A new geological map of the crustal-scale detachment on Kea (Western Cyclades, Greece)

A. Hugh N. RICE[1)*)], Christoph IGLSEDER[2)], Bernhard GRASEMANN[1)], András ZÁMOLYI[1)],
Konstantinos G. NIKOLAKOPOULOS[3)], Dimitrios MITROPOULOS[3)], Klaus VOIT[1)], Monika MÜLLER[1)],
Erich DRAGANITS[1)4)], Monika ROCKENSCHAUB[1)] & Panagiotis I. TSOMBOS[3)]

[1)] Department of Geodynamics & Sedimentology, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria;

[2)] Geological Survey of Austria, Neulinggasse 38, 1030 Vienna, Austria;

[3)] Institute of Geology and Mineral Exploration, Department of General Geology and Geological Mapping, Olympic Village, Acharnai, 13677 Athens, Greece;

[4)] Department of Prehistoric and Medieval Archaeology, University of Vienna, Franz-Klein-Gasse 1, 1190 Vienna, Austria;

[*)] Corresponding author, alexander.hugh.rice@univie.ac.at

KEYWORDS

West Cycladic Detachment System
Cycladic Blueschist Unit
low-angled normal fault
Cyclades
Greece
Kea

Abstract

This paper presents a new geological map of Kea, in the western Cyclades of Greece. The map shows the three-part tectonostratigraphy typical of many Cycladic islands: (i) Footwall of blue-grey calcitic marble mylonites and likely volcanoclastic-derived schists of the Cycladic Blueschist Unit, almost completely retrogressed to greenschist facies; (ii) Detachment zone of phyllonites, schist-derived protocataclasites and foliated cataclasites, white calcitic marble ultramylonites and dolostone (ultra)-cataclasites; (iii) Hanging wall of dolostones, with a variable protocataclastic deformation, and occasional foliated calcitic marbles. In the footwall, relict blueschist facies assemblages are rare, being best preserved in gneisses and Fe-Mn-rich rocks (both uncommon lithologies). The blue-grey calcitic marble mylonites, which are generally thicker than elsewhere in the Western Cyclades are more common on the eastern side of the island. This may reflect a lateral ramp geometry between the footwall and overlying detachment-zone. Structural data indicate a consistent top-to-SW to S directed deformation, confirming that the detachment on Kea is part of the West Cycladic Detachment System. Few significant steep faults were observed on the island, although the linear coastlines and valleys suggest that many minor faults or fracture zones may be present.

Diese Arbeit präsentiert eine neue geologische Karte von der Insel Kea in den West Kykladen in Griechenland. Drei tektono-stratigraphische Einheiten können unterschieden werden: (i) Eine liegende Einheit besteht aus blau-grauen Marmor-Myloniten und aus meta-vulkano-klastischen Schiefern, welche zur Kykladischen Blauschiefer Einheit gehören. Die Einheiten sind retrograd stark überprägt und bestehen heute hauptsächlich aus Grünschiefern. (ii) Ein tektonischer Abscherhorizont (Detachment) besteht aus Phylloniten, protokataklastischen Schiefern und verschieferten Kataklasiten in Vergesellschaftung mit ultramylonitischen Marmoren. (iii) Die hangendste Einheit besteht aus dolomitischen Karbonaten welche im unterschiedlichen Ausmaß kataklastisch überprägt sind.

Blauschiefer-fazielle Relikte sind selten und kommen nur in der tektonisch tiefsten Einheit in Fe-Mn-reichen Gneisen vor. Die blau-grauen Marmor-Mylonite sind deutlich mächtiger als auf anderen Kykladen Inseln und sind hauptsächlich im Ostteil der Insel aufgeschlossen, ein Umstand, der möglicher Weise mit einer lateralen Rampe im Abscherhorizont erklärt werden kann. Als Teil des West-Kykladischen-Detachment-System, zeigen kinematische Indikatoren einen sehr konsistenten nach SW- bis S-gerichteten Schersinn an. Obwohl die Geomorphologie der Insel die Anwesenheit von steilen Störungen nahe legt, konnten nur wenige steile Abschiebungen mit geringem Versatz kartiert werden.

1. Introduction

Kea, a small island SE of Attica, lies within the Western Cycladic Detachment System, a region of top-to-SW to S directed Miocene extension in the Aegean and the adjacent mainland (Fig. 1; Grasemann & Petrakakis 2007, Grasemann et al. 2012, Iglseder et al. 2009, 2011, Tschegg & Grasemann 2009). This zone is important because all other parts of the Cyclades show a top-to-N or NE Miocene shear-sense (cf Jolivet et al. 2010) and this alone has been used in most recent models for the evolution of the Aegean.

Here, the results of a detailed geological remapping of Kea are presented, based on a structural re-interpretation of the island. This work updates the previous geological map (Davis 1972, 1982), which presented a very simplistic and erroneous picture of the geology of Kea; important fault-rocks forming a major extensional detachment were not identified. A brief description of the geology is given, largely based on the detailed documentation of the structural evolution, metamorphism and age of deformation of the island given by Igleseder et al. (2011).

The map (Fig. 2), which is available on-line at A1 size, with and without hillshading (www.univie.ac.at/ajes/archive/volume_105_3/), is based on mapping by Voit (2008) and Müller (2009) in the northeast and north-northwest, respectively, by Iglseder (cf Iglseder et al. 2011) in the south and in the Aghios Simeon, Kefala and Dhichales areas and by Rice, Nikolakopoulos and Mitropoulos in the intervening areas, as well as at Aghios Simeon and Kefala.

The article also gives a number of localities where the features described can be easily seen; it thus has a secondary use as a simple field-guide to the island.

2. Cycladic geology

The Cyclades underwent major continental crustal extension during the Miocene when low-angled faulting and associated greenschist facies (and lower grade) metamorphism (M2/D2) overprinted Eocene subduction-related blueschist and eclogite facies metamorphism (M1/D1). In the northern, central and eastern parts of the Cyclades (Fig. 1), this low-angled extension had a top-to-N to NE shear sense (Lister et al. 1984, Bröcker and Franz 2006, Gautier et al. 1993, Lee & Lister 1992, Trotet et al. 2001, Jolivet et al. 2003, Tirel et al. 2009, Huet et al. 2009; Jolivat at al. 2010) with a displacement estimated to be the order of 580 km (Brun & Facenna 2008). In contrast, low-angled extension in the Western Cyclades, involving the same tectonostratigraphic units as elsewhere in the region, was top-to-SW to S (Grasemann & Petrakakis 2007, Grasemann et al. 2012, Tschegg & Grasemann 2009, Iglseder et al. 2009, 2011, Brichau et al. 2010; Ring et al. 2011). Overall, this extension was caused by roll-back of the African oceanic lithosphere, pulling the north-dipping Hellenic trench southwards (Gautier & Brun 1994, Jolivet et al. 2003). This occurred at the same time as a clockwise rotation of the Cyclades (Morris & Anderson 1996, van Hinsbergen et al. 2005; Walcott and White, 1998).

3. Kea

Kea lies towards the northeastern end of the NW-SE oriented Western Cycladic archipelago, with Kythnos to the southeast and Makronisos to the northwest, only 5 kilometres from the Attica mainland (Fig. 1). The island is broadly elliptical in shape, with a NNE-SSW oriented 19.7 km long major axis and a 9.9 km minor axis, and a maximum height of 562 m. The island, which has a relatively steep relief with two major inland wooded valleys, is sparsely populated, even in summer; there are few hard roads and extremely limited facilities outside the Korissia-Vourkari area and Loulida, both in the north (Fig. 2).

3.1 Tectonostratigraphy

Three tectonostratigraphic units, all parts of the Attic Cycladic Crystalline (Bonneau, 1984), have been recognised; a footwall, a hanging wall and an intervening detachment zone. These deformed rocks were affected by iron-rich hydrothermal fluids and are overlain by three essentially post-tectonic, Pleistocene-Holocene deposits; bioclastic sandstones, alluvial valley-fill and beach sediments, and mass-movement deposits.

3.1.1 Footwall

The footwall forms most of the island, with a maximum observed tectonic thickness of ca. 450 m, seen in the valley to the east of Pisses (N4164891 E263044; Iglseder et al. 2011). Two dominant lithologies occur; marbles and schists.

Marbles are mostly calcitic and typically blue-grey coloured (Fig. 3A-D), although they may be locally white or have thin white layers (Fig. 3A). Small lenses, likely boudins, of buff-yellow weathered brecciated grey dolostone are also present (Fig. 3B, e.g. N4170087 E262198), but these are rare. In nearly all cases, the blue-grey marbles are fine grained and carry a mylonitic fabric parallel to the compositional layering. Ultramylonitic fabrics are also developed in the blue-grey marbles (e.g. N4171136 E261770), these having a characteristic conchoidal fracture and metallic clang when hammered. Thin (typically < 2 cm thick, but sometimes up to 0.5 m) layers with a quartz-rich composition are frequently seen within the blue-grey marbles, especially in fold hinges, where they are thicker and often weather proud, revealing the fold geometry in 3-D (Fig. 3C). The ca. 20 m thick blue-grey marble east of Pisses (N4164891 E262537), cropping out in a minor quarry between the road as it passes around a hairpin bend, is the only weakly deformed outcrop found, having a granular texture and a poor or absent foliation. This is presumed to be the core of a very large boudin.

Due to their relative hardness compared to the schists, the blue-grey marbles tend to form cliffs where thick or distinct steps in the topography where thinner. Even when thin, they are often well exposed and visible from a considerable distance. Except where field evidence is compelling, no attempt has been made to link isolated small outcrops of marbles. Such thin layers inevitably have an exaggerated thickness on the map.

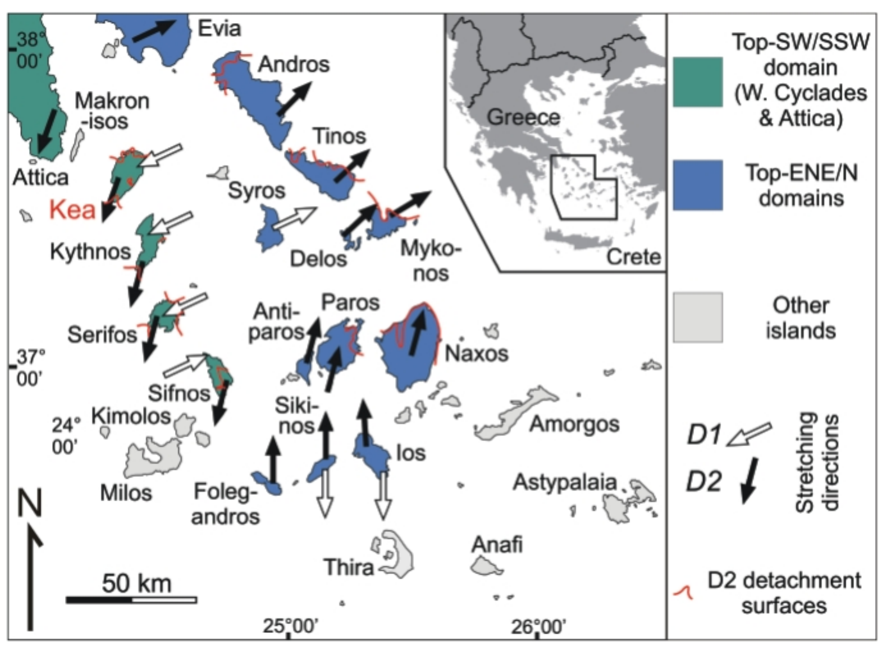
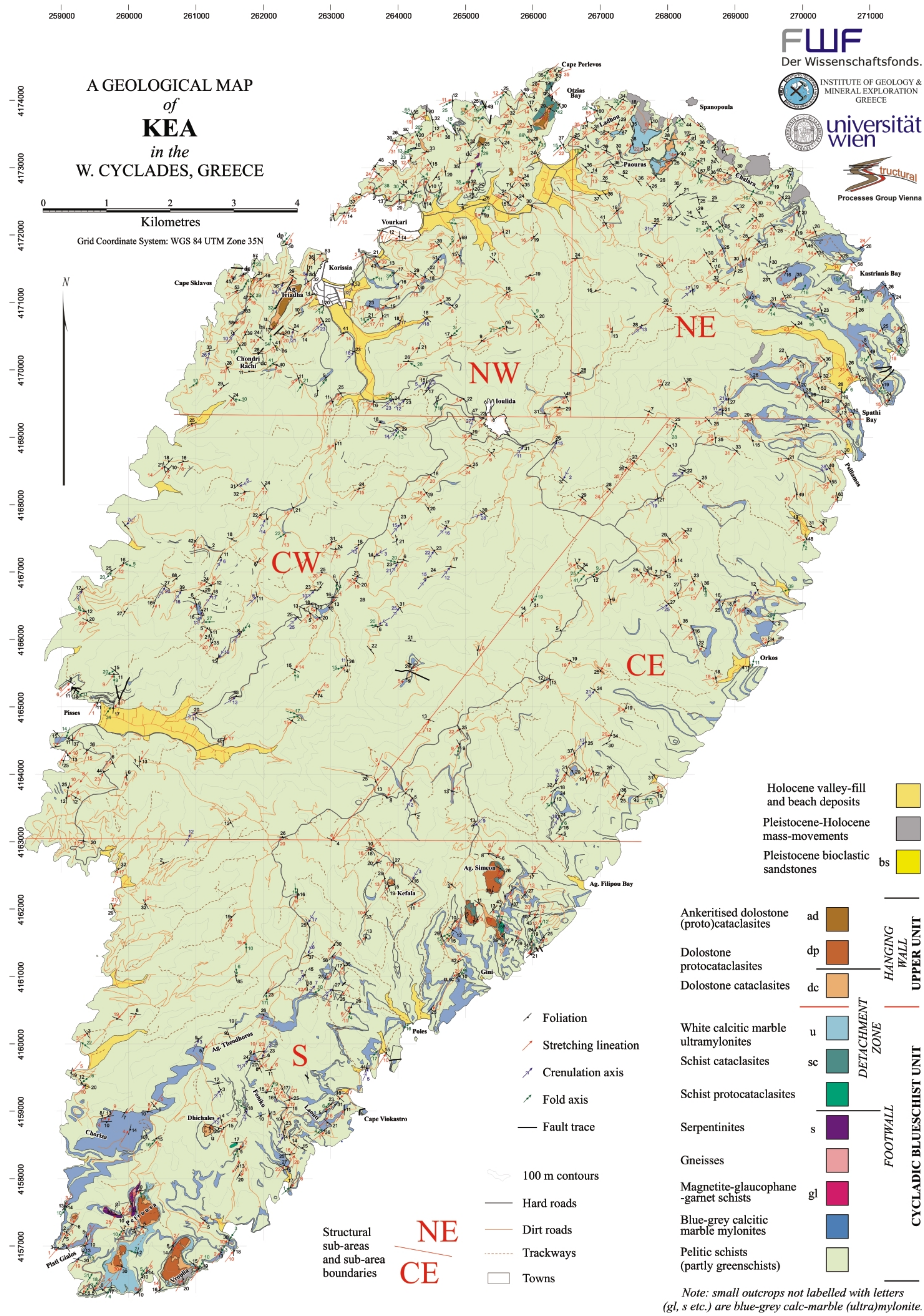


Figure 1: Simplified geological map showing the dominant stretching directions for D1 (Eocene high-pressure) and D2 (Miocene low-pressure) metamorphism/deformation, with the arrows pointing in the top-to shear-sense direction. (Modified after Grasemann et al. 2012).

Figure 2



Field mapping by Rice, A. H. N., Iglseder, C., Nikolakopoulos, K. G., Mitropoulos, D., Voit, K., Müller, M., Draganits, E. & Rockenschaub, M. 2006-2008.
Map compilation and digitization by Rice, A. H. N. & Zámolyi, A.
Reference to map: Rice, A. H. N., Iglseder, C., Grasemann, B., Zámolyi, A., Nikolakopoulos, K. G., Mitropoulos, D., Voit, K., Müller, M., Draganits, E., Rockenschaub, M. & Tsombos, P. I. (2012). A new geological map of the crustal-scale detachment on Kea (Western Cyclades, Greece). Austrian Journal of Earth Sciences 105/3, 108-124. www.univie.ac.at/ajes/archive/volume_105_3/

Along the northeastern and southeastern to southern coasts of the island, the blue-grey marbles are thick and common (Kastrianis Bay to Psiliamos and Aghiou Filipou Bay to Choriza, respectively; Fig. 2). These outcrops, especially in the former area, can be readily seen from the road. In the intervening eastern coastal area marbles are somewhat less common; this may in part be due to the poorer road access. The marbles were in some cases mapped in great detail directly from satellite images, with subsequent field checks to confirm the outcrop pattern.

Thick marble layers show large-scale pinch-and-swell, with well-exposed cliff sections up to several tens of metres thick, linked by areas where they have thinned down to a few metres, or even less (Fig. 3D). Inspection of the area between the thicker outcrops generally revealed a continuity of outcrop. Along the southeastern coast, the layering is essentially subparallel to the regional topographic slope, such that marbles frequently form either a ring-shaped outcrop around hilltops (N4166019 E268558) or a marked zig-zag pattern, such as between Poles and Foniko (N4160216 E263003; Fig. 2). The marbles in this region are inter-fingered with pelitic schists, with one or other lithology wedging out laterally. This might be reflecting either primary sedimentary variations or very early folding, although no evidence of a folded relict compositional layering (bedding) or an early foliation has been recorded in what would be the isoclinal fold hinges. A consequence of this uncertainty is that although there are often several distinct bands of marble (e.g. south of Orkos, at N4165596 E269297, six bands of marble have been mapped) there is no constraint on the number of marble layers within the original sedimentary succession. Detailed structural mapping might resolve this.

The largest outcrop of blue-grey marble occurs in the quarries in the Choriza area (N4158332 E259796). Overall the marble-rich succession here may be up to 200 m thick, although in detail there are several wedges of pelitic schist within the marbles. Access to the quarries was restricted and hence these schist layers are not shown; as the quarry is active, their outcrop distribution will be changing regularly. This massive thickness of marbles thins rapidly to the northeast, within only a few hundreds of metres, suggesting that it represents a large fold core, similar to that seen at Pisses (N4165131 E259682; see below).

In the central and western parts of the island, where marbles are relatively uncommon, only small and isolated lenses of marble, likely pinch-and-swell type boudins, generally less than a few metres thick and in some cases only a few tens of centimetres thick, have been mapped.

Southeast of Pisses no marbles have been found in an area of ca. 25 km².

The intervening schists, which are the dominant lithology on the island, show a wide range of metamorphic mineral assemblages but, due to their gradational contacts, these have not been mapped in detail. Bright green schists are common; these are rich in chlorite and/or actinolite and/or epidote and varying amounts of plagioclase and quartz. These reflect a variable input of metabasic volcanoclastic sediments. Such rocks can be clearly seen when approaching Korissia harbour by boat and good examples are exposed in the southeast corner of the harbour (Fig. 4A; N4171322 E263371). Subidiomorphic to idiomorphic albite porphyroblasts up to 1.5 mm in size are locally common in these rocks, as are concentrations of epidote group minerals; both of these phases may contain relicts of Eocene blueschist-facies assemblages, although at only one locality have macroscopically visible blue amphiboles been found in the schists, in a 1.5 m thick boudin/lens in the Chalara area (N4172872 E128 268580).

Other schists, likely containing a more acidic volcanoclastic component, have more quartzofelspathic minerals, with a higher white-mica content and sometimes with abundant quartz pods (Fig. 4B); these latter might be meta-conglomerates. Carbonate, weathering to a rusty colour, is a component of some schists, as is graphite. The schists in the immediate footwall of the detachment are often phyllonitic.

Fe-Mn-rich metasediments, now forming garnet-glaucophane rocks (± magnetite, plagioclase, quartz, tourmaline and epidote), also occur in the upper part of the footwall, within the mica-schists. These appear as dark rusty brown to almost black, strongly foliated (mylonitic in places) lenses or layers, often with abundant fractures filled with quartz or calcite. In the south, on Petroussa, these metalliferous sediments are up to 5 m thick and several metres or tens of metres long (Fig. 4C; N4157637 E260048 & N4157467 E259809). Smaller (<3m long, 0.5 m thick) bodies are exposed in the fresh outcrops on the north side of the road at Chalara (N4172872 E268580 & N4173369 E268300). Several thin lenses of piemontite-rich schists occur in the areas south and west of Otzias Bay (Fig. 4D; N4172672 E266324).

Gneisses (IUGS definition) occur in the south of the island, in the Petroussa area (N4157494 E259778), spatially associated with the Fe-Mn-rich rocks. These have a predominantly quartz-feldspar-mica mineralogy, although blue amphiboles, garnet, chlorite and epidote are locally abundant. These are (proto-)mylonitic in part.

Serpentinites, which may be partially altered to talc and talc schists, occur in the upper part of the footwall schists (in the phyllonite zone, where present; see below), in bodies up to several metres long and thick, sometimes in association with sub-horizontal layers of cataclasites. Their scarcity suggests that it is unlikely that they are boudins of a once more continuous layer, but whether they are mega-clasts deposited in a conglomerate (melange?) or relicts of ultramafic intrusions is not known. Such bodies have been found near the detachment at several places in the north and south of Kea and also near the outcrop of the detachment southeast of Aghios Simeon (N4161495 E265643). A good example, well exposed in a roadside outcrop, lies on the west side of Otzias Bay, in the

Figure 2: Geological map of Kea. The same map, for printing at A1 size, is available free on-line.

north of Kea (N4173806 E266169).

3.1.2 Detachment Zone.

Rocks forming the up to ca. 60 m thick detachment zone are defined as those which carry a localised high(er) strain related to the low-angled normal ductile to brittle faulting that occurred between the hanging wall and footwall. Both ultra-mylonites and proto- to ultra-cataclasites occur and rocks derived from both the footwall and hanging wall were affected by this event. Outcrops of the detachment occur in the north and northwest and in the south and southeast of the island. The larger outcrops are in the south of the island; many of the large exposures of the detachment rocks seen in the north of the island are parts of essentially intact down-slope mass-movements (see below).

Although many occurrences of the detachment zone are relatively large, numerous small outcrops, forming thin scabs of fault-rock, sometimes only few 10's of cm^2 in size and only a few centimetres or metres thick, have been documented in the area between Otzias Bay and Cape Sklavos. Generally, but not always (e.g. GridRef N4171430 E261735), this apparent small size (on the map) is due to the impenetrably thick and thorny *maquis* vegetation hindering mapping of their true dimensions.

The detachment zone is here described from the lowest to highest tectonostratigraphic level. Zones of higher ductile strains occur throughout the footwall schists, forming phyllonites (mica schists with a penetrative S-C' fabric); these tend to occur more frequently in association with the detachment zone and are likely genetically linked, especially in the north of the island. However, as they grade very gradually down into the 'normal' schists, making defining a boundary very subjective, this lithology has not been mapped and such rocks are included in the footwall.

Two forms of brittle deformation of the footwall schists occur, forming the structurally lowest recognised units of the detachment zone. Rarely, the schists have been deformed and preserved as a coarse (proto)cataclasite, with clasts having sizes of up to several centimetres (Fig. 5A). These are well seen in the outcrops northeast of Dhichales (N4158474 E261496), just east of the road, although no higher units of the detachment zone are present there, and also in the area around N4 158474 E261496, south of Aghios Simeon. More commonly, the upper parts of the schists have been thoroughly reworked by brittle deformation mechanisms into a foliated pelitic cataclasite that may contain SC' fabrics, invariably indicating a top-to-SW to S movement. These cataclasites are well exposed on the south side of the road immediately north of Aghios Si-

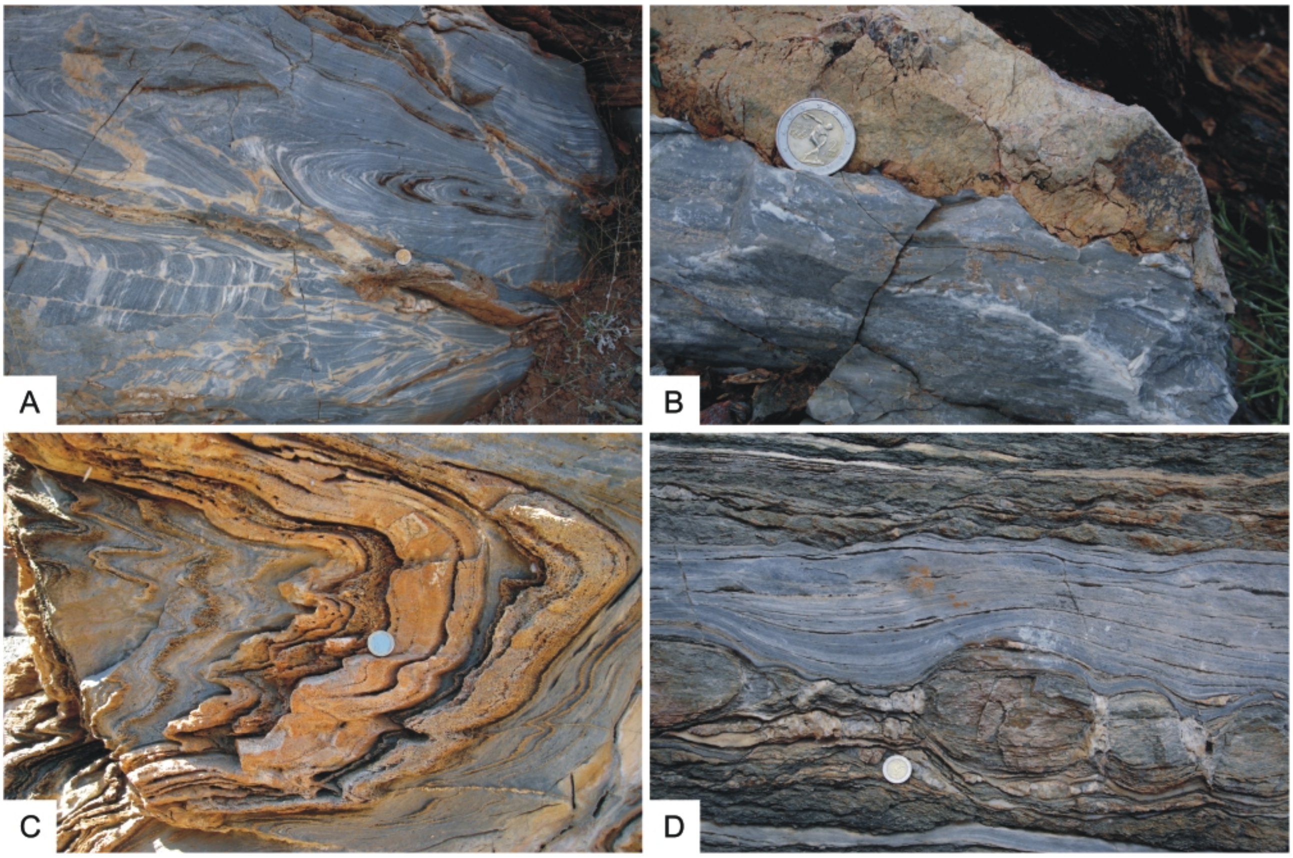


Figure 3: Illustrations of the blue-grey marble. A. Blue-grey marble with abundant thin white layers, cut by a number of rotated brittle fractures. (E265613 N4170635). B. Contact of brittle deformed pale buff dolostone and blue-grey marble mylonite. (N4171306 E261754). C. Hinge of fold in blue-grey marble and quartzites showing the fold geometry in 3-D. (N4160429 E264221). D. Strongly thinned layer of blue-grey marble (ultra-)mylonite overlain by mica-quartz schists showing S-C-C' structures. A thicker layer of quartz schist within similar schists below the marble has been both symmetrically and asymmetrically boudinaged, with quartz deposited in the boudin necks. (N4164451 E264909).

meon (N4162725 E265440) and on the west side of the road east of that hill (N4162650 E265450). A small quarry in these rocks has also been made between the two roads on the east side of Aghios Simeon (N4162620 E265495), revealing that the foliated cataclasites may be up to 10 m thick in some places. The cataclasites have frequently been eroded away under cliffs of higher units (Fig. 5B) and hence cannot be drawn on the map.

In most cases, the footwall-derived cataclasites are overlain by calcitic marble ultramylonites that are typically both white-weathering and white on fresh surfaces (Figs. 5B, D), but may be interlayered with or altered to reddish, pale buff or grey colours. The thickest exposures, showing up to 30 m of calcite ultramylonite, occur in large, geomorphologically prominent klippen in the north and south of the island (Fig. 2). In the intervening area, the ultramylonites may be only a few metres or less thick (e.g. Kefala; N4162377 E263864), although in such cases they often form a distinct step in the topography (Fig. 6A, 7A).

These ultramylonites are overlain on a knife-sharp contact (Fig. 5C) by up to several metres of cohesive dolomitic or calcitic cataclasites with a buff-brown colour. These are usually without a cataclastic foliation (Fig. 5E). Locally, calcitic marble (proto-)mylonites up to 5 m thick crop out. This succession represents the deformed base of the hanging wall. In one outcrop on the coast west of Korissia (N4171894 E262303), a small, strongly deformed clast of clastic rocks, including very dark grey low metamorphic grade metapelites occurs within the breccias (Fig. 5F). Imbrication of the hanging wall sequence of carbonate rocks with the footwall cataclastic schists has been recorded at Aghios Simeon (Fig. 2) and also in the klippe immediately to the south, at N4161866 E265108 (Fig. 6B).

On the west side of Otzias Bay, a prominent detachment surface above the calcitic marble ultramylonites is directly overlain by coarse cataclasites (Fig. 5C). These show a spaced (ca. 10 cm scale) sub-horizontal cleavage cutting across the more penetrative cataclastic foliation, with an S-C geometry. In part, this developed into an ultracataclasite with a penetrative, finely banded fabric, containing abundant small, often asymmetrically shaped clasts (Fig. 5G).

3.1.3 Hanging wall.

Many outcrops of the detachment zone are overlain by up to 40 m of weakly metamorphosed hanging wall rocks (Fig. 6A). Large outcrops occur in the Paouras (N4173552 E267532) area in the north, in several places at and south of Aghios Simeon in the southeast and, especially, in large areas in the extreme south (Fig. 2; see Iglseder et al. 2011). Smaller exposures occur at the klippen at Dhichales (N4158685 E261132) and Kefala (N4162427 E263885) and very small patches have

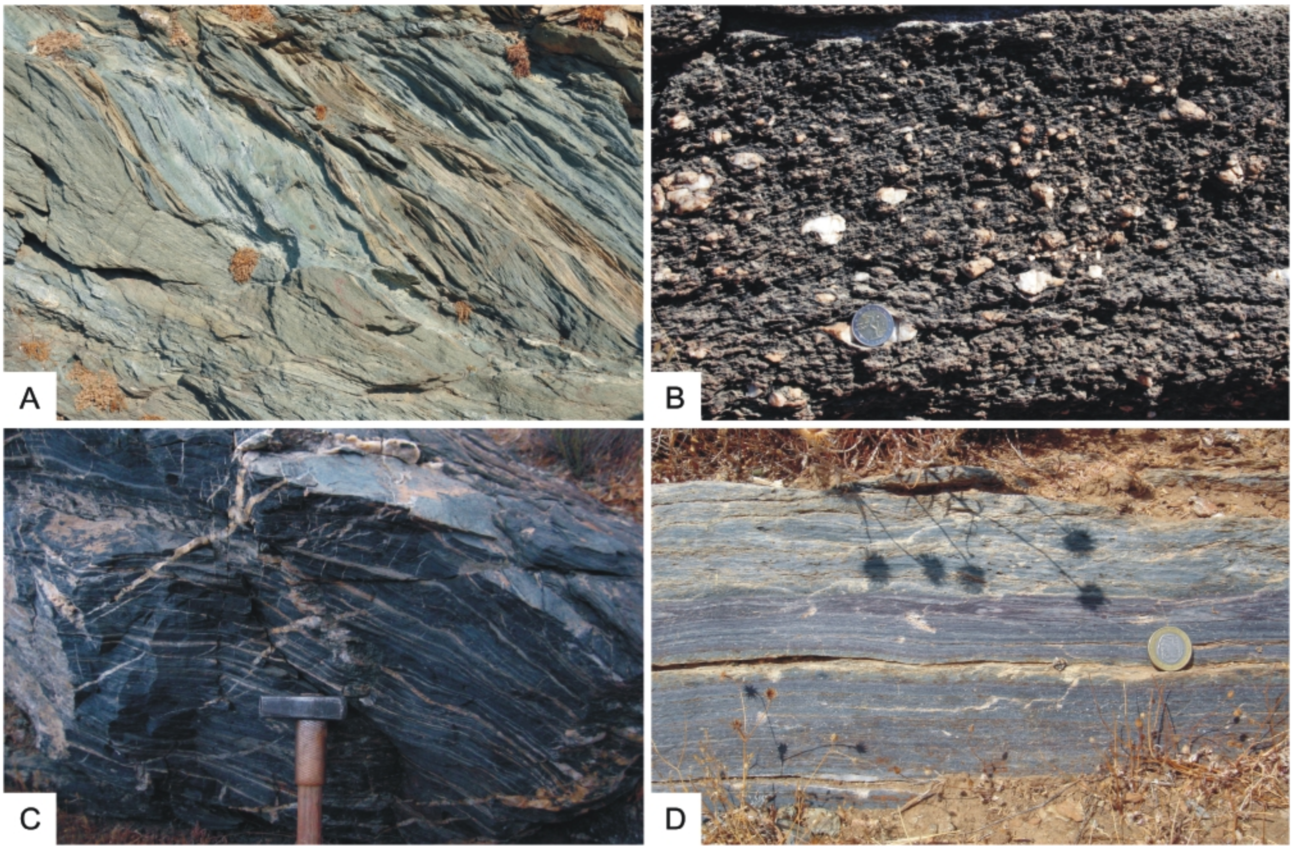


Figure 4: Illustrations of the pelitic schists. A. Chlorite-rich basic schists with a well-developed large-scale S-C' fabric. (N4171295 E263338). B. Coarse grained chloritic schist with abundant quartz pods. (N4160153 E259386). C. Garnet-blue-amphibole-magnetite schists (Fe-Mn-rich schist) with numerous quartz and calcite-filled fractures, reflecting its high competence compared to the neighbouring rocks. (N4157472 E259825). D. Thin piemontite-rich schists (purple-tinged layer above the level of coin and below the shadows of the flowers. (N4172672 E266324).

been found in the north and northwest, between Otzias Bay and Cape Sklavos. The boundary to the underlying detachment zone cataclasites is often gradational.

The basal part consists of white to brown coloured cohesive proto-cataclasites interlayered at a ca. 1 m scale. In the south and southeast, these are overlain by up to 10 m of medium to

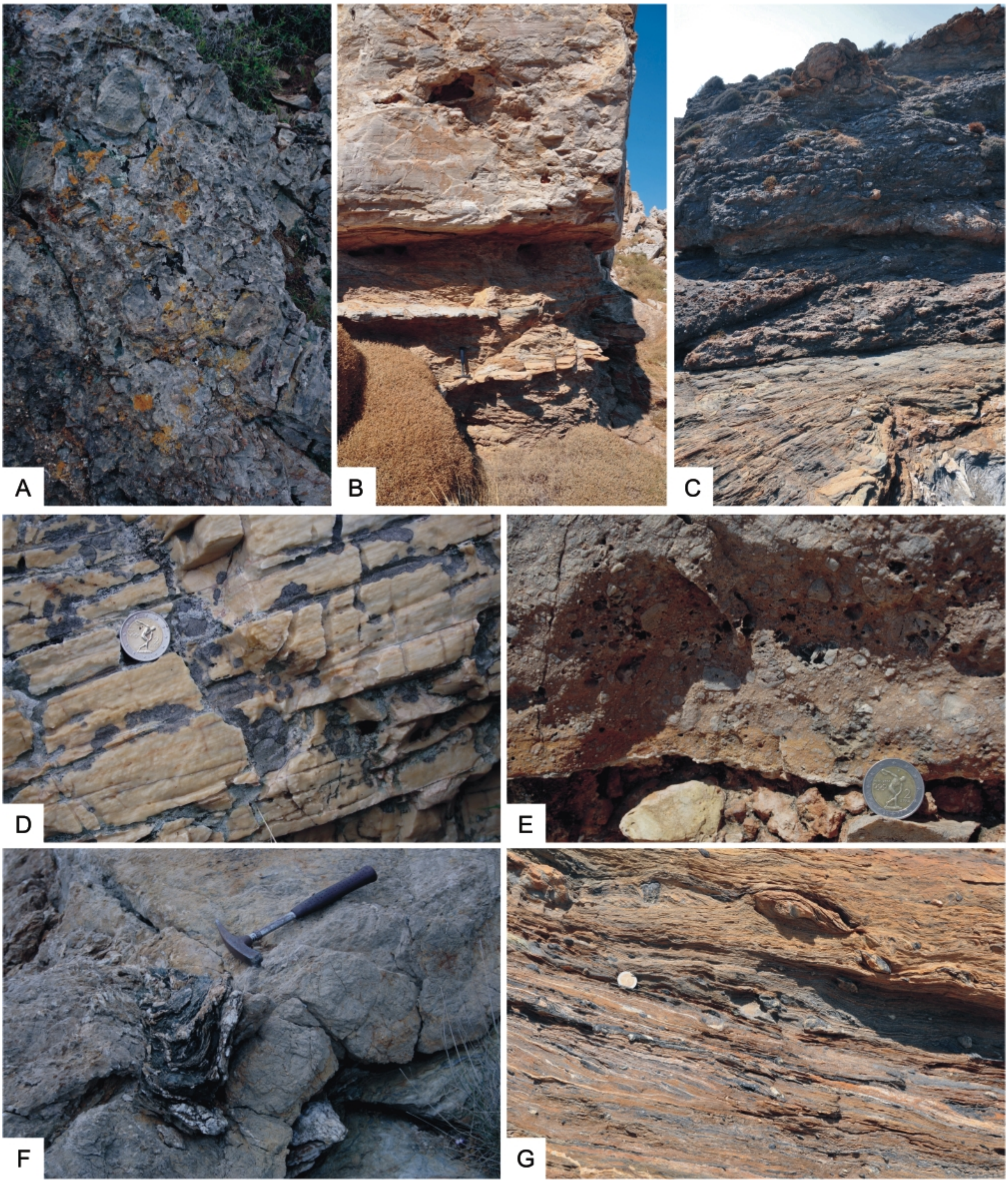


Figure 5: Illustrations of the rocks in the detachment zone. A. Protocataclasite developed in schist. (N416179 E265528). B. Foliated cataclasites in schists below the calcite marble ultramylonite. Note that weathering of the cataclasites under the ultramylonite to form an overhang means that it does not appear on the map. (N4173722 E267541). C. Detachment surface overlain by coarse dolostone cataclasites showing a poorly developed inclined fabric dipping to the east (left in the picture) cut by a spaced subhorizontal C fabric. (N4174066 E266238). D. Typical calcitic marble ultramylonite. (N4161600 E265552). E. Unfoliated massive dolostone cataclasite lying directly above calcitic marble ultramylonites. (N4161840 E265178). F. Strongly deformed metapelitic clast within dolostone proto-cataclasite of the hanging wall. (N4171883 E262295). G. Foliated cataclasites with abundant medium- to small-scale asymmetric porphyroclasts indicating top-to-south displacement. (N4174067 E266234).

coarse-grained blue-grey dolostone with a pressure-solution cleavage (e.g. at Dhichales, N4158685 E261132). In addition, dark-grey coarse- to medium-grained undeformed dolostones form up to 5 m thick lenses on Chondri Rachi, in northwest Kea (N4170097 E261912). At Aghios Simeon, course-to medium-grained dark grey to black dolostones, visible on the road, have been weakly brecciated (N4162559 E265355). These rocks are interlayered with slightly foliated calcitic (proto-)mylonitic marbles, up to 2 m thick. The occurrence of ductile deformation in calcite constrains the metamorphic temperature to have been >200°C (very-low grade metamorphism).

3.1.4 Fluid infiltration.

Both during and subsequent to the greenschist facies metamorphism, infiltration of hot Fe-rich fluids occurred, strongly affecting the country rock. The fluids caused locally intense alteration of carbonates to ankeritic carbonates, with associated limonitization (Fig. 7B). Carbonate fluids were then transported and deposited within siliciclastic rocks, with varying amounts of iron. In some instances, these iron deposits were large enough to be mined on a very small-scale. In the Aghios Theodhoros area (N4159807 E261822) rough hewn blocks of Fe-ore (mostly hematite) have been neatly stacked in preparation for transportation. Other fluids resulted in the silicification or dolomitization of carbonates. Barite deposits have also been recorded.

Fluid infiltration processes particularly affected the porous parts of the detachment zone; specifically, many of the cataclastic carbonate rocks have been strongly ankeritised and now have a dark brown to rusty colour (e.g. SSW of Aghios Triadha (N4170887 E262257).

Deposition of Fe-Mn-Pb-Au ores along brittle/ductile to brittle high-angle faults also occurred (Photos-Jones et al. 1997). This was likely related to unexposed magmatic activity, as in the Lavrion mining district of Attica (Skarpelis 2007, Skarpelis et al. 2008).

3.1.5 Pleistocene-Holocene deposits.

Three post-low-angled normal faulting lithologies have been mapped; bioclastic sandstones, valley-fill and beach deposits and mass-movement deposits.

The oldest post-tectonic rocks mapped form two relatively small and several extremely minor outcrops of bioclastic sandstones (Fig. 2), sometimes referred to as poros in the Cycla-

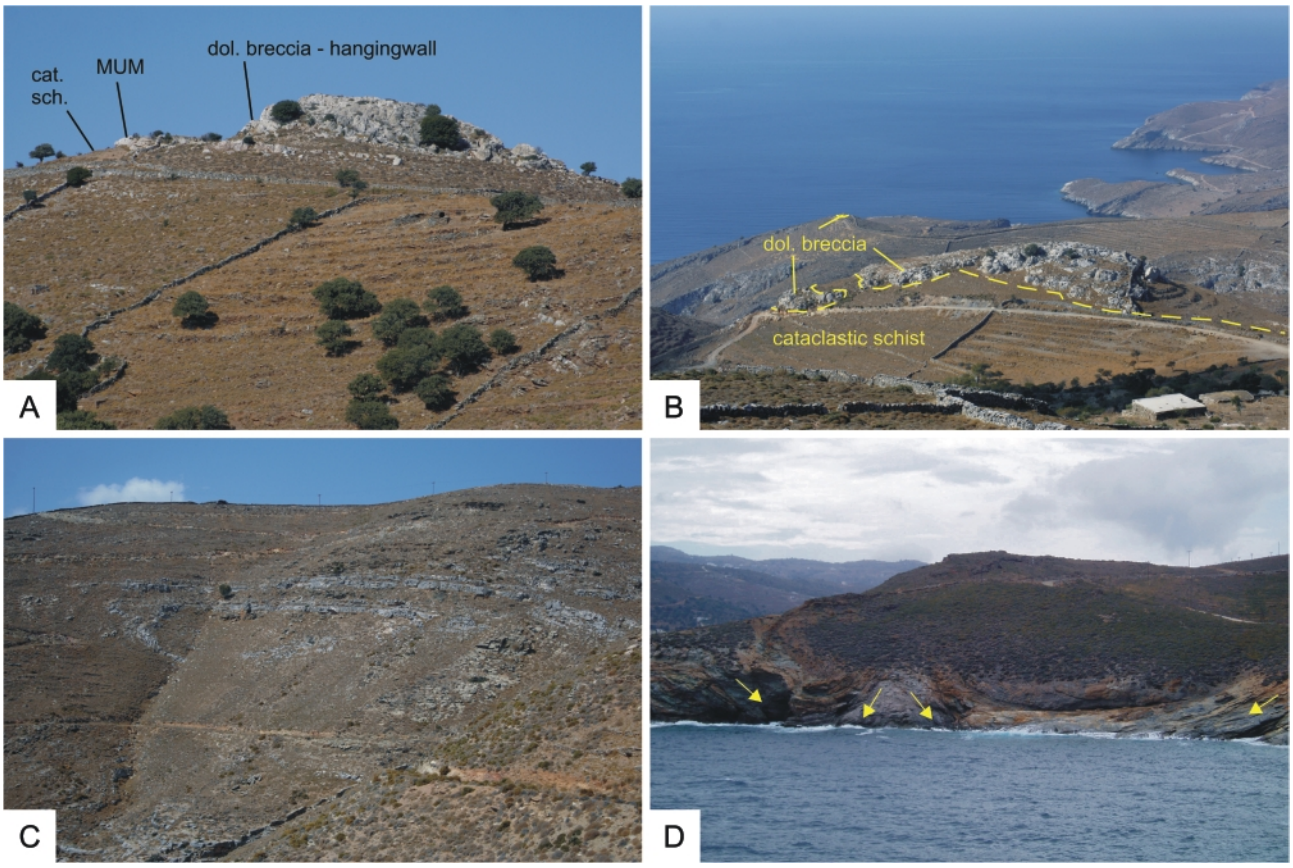


Figure 6: A. Klippe of detachment zone and overlying hanging wall at Kefala, taken from Aghios Simeon. Note the distinct step in the topography caused by the here thin layer of calcite marble ultramylonite. (N4162428 E263888). B. View to the south from the road immediately south of the summit of Aghios Simeon, looking at the imbricated cataclastic schists and dolostone breccias in the outcrops to the south. (N4162583 E265373). In the far distance, the very small outcrop of the detachment zone and hanging wall at (N4161039 E264870) is just visible. Note how steeply the detachment surface dips to the south by comparing the altitude of the exposures visible in the picture. C. Eastwards closing large-scale fold hinge visible in blue-grey marbles at Laouti, looking towards the southwest. (N4158708 E262429). D. Intermediate and small-scale folding of the detachment surface at Otzias Bay. Looking south-southwest. (N4174016 E266281).

dic literature. However, due to the varied use of this term (or porolithos), including porous lithologies such as travertine, clastic sandstones and volcanic rocks (Papageorgakis & Mposkos 1988), this term should be avoided (Draganits 2009). The outcrops all occur in the valley northeast of Chondri Rachi and southwest of Korissia, with the largest exposures at N4170365 E262188 and N4170496 E261986, with several minor exposures nearby, in the same valley. Similar rocks have not been found elsewhere on Kea, but have been recorded on almost all Cycladic islands and on Attica, from below sea-level up to 90 m.a.s.l. (Fytrolakis & Papanikolaou 1977, Draganits et al. 2010). A late Pleistocene $^{14}C/^{12}C$ age has been determined for the calc-arenites on Amtiparos (Bickle 2011).

Up to 6 m thickness of well-sorted and well-rounded, soft pale brown to orangy-buff coloured bioclastic sandstones occur at a single outcrop, overlying a reddish-brown palaeosol that rests on metamorphic rocks. The sandstone is dominated by bioclasts, including corallinaceae, forams and shell fragments, but also contains crystalline lithoclasts. Only a poor internal layering is developed, dipping essentially parallel to the surface slope it was deposited on. Up to 25 m of topographic height are encompassed by the deposits, but as the layering is topography-parallel, the actual thickness of the deposits was likely much less. This large altitude range, together with the occurrence of vadose cements, terrestrial snails and terrestrial trackways, indicate that the bioclastic sandstones are an aeolian deposit (Draganits et al. 2010, Bickel 2011).

Several deep-seated mass-movements of various types, commonly affecting the detachment zone rocks, occur in the north (mainly between Otzias Bay and Kastrianis Bay; Draganits et al. 2006), with one example at Vroulia in south Kea (Fig. 7C; N4156522 E260776). These are thought to be of Pleistocene-Holocene age and formed by the down-slope movement of coherent large blocks, likely initially using the underlying schist-derived foliated cataclasites as a mechanically weak slip surface. These are separated from the in-situ body by an uneven head area (Fig. 7C). With further movement, these blocks progressively broke-up into smaller fragments (Fig. 7D). Spanopoula (N4173992 E268368), the small island immediately north of Kea, is most likely a very large block of ultramylonite that has slipped down-slope into the sea.

At Chalara (N4173135 E268850), stretching lineations oriented NW-SE to E-W, markedly obliquely to the regional orientation, occur in the pelitic schists close to displaced blocks of marble ultramylonite. The oblique lineation directions indicate that these schists have been affected by the mass-movement, but whether they are significantly displaced is not known.

The mass-movement on the south side of the steeply incised

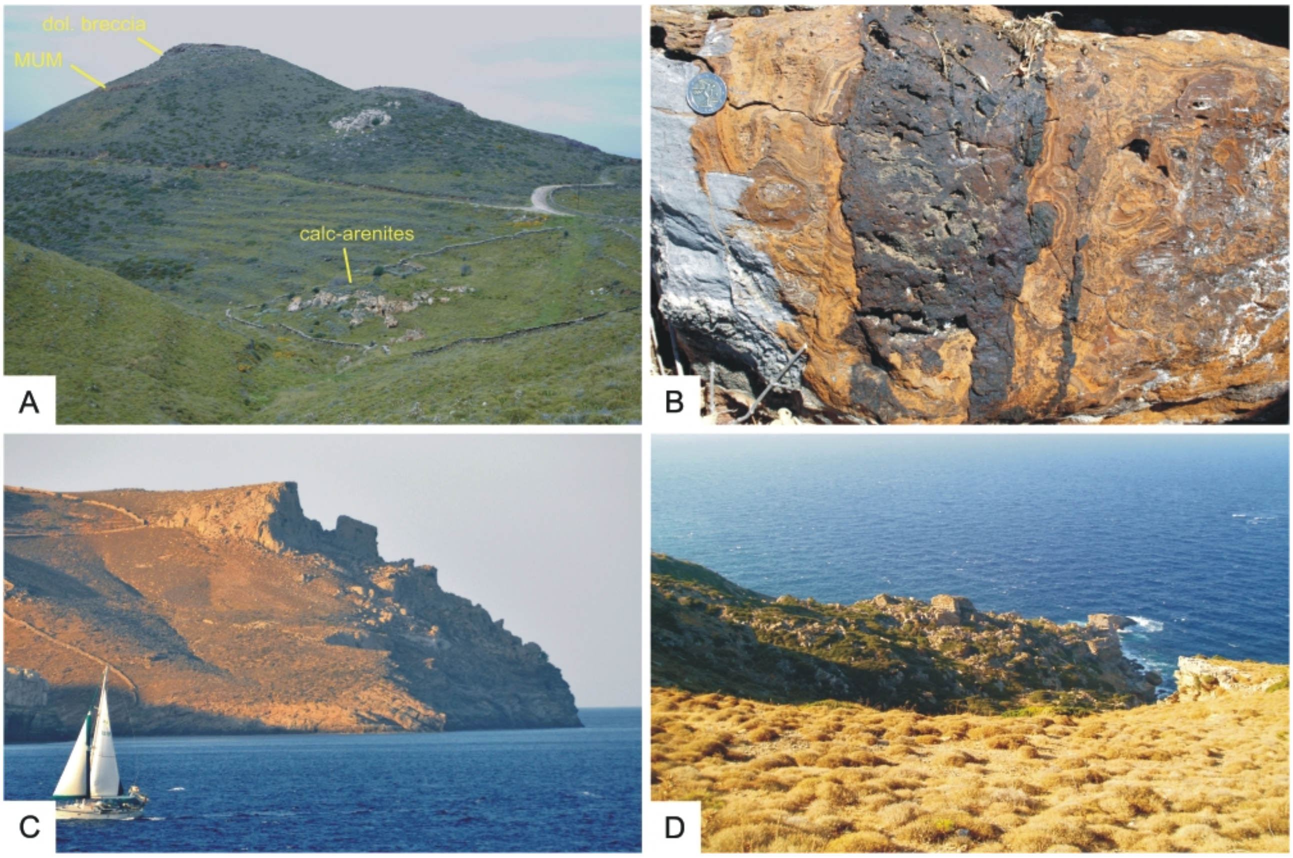


Figure 7: A. View of the largest outcrop of calcareous arenites. On the hillside behind, a thin layer of calcite marble ultramylonite dips steeply to the west. Looking north from N4170110 E262185. B. Massive alteration of blue-grey marble by iron-rich fluids. The darker brown core is similar to the material mined. (N4169889 E262926). C. Mass-movement of calcite marble ultramylonite at Petroussa, south Kea. Looking east-northeast at N415858 E260763. D. Overgrown mass-movement comprising smaller blocks of marble ultramylonite. The large block of calcite marble ultramylonite in the sea (Ghaidharos) is a part of this movement. Looking north from Chalara, N Kea (N4173410 E268337).

valley leading down to Spathi Bay (N4170135 E269292) is the only one recorded inland; this comprises both superficial deposits and large blocks of rock. According to an ear-witness who lives directly below the debris flow, this slope is known to undergo episodic movements; the last one occurred during the night of 24 to 25 March 1999, after a day of unexceptionable weather.

The Holocene valley-fill deposits, found in many of the broader river valleys, and beach deposits (Fig. 2), including deposits of beach-rock, have not been studied in detail. The valley-fill deposits form an essentially flat-lying or gently sloping surface, frequently used for market-gardening. In nearly all cases, these deposits lie below 10 m.a.s.l. and never rise above 20 m.a.s.l..

3.2 Structure

Except for dolostones in all units and the protocataclasites in the detachment zone, all the rocks carry a penetrative foliation; this is typically parallel to the compositional layering observed at outcrop scale; the commonest exceptions are at the margins of large pinch-and-swell boudins in the blue-grey mar-

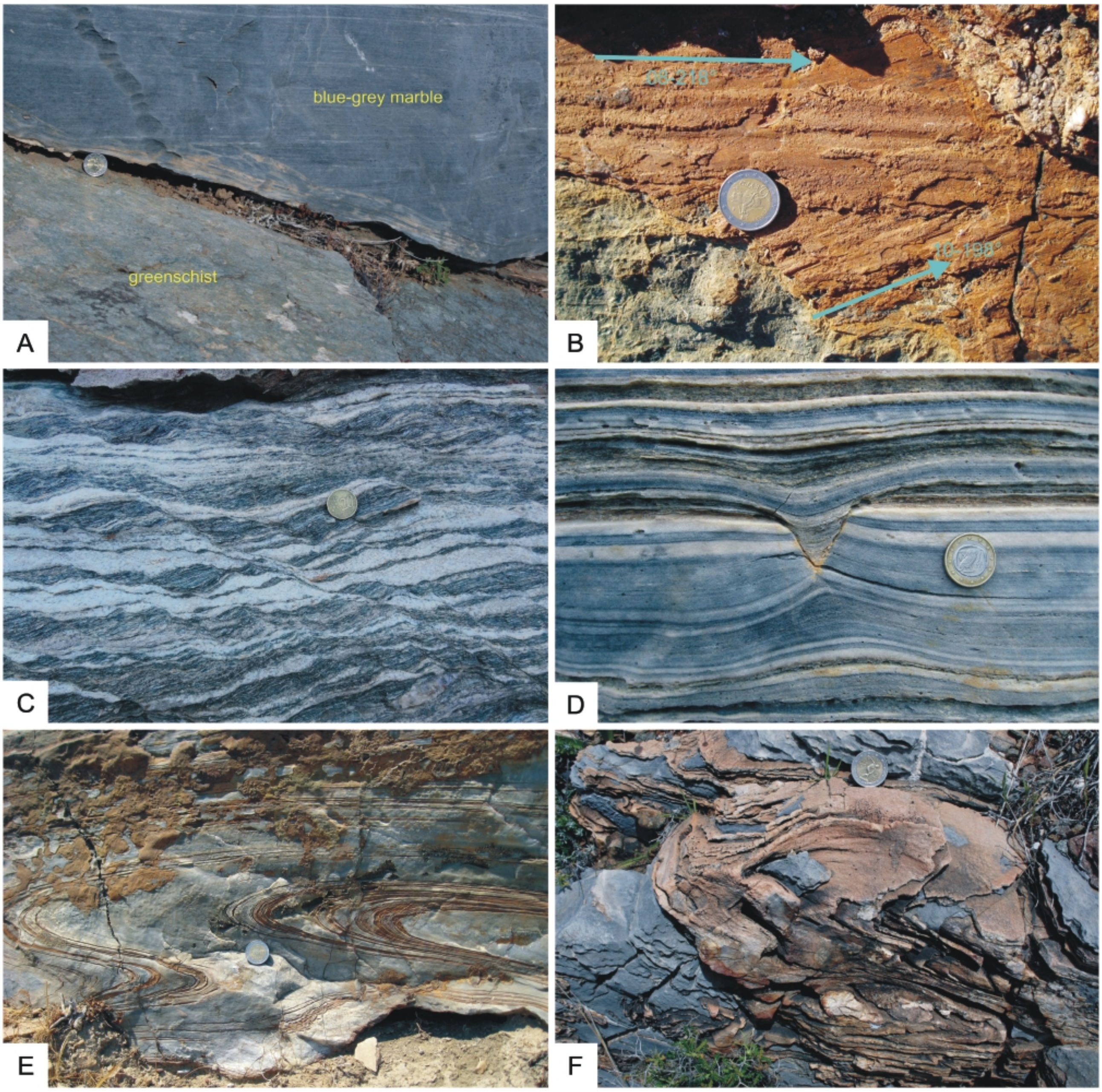


Figure 8: A. Margin of large boudin of calcite ultramylonite showing an internal fabric parallel to the regional compositional layering and a narrow, anastamosing margin-parallel mylonitic fabric. Uphill, west of the road south of Korissia, looking west. (N4170717 E262889). B. Brittle lineations on the contact surface between the underlying calcite marble ultramylonites and the overlying dolomitic cataclasites at Otzias Bay. (N4174103 E266226). C. S-C-C' structure in banded schists in the outcrops between the road and sea on the east side of Korissia harbour. These indicate a top-to-southwest displacement. Looking southeast. (N4171727 E263515). D. Boudinage in thin-banded mylonitic blue-grey and white marbles. Coast west of Cape Perlevos (N4174391 E266085) E. Isoclinal fold in interlayered marble and thin quartz-rich layers at Poles (N4160341 E264214). F. Refolded blue-grey marbles and quartz-rich layers in the hinge zone of large-scale recumbent isoclinal fold. NE of Gini (N4161426 E265997).

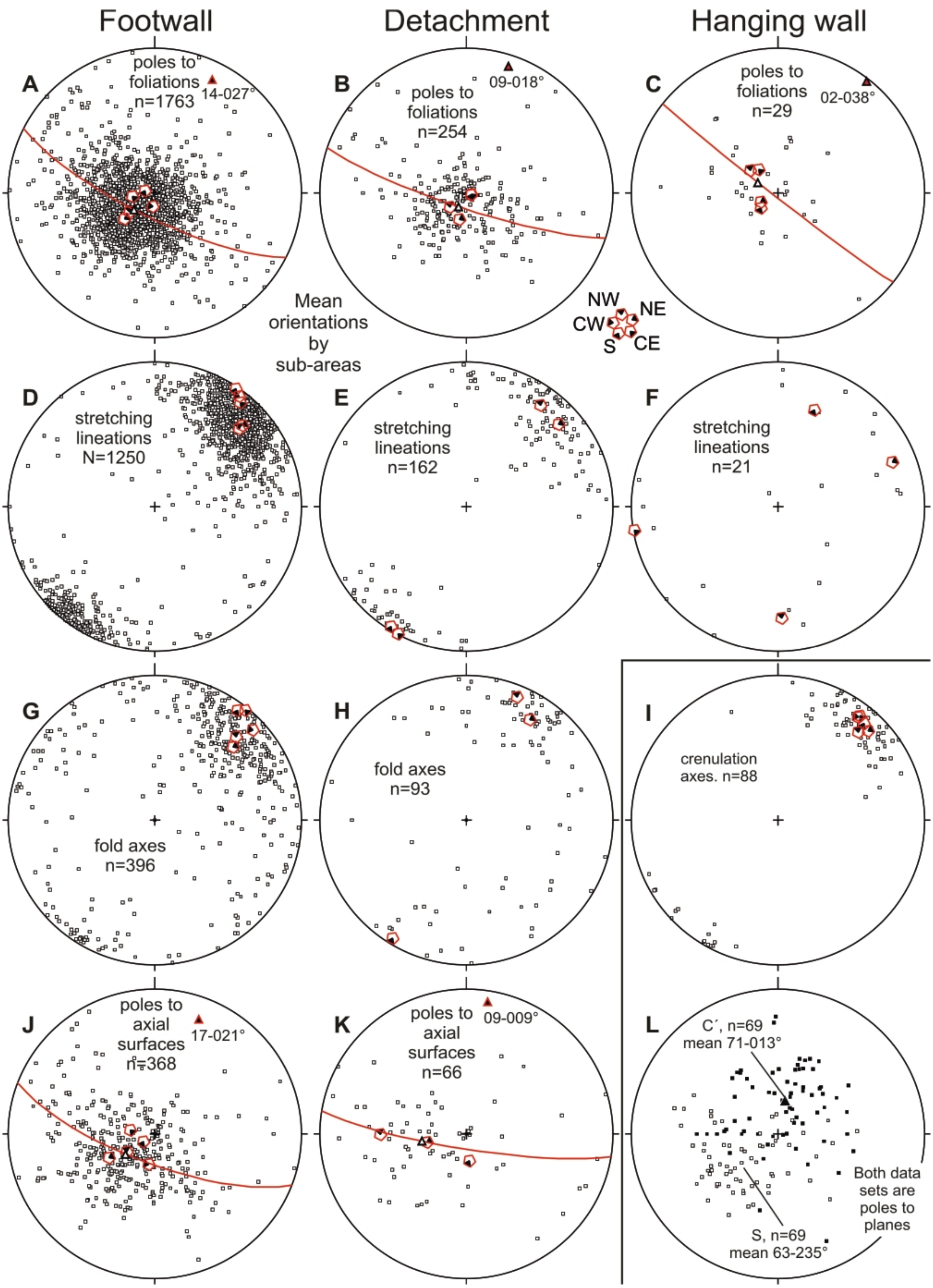


Figure 9: Equal-area lower hemisphere projections of structural data from Kea. Foliation, stretching lineation, fold axis and fold axial surface data are divided into that from the footwall, detachment zone and hanging wall. Crenulation axis and S-C' data are combined from the three tectonic levels, although most data comes from the footwall. Mean orientations for the five subareas are indicated. Planes are presented as poles and the best fit-great circle and ß-axis is given for the combined data set.

bles, where an internal penetrative mylonitic fabric is cut by a boudin-margin parallel fabric (Fig. 8A). The penetrative fabric is termed S2, since relicts of an earlier fabric, often containing blue-amphiboles, occur within porphyroblasts and are taken to be a high-pressure S1 fabric.

The five subareas defined (northwest, northeast, central east, south and central west; Fig. 2) are the same as those used by Iglseder et al. (2011).

S2 typically dips gently to the northeast quadrant (Fig. 9A, B, C), with the poles to foliation altogether defining an open antiformal structure. In the footwall, the ß-axis plunges at 14-027°. In more detail, the fold is very gently periclinal, with the mean pole orientations gradually steepening towards the south. However, only in the extreme south of the island, where large klippen of the detachment zone and hanging wall crop out, does S2 consistently dip gently southwards (Fig. 2). Poles to the foliation data from the detachment zone give a ß-axis with a more northerly azimuth and lower plunge (09-018°). The mean pole orientations from the northern part of the island plunge steeply south whilst those from the south and central east subareas are essentially identical and plunge to the east (Fig. 9B). The very limited foliation data from the hanging wall rocks give a regional fold axis plunging at 02-038°; the reliability of this is uncertain. (Fig. 9C).

Ductile stretching lineations in the footwall show a predominant ENE-WSW to NNE-SSW orientation, with a very large scatter, in part due to close to isoclinal, moderately inclined to recumbent folding of the foliation and lineation. The mean lineation orientation gradually swings from plunging towards ≈ 045° in the southern subarea to ≈ 035° in the northern subareas (Fig. 9D). Igleseder et al. (2011) noted that rocks with a relict blueschist facies assemblage had a more ENE-WSW lineation direction compared to other rocks and postulated that many of the other ENE-WSW oriented stretching lineations were also of D1 (Eocene blueschist facies) origin. A similar patterns is seen in the data from the detachment zone (Fig. 9E), with data from the northeast and northwest subareas having mean orientations with a greater E-W component than the south and central east subareas.

Close examination of the detachment surface in some areas reveals two sub-horizontal brittle lineation directions with ca. 25° difference in trend (Fig. 8B; Grasemann et al. 2012). Based on their identical field appearance (and hence likely deformation style) these are inferred to be essentially contemporaneous in age. They mark the movement direction(s) of the low-temperature period of displacement in the detachment zone (here detachment surface) and in this sense are comparable structures to the ductile stretching lineations, but younger.

Crenulations with upright axial surfaces are common in the schists, with mean axis parallel to the regional stretching lineation (Fig. 9I), although the data show a wide range. These indicate WNW-ESE shortening contemporary with and perpendicular to the top-to-SSW-directed extension.

Shear-criteria, especially S-C-C' fabrics, are common throughout the footwall schists (Figs. 3D, 4A, 8C). These show a consistent top-to-SW/SSW shear sense (Fig. 9L) as do quartz σ- and δ-clasts, which are more common in the marbles. Symmetrical extensional structures are less common (Fig. 3D, 8D).

Small-scale folds are relatively common, particularly in the blue-grey marbles, where they are easier to see than in the often badly weathered and overgrown schist outcrops. The fold geometry ranges from close to isoclinal, moderately inclined to recumbent (Figs. 3A, 3C, 8E). All the folds observed fold the foliation, even where refolds have been found; such structures are most common in blue-grey marbles with thin bands of pink-grey quartz (Fig. 8F) and are well developed at the N end of Pisses Bay (N4165101 E259613). An axial planar crenulation cleavage is generally only very poorly developed. Sheath folds, indicating high shear-strains, have been observed north of Plati Gialos, in the grey-blue marbles (N4156916 E259321) and in the ultramylonitic marbles of the detachment zone (e.g. N4157225 E259066).

Chevron/kink folds occur within the strongly anisotropic marble ultramylonites in the detachment zone, with fold axes always parallel to the stretching lineation. In some cases, these are associated with brittle thrust planes. These important structures indicate that late, low-temperature (<200°C) brittle shortening occurred perpendicular to the extension direction.

Mean fold axes in the footwall plunge to between 047° and 037° whilst those in the detachment zone plunge to between 035° and 020° (Fig. 9G, H). These directions are essentially the same as for the stretching lineations. Poles to fold axial surfaces give similar fold axis orientations as the poles to foliations (Fig. 9J, K).

Large-scale post-regional foliation gently inclined to recumbent, essentially isoclinal folds have been recorded in several areas, most having fold axes (sub-)parallel to the NNE-SSW trending regional stretching direction:

1) At Pisses, on the west coast, the cliff on the north side of the bay (N4165121 E259749) shows isoclinal folding of what may be only a single blue-grey marble layer, which rises in a series of recumbent and more-or-less symmetrical (M type) folds from sea level to ca. 160 m above sea level. No equivalent structure occurs on the south side of Pisses Bay (Fig. 2). The large-scale fold axis trends NW-SE (Keiter, pers. comm.) but some minor folds within the marbles and schists in the area nearby trend NE-SW, suggesting that the large-scale fold is a late-stage structure.
2) South of Laouti, a large-scale eastward closing fold hinge is exposed in the hillside at the west end of the bay (Fig. 6C; N4158739 E266439); this is clearly visible from the road. No linked west closing hinge is exposed.
3) SE of Aghios Simeon, directly at the coast (N4161567 E266109), the hinge of a westward-closing isoclinal fold within the blue-grey marble can be seen in three places in a relatively small area (Fig. 2). Two of these closures are linked to give the appearance of a refold structure, but no refolding occurred. The axial surface is essentially parallel to the topography. No associated eastward closing fold has been preserved and hence the overall fold asymmetry is unknown.

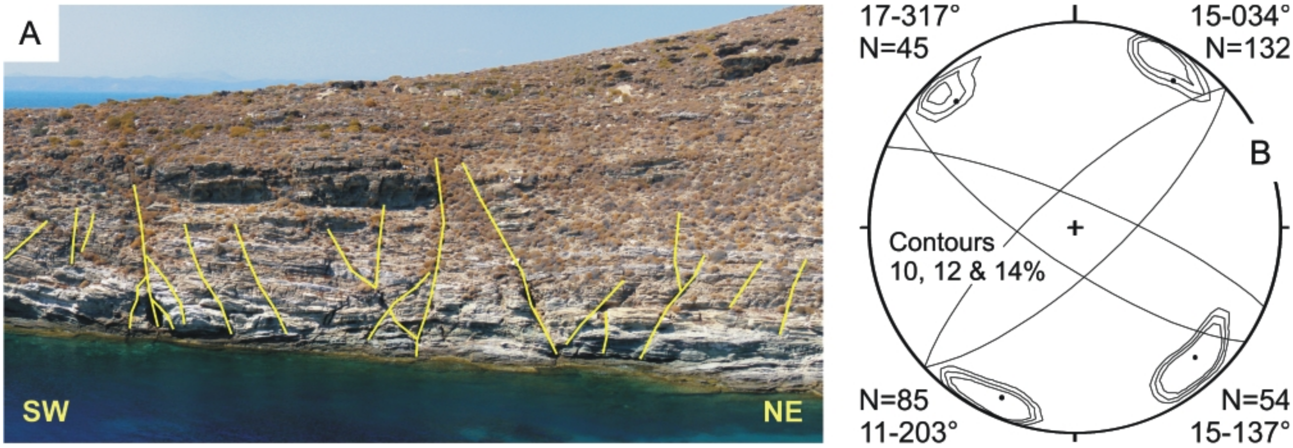


FIGURE 10: A. Symmetrical conjugate upright faults on the peninsula WNW of Pisses Bay (N4165361 E259086). B. Lower hemisphere equal area net showing contoured poles to the two sets of conjugate faults in the Pisses area, based on a detailed study by Rockenschaub (2011). The directions given refer to the dots and are the maximum eigenvalue orientations.

4) Cape Viokastro, in the southwest (N4158993 E263464), exposes an intermediate-scale complex westwards verging fold closure in three layers of marble within schists, with a steeply east-dipping enveloping surface on the lower limb (Fig. 2; this is simplified on the map). The upper limb of the middle marble layer consists of an isoclinal fold.

Boudinage as pinch-and-swell (often very large-scale) is common within the blue-grey marbles, although measuring the neck orientation is in most cases not possible. As noted above, the rims of larger boudins typically carry a margin parallel foliation cutting an earlier layer parallel foliation (Fig. 8A). Evidence for brittle deformation (higher strain-rates) is seen in the abundant rotated fractures within many thicker boudins (Fig. 3A).

Two conjugate late-stage brittle fault/fracture sets (ie four sets of faults/fractures) have been observed over the whole island (Fig. 10A). One set generally strikes NW-SE, roughly perpendicular to the stretching lineation, whereas in map view the second set forms either a rhombic or rectangular intersection pattern (combined in Fig. 10B, the results of a detailed study in the Pisses area by Rockenschaub 2011). Both sets have essentially horizontal intersections with a vertical angular bisector. This geometry suggests (but does not prove) an overall chocolate-tablet type of fracturing; as lineations were only very rarely observed on the fault surfaces, this cannot be confirmed. Where it can be quantified, faults show minor, subvertical offsets. The high-angle faults can some instances be seen to link with layer parallel low-angle normal faults, giving a very small sub-horizontal displacement.

The deformation mechanism in the low-angle faults was dominated by dissolution-precipitation creep, resulting in a strong SCC' fabric that indicates a top-to-SW to S shear sense (Rockenschaub 2011). The high-angle faults initially formed on discontinuities such as joints or veins and accommodated offsets in the order of several tens of centimetres by rotation of the faults into the shear direction. Deformation mechanisms within the high angle faults were dominated by cataclastic flow. The cataclasites contain both fragments of the host rock schists and crushed vein material (mostly calcite; Rockenschaub 2011).

Large-scale steep faults that clearly offset lithological boundaries were rarely observed, perhaps in part because over most of the island only marbles and undifferentiated schists were mapped. Although it is likely that many of the straight valleys and the straight coastlines of Kea reflect brittle faults (or fracture sets), the offsets are smaller than that which makes it absolutely necessary to infer their presence with any confidence. As the map essentially represents what was seen in the field and not what is suspected, inferred faults traces have not been drawn.

3.4 Metamorphism

In the schists, there is generally only evidence for the Miocene D2/M2 greenschist facies metamorphism, with the typical assemblage of chlorite +epidote +plagioclase +white mica +quartz ±amphibole (cf Igleseder et al. 2011). Garnet has not been recorded within these rocks, possibly because of the high Ca content, reflected by the abundance of epidote group minerals and calcic-amphiboles. In many cases, the rocks are characterised by a differentiation into quartz/feldspar-rich and -poor layers, the latter having more amphibole, epidote and chlorite.

Detailed work on the equilibrium of chlorite-white-mica pairs (cf Vidal and Parra, 2000; Parra et al. 2002) from four structural settings, passing from early to late growths stages (inclusions pairs in albite porphyroblasts, pairs within porphyroblast strain shadows, pairs in the main foliation and pairs in C and C' planes) showed a variation in P-T conditions from 7-5.5 kbar at 450-360°C to 3-2 kbar at 350-280°C (Igleseder et al. 2011). The main greenschist facies event, defined by phyllosilicates lying within the foliation gave conditions of between 5.5 kbar at 400°C and 3 kbar at 350°C. Overall, this suggests cooling during exhumation from HP/LT conditions. Within each sample analysed, younger growth generations gave lower P-T conditions than older generations. However, P-T estimates determined for the same generation of chlorite-white-mica pairs varied considerably between samples (Iglseder et al. 2011).

Relicts blueschist facies assemblages have been found in some footwall meta-pelitic samples, usually within M2 porphyroblasts (Iglseder et al. 2011). Only one small outcrop of blueschist has been found within the schists (see above). Blue amphiboles also occur within the gneisses and in the few outcrops of Fe-Mn-rich rocks described above, as do garnets, likely a result of the high Mn concentration. These are the only evidence remaining on Kea for the Eocene D1/M1 high-pressure metamorphism widespread throughout the Cyclades (cf Jolivet et al. 2010).

4. Discussion

4.1 Comparisons within the W. Cyclades

The greenschist facies footwall lithologies are very similar to those on Kythnos and parts of Serifos, to the southeast (De Smeth 1975, Grasemann & Petrakakis 2007, Fig. 1). These islands also have successions comprising greenschist facies metapelites containing relict blueschist facies assemblages and blue-grey calcitic marbles mylonites that have been assigned to the Cycladic Blueschist Unit (Schliestedt et al. 1994, Salemink & Schuiling 1987). Both Kythnos and Kea have serpentinites and Fe-Mn rich rocks (Lenauer 2009, Laner 2009, Chrysanthaki & Baltatzis 2003). The piemontite-schists recorded in the north of the island are likely more 'diluted' examples of this Fe-Mn sediment enrichment. The greenschist facies metapelites are similar in the field to rocks on Attica and other Cycladic islands where retrogressed Cycladic Blueschist Units have been recorded (e.g. Andros, Tinos, Ios; Fig. 1; Benjamin Huet and Kostis Soukis pers. comm.).

Similarly, the architecture of the detachment zone is comparable to that seen elsewhere in the Cyclades. Predominantly white ultramylonites of very variable thickness contain kink-type folds with fold axes parallel to the stretching lineation. These mylonites are overlain on a knife-sharp contact by dolostones that underwent brittle deformation, frequently forming foliated ultracataclasites with S-C-C’ fabrics at the base. This surface, which is the brittle detachment surface overprinting the earlier ductile detachment zone, may show lineations indicating two different but broadly contemporary slip directions, as also seen on Serifos (Fig. 8B; Grasemann et al. 2012). Kea differs from Kythnos and Serifos in that the highly strained phyllonitic schists under the ultramylonites also underwent extensive later brittle reworking, forming local protocataclasites and extensive foliated cataclasites with SC' fabrics.

The hanging wall lithologies are comparable to Late Cretaceous limestones in Attica that are partly brecciated and ankeritized (cf Photiades et al. 2007; Skarpelis et al. 2007, 2008, Iglseder et al. 2011). These are probably part of the Upper Unit of the ACC, but due to brittle deformation and hydrothermal activity the primary lithostratigraphy is no longer recognisable (cf Iglseder et al. 2011 for details).

Structural comparisons show a systematic variation in the distribution of D1 and D2 footwall strains within the western Cyclades (Grasemann et al. 2012). On Kea, the entire footwall (> 450 m structural thickness) has been overprinted by D2 deformation; NE-SW to NNE-SSW trending lineations predominate, with WNW-ESE trending D1 lineations likely restricted to relict blueschist facies rocks (Igleseder et al. 2011). On Kythnos, some 26 km to the SSE (Fig. 1), the central and northern parts of the island are dominated by D1 lineations, with D2 deformation concentrated towards the south of the island. Still further SSE, on Serifos, D2 deformation is restricted to the uppermost few metres of the footwall marbles and schists, with top-to-WSW D1 deformation prevalent over most of the island (Grasemann & Petrakakis 2007, Grasemann et al. 2012). Thus both a lithological and structural continuity exists within the western Cyclades, supporting the idea that the detachments above the greenschists with relict blue amphiboles are all part of a single major detachment (cf Grasemann et al. 2012).

On all three islands, crenulations with upright axial surfaces are parallel to the NNE-SSW trending stretching lineations. These reflect WNW-ESE oriented ductile shortening contemporary with top-to-SSW extension; this is typical for many areas of low-angled extension (Mancktelow & Pavlis 1994).

4.2 Detachment Geometry

Klippen of the detachment zone (and in some cases the overlying hanging wall) are asymmetrically distributed over the island and thus give only a poor constraint on the large-scale geometry of the detachment. In Fig. 11, topographic profiles have been drawn essentially normal to the large-scale NNE-SSW trending periclinal fold axis, through all the major out-

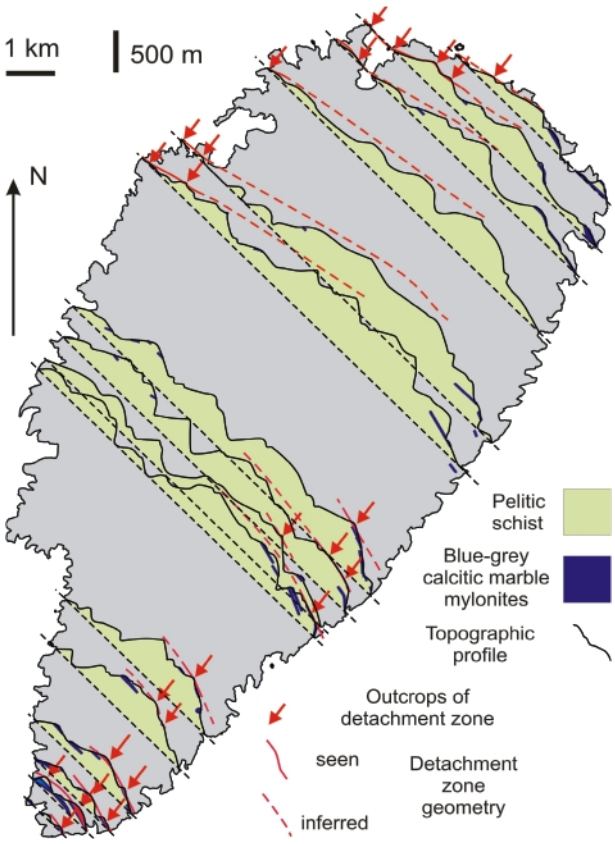


Figure 11: Sequential profiles across Kea orthogonal to the long axis of the island, showing the constraints on the geometry of the detachment zone, indicated by the red lines.

crops of the detachment zone. The lowest possible geometry of the detachment zone has then been inferred using the detachment zone outcrops and the topography of the footwall metasediments.

In the northern part of the island, all detachment outcrops lie in the north and northwest, in contrast to their abundance on the south and southeast sides of the island in the south. In all areas, outcrops further from the regional antiformal hinge along the centre of the island lie at gradually decreasing topographic levels. In the northwest and southeast, the lowest detachment geometry possible defines only one side of the regional antiform. As with the data from the regional foliation, the dip of the detachment surface is steeper on the southeast side. Only in the extreme south of the island does the detachment lie on both sides of the antiformal axis, although here the dominant dipdirection of the foliation in both the footwall and detachment zone is southwestwards.

In the north, the detachment in the Otzias Bay area has been folded on an intermediate scale (tens to hundreds of metres) with NNE-SSW axes and upright axial surfaces; this is clearly seen in outcrop (Fig. 6D). Such shortening is a larger-scale manifestation of the shortening recorded in the crenulations in the footwall schists, as is the overall NNE-SSW trending antiformal structure of the island. These folds formed during ductile deformation and were superimposed on by brittle deformation. There is no evidence yet available that the brittle phase of movement cut across earlier ductile upright folds.

In the eastern part of Kea, blue-grey marble is a common lithology, in thick, often anatomising layers with slices of schists between. In contrast, thinner marble layers, usually less than a couple of metres to only a few tens of centimetres thick and often in lensoid outcrops (pinch-and-swell) are present in the central and west areas, and these are not common (Fig. 2). Southeast of Pisses, no marbles have been recorded at all in a large area. Although further field work would undoubtedly lead to the discovery of more marble layers in these areas, it would not change the basic asymmetry in its distribution across the island. This difference in abundance in blue-grey marbles from west to east across Kea could be due to lateral changes in sedimentary facies or to the two areas reflecting different stratigraphic levels. Both the mean poles to foliation and the ß-axes data (Fig. 9) suggest that S2 in the footwall and detachment zone are not parallel. Mean poles from the footwall have a more easterly component than the corresponding pole from the detachment zone; this is greater for the northeast and central east subareas than for the northwest and south subareas. Overall, the regional fold axis in the footwall plunges at 14-027° and in the detachment zone at 09-018°. This would support, but not prove, an interpretation that the variation in distribution of blue-grey marbles across the island is because the detachment is an extensional lateral ramp.

5. Conclusions

Remapping of Kea, in the Western Cyclades, has revealed a three-level tectonstratigraphy; footwall of greenschist facies volcanoclastic schists and blue-grey calcitic marbles, with rare dolostones, relict blueschists, gneisses and Fe-Mn-rich schists; detachment zone of cataclastic schists, marble ultramylonites and dolostone breccias; hanging wall of proto-cataclastic dolostones and sometimes foliated calcitic marbles.

Kea exhibits higher strains than the other islands of the Western Cyclades (Kythnos, Serifos), in both the footwall and in the detachment zone. The former tectonostratigraphic level is penetratively deformed by top-to-SW to S extension throughout its ~450 m thickness, with only rarely preserved evidence of D1/M1. The latter level shows pervasive evidence of brittle deformation (ultracataclasites) in the uppermost part of the schists underlying the marble ultramylonites that typically form the basal part of the detachment zone; such deformation is not present on Kythnos or Serifos.

During the later part of extension, two sets of high-angled conjugate faults developed, suggesting a chocolate-tablet type of fracturing and extension. In sections parallel to the stretching lineation these faults are seen in some cases to link with late sub-horizontal top-to-SW to S shear zones in the footwall schists.

Acknowledgements

This work was financially supported by the Austrian Science Fund (FWF) grant number P18823-N19 to Bernhard Grasemann. The Institute of Geology and Mineral Exploration, Athens, is thanked for providing field-work permissions and the vehicles used during the work by AHNR, DP and KN. We thank Mike Edwards and Benjamin Huet for discussions. AHNR, KN & DM thank Vasili, Heraklia, Paniotis and Yannis Thodorus for warm hospitality at the Ραβαϊσι restaurant in Korissia during fieldwork. We thank Dana Homolova, Steffi Neuhuber and Norbert Irnberger for help with the hillshading in ArcGIS and importing into CorelDraw. We thank Mark Keiter and Kostis Soukis for very constructive reviews of the paper.

References

Bickel, L. 2011. The Quaternary sediments of NW Antiparos (Aegean): lithostratigraphy and depositional environment. MSc Thesis, University of Vienna. 98p.

Bonneau, M., 1984. Correlation of the Hellenic nappes in the south-east Aegean and their tectonic reconstruction. In: J.E. Dixon and A.H.F. Robertson (Editors), The Geological Evolution of the Eastern Mediterranean. Blackwell Scientific Publications, Oxford, Special Publication Geological Society of London, pp. 517-527.

Brichau, S., Thomson, S. and Ring, U., 2010. Thermochronometric constraints on the tectonic evolution of the Serifos detachment, Aegean Sea, Greece. International. Journal of Earth Sciences, 99, 379-393.

Bröcker, M. and Franz, L., 2006. Dating metamorphism and tectonic juxtaposition on Andros Island (Cyclades, Greece): results of a Rb-Sr study. Geological Magazine, 153, 609-620.

Brun, J.-P. and Faccenna, C., 2008. Exhumation of high-pressure rocks driven by slab rollback. Earth and Planetary Science Letters, 272, 1-7.

Chrysanthaki, A. and Baltatzis, E. M. M., 2003. Geochemistry and depositional environment of ferromanganoan metasediments on the Island of Kythnos, Cyclades, Greece. Neues Jahrbuch für Mineralogie - Monatshefte, 1, 1-17.

Davis, E. N. 1972. Geological structure of Kea Island, Bull. Geol. Soc. Greece, 9(2), 252-265.

Davis, E. N. 1982. Geological map of Greece, Kea Island. Institute of Geology and Mineral Exploration, Athens.

De Smeth, J. B. 1975. Geological Map of Greece 1:50 000, Kythnos Island. Institute for Geological and Mineral Exploration, Athens.

Draganits, E., Voit, K., Müller, M., Grasemann, B., Exner, U., Zámolyi, A., Preh, A., Iglseder, C., Petrakakis, K. and Edwards, M. 2006. Spectacular diversity of different types of mass-movements from northern Kea (Cyclades, Greece). European Geosciences Union General Assembly 2006, Vienna, 02-07 April, Geophysical Research Abstracts, 8, 09996.

Draganits, E. 2009. Archaic sanctuary on Despotiko Island (Cyclades): Geological situation, lithological characterization of the building stones and their possible provenance. Austrian Journal of Earth Sciences, 102, 91-102.

Draganits, E., Zuschin, M., Gier, S. and Bickel, L. 2010. Pleistocene sand ramp deposits in the Aegean (Cyclades, Greece). European Geosciences Union General Assembly 2010, Vienna, 02 -07 May, Geophysical Research Abstracts, 12, 12729.

Fytrolakis, N. and Papanikolaou, D. 1977. Some new occurrences of Quaternary sandstones in the Cyclades and their paleogeographic importance. 6th Colloquium on the Geology of the Aegean region, Vol. 1, Athens, 1977, 1, 459-467.

Gautier, P. and Brun, J.-P. 1994. Crustal-scale geometry and kinematics of late-orogenic extension in the central Aegean (Cyclades and Evvia Island). Tectonophysics, 7, 57-85.

Gautier, P., Brun, J.-P. and Jolivet, L. 1993. Structure and kinematics of upper Cenozoic extensional detachment on Naxos and Paros (Cyclades islands, Greece). Tectonics, 12, 1180-1194.

Grasemann, B. and Petrakakis, K. 2007. Evolution of the Serifos Metamorphic Core Complex. Journal of the Virtual Explorer, 28/2, 33-52.

Grasemann, B., Schneider, D., Stöckli, D. and Iglseder, C. 2012. Miocene bivergent crustal extension: evidence from the western Cyclades (Greece). Lithosphere, doi 10:1130/L164.1.

Huet, B., Labrousse, L. and Jolivet, L. 2009. Thrust or detachment? Exhumation processes in the Aegean: Insight from a field study on Ios (Cyclades, Greece). Tectonics 28, TC3007.

Iglseder, C., Grasemann, B., Schneider, D. A., Petrakakis, K., Miller, C. Klötzli, U. S., Thöni, M., Zámolyi, A. and Rambousek, C. 2009. I and S-type plutonism on Serifos (W-Cyclades, Greece). Tectonophysics, 473, 69-83.

Iglseder, C., Grasemann, B., Rice, A. H. N., Petrakakis, K. and Schneider, D. A., 2011. Miocene south directed low-angle normal fault evolution on Kea Island (West Cycladic Detachment System, Greece). Tectonics, 30(4), TC4013. doi: 10.1029/2010tc002802

Jolivet, L., Faccenna, C., Goffe, B., Burov, E. and Agard, P., 2003. Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens. American Journal of Science, 303, 353-409.

Jolivet, L., Lecomte, E., Huet, B., Denèle, Y., Lacombe, O., Labrousse, L., Le Pourhiet, L. and Mehl, C., 2010. The North Cycladic Detachment System. Earth and Planetary Science Letters, 289, 87-104.

Laner, G., 2009. Fluid-rock interaction in a low-angle normal fault, Kythnos, western Cyclades, Greece. Master's Thesis, University of Vienna. 88 p.

Lee, J. and Lister, G.S., 1992. Late Miocene ductile extension and detachment faulting, Mykonos, Greece. Geology 20, 121-124.

Lenauer, I., 2009. Structural and petrological investigations along a low angle normal fault on Kythnos, Greece. Master's Thesis, University of Vienna. 88 p.

Lister, G. S., Banga, G. and Feenstra, A., 1984. Metamorphic core complexes of Cordilleran type in the Cyclades, Aegean Sea, Greece. Geology, 12:221-225.

Mancktelow, N. S. and Pavlis, T. L., 1994. Fold-fault relationships in low-angle detachment systems. Tectonics 13, 668-685.

Morris, A. and Anderson, A., 1996. First palaeomagnetic results from the Cycladic Massif, Greece, and their implications for Miocene extension directions and tectonic models in the Aegean. Earth & Planetary Science Letters 142, 397-408.

Müller, M., 2009. Structural Investigations/Observations along a Low-angle Normal Fault and their Implication for the Geology on Northwest Kea – Examining a Major Shear Zone (Western Cyclades, Greece). MSc Thesis, University of Vienna, Vienna, 110 pp.

Papageorgakis, J. and Mposkos, E., 1988. Building stones of the Minoan Palace of Knossos. In: P.G. Marinos and G.C. Koukis (eds.), The Engineering Geology of Ancient Works, Monuments and Historical Sites: Preservation and Protection. Vol. 2, Proceedings of an International Symposium organized by the Greek National Group of IAEG, 19-23 September 1988, Athens, Rotterdam, Balkema, pp. 649-659.

Parra, T., Vidal, O. and Agard, P., 2002. A thermodynamic model for Fe-Mg dioctahedral K white micas using data from phase-equilibrium experiments and natural pelitic assemblages. Contributions to Mineralogy and Petrology, 143, 706-732.

Photiades, A., Carras, N. and Kanaki-Mavridou, F., 2007. Geological map of Greece in scale 1:50000; Lavrion-sheet, Institute of Geology and Mineral Exploration, Athens.

Photos-Jones, E., Cottier, A., Hall, J. and Mendoni, L. G. 1997. Kean Miltos: The well known iron oxides of antiquity. Annual of the British School in Athens 92, 359-371.

Ring, U., Glodny, J., Will, T. M. and Thomson, S., 2011. Normal faulting on Sifnos and the South Cycladic Detachment System, Aegean Sea, Greece. Journal of the Geological Society, London, 168, 751-768.

Rockenschaub, M., 2011. An extensional brittle-ductile high- and low-angle fault system on the island of Kea (W. Cyclades, Greece). MSc Thesis, University of Vienna, Vienna.

Salemink, J. and Schuiling, R. D., 1987. A two-stage, transient heat and mass transfer model for the granodiorite intrusion at Seriphos, Greece, and the associated formation of contact metasomatic skarn and Fe-ore deposits. In: Helgeson, H. C. (ed.), Chemical transport in metasomatic processes, Volume 218, NATO ASI Series. Series C: Mathematical and Physical Sciences, 547-575.

Schliestedt, M., Bartsch, V., Carl, M., Matthews, A. and Henjes-Kunst, F., 1994. The P-T Path of greenschist-facies rocks from the Island of Kithnos (Cyclades, Greece). Chemie der Erde 54, 281-296.

Skarpelis, N., 2007. The Lavrion deposit (SE Attica, Greece): geology, mineralogy and minor elements chemistry, Neues Jahrbuch für Mineralogie Abhandlung, 183, 227-249.

Skarpelis, N., Tsikouras, B. and Pe-Piper, G. 2008. The Miocene igneous rocks in the basal unit of Lavrion (SE Attica, Greece): petrology and geodynamic implications. Geological Magazine 145, 1-15.

Tirel, C., Gautier, P., van Hinsbergen, D.J.J. and Wortel, M.J. R., 2009. Sequential development of interfering metamorphic core complexes; numerical experiments and comparison with the Cyclades, Greece. Geological Society, London, Special Publication 311, 257-292.

Trotet, F., Jolivet, L. and Vidal, O. 2001. Tectono-metamorphic evolution of Syros and Sifnos islands (Cyclades, Greece). Tectonophysics, 338, 179-206.

Tschegg, C. and Grasemann, B., 2009. Deformation and alteration of a granodiorite during low-angle normal faulting (Serifos, Greece). Lithosphere, 1, 139-154.

van Hinsbergen, D. J. J., Langereis, C. G. and Meulenkamp, J. E. 2005. Revision of the timing, magnitude and distribution of Neogene rotations in the western Aegean region. Tectonophysics, 396, 1-34.

Vidal, O. and Parra, T., 2000. Exhumation paths of high-pressure metapelites obtained from local equilibria for chlorite-phengite assemblages, Journal of Geology, 35, 139-161.

Voit, K., 2008. Structural Geology and Geomorphology of Northern Kea - A crustal scale Viscous-frictional Shear Zone (Western Cyclades, Greece). MSc Thesis, University of Vienna, Vienna, 191 pp.

Walcott, C. R. and White, S. H., 1998. Constraints on the kinematics of post-orogenic extension imposed by stretching lineations in the Aegean region. Tectonophysics, 298, 155-175.

Received: 13 June 2012
Accepted: 15 November 2012

A. Hugh N. RICE[1)*)], Christoph IGLSEDER[2)], Bernhard GRASEMANN[1)], András ZÁMOLYI[1)], Konstantinos G. NIKOLAKOPOULOS[3)], Dimitrios MITROPOULOS[3)], Klaus VOIT[1)], Monika MÜLLER[1)], Erich DRAGANITS[1)4)], Monika ROCKENSCHAUB[1)] & Panagiotis I. TSOMBOS[3)]

[1)] Department of Geodynamics & Sedimentology, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria;

[2)] Geological Survey of Austria, Neulinggasse 38, 1030 Vienna, Austria;

[3)] Institute of Geology and Mineral Exploration, Department of General Geology and Geological Mapping, Olympic Village, Acharnai, 13677 Athens, Greece;

[4)] Department of Prehistoric and Medieval Archaeology, University of Vienna, Franz-Klein-Gasse 1, 1190 Vienna, Austria;

[*)] Corresponding author, alexander.hugh.rice@univie.ac.at