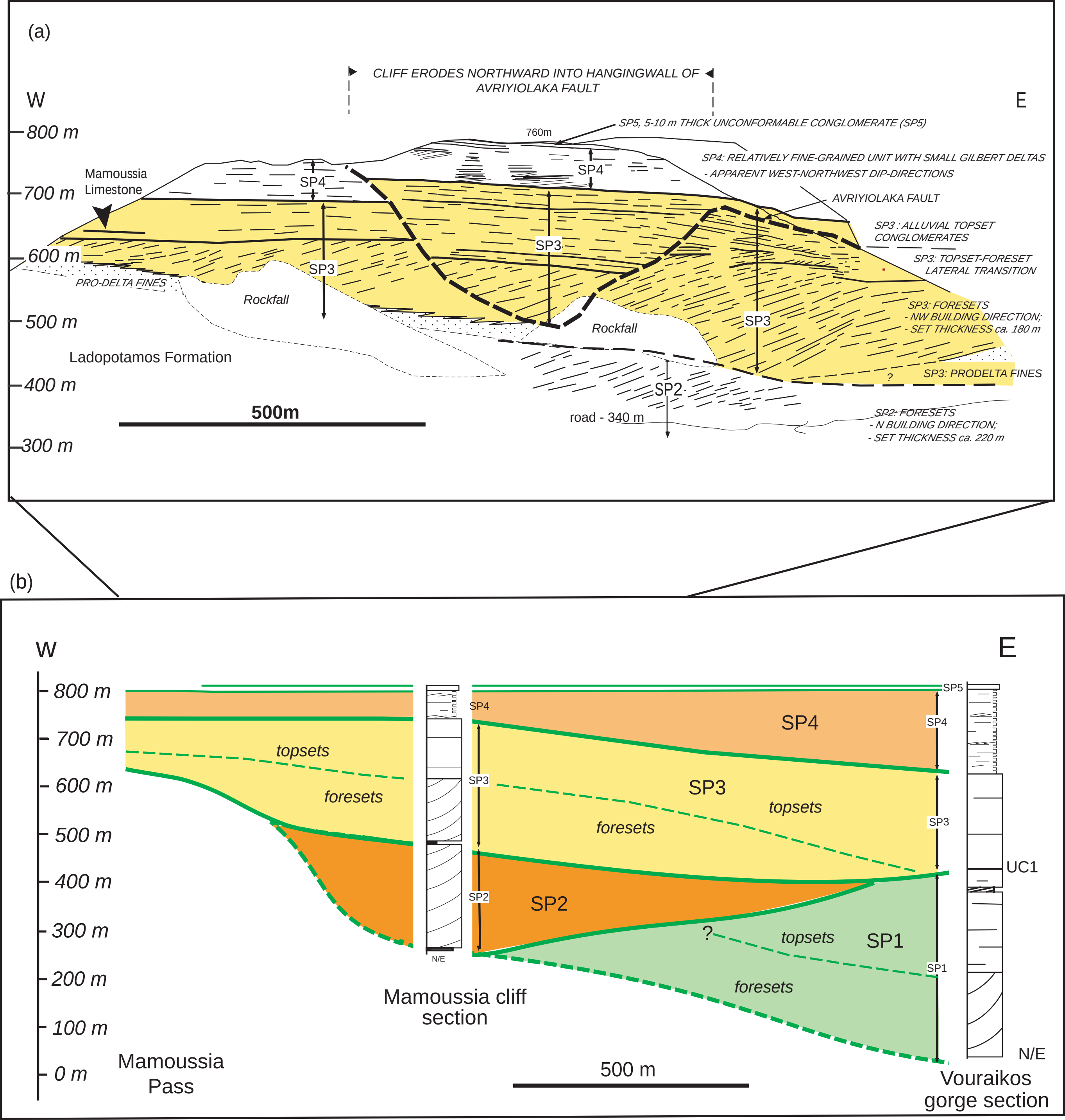


Centre of Vouraikos Delta
SSW
NNE
Asomati Plateau
Pirgaki-Mamoussia F.
Derveni Fault
AF
Helike Fault
823m
614m
SP5
SP4
SP3
SP2
SP1
SP4?
UC1
TOPSETS
FORESETS
Pre-Rift
Altitude (m asl)
1000m
2000m
3000m
4000m
5000m
A
B
C
D
Dated sediments
Western side of Vouraikos Delta
SSW
NNE
Asomati Plateau
Asomati Fault
Derveni Fault
Pirgaki-Mamoussia F.
Marathia Fault
Helike Fault
839m
Mamoussia Limestone
Marathia Limestone
NW dipping foresets
highly fractured
W-WNW dipping foresets
Pro-delta sltst + fine sst
Fluvial sst +cgs
village of Derveni
W-dipping foresets
SP4
SP3
SP4?
Pre-Rift
Altitude (m asl)
1000m
2000m
3000m
4000m
5000m

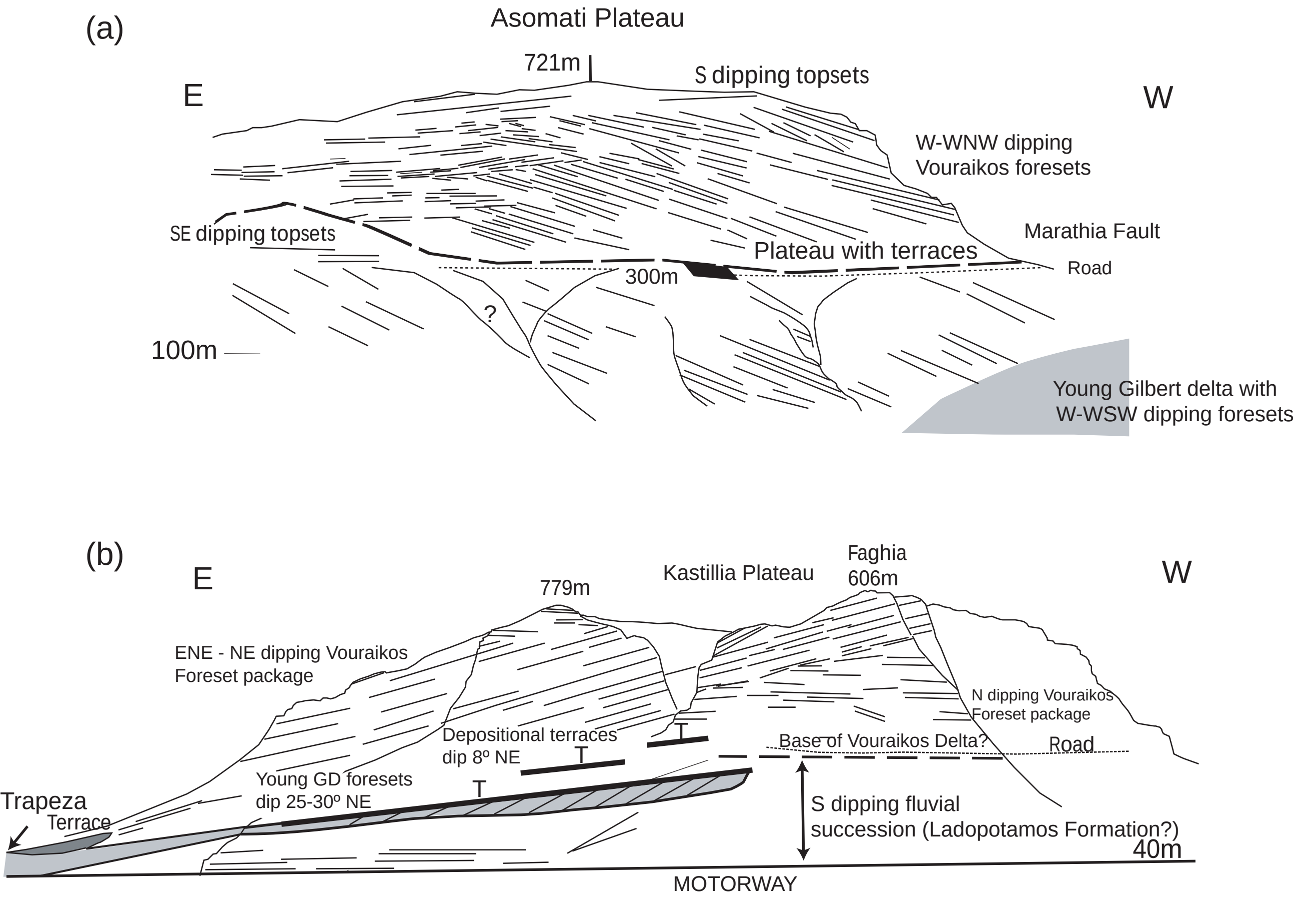

(a)
(b)
frame of photograph
SSW
NNE
321 m
Toplap contact
x
Alluvial topsets
Rotated foresets
Rotated foresets
Pre-Rift sequence (Flysch)
Pirgaki-Mamoussia Fault
-- 120 m
(c)
W
E
flat, very well-stratified conglomerates
321 m
fine sst bedset
massive, crudely-bedded conglomerates
heterolithic inclined strataset
well-bedded conglomerates with apparent W-building clinoforms
x
Gilbert-delta foresets
VERTICAL CLIFF
VALLEY


(a)
SP5
SP4
SP3
SP3
SP3
330m
SP2
SP1
(c)
S
N
Mesozoic limestones and 'flysch'
SP5
823m
SP4
PM Fault
SP3
C05-11
330m
SP1
fault surface
(b)
SW
NE
SP5
PM Fault
AF
SP4
AF
SP4
SP3
TS
TS
AF
SP4
SP4
SP3
TS
TS
SP3
FS
FS
BS facies
AF
UC1
UC1
SP2
SP1
TS
Pre-rift lithologies
FS
SP1
Tilted blocks (Fig.15)
(d)
S
N
SP5
Derveni Fault
SP4
UC1
SP3
TS
330m
Coastal facies Fig.10
TS
Topsets tilted south
SP1
Avriolaka Fault Surface
topset-foreset boundary
ridge
FS
FS
FS
Foresets tilted to horizontal

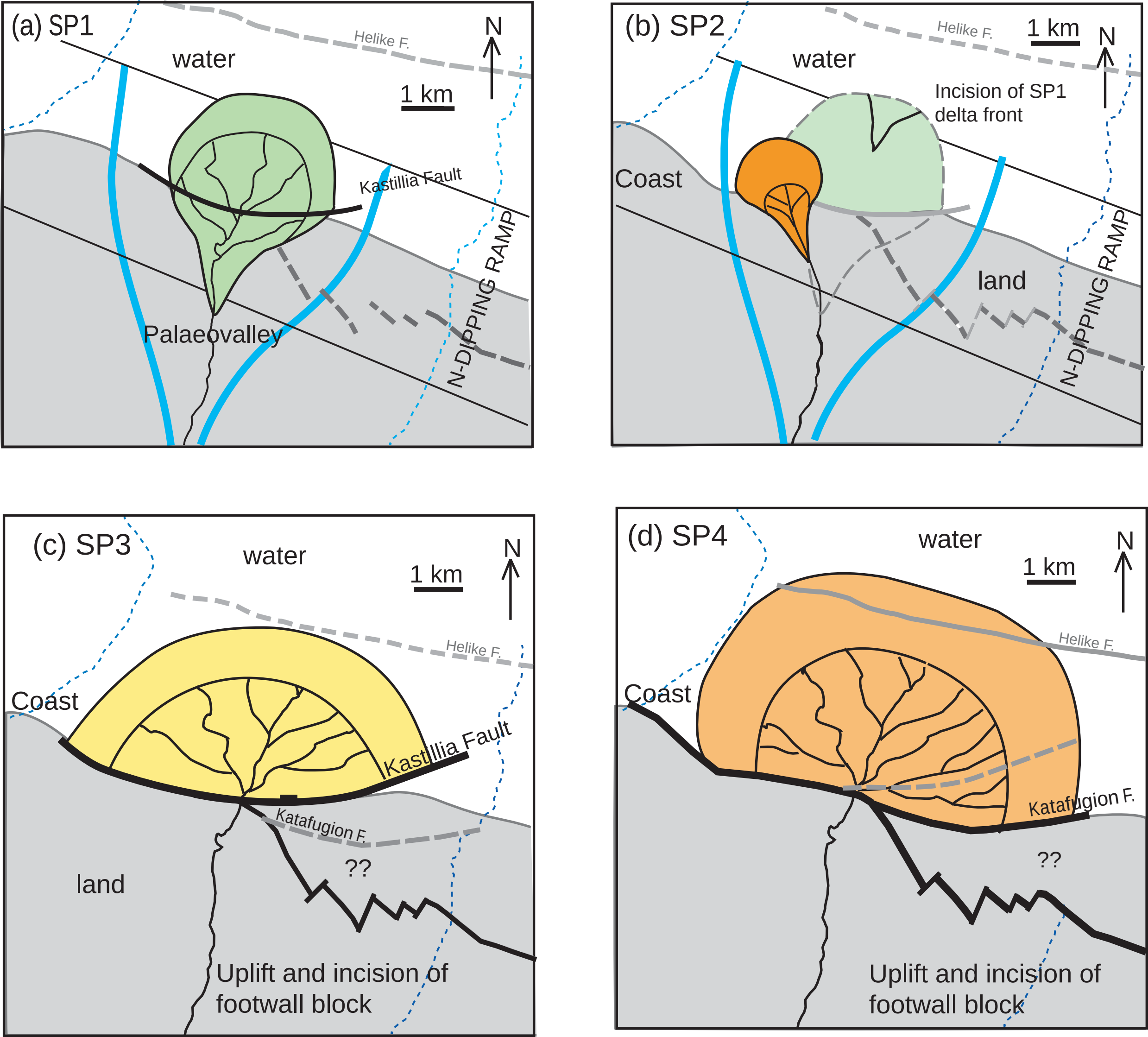

(a)
(c)
(b)
W
E
minor fault
Subhorizontal topsets
SP3
SP3
SP3
20m
Topsets tilted south
SP1
Foresets
dipping north
820m
(d)
E
W
Alluvial Topsets
10m thick
Foreset Package
PD
PD
PD
PD
10m
4-5m thick
Foreset Package



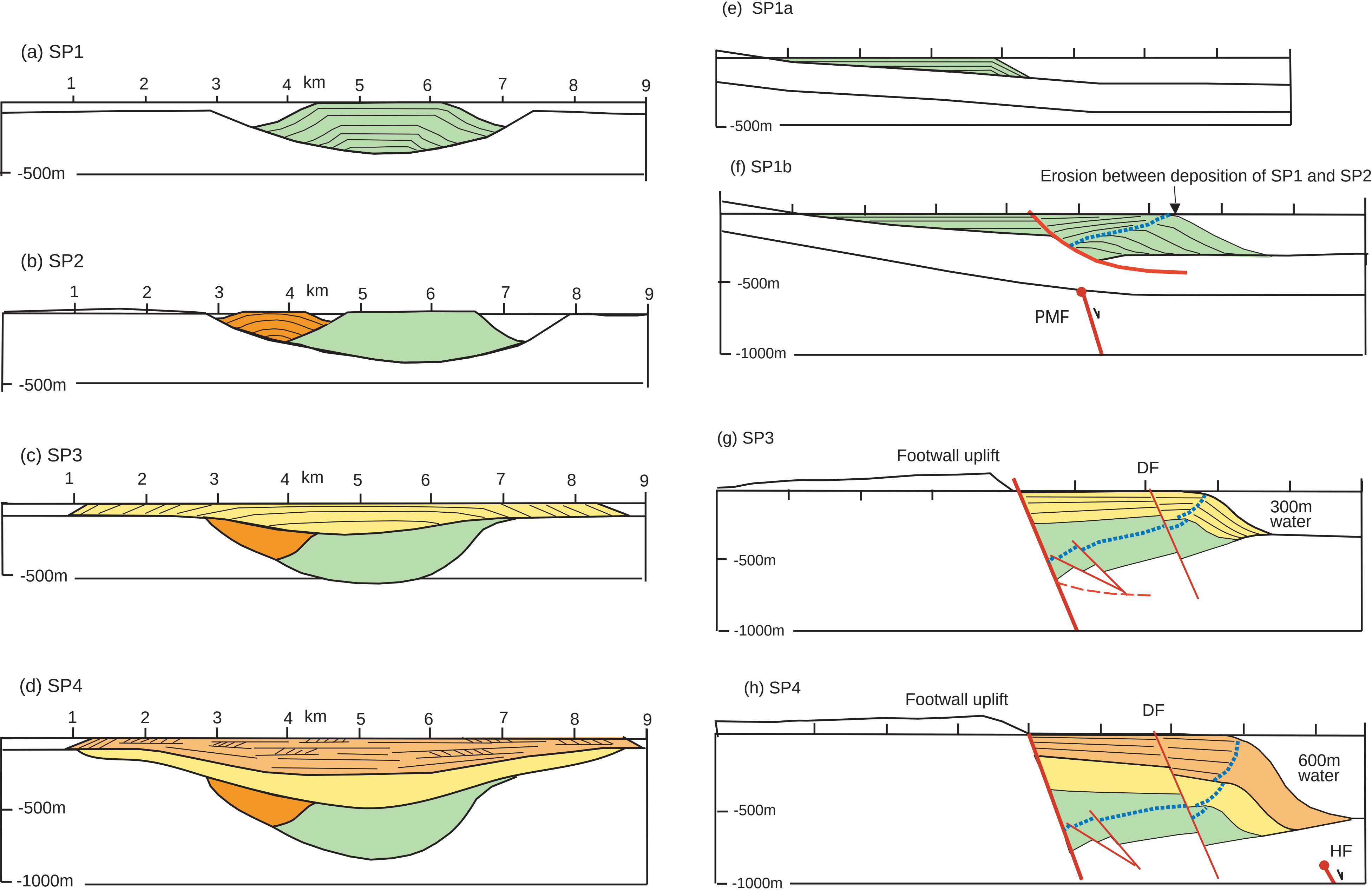
(a)
W
E
CLIFF ERODES NORTHWARD INTO HANGINGWALL OF AVRIYIOLAKA FAULT
800 m
700 m
600 m
500 m
400 m
300 m
760m
SP5, 5-10 m THICK UNCONFORMABLE CONGLOMERATE (SP5)
SP4: RELATIVELY FINE-GRAINED UNIT WITH SMALL GILBERT DELTAS
- APPARENT WEST-NORTHWEST DIP-DIRECTIONS
AVRIYIOLAKA FAULT
SP3 : ALLUVIAL TOPSET CONGLOMERATES
SP3: TOPSET-FORESET LATERAL TRANSITION
SP3: FORESETS
- NW BUILDING DIRECTION;
- SET THICKNESS ca. 180 m
SP3: PRODELTA FINES
SP2: FORESETS
- N BUILDING DIRECTION;
- SET THICKNESS ca. 220 m
Mamoussia Limestone
SP4
SP3
SP2
PRO-DELTA FINES
Rockfall
Ladopotamos Formation
500m
road - 340 m
(b)
W
E
800 m
700 m
600 m
500 m
400 m
300 m
200 m
100 m
0 m
topsets
foresets
SP5
SP4
SP3
SP2
SP1
UC1
N/E
Mamoussia Pass
Mamoussia cliff section
500 m
Vouraikos gorge section



(a)
Asomati Plateau
721m
S dipping topsets
E
W
W-WNW dipping
Vouraikos foresets
SE dipping topsets
Marathia Fault
Plateau with terraces
300m
Road
?
100m
Young Gilbert delta with
W-WSW dipping foresets
(b)
E
Kastillia Plateau
Faghia
606m
W
779m
ENE - NE dipping Vouraikos
Foreset package
N dipping Vouraikos
Foreset package
Depositional terraces
dip 8º NE
T
Base of Vouraikos Delta?
Road
Young GD foresets
dip 25-30º NE
Trapeza
Terrace
S dipping fluvial
succession (Ladopotamos Formation?)
40m
MOTORWAY



(a) SP1
water
Helike F.
N
1 km
Kastillia Fault
Palaeovalley
N-DIPPING RAMP
(b) SP2
water
Helike F.
1 km
N
Incision of SP1
delta front
Coast
land
N-DIPPING RAMP
(c) SP3
water
1 km
N
Helike F.
Coast
Kastillia Fault
Katafugion F.
??
land
Uplift and incision of
footwall block
(d) SP4
water
1 km
N
Helike F.
Coast
Katafugion F.
??
Uplift and incision of
footwall block



(a) SP1
1
2
3
4
km
5
6
7
8
9
-500m
(b) SP2
1
2
3
4
km
5
6
7
8
9
-500m
(c) SP3
1
2
3
4
km
5
6
7
8
9
-500m
(d) SP4
1
2
3
4
km
5
6
7
8
9
-500m
-1000m
(e) SP1a
-500m
(f) SP1b
Erosion between deposition of SP1 and SP2
-500m
PMF
-1000m
(g) SP3
Footwall uplift
DF
300m water
-500m
-1000m
(h) SP4
Footwall uplift
DF
600m water
-500m
HF
-1000m