East-west extension and Holocene normal-fault scarps in the Hellenic arc

R. Armijo, H. Lyon-Caen   Institut de Physique du Globe, 4 place Jussieu, 75252 Paris Cedex 05, France

D. Papanastassiou   National Observatory of Athens, P.O. Box 20048, 11810 Athens, Greece

ABSTRACT

Examination of surface fault traces with Spot images and in the field corroborates the inference that the active tectonics of southern Peloponnesus and Crete are dominated by approximately north-south normal faulting and approximately east-west extension. The heights of Holocene normal-fault scarps yield first-order regional estimates of fault slip rates between 0.1 and 2–3 mm/yr. Most of the surface scarps probably ruptured during past earthquakes, such as that which destroyed Sparta in 464 B.C. On the Sparta fault the Holocene average slip rate and the recurrence time of large earthquakes may be ~1 mm/yr and 3000 yr, respectively. The regional pattern of Quaternary faulting suggests that the east-west extension near the Hellenic subduction zone is fast (about 5%–10%/m.y.). The change from north-south to east-west extension in the late Pliocene (~2–4 Ma) implies that the Aegean is starting to collide with the northern margin of Africa.

INTRODUCTION

Much of the seismicity in the Aegean region results from fast crustal extension and normal faulting north of the Hellenic trench (Fig. 1) and is not produced by slip along the subduction-plate contact, which appears to be mostly aseismic (Jackson and McKenzie, 1988). The direction of extension is about north-south in most of the Aegean (McKenzie, 1978; Angelier et al., 1982). Near the trench, however, whether the present tectonic regime is dominated by radial extension and north-south strike-slip faults

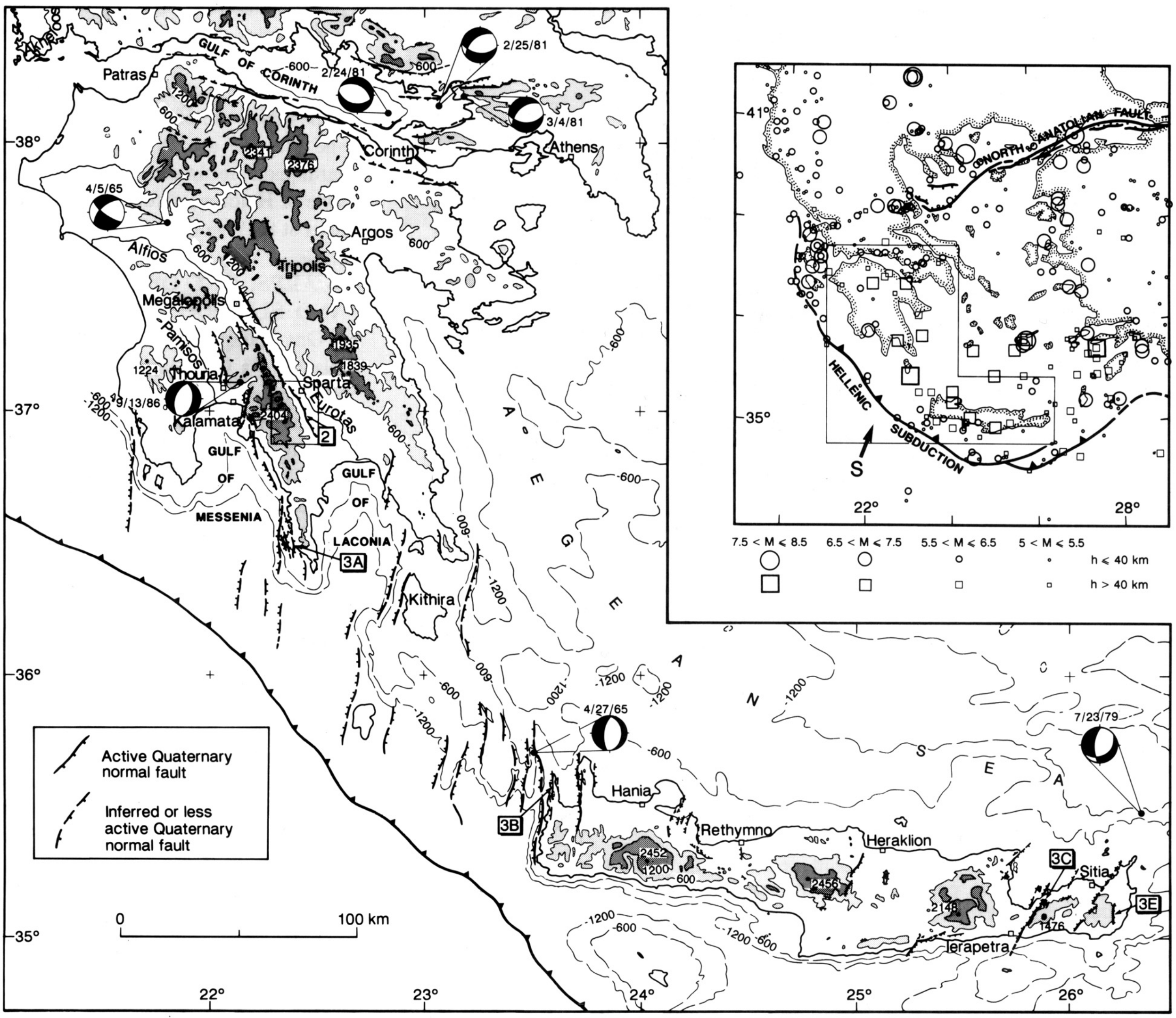

Figure 1. Seismotectonic map of Peloponnesus and Crete. Topography and bathymetry in metres. Active faults and focal mechanisms of events in overriding plate compiled as in Lyon-Caen et al. (1988). Mechanism of 1979 event from Dziewonski et al. (1987). Numbers show locations of photos in Figure 3. Inset: Tectonic framework and A.D. 1900–1986 seismicity; arrow with S = average azimuth of slip vectors of subduction earthquakes.

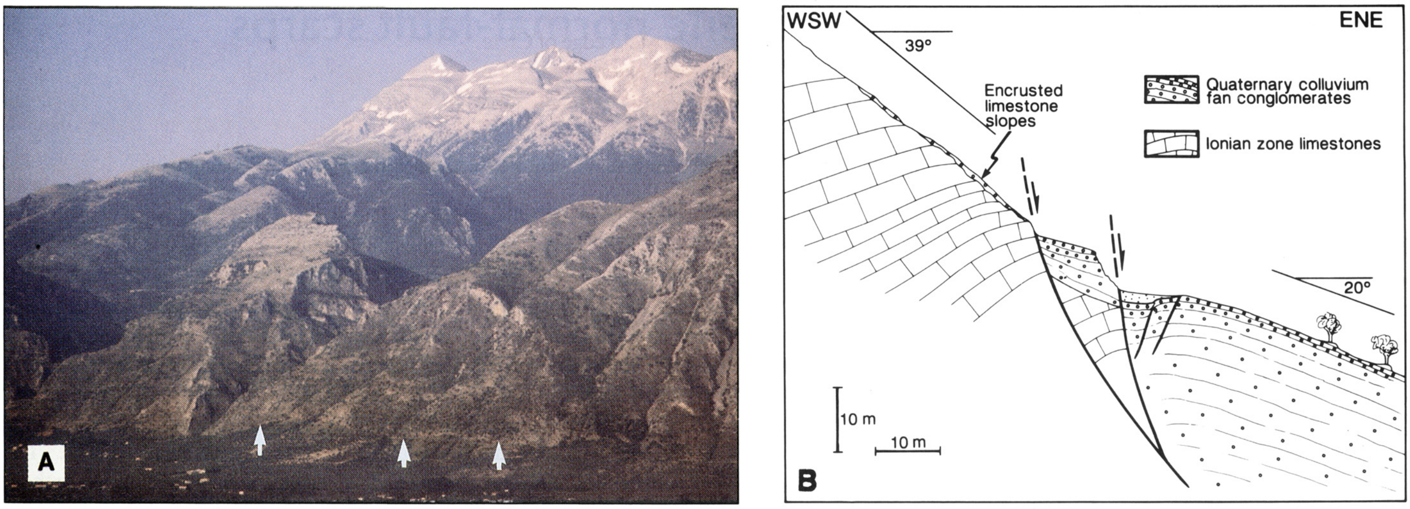

Figure 2. Sparta fault. A: Taygetos Mountain front, looking southeast. Arrows indicate scarp. B: Section across fault scarp.

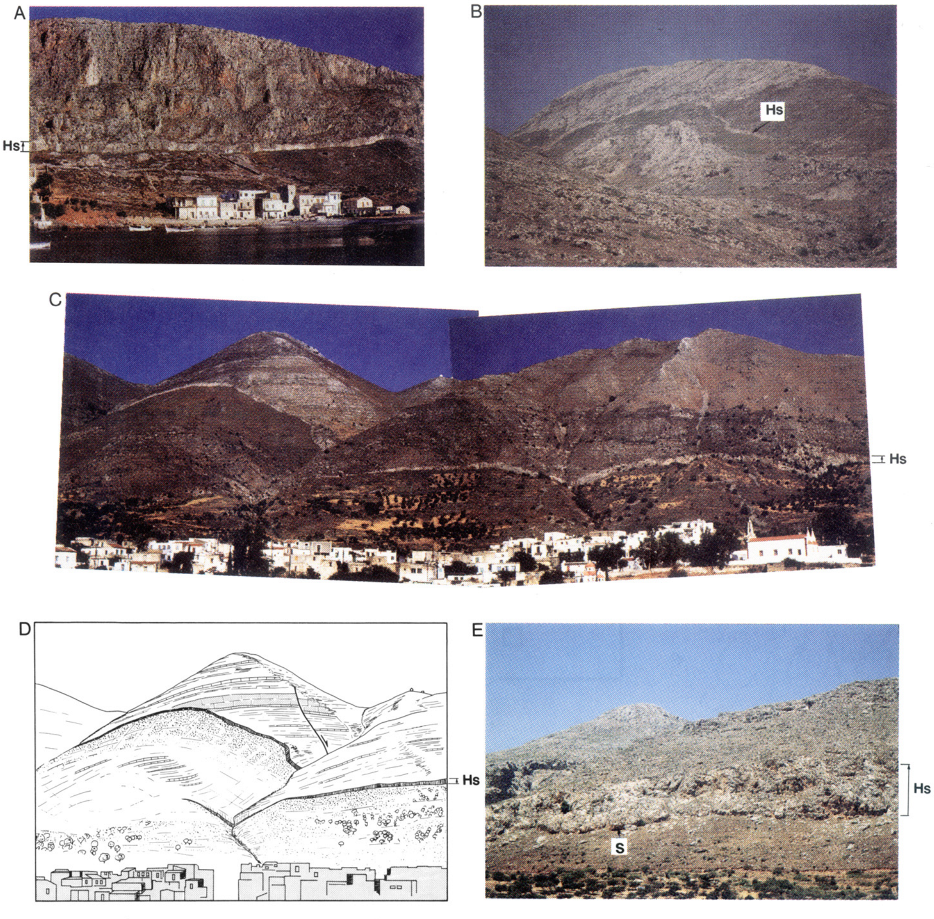

Figure 3. Holocene north-south–striking fault scarps (Hs). A: At Gerolimin, looking east-northeast. B: At Gramvousa peninsula, looking northeast. C: At Lastros, looking west-southwest. D: Interpretation of C (left). E: At Zakros, looking west. Scarplet (s) at base of Hs is ~0.5 m high.

(Angelier et al., 1982) or by approximately east-west extension (Lyon-Caen et al., 1988) is controversial. Lack of information on large earthquakes in that region hampers the evaluation of rates and styles of active deformation. Here we address these problems by looking at the morphology of recent surface fault traces. On the basis of Spot satellite image analysis and field observations we describe sets of young, mostly north-south–striking, normal-fault scarps in the southern Peloponnesus and Crete. The scarps probably correspond to several earthquakes, total heights of about 1 to 10 m, and offset calcareous range-front slopes with uniform morphology. We examine the hypothesis that the slope offsets are of Holocene age (≤10–11 ka) and may be used to estimate slip rates and earthquake recurrence times. We discuss the style of Holocene deformation and its implications at the regional scale.

SCARPS, AGE OF FAULTING, AND SLIP RATES

One example of a surface break that may be related to a large earthquake in Greece is the fault scarp visible at the base of the Taygetos Mountains (Fig. 2A). By combining historical and morphological evidence, Armijo et al. (1991) proposed that rupture of this north-northwest–south-southeast–striking normal fault is the most probable source of the earthquake that destroyed ancient Sparta in 464 B.C. The earthquake could have had a moment M_o ~3.0 × 10^{19} Nm and magnitude M_s ~7.2, corresponding to an average slip of ~3–4 m along a 20-km-long surface break. The Sparta fault has a zigzag-shaped surface trace that is made up of left-stepping en echelon segments striking ~N170°E linked by shorter segments striking ~N140°E (Armijo et al., 1991). The latter fault segments parallel the fold axes in the underlying rocks, here largely late Senonian–Eocene limestones of the Ionian unit. This arrangement suggests that the extension direction is nearly east-west. Overall, the total scarp height implies a maximum throw of about 10–12 m (Fig. 2B) and might correspond to three events with slip comparable to that of the 464 B.C. event (Armijo et al., 1991). The most continuous and better preserved parts of the scarp are along the base of distinct triangular faceted spurs up to 700 m high, and they mark the main contact between the bedrock and the Quaternary colluvium and alluvium filling the Eurotas valley (Fig. 2A). The surface disrupted and offset by the scarp (Fig. 2B) corresponds to the waning lowermost slopes of the facets, just above the uppermost piedmont slopes. This surface is encrusted and blanketed by a layer of lime-indurated conglomerates directly derived from erosion of the calcareous mountain front; the thickness of the conglomerates increases dramatically across the fault toward the valley (Fig. 2B). At certain places a wedge of these conglomerates has been uplifted with the limestone bedrock in a secondary step that overhangs the fresher part of the scarp (Fig. 2B).

Many young scarps similar to that along the Sparta fault have been observed along other active normal faults in Greece (Stewart and Hancock, 1991). For example, the March 4, 1981, Corinth earthquake produced a rupture about 0.5 m high at the base of an older, 3-m-high scarp near Kaparelli (Jackson et al., 1982). Similarly, a 0.15-m-high step was added to a 2-m-high slickensided scarp during the 1986 Kalamata earthquake (Lyon-Caen et al., 1988). As along the Sparta fault, these scarps offset calcareous slopes near the mountain-piedmont junction. The slopes are chiefly made of encrusted limestone on the footwall; on the hanging wall they are the same limestone bedrock covered by indurated conglomerates of variable thickness. These uniform, commonly steep slopes (⩾30°) are thought to have formed in a cold dry climate during the Pleistocene glaciations (Dufaure, 1977). Such conditions apparently favored smooth, efficient erosion of the footwall and sediment accumulation on the hanging wall, so that the combined erosion and sedimentation rates on the slopes kept pace with, or outpaced, the slip rate on the faults. In addition, cementation of the slopes by soluble carbonates probably favored rapid annealing of fault-scarp increments during that period. Thus, when glacial conditions ceased about 10–11 ka (Van Zeist and Bottema, 1982), the range-front slopes probably constituted regionally uniform markers for subsequent Holocene fault displacements, when the slip rate outpaced erosion and sedimentation rates.

Examples of sharp, steep, probably Holocene normal-fault scarps cutting calcareous slopes in southern Peloponnesus and Crete are shown in Figure 3. Many faults at the western edge of the Mani peninsula near Gerolimin (Figs. 1 and 3A) offset, uplift, and tilt a marine abrasion surface of Pliocene-Quaternary age (Dufaure, 1977). Total vertical offsets of this surface by the faults reach about 100 m, and the smaller, probably Holocene scarps along the base of the reliefs indicate recent throws between 1 and about 20–30 m. That the highest slope offsets of the steep recent scarps are located in front of the highest offsets of the top erosion surface implies consistency between Holocene throws and longer term offsets. The strikes of the normal-fault scarps mapped at the western edge of Crete are compatible with east-west extension and the mechanism of the nearby A.D. 1965 earthquake (Lyon-Caen et al., 1988) (Figs. 1 and 3B). In eastern Crete, normal faults are marked by sharp Holocene scarps that in many places offset gullies on the calcareous slopes (Fig. 3C) or show clear traces of very recent reactivation (Fig. 3E). Unlike in Sparta, Kalamata, or Gerolimin, where the normal-fault strikes are nearly parallel to bedding strikes in the limestones, the active north-south normal faults of Crete are nearly orthogonal to east-west–trending folds (Fig. 3, C and D). These faults commonly cut older east-west–striking normal faults that postdate folding but have no surface scarps (Fig. 3, C and D). As near Gerolimin, the steep scarps visible throughout the southern Peloponnesus and Crete (Fig. 1) imply throws between 1 and 20–30 m. Taking the age of the offset slopes to be about 10 ka would yield vertical components of slip rates on the faults of 0.1 to 2–3 mm/yr. Conversely, that this range of slip rates encompasses rates estimated on active normal faults elsewhere (e.g., Sieh, 1981) argues for a uniform Holocene age of the scarps. This line of reasoning is in keeping with a Holocene slip rate of about 1 mm/yr on the Sparta fault and, if three events produced the observed 10-m-high scarp, with a recurrence time for large earthquakes on that fault of about 3000 yr.

EAST-WEST EXTENSION: ONSET OF CONTINENTAL COLLISION?

The reliable mechanisms of subduction earthquakes in the Hellenic arc imply an average slip vector striking about N21°E (Taymaz et al., 1990). North of the subduction zone, the active deformation in the overriding plate is constrained by three earthquake mechanisms (Fig. 1), by a detailed study of the surface rupture and the aftershock mechanisms of the A.D. 1986, M_s = 5.8 Kalamata earthquake (Lyon-Caen et al., 1988), and by two studies of microseismicity in the southern Peloponnesus (Hatzfeld et al., 1990) and in western Crete (De Chabalier et al., 1992). All these data point to east-west to east-southeast–west-northwest extension, nearly orthogonal to the subduction average slip vector (Fig. 1). The 464 B.C. Sparta earthquake, which is the only documented example of a large historical event within the overriding plate, is also consistent with east-west extension.

We argue that a large number of seismic and Holocene fault scarps exist in southern Peloponnesus and Crete. Most of these scarps correspond to normal faults with an average strike of

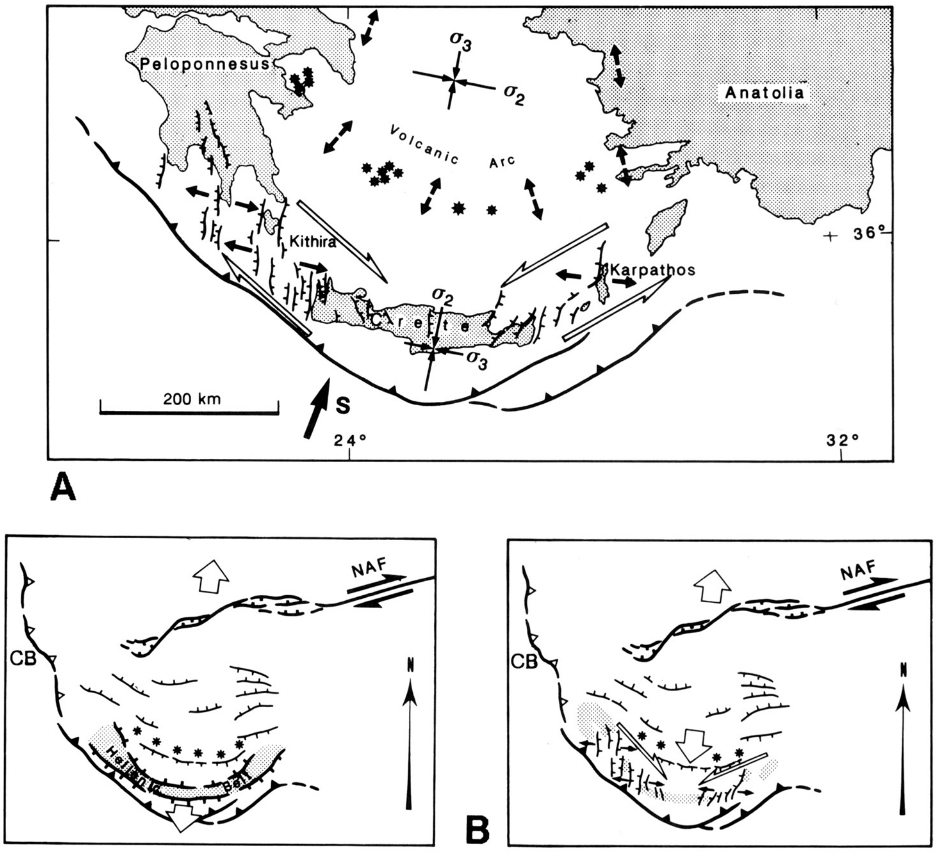

Figure 4. A: Present-day deformation in Aegean. Small solid arrows are directions of local extension. Half arrows represent horizontal shear implied by en echelon faulting. Average direction of extension (σ_3) in arc is nearly orthogonal to average azimuth of slip vectors of subduction earthquakes (S). B: Evolution from late Miocene–Pliocene (left) to Pliocene-Quaternary (right). NAF is North Anatolian fault; CB is collisional boundary with Apulia.

about N10°E (Fig. 1). Like the Kalamata and Sparta faults (Lyon-Caen et al., 1988; Armijo et al., 1991), the majority of these faults also bear morphologic evidence of sustained Quaternary activity, with throws of the order of 1 km to a few kilometres. The large, approximately north-south–oriented bathymetric escarpments between the Peloponnesus and Crete (Lyberis et al., 1982) probably correspond to similar normal faults (Fig. 1). This corroborates the inference, drawn from satellite imagery interpretation (Armijo et al., 1986a) and from seismicity, that the crust of the Hellenic arc is currently extending east-southeast–west-northwest (Fig. 4A). The approximately north-south normal faults cut the structure of the Hellenic belt with angles that vary gradually along the arc. These angles are low in Sparta, higher in Kithira, and orthogonal in Crete (Fig. 1). The north-south normal faults also cut earlier normal faults that parallel the Hellenic belt (Fig. 3E). These latter faults were probably produced by the overall north-south extensional regime that was widespread at about about 5 Ma (Jackson and McKenzie, 1988) and is still active and dominant in most of the Aegean (Fig. 4A). In Crete, the change from north-south to east-west extension, which has been documented by microtectonic measurements, took place during the Pliocene (Angelier, 1979). The dimensions, throws, and density of north-south normal faults (Fig. 1) imply a significant amount of east-west, late Pliocene to Quaternary extension. Before the onset of east-west extension the Hellenic belt was probably continuous from the southern Peloponnesus to southwest Anatolia, through Crete (Fig. 4B). Therefore, the present difference in elevation and thickness between emerged segments of the belt and the segments now under water near Kithira and Karpathos (Fig. 4) may result from approximately east-west stretching in the past ~2–4 m.y. If we take the average elevation of 0.5 km and crustal thickness of 32 km of Crete (Makris, 1978) to characterize the initial state, isostatic equilibrium implies that the most stretched parts of the belt, having a mean seafloor level of about 0.5 km, have been thinned to a crustal thickness of 26.3 km. This corresponds to about 20% of maximum extension, or about 17 km of spreading, if extension is distributed over a 100-km-long, east-west section across the arc near Kithira. The corresponding maximum strain rate in the past ~2–4 m.y. would be fast, about 5%–10%/m.y. ($1.5–3 \times 10^{-15}$/s), and the average spreading rate would be between 4.3 and 8.6 mm/yr. Such a fast strain rate is in keeping with that estimated for the overall stretching in the Aegean (Jackson and McKenzie, 1988), but the inferred rate of east-west spreading near Kithira is much smaller than the present-day north-south spreading rate across the Aegean (~40–60 mm/yr) (Taymaz et al., 1990). The scalar moment rate calculated from the two approximately north-south–striking normal-fault earthquakes in the overriding plate between the southern Peloponnesus and Crete (April 27, 1965, and September 13, 1986; Lyon-Caen et al., 1988) and from the three other $M_s \geqslant 5.7$ shallow events located in the same region and inferred to have a similar mechanism (January 23, 1899; July 1, 1927; October 6, 1947; Ambraseys and Jackson, 1990) is $2.6 \pm 1.3 \times 10^{17}$ Nm/yr. Assuming that the volume of the seismogenic deforming zone concerned is $100 \times 100 \times 10$ km^3, the strain rate in the past century would be $1.25 \pm 0.63 \times 10^{-15}$/s, consistent with the rate estimated for the past ~2–4 m.y. This suggests that a large part of the extensional deformation here is seismic, as in the rest of the Aegean (Jackson and McKenzie, 1988).

Lyon-Caen et al. (1988) suggested that the change of extensional regime within the Hellenic belt at about 2–4 Ma implies a change in the boundary conditions, probably at the nearby subduction zone (Fig. 4B), and could be due to incipient collision of the arc with the increasingly buoyant crust of the African margin, as is north-south shortening along the Mediterranean ridge. That widespread north-south normal faulting characterizes the Quaternary tectonics of the Hellenic belt supports this view. As in Tibet, the average strike of the newly formed normal faults in the overriding continent would coincide with the azimuth of the horizontal force transmitted by the incoming southern continent across the subduction interface (Armijo et al., 1986b). That the new fault pattern is limited to the Hellenic arc, and has not propagated far into the Aegean, supports the inference that the Aegean lithosphere is very weak (e.g., McKenzie, 1978).

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