A possible normal-fault rupture for the 464 BC Sparta earthquake

R. Armijo*, H. Lyon-Caen* & D. Papanastassiou†

* Institut de Physique du Globe, 4 place Jussieu, 75252 Paris Cedex 05, France
† National Observatory of Athens, PO Box 20048, 11810 Athens, Greece

SURFACE ruptures have been identified for some normal-faulting earthquakes in the Aegean region[1–3], but for most historical earthquakes the associated faults are unknown. This hampers the evaluation of the rates and styles of present-day deformation, and the assessment of seismic hazard in the region[4]. Here we examine the famous earthquake that destroyed Sparta in 464 BC. Using SPOT satellite images and fieldwork, we have mapped a 20-km-long normal fault scarp trending approximately north–south, a few kilometres west of the ancient city. Our observations, combined with an examination of historical descriptions of the earthquake damage, suggest that the Sparta earthquake ruptured this fault scarp in an event of magnitude $M_s \approx 7.2$. The Holocene slip rate and the recurrence time for such large events on the Sparta fault would be $\sim$1 mm yr^{-1} and $\sim$3,000 yr, respectively.

To many historians of the Greek classical period[5–8], the earthquake that destroyed Sparta in ~464 BC was an important reference. Ducat[9] points out that there exist three independent contemporaneous descriptions of the 464 BC earthquake: by Thucydides, who reports the event in his History of the Peloponnesian War[5], and whose description has been followed by that of Pausanias[6]; by Ephorus, who apparently provided the source for Diodorus of Sicily[7]; and an unidentified hellenistic author, followed later by Cicero, Pliny and Plutarch[8]. The earthquake was large, according to Thucydides, who refers to it as the "great earthquake in Sparta" (ref. 5, I, 128). Diodorus gives an estimate of the death toll and an indication of multiple shocks: "the houses collapsed from their foundations and more than twenty thousand Lacedemonians perished. And since the tumbling down of the city and the falling in of the houses continued uninterruptedly over a long period, many persons were caught and crushed in the collapse of the walls" (ref. 7, XI, 63). Plutarch provides an idea of the local effects and details the devastation:

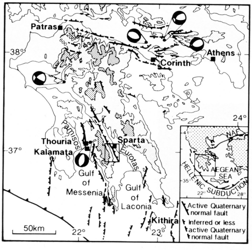
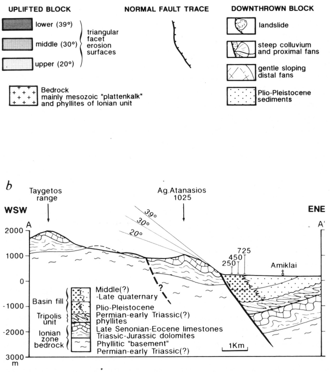


FIG. 1 Seismotectonic map of Peloponnesus (modified from ref. 1). Focal mechanisms from refs 1, 3. Insert shows the location of Fig. 2*a*; NAF denotes the North Anatolian fault.

"a greater earthquake than any before reported rent the land of the Lacedemonians into many chasms, shook Taygetus so that sundry peaks were torn away, and demolished the entire city with the exception of five houses" (ref. 8, XVI, 4). Plutarch also reports the existence, five centuries later, of "archaeological evidence" of the events: "Their tomb, even down to the present day, they call Seismatias" (ref. 8, XVI, 5). Clearly, the Sparta earthquake was large and destructive, probably accompanied by ground fissures, landslides, rock falls and other surface effects. This is compatible with a maximum intensity $I \geqslant$ X MSK (ref. 10) on the Mercalli scale. The death toll was probably very high, but the figure given by Diodorus (20,000 or about half of the inhabitants of the city[11]) seems to be overestimated[9,12].

The earthquake had immediate political consequences. Thucydides reports "the simultaneous revolt and secession to Ithome of the Helots and of some of the Perioeci (those of Thouria and of Aithaia)" (ref. 5, I, 101). According to Diodorus, "The Helots and Messenians . . . stood in fear of the eminent position and power of Sparta; but when they observed that the larger part of them had perished of the earthquake, they held in contempt the survivors, who were few" (ref. 7, XI, 63.4). Although the importance of the revolt of the Helots of Laconia (southeast Peloponnesus) is not well established, all scholars agree on the significance of the revolt and secession of the Messenians (Helots and Perioikoi of Messenia, southwest Peloponnesus) after the earthquake: the so-called Third Messenian War[12]. The historical record thus strongly suggests that the destruction caused by the earthquake was much less in the Pamisos valley, where the Messenians were settled, than in Sparta and the Eurotas valley (Fig. 1). Given the short distance between the two valleys (Thouria is only 40 km west of Sparta), we infer that the 464 BC earthquake was not of subduction type but a shallow crustal event located not far from Sparta. A comparable example of local destruction is the normal-faulting earthquake that heavily damaged Kalamata in 1986[1].

The eastern front of the Taygetos range is bounded by an east-dipping, 60-km-long, normal-fault system made up of several left-stepping, NNW-SSE striking, en échelon segments (Fig. 1). This fault system is similar, but antithetic, to the west-dipping system formed by the Kalamata fault and the en échelon normal-fault segments located offshore of the Mani peninsula[1] (Fig. 1). The rock types that crop out on the Taygetos range near Sparta are mainly phyllites of Permian to early Triassic age and late Senonian–Eocene limestones of the Ionian unit[13]. These latter limestones mark remarkably well the normal-fault landforms (Fig. 2*a*), which are very similar to features seen more clearly in other extensional environments such as the Basin and Range or Tibet[14–16]. East and south of Sparta, a 20-km-long fault segment with particularly young morphology[17] (here referred to as the Sparta fault) is composed of three sub-segments (Fig. 2*a*). The mountain front has a maximum local relief of more than 700 m at the central fault sub-segment (Fig. 2*b*). The front is formed by steep triangular/trapezoidal facets separated by distinct V-shaped valleys and 'wineglass canyons' (Fig. 3*a*). Three sets of triangular facets can be discerned, with maximum heights of about 725, 450 and 250 m, and slopes of ~20°, 30° and 40°, respectively (Figs 2, 3*a*). The decrease in facet heights towards the north and south defines the length and the individuality of the Sparta fault segment. The fault trace is linear, continuous and follows the mountain–piedmont junction (Fig. 2*a*). The large alluvial fans on the piedmont are mostly undissected and still active, but there is some young fanhead entrenchment, ~2-4 m deep near the fault trace. All of these observations suggest recent, sustained uplift of the front, and young faulting activity[18]. Furthermore, the existence along the three sub-segments of the Sparta fault of an almost continuous fresh scarp cutting across bedrock and indurated conglomerates (Fig. 3*b*, *c*, *d*) is definite evidence for recent, most probably seismic, faulting events. Although hanging-wall erosion may have increased the scarp height at some places, the uniform



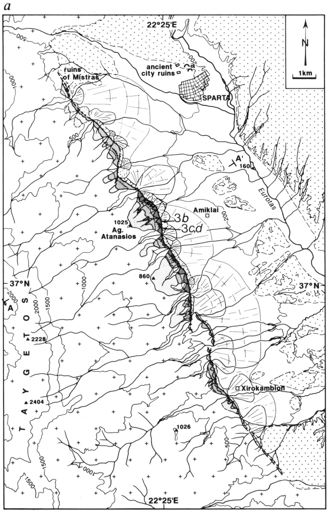


FIG. 2 *a*, Map of Sparta fault. Topography from ref. 21. Arrows are locations of Fig. 3*b* and *c*. *b*, Interpretative section at A–A′. Geology simplified from ref. 13. Total throw is probably greater than 2 km. Dashed fault is inactive.

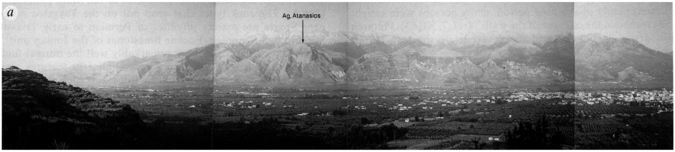


FIG. 3 *a*, Sparta mountain front. Panoramic view from the west. *b*, Fault scarp along base of triangular facet. *c*, Detail of scarp with uplifted conglomerates. *d*, Section of Sparta fault scarp at *c*.

shape of the scarp along strike implies a reliable maximum throw (vertical displacement) of ~10-12 m on the central fault sub-segment. Not having dug trenches, we cannot assess unambiguously whether this maximum throw corresponds to one or to many events. The observation, however, that a conglomerate wedge lies against the bedrock along a smaller inner scarp (~1/3 of the total throw), and that this wedge overhangs a main, fresher outer scarp (~2/3 of the total throw) (Fig. 3*c*, *d*), suggest that the total throw resulted from cumulation of at least two or three faulting events. In view of the historical record and of this field evidence, we suggest that the 464 BC earthquake could correspond to the last of these events.

To characterize a possible seismic rupture along the Sparta fault, we assume the fault geometry at depth to be the same as that of the Kalamata fault (Fig. 1), whose dip of ~45° is well constrained down to a depth of 10 km (ref. 1). Such a depth of the brittle/ductile transition zone seems to be implied by most studies of recent earthquakes in the region[19]. A rupture of the Sparta fault (20 × 14 km) with an average slip of 10 m (total displacement corresponding to the observed scarp) and shear modulus $\mu = 3.23 \times 10^{10}$ N m^{-2} would yield an earthquake with moment $M_0 = 9 \times 10^{19}$ N m. The large slip compared to the width of the fault would require a particularly high static stress drop (~17 MPa). An event with the same fault surface but a third of the displacement above yields a moment $M_0 = 3 \times 10^{19}$ N m, similar to the 1980 earthquake at Irpinia, Italy[20]. Our observations suggest that such an event is the most likely maximum-magnitude event along the Sparta fault. On the other hand, an average slip of only 0.5 m on the Sparta fault would yield a moment similar to those of the largest recent earthquakes of Thessaloniki (1978) and Corinth (1981) ($M_0 = 0.52$ and 0.68×10^{19} N m)[2,3]. We conclude that the 464 BC earthquake most probably had a moment M_0 of the order of 3.0×10^{19} N m and a magnitude $M_s = 7.2$. A comparison of the scarp along the Sparta fault with other scarps with similar morphology in southern Peleponnesus and Crete (R.A., H.L.-C. and D. Papanastassiou, manuscript in preparation) suggests that these scarps are of Holocene age (≥10 kyr). In this event the slip rate of the Sparta fault would be ~1 mm yr^{-1}, and, if at least three events produced the observed 10-m-high scarp ($M_s \approx 7.2$ each), the corresponding maximum recurrence time for large earthquakes would be of the order of 3,000 yr. □

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