Extension and Exhumation of the Hellenic Forearc Ridge in Kythera

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ABSTRACT

Detailed mapping and new structural observations on Kythera demonstrate that there is a major detachment fault, here termed the Potamos detachment fault (PDF), exposed on the northern part of the island and bordering the domed structure of a metamorphic core complex. The detachment forms the contact of contrasting metamorphic and nonmetamorphic units, and both ductile and brittle structures are found, related to its extensional development. The earliest Potamos mylonites, as well as some other early ductile structures near the mapped detachment fault, indicate initiation of the PDF under NE-trending extension, in mid- to late Miocene time. Later ductile, ductile-brittle, and some brittle structures in the metamorphic unit near the detachment indicate (in contrast) a significant NW-SE extension along the forearc ridge. The younger brittle structures indicate return to NE-SW extension. Late Miocene–Pliocene strata cover the detachment unconformably and are affected only by the late faults. Trench rollback and slab retreat of the subducting African lithosphere in the late Miocene requires expansion and increased curvature of the Hellenic (Crete-Peloponnese) forearc ridge. Differential movement between and vertical axis rotation of segments of the forearc ridge may have localized along-arc stretching. Cross-ridge strike-slip faults may be linked to the later parts of this process. Evidence of young E-W dextral faulting is seen in northern Kythera outcrops, related to a significant submarine fault of this type located between Kythera and the Peloponnese.

Online enhancements: PDFs.

Introduction and Geological Setting

Kythera Island is located in the southwestern part of the South Aegean Hellenic Arc on the prominent horst of the forearc ridge that connects the Peloponnese and Crete. The rocks of the pre-Neogene nappes of the External Hellenides that occur on Kythera Island resulted from northward subduction and late Eocene collision between Apulia and the Pelagonian microcontinent (Mountrakis 1986; Robertson et al. 1991; Doutsos et al. 1993). There are three lithotectonic units exposed in the northern part of Kythera. The structurally lower metamorphic unit consists of mainly phyllites and quartzites, some mylonitic, with uncommon intercalations of marbles, and blueschists, as well as rare, small occurrences of metagranite and gneiss. The Pindos and Tripolis limestone units form the overlying unmetamorphosed lithotectonic units. The protolith of the metamorphic Phyllite-Quartzite unit (PQU) has been suggested to have formed as a mid-Carboniferous to Triassic rift sequence (Krahl et al. 1983) resulting from the opening of a southern branch of the Neotethyan ocean (Pe-Piper 1982; Seidel et al. 1982; Robertson and Dixon 1984). The basement of the sequence is not exposed.

Field mapping of the north part of Kythera in 2005 (Marsellos 2006; Marsellos and Kidd 2006) demonstrated the existence of the Potamos detachment fault (PDF; fig. 1), a major extensional detachment between the PQU metamorphics and the overlying sedimentary lithotectonic units. (A larger and colored version of the geological map used to make fig. 1 contains structural measurement data symbols and is available as a PDF in the online edition or from the *Journal of Geology* office.) The sense of movement on the PDF and other shear zones in the PQU was determined by shear sense kinematic indicators in outcrops and in samples as described by Simpson and Schmid (1983), Hanmer (1986), Goldstein (1988), Mawer (1989), Smith (1995, 1996), and Passchier and Trouw (2005). Young faults were identified from the study of the inland and submarine topography by using field observations, a digital elevation model, and a bathymetric slope map. The purpose of this

Manuscript received February 27, 2008; accepted May 23, 2008.

[The Journal of Geology, 2008, volume 116, p. 640–651] © 2008 by The University of Chicago.

0022-1376/2008/11606-0007$15.00 DOI: 10.1086/591995

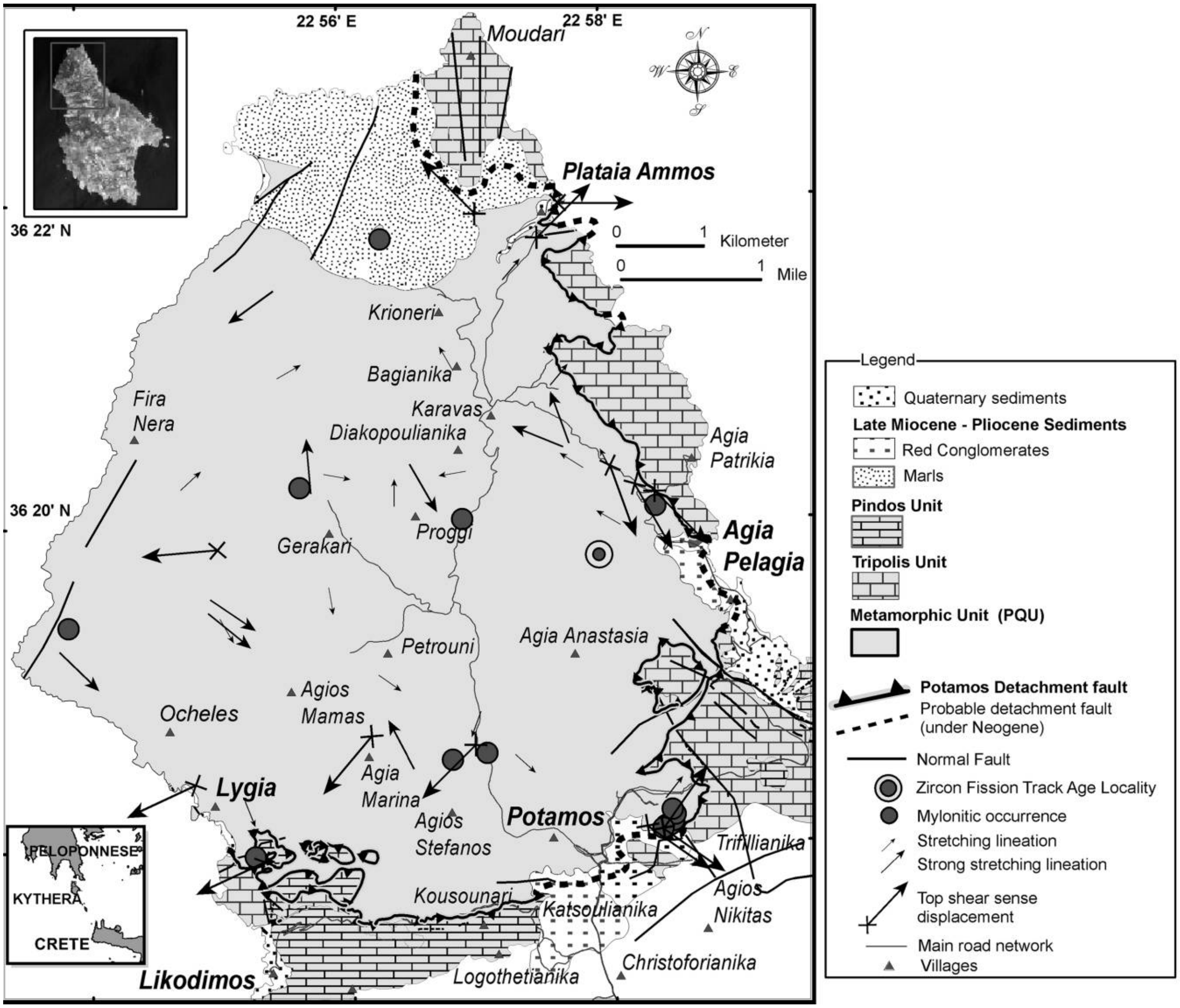

Figure 1. *Left*, geological map of north Kythera, including the Potamos detachment fault (PDF; Marsellos 2006). *Right*, legend for the geological map of north Kythera (Marsellos 2006).

article is to report evidence for the existence of this detachment and the major change in extension direction during its development and to place this in the context of the tectonics of the Hellenic subduction system.

Geodynamic Context of Kythera: Extension in the Peloponnese-Cretan Ridge

Extension of what is now the Aegean and southern Greece started in the early Miocene, accommodated by a series of well-documented large-scale, low-angle normal faults (detachments; Lister et al. 1984; Buick 1991; Jolivet et al. 1996; Forster and Lister 1999; Ring et al. 2001). These detachments caused tectonic denudation and subsidence ("collapse") of the internal zones, while subduction of the eastern Mediterranean remnant of the Neotethys continued from the south (Pe-Piper et al. 2002).

Kythera Island is located on a 100-km-long NNW-SSE ridge (fig. 2) within the southwestern part of the Hellenic forearc, between the Peloponnese and Crete. The forearc ridge here separates the 3000–5000-m-deep Hellenic trench to the southwest from the 1000–2000-m-deep Cretan Sea basin to the east. The Late Miocene–Recent extensional opening of the Cretan Sea has affected the Peloponnese-Cretan Ridge, which is bounded by major normal faults and scarps on both sides. Lyberis et al. (1982) concluded that the submersion of the Kythera-Antikythera strait is a consequence of extension related to normal faulting, with the

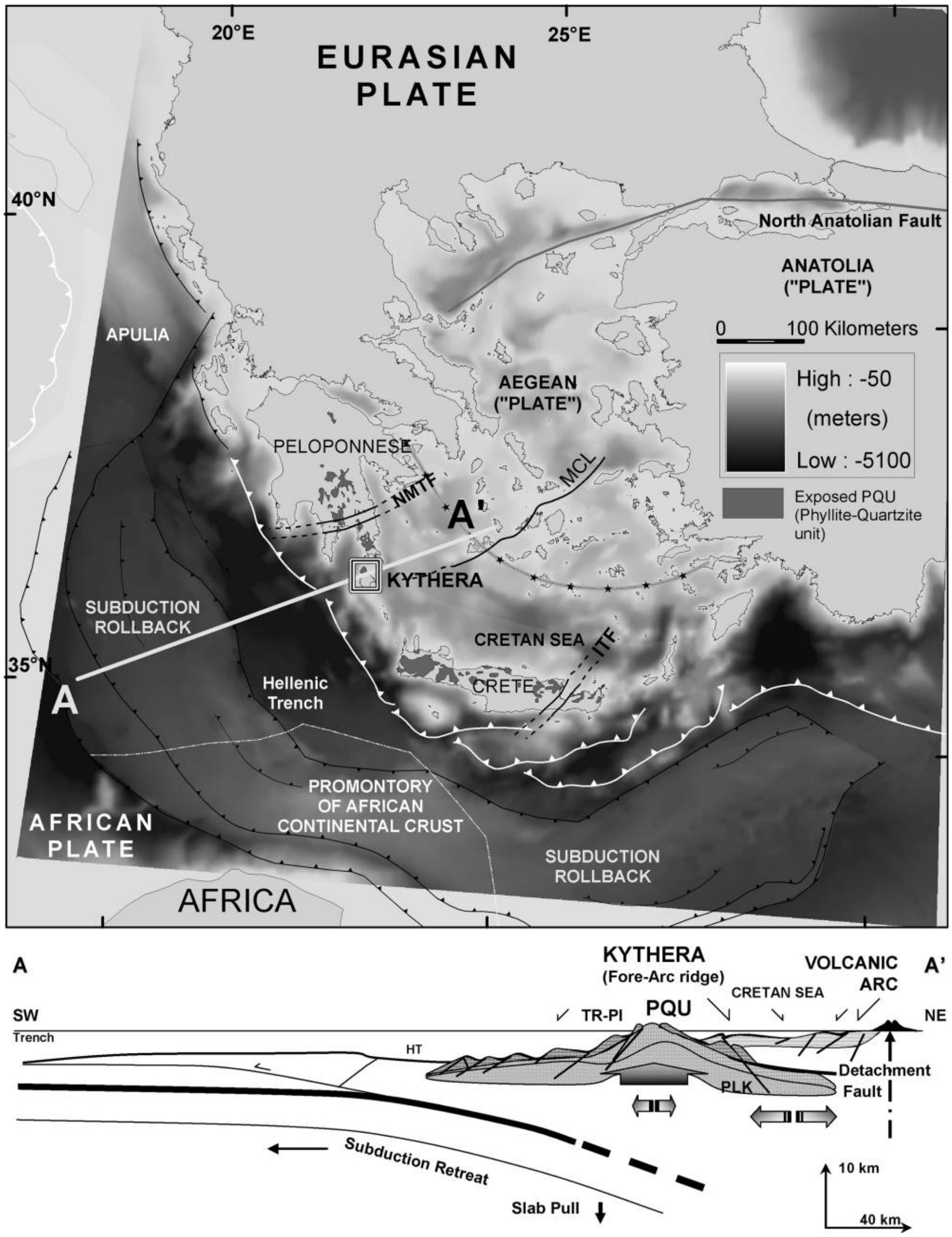

Figure 2. Tectonic setting of the South Aegean Arc. Bathymetry shown by a semitransparent digital elevation model layer; a cross-section line A-A′ along a NE-SW line through the Kythera strait. (A color version of this figure is available in the online edition or from the *Journal of Geology* office.)

extension rate being faster than that in adjacent segments of the forearc. The observations that NW-striking normal faults in Kythera are synsedimentary and that Late Miocene strata were tilted before Pliocene deposition suggest that the brittle extensional deformation was active in the Late Miocene (Christodoulou 1965; Freyberg 1967; Theodoropoulos 1973). Drooger and Meulenkamp (1973) suggested that the disruption of the southern Aegean land mass into a mosaic of uplifted and subsided fault blocks began during the Late Serravallian, at the close of the Middle Miocene, and that the fault pattern of NW-striking faults in the western Hellenic forearc ridge also began at about the same time, at approximately 13 Ma.

Three Stages of Cenozoic Extension in Kythera

Our structural observations from the PQU metamorphics of northern Kythera show that three stages of extension can be distinguished on the basis of substantial changes in extension direction (fig. 3). The earliest stage shows NE-SW displacement from entirely ductile shear sense kinematic indicators in the exposed mylonites as well as elsewhere in the PQU, and we associate these with the initiation of the PDF under NE-trending extension, perpendicular to the arc.

Late ductile and ductile-brittle transition structures in the north part of Kythera have a consistent orientation of extension that is NW-SE trending. This represents extension parallel with the arc, has a top-to-the-SE shear sense in most locations, and is at a high angle to the earlier extension direction.

Younger, exclusively brittle structures occur both above and below the detachment and include large faults defined by scarps in the inland and submarine topography. They show a return to NE-SW-trending extension perpendicular to the arc. Faults of this third extensional stage cut and overprint all of the earlier ductile and ductile-brittle structures, including the PDF.

Ductile Structures. Mylonites of planar-laminated, very fine-grained aspect form part of the overall PDF mylonites east of the village of Potamos. Delta-type porphyroclasts in these mylonites have very narrow wings and characteristic embayments in the wings adjacent to the porphyroclast. The internal asymmetry indicates a shear sense of top-to-the-NE displacement along the associated stretching lineation. West of the Potamos area, asymmetric quartz boudins ("fish"), as well as sigma-type porphyroclasts of feldspar, show kinematics of top-to-the-SW shear sense along a NE-SW-trending lineation.

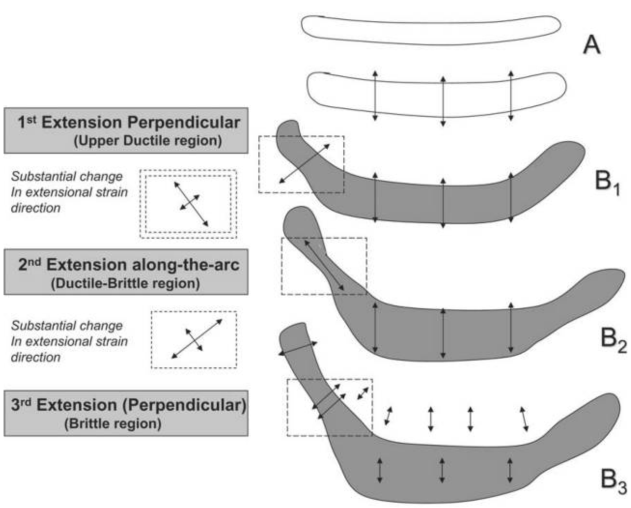

Figure 3. Extensional episodes of the southwest part of the Hellenic forearc ridge (Marsellos and Kidd 2006). Boxed areas represent the region including Kythera.

Ductile-Brittle Structures. In outcrops of the exposed metamorphic unit close to both east and west coasts of Kythera, a prominent NW-SE-trending stretching lineation is commonly observed. Tight folds expressed in quartzites of the PQU have hinges oriented parallel with this lineation (well exposed at the locality of fig. 4, near Agia Pelagia, where uncommon ductile shear sense indicators show a top-to-the-SE sense of shear).

C surfaces parallel to the shear zone margin and S surfaces oblique to the C surfaces can be seen in quartzites northwest of Potamos (fig. 5). The S-C surfaces form angles between 20° and 45°, with the density of C surfaces increasing as the S-C angle decreases. These also define a NW-SE-oriented extension with top-to-the-SE displacement.

In the same outcrops east of Potamos that host the early PDF mylonites, extensional structures formed during brittle-ductile transition are seen cutting the one well-developed foliation. They include asymmetric shear band structures (fig. 6); these have a NW-SE arc-parallel extension direction. A number of outcrops showing these structures, some of substantial scale, demonstrate consistent top-to-the-SE displacement and NW-SE-oriented extension.

Asymmetric extensional shear boudins (fig. 7) developed from pinch-and-swell structure (occurring less than 150 m from the PDF) show a rotation interpreted to be antithetic (back-rotation) with respect to the shear sense (Hanmer 1986), which also gives top-to-the-SE displacement, with NW-SE-trending extension. These boudins also contain and their margins are cut by small normal faults, localized in and near the boudins, which accommodated brittle additional stretching along the layering. The overall transitional ductile-brittle behavior represented here is consistent with the structures associated with the SE-NW stretching direction seen in the other localities.

No structures have been observed that could have significantly modified the orientation and shear sense of all of these locally developed ductile-brittle transitional fabrics. In particular, the tilting associated both with the gentle doming of the northern Kythera PQU and with the mildly tilted late Miocene sediments is quite insufficient to provide large changes in orientation; any evidence for widespread later regional folding has not been seen on Kythera. Accordingly, the NW-SE stretching lineation is thought to represent the later ductile principal relative transport vector. It is inferred to be relatively younger than the NE-trending

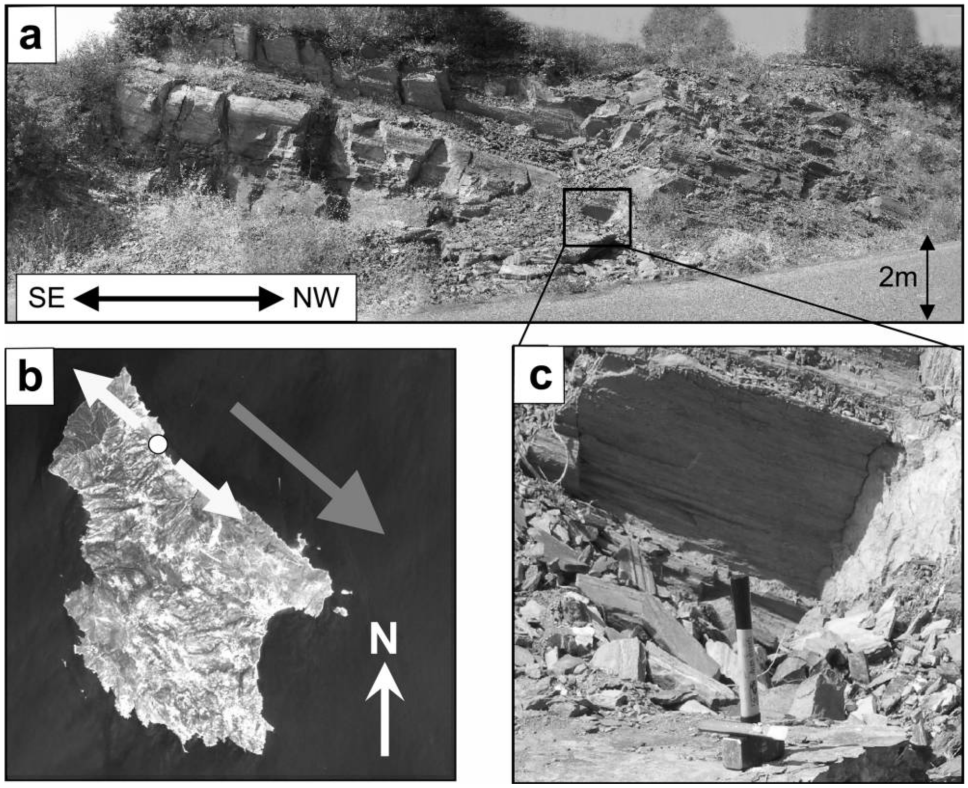

Figure 4. *a*, *c*, Strong stretching lineation (the principal transport vector) plunging gently northwest, in an outcrop close to Agia Pelagia. *b*, Map showing the outcrop location (*white circle*), the extension direction (*white arrows*), and the shear sense (top to the SE; *gray arrow*). (A color version of this figure is available in the online edition or from the *Journal of Geology* office.)

lineation of the initial stage of the ductile strain in the PDF and the PQU because the latter is associated only with fully ductile fabrics, including true planar-foliated mylonites, while the NW-SE-oriented extension fabrics include S/C mylonite fabrics and fabrics transitional between ductile and brittle conditions. Additionally, shear band fabrics cut the early mylonite foliation (and NE-directed lineation) in exposures near Potamos.

Brittle Structures. Neogene brittle structures occur in all bedrock units and in Neogene sediments. Young faults most commonly are normal faults with associated slickensides, veins, and fractures. Many faults show clearly offset markers, mostly bent and offset veins, or layers. The larger normal faults have downthrow mostly away from the main topographic axis of Kythera and express NE-SW-trending extension. In the central part of Kythera, the inland high-angle faults define a NW-SE-trending graben. Both NE-SW- and NW-SE-striking fault families occur in the central and southern parts of Kythera, and most of these are probably related to the youngest extensional phase of Late Miocene to Recent age; the NW-SE faults are dominant, with steeply pitching slickenside lineations expressing regional NE-SW extension.

On the mountain ridges of Agia Moni and Agia Elesa, the shuttle radar terrain model (fig. 8) and aerial photos reveal faults of approximately E-W orientation that offset the ridge crests. The offsets show dextral slip sense on faults of near E-W strike; they may be Riedel fractures in a wider zone of shear. Small strike-slip faults also have been identified in outcrops at Plataia Ammos on the east coast. Here, quartz tension gashes and extensional fractures in recrystallized limestones have been displaced by dextral faults of E-W strike. Large submarine faults identified from scarps on the bathymetric slope map of the area around Kythera (fig. 9) show an approximately E-W-trending zone of apparent dextral shear expressed by local changes in strike of these fault scarp slopes and in the existence of an apparent pull-apart basin between Kythera and the Neapolis peninsula of the Peloponnese. This zone is consistent with the observed E-W dextral brittle structures observed in northern Kythera.

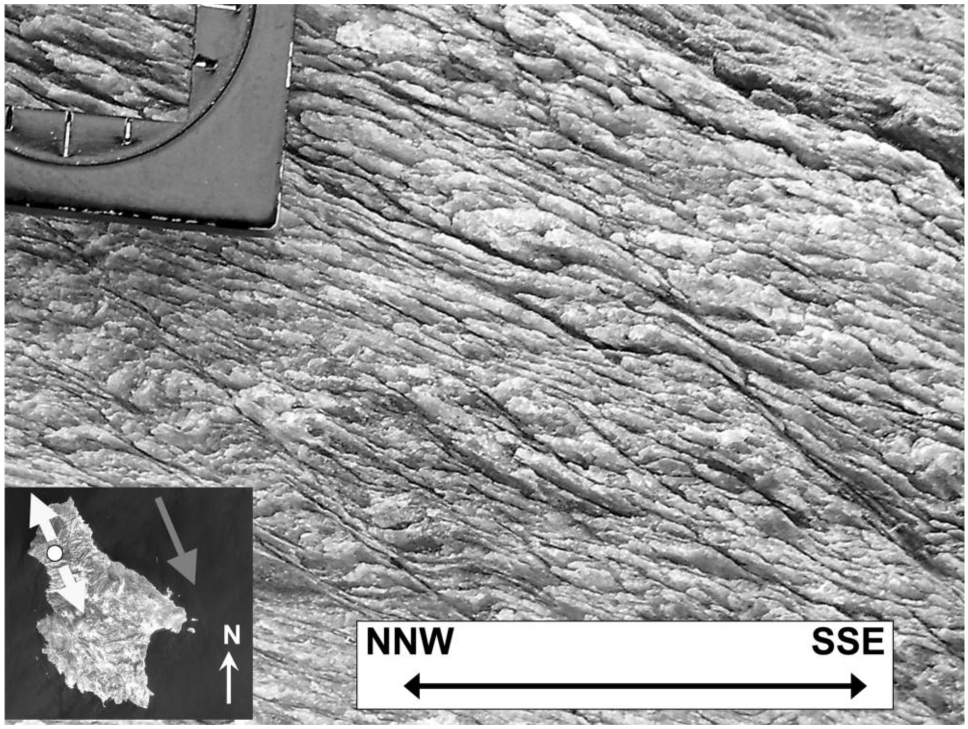

Figure 5. Vertical outcrop face showing asymmetric structure of an S/C fabric in an outcrop north of Potamos village. The map inset shows the outcrop location (*white circle*), the extension direction (*white arrows*), and the shear sense (top to the SSE; *gray arrow*). (A color version of this figure is available in the online edition or from the *Journal of Geology* office.)

Zircon Fission-Track Age

A zircon fission-track (FT) cooling age was obtained from a selected sample from Kythera by using the external detector method. Zircons separated from a quartzite sample taken near Agia Pelagia from a site just below the PDF (see fig. 1, *left*) gave a zircon FT age of 11.4 ± 1.1 Ma. (A data table supporting this age is available as a PDF in the online edition or from the *Journal of Geology* office.) Given the zircon FT annealing temperature (Brandon et al. 1998) of about 240°C, we infer that this corresponds to the later part of stage 2 of extension, shortly after the rocks entered the brittle regime during rapid exhumation. This age is consistent with fossil-dated late Miocene beds (Christodoulou 1965; Freyberg 1967; Theodoropoulos 1973) being cut only by normal faults of extension stage 3. More samples are currently being processed for additional zircon FT ages.

Arc Fragmentation and Possible Causes of Along-Arc Stretching

Neogene Differential Rotations in the Peloponnese-Cretan Ridge. In the interval from the end of the Early Miocene to the beginning of the Late Miocene, the Hellenic Arc was almost rectilinear (Kissel and Laj 1988; Ten Veen et al. 1998; Walcot and White 1998), with an E-W trend (*A* in fig. 3); according to these authors, the present curvature has been acquired tectonically in two major rotation phases. During the Middle Miocene, a first phase of deformation is characterized by clockwise and counterclockwise rotations in the west (Epirus) and east (SE Anatolia), respectively (Kissel and Laj 1988). The second rotation phase occurred during the last 5 m.yr., after the propagation of the North Anatolian Fault, and imposed clockwise rotation only on the northwest part of the arc, about a pole situated in the South Adriatic Sea (Kissel and Laj 1988).

From paleomagnetic data, significant counterclockwise rotations of around 40° are observed (Duermeijer et al. 1998) in Miocene strata of central Crete. In contrast, a clockwise rotation of 25° has been measured in late Miocene–Pliocene sediments of the Peloponnese, while late Miocene–Pliocene sediments of Kythera indicate both counterclockwise and clockwise rotations of insignificant size compared with the neighboring areas (Meulenkamp et al. 1977; Steenbrink 2001; Van Hinsbergen et al. 2005).

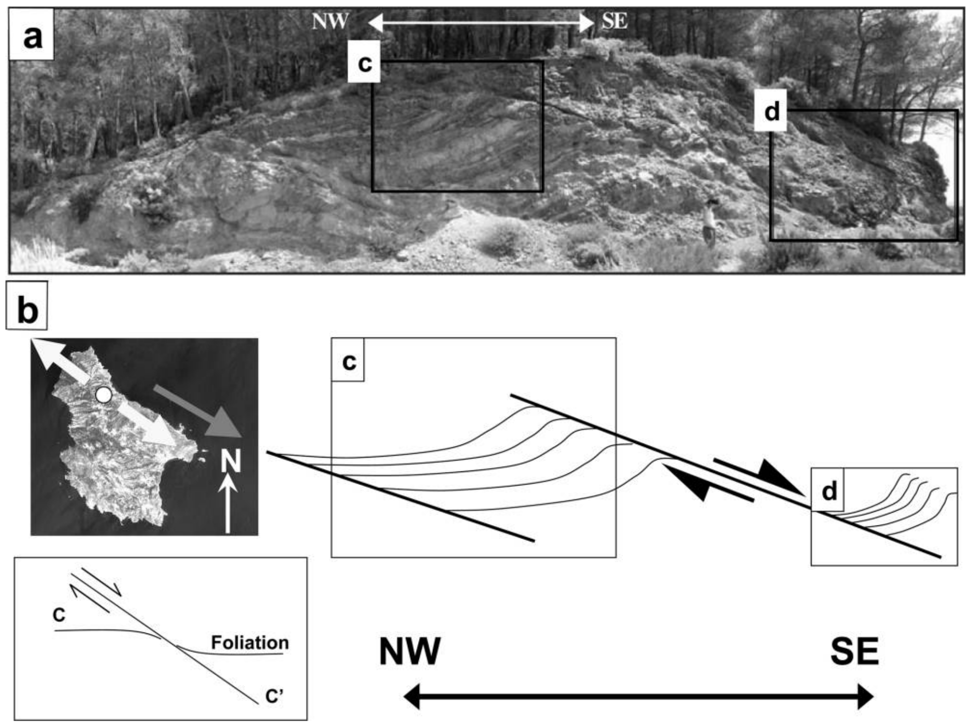

Figure 6. *a*, Outcrop of a C/C′ shear band fabric close to the detachment and mylonite in the Potamos area. *b*, Interpretation of this structure. The index map shows the outcrop location (*white circle*), the extension direction (*white arrows*), and the shear sense (top to the SE; *gray arrow*). (A color version of this figure is available in the online edition or from the *Journal of Geology* office.)

Assuming that these rotations are correctly interpreted as regionally significant and that they are not just local effects near strike-slip faults (Duermeijer et al. 1998), then inhomogeneous extension in the southwestern part of the forearc ridge must occur, caused by the differential strain between the two oppositely rotated areas of the Peloponnese and Crete. The opposing rotations between Peloponnese–western Aegean and Crete–eastern Aegean parts coincide temporally with the Late Middle Miocene rollback and slab retreat of the African oceanic subducted slab. This tectonic process requires that the overriding Aegean forearc expanded and increased its curvature, and, in conjunction with the opposite rotations of the two parts, this would generate localized extension along the arc.

The shear zones parallel to the Mid-Cycladic Lineament (MCL; fig. 2) indicate a broad zone of displacement between the west and the east Aegean crustal blocks rotating in opposing directions as rollback took place at the Hellenic subduction zone (Pe-Piper et al. 2001). The continuity of the MCL from the Cyclades area to its end in the Kythera segment of the Peloponnese-Cretan Ridge constrains the location of the region that accommodates the opposing rotations and related extension to within this segment of the arc. Progressive and accelerated rotation of the west Aegean block from 7° to 23° by the Late Miocene (Avigad et al. 1998; Walcott and White 1998) coincides with the rollback of the subducting slab, which would require higher rates of extension along the arc during this interval.

Late Neogene–Recent Segmentation of the Hellenic Arc. A series of transverse faults cut through the Peloponnese-Cretan Ridge. In the southern Peloponnese, an E-W- to ENE-WSW-trending prominent left-lateral fault, the North Mani Transverse Fault (NMTF), has an offset of 10 km (Lallemant et al. 1984; Le Pichon et al. 2002), and Le Pichon et al. (2002) also identify another similar feature in eastern Crete, the Ierapetra Transverse Fault. In between those two faults, there are other transverse faults that segment the forearc ridge, and all of these permit differential movements of arc segments toward the subduction trench. The North Kythera Transverse Fault we have identified is a right-lateral fault zone of E-W trend (similar to the NMTF) that accommodates faster movement of the

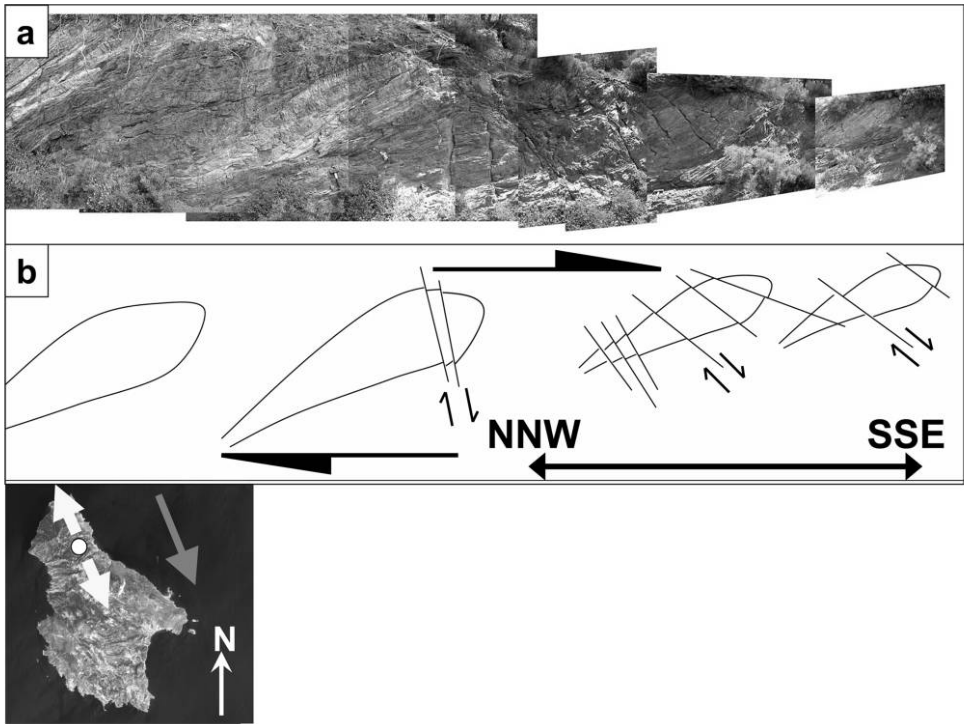

Figure 7. Quartzite layers (*lighter areas*) in phyllite series (*darker areas*), showing boudinage from NNE-SSW-trending extension, close to Potamos mylonites. The index map shows the outcrop location (*white circle*), the extension direction (*white arrows*), and the shear sense (top to the SSE; *gray arrow*). (A color version of this figure is available in the online edition or from the *Journal of Geology* office.)

Kythera segment of the forearc ridge toward the trench compared with the adjacent Peloponnese segment.

Late Brittle Deformation and a Comparison with the Cyclades and Crete

Mio-Pliocene clastic sediments in the hanging wall represent the infilling of half-grabens opened in between major normal faults. In Kythera, these sediments are as old as Late Miocene and must be younger than the ductile extension in the footwall because unconformable contacts are observed on the metamorphic rocks. This provides a minimum age for the onset of brittle extension in Kythera (Christodoulou 1965; Freyberg 1967; Meulenkamp et al. 1977; Lyberis et al. 1982) that appears significantly younger than that for most reported Cyclades detachments as well as those of eastern Crete (Jolivet et al. 1996), which host sediments as old as Early-Middle Miocene (Kopp and Richter 1983). In addition, on Kythera, inclined bedding of the Late Miocene–Pliocene Mitata sediments contrasts with the overlying Likodimos Pleistocene sediments that are almost horizontal. This mild (5°–10°) tilting of late Miocene–Pliocene strata is not due to compressional folding or to local bending ("drag") adjacent to normal faults but is a rotational strain in tilted blocks and/or in the hanging wall cutoff of one or more listric normal faults; we think that it may be evidence of activity of a young still-buried extensional detachment.

The Cyclades detachment faults correspond to the uprise of the lower ductile crust expressed by migmatite domes (Gautier 1993) or by granite intrusions in the middle crust (e.g., Naxos, Tinos; Keay et al. 2001). This applies to a previously thickened continental lithosphere that afterward suffered thermal relaxation and weakening, allowing extensional deformation to occur during and subsequent to high-temperature metamorphism. In contrast, the PDF, like those on Crete and elsewhere along the Hellenic Arc, appears not to be associated with accompanying magmatism.

The partial subduction and buoyant "oblique escape" model presented by Thomson et al. (1999, especially their fig. 11) for the origin and tectonic transport and emplacement of the PQU and its surroundings in Crete is clearly the most plausible explanation for the occurrence of these rocks and the overlying detachment. We think that

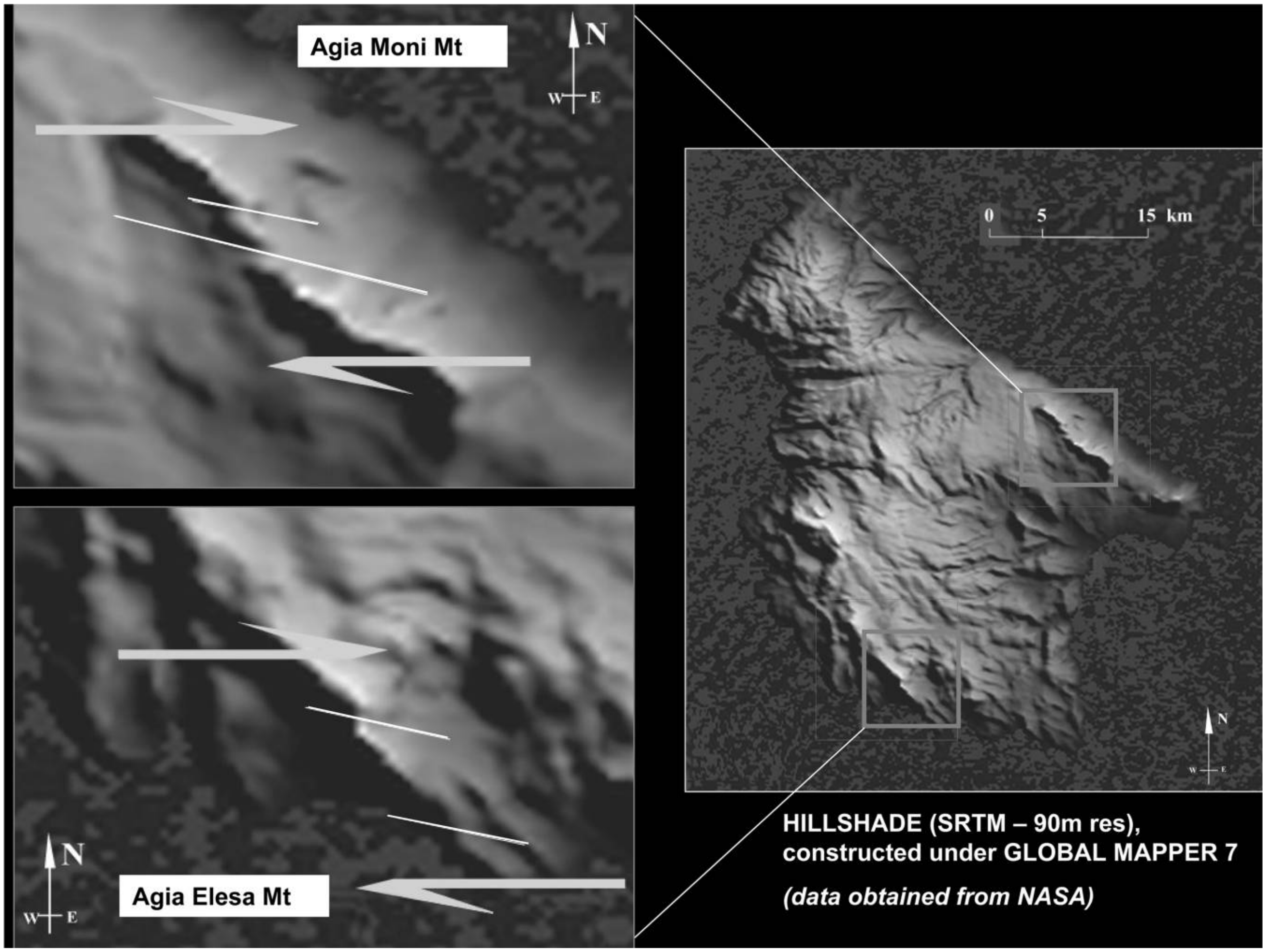

Figure 8. *Right*, grayscale gradient digital elevation model (DEM) of Kythera constructed from shuttle radar terrain model of 3″ resolution. *Left*, enlargement of parts of the DEM. *Top left*, Agia Moni; *bottom left*, Agia Elesa. The ridgeline offsets suggest dextral slip sense on faults of near E-W strike; they may be Riedel fractures in a wider zone of shear.

it applies also in Kythera, except that the exhumation through the brittle-ductile transition and deposition of sediments onto the exposed detachment are about 4 m.yr. younger and the exposed rocks began their exhumation from a greater maximum depth (Gerolymatos 1994).

Conclusions

A major extensional detachment fault, here termed the PDF, is exposed in northern Kythera, between the PQU and the overlying unmetamorphosed units, paralleling and defining the surface of the domed structure of the metamorphic core complex. The exposed Potamos mylonites, as well as other ductile structures along the mapped detachment shear zone and fault, indicate an early NE-SW-trending extensional displacement of mid-late Miocene age, which appears to record both top-to-the-NE and top-to-the-SW displacement. Late ductile, ductile-brittle, and some brittle structures indicate a significant NW-SE extension along the forearc ridge in Kythera. The youngest brittle structures indicate a return to NE-SW extension and cessation of the previous (probably localized) arc-parallel extension. The zircon FT cooling age we report from Kythera is likely to be close to the time of the along-arc extension and the passage through the brittle-ductile transition and implies that exhumation of the PQU of Kythera was active at about 12 Ma.

We suggest that slab retreat and trench rollback, which must have caused the expansion of the Hellenic forearc ridge, can explain the development of localized along-arc extension. We think that the localization of this strain was connected with the significant differential rotations experienced in the Neogene by the two main parts of the forearc ridge, and with the major change in rotation amount evi-

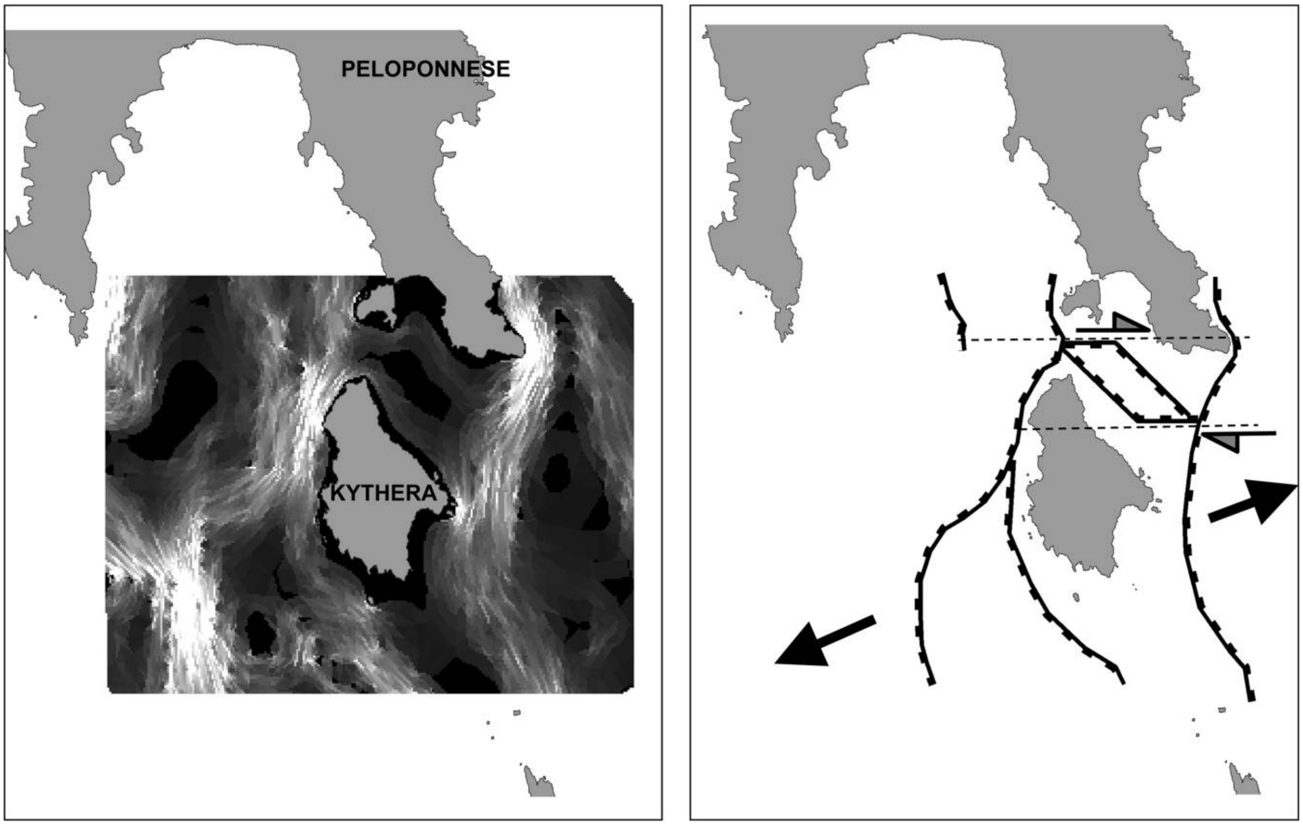

Figure 9. Interpretation of the present major submarine faults around Kythera. The background image is a submarine slope map in which probable submarine faults form areas of highest slope (*white*). These scarps show systematic dextral bending in a zone (*dashed lines*) running near the north end of Kythera, and a probable small dextral pull-apart basin between the Peloponnese and Kythera. Black arrows show orientation of inferred active extension perpendicular to dominant fault strike.

dent from the paleomagnetic results from the Peloponnese compared with Kythera. If substantial changes in rates of slab rollback have occurred during the Neogene, the along-arc stretching event seen in Kythera might correspond to a time of a high rate of rollback.

ACKNOWLEDGMENTS

We thank J. Garver and M. Montario for essential assistance in determining the zircon fission-track cooling age reported here and S. Perry for help with the mineral separation. We thank J. Garver for providing access to the Union College facilities and F. Spear and an anonymous reviewer for helpful reviews. Funding for this research was provided by the Geological Society of America, the Department of Earth and Atmospheric Sciences, University at Albany, and the Graduate Student Organization of the University at Albany. Also, we thank K. Kyriakopoulos for assistance in mineral identification and all the local people in Fratsia village (Kythera) for their hospitality and accommodation.

REFERENCES CITED

Avigad, D.; Baer, G.; and Heimann, A. 1998, Block rotations and continental extension in the central Aegean Sea: palaeomagnetic and structural evidence from Tinos and Mykonos (Cyclades, Greece). Earth Planet. Sci. Lett. 157:23–40.

Brandon, M. T.; Roden-Tice, M. R.; and Garver, J. I. 1998. Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington state. Geol. Soc. Am. Bull. 110:985–1009.

Buick, I. S. 1991. The late-Alpine evolution of an extensional shear zone, Naxos, Greece. J. Geol. Soc. Lond. 152:639–654.

Christodoulou, G. 1965. Quelques observations sur la géologie de Cythère et examen micropaléontologique des formations néogènes de l'île. Bull. Soc. Geol. Greece 6:385–399.

Doutsos, T.; Piper, G.; Boronkay, K.; and Koukouvelas, I. 1993. Kinematics of the central Hellenides. Tectonics 12:936–953.

Drooger, C. W., and Meulenkamp, J. E. 1973. Stratigraphic contributions to geodynamics in the Mediterranean area: Crete as a case history. Bull. Soc. Geol. Greece 10: 193–200.

Duermeijer, C. E.; Krijgsman, W.; Langereis, C. G.; and Ten Veen, J. H. 1998. Post-early Messinian counter-clockwise rotations on Crete: implications for Late Miocene to Recent kinematics of the southern Hellenic Arc. Tectonophysics 298:177–189.

Forster, D. A., and Lister, G. S. 1999. Detachment faults in the Aegean core complex of Ios, Cyclades, Greece. *In* Ring, U.; Brandon, M. T.; Lister, G. S.; andWillett, S. D., eds. Exhumation processes: normal faulting, ductile flow and erosion. Geol. Soc. Lond. Spec. Publ. 154: 305–323.

Freyberg, B. 1967. Die Neogen Diskordanz in central Kythira. Prakt. Akad. Athinon. 42:361–381.

Gautier, P., and Brun, J. P. 1993. Structure and kinematics of Upper Cenozoic extensional detachment on Naxos and Paros (Cyclades Islands, Greece). Tectonics 12: 1180–1194.

Gerolymatos, I. K. 1994. Metamorphose und Tectonik der Phyllit-Quartzit-Serie und der Tyros-Schichten auf dem Peloponnes und Kythira. Berl. Geowiss. Abh. A 164:1–101.

Goldstein, A. G. 1988. Factors affecting the kinematic interpretation of asymmetric boudinage in shear zones. J. Struct. Geol. 10:707–715.

Hanmer, S. 1986. Asymmetrical pull-aparts and foliation fish as kinematic indicators. J. Struct. Geol. 8:111–122.

Jolivet, L.; Goffe, B.; Monie, P.; Truffert-Luxey, C.; Patriat, M.; and Bonneau, M. 1996. Miocene detachment in Crete and exhumation P-T-t paths of high-pressure metamorphic rocks. Tectonics 15:1129–1153.

Keay, S.; Lister, G. S.; and Buick, I. 2001. The timing of partial melting, Barrovian metamorphism and granite intrusion in the Naxos metamorphic core complex, Cyclades, Aegean Sea, Greece. Tectonophysics 342: 275–312.

Kissel, C., and Laj, C. 1988. The Tertiary geodynamical evolution of the Aegean Arc: a paleomagnetic reconstruction. Tectonophysics 146:183–201.

Kopp, K. O., and Richter, D. 1983. Synorogenetische Schuttbildungen und die Eigenstandigkeit der Phyllit-Gruppe auf Kreta. Neues Jahrb. Geol. Paleontol. Abh. 165:228–253.

Krahl, J.; Kauffmann, G.; Kozur, H.; Richter, D.; Forster, O.; and Heinritzi, F. 1983. Neue Daten zur Biostratigraphie and zur tectonischen Lagerun der Phyllit-Gruppe und der Trypali-Gruppe auf der Insel Kreta (Griechenland). Geol. Rundsch. 72:1147–1166.

Lallemant, S. 1984. La transversale nord-mani: étude géologique et aéromagnetique d'une structure transverse à l'Arc Egéen externe (thèse troisième cycle, University Pierre et Marie Curie). Sci. Terre Mem. 84:1–164.

Le Pichon, X.; Lallemant, S. J.; Chamot-Rooke, N.; Lemeur, D.; and Pascal, G. 2002. The Mediterranean Ridge backstop and the Hellenic nappes. Mar. Geol. 186:111–125.

Lister, G. S., and Snoke, A. E. 1984. S-C mylonites. J. Struct. Geol. 6:617–638.

Lyberis, N.; Angelier, J.; and Barrier, E. 1982. Active deformation of a segment of arc: the strait of Kythira, Hellenic arc, Greece. J. Struct. Geol. 3:299–311.

Marsellos, A. E. 2006. Mapping of the detachment fault in Kythera Island and study of the related structural shear sense indicators. MS thesis, State University of New York, Albany, 201 p.

Marsellos, A. E., and Kidd, W. S. F. 2006. Detachment fault and shear zone of the Cretan-Peloponnese Ridge in Kythera Island. Geol. Soc. Am. Abstr. Program 38:238.

Mawer, C. K. 1989. Kinematic indicators in shear zones. Int. Basement Tectonics Assoc. Publ. 8:67–81.

Meulenkamp, J. E.; Theodoropoulos, P.; and Tsapralis, V. 1977. Remarks on the Neogene of Kythira, Greece. Proc. XI Colloq. Geol. Aegean Reg. 1:355–362.

Mountrakis, D. 1986. The Pelagonian zone in Greece: a polyphase-deformed fragment of the Cimmerian continent and its role in the geotectonic evolution of the eastern Mediterranean. J. Geol. 94:335–347.

Passchier, C. W., and Trouw, R. A. J. 2005. Microtectonics. Berlin, Springer, 366 p.

Pe-Piper, G. 1982. Geochemistry, tectonic setting and metamorphism of mid-Triassic volcanic rocks of Greece. Tectonophysics 85:253–272.

Pe-Piper, G., and Piper, D. J. W. 2002. The igneous rocks in Greece: the anatomy of an orogen. Berlin, Borntraeger, 573 p.

Pe-Piper, G.; Piper, D. J. W.; and Matarangas, D. 2001. Regional implications of geochemistry and style of emplacement of Miocene I-type diorite and granite, Delos, Cyclades, Greece. Lithos 60:47–66.

Ring, U.; Brachert, T.; and Fassoulas, C. 2001. Middle Miocene graben development in Crete and its possible relation to large-scale detachment faults in the southern Aegean. Terra Nova 13:297–304.

Robertson, A. H. F.; Clift, P. D.; Degnan, P.; and Jones, G. 1991. Paleoceanography of the eastern Mediterranean Neotethys. Palaeogeogr. Palaeoclimatol. Palaeoecol. 87:289–343.

Robertson, A. H. F., and Dixon, J. E. 1984. Introduction: aspects of the geological evolution of the eastern Mediterranean. *In* Dixon, J. E., and Robertson, A. H. F., eds. The geological evolution of the eastern Mediterranean. Geol. Soc. Lond. Spec. Publ. 17:1–74.

Seidel, E.; Kreuzer, H.; and Harre, W. 1982. A Late Oligocene/Early Miocene high-pressure belt in the external Hellenides. Geol. Jahrb. E23:165–206.

Simpson, C., and Schmid, S. M. 1983. An evaluation of criteria to determine the sense of movement in sheared rocks. Geol. Soc. Am. Bull. 94:1281–1288.

Smith, J. V. 1995. True and apparent geometric variability of en-echelon vein arrays. J. Struct. Geol. 17: 1621–1626.

———. 1996. Geometry and kinematics of convergent conjugate vein array systems. J. Struct. Geol. 18: 1291–1300.

Steenbrink, J. 2001. Orbital signatures in lacustrine sediments: the late Neogene intramontane Florina-Ptolemais-Servia Basin, northwestern Greece. Geol. Ultraiect. 205:167.

Ten Veen, J. H., and Meijer, P. T. 1998. Late Miocene to recent tectonic evolution of Crete (Greece): geological observations and model analysis. Tectonophysics 298: 191–208.

Theodoropoulos, D. 1973. Physical geology of Kythera Island. PhD thesis, Athens University, 94 p.

Thomson, S. N.; Stockhert, B.; and Brix, M. R. 1999. Miocene high-pressure metamorphic rocks of Crete, Greece: rapid exhumation by buoyant escape. *In* Ring, U.; Brandon, M. T.; Lister, G. S.; and Willett, S. D., eds. Exhumation processes: normal faulting, ductile flow and erosion. Geol. Soc. Lond. Spec. Publ. 154: 87–107.

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.

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.