TEKTONIKA

The Antique Sparta Earthquake (Peloponnesus, Greece) and Limestone Scarps on Active Faults: a Field Guide

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Abstract The 464 BCE Sparta earthquake (Greece) is one of the main historically documented seismic events in the Mediterranean, yet its tectonic source and magnitude remained unknown until the 1990's. This field guide synthesizes historical accounts and integrates field observations with seminal works (*Armijo et al.*, 1991, 1992; *Benedetti et al.*, 2002) to assess the seismotectonic context of the Sparta Fault, a prominent normal fault bounding the Taygetus mountain range (highest mountain of the Peloponnesus). Along the fault, and at the base of spectacular triangular facets, a steep 10 m high limestone scarp points to repeated surface-rupturing earthquakes. Field observations and cosmogenic dating (*Benedetti et al.*, 2002) show that the scarp formed through the accumulation of at least 4 to 5 Holocene earthquakes with ~2 m displacement, the most recent one being the 464 BCE event. We detail a series of field stops, progressing from large-scale panoramic views of the fault system to close-up observations of the scarp itself. We conclude by outlining the field-based discussions that can be conducted with participants to the excursion regarding the interactions between fault activity, climate-driven landscape evolution, and seismic hazard assessment.

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1 Introduction

In regions where written records date back centuries or even millennia, such as in the eastern Mediterranean countries, many ancient earthquakes are described from historical texts (*Ambraseys*, 2009). However, these texts are often limited, difficult to interpret, and sometimes biased in the geographical coverage of their descriptions. They are more targeted to political and societal issues and never describe the fault or surface ruptures. This implies that identifying the active fault responsible for any of these past earthquakes is usually very challenging. In an article published in the early 1990's (*Armijo et al.*, 1991), R. Armijo and colleagues discussed what the likely tectonic source of the famous Sparta (southern Peloponnesus, Greece) earthquake of 464 BCE[1] might be. This antique earthquake is exceptional because of its important political repercussions: it triggered a revolt against Spartan rule, significantly weakened Sparta's power for a decade or more, and served as a trigger for the Third Messenian War (*Cartledge*, 2001). *Armijo et al.* (1991) linked the earthquake to a prominent limestone fault scarp along the front of the Taygetus ($T\alpha\ddot{\upsilon}\gamma\epsilon\tau o\varsigma$) mountain range west of the city of Sparta ($\Sigma\pi\acute{\alpha}\rho\tau\eta$). In a companion paper (*Armijo et al.*, 1992), the same authors then examined the significance and age of the numerous limestone scarps discovered in the Peloponnesus and Crete, features that are in fact widespread in many Mediterranean countries (e.g., *Giraudi*, 1995; *Piccardi et al.*, 1999; *Mitchell et al.*, 2001; *Palumbo et al.*, 2004). A decade later, in another seminal paper, *Benedetti et al.* (2002) used ^{36}Cl cosmogenic exposure dating to constrain the number and timing of successive earthquakes that cumulatively formed the scarp, and derive an estimate of the scarp's total age.

Here we first briefly summarize the historical record and the seismotectonic context of the 464 BCE earthquake. We subsequently describe a brief field excursion designed to investigate the geomorphology of the Taygetus mountain front which is delineated by the active normal Sparta Fault (Figure 1). The fault is characterized by a steep, continuous scarp reaching heights of approximately 10 meters. During the excursion, we will visit one of the two sites where the scarp was sampled and dated using ^{36}Cl by *Benedetti et al.* (2002). This field excursion is inspired by the field course "Failles Vivantes" organized for years for M.Sc. and PhD students from IPGP (Institut de physique du globe de Paris) and University Paris Cité. As we ask participants in this course, we recommend reading in advance the articles by *Armijo et al.* (1991, 1992) and

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[1]The exact date of this major earthquake is uncertain–between 469 and 463 BCE according to Ambraseys (2009). Here we keep the date of 464 BCE retained by Armijo and the articles that followed. Note that hereafter we will use BCE and CE for the dates (meaning Before Common Era, and Common Era, respectively).

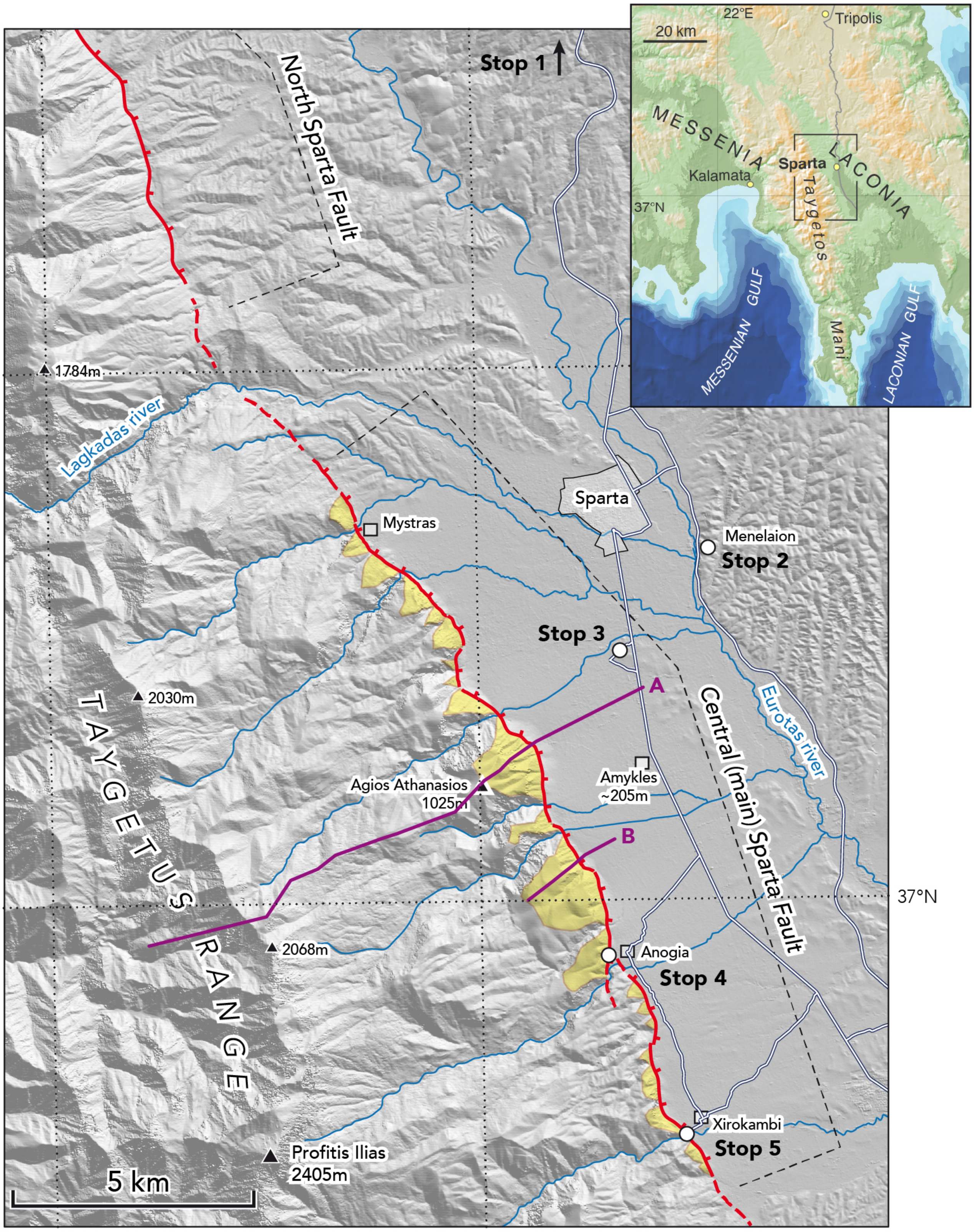

Figure 1 – Map of the main Sparta Fault. Inset to the top right shows map location in the frame of southern Peloponnesus together with geographic names mentioned in text. Black and white shaded topography is from TanDEM-X 5m resolution DEM. Active trace of the Sparta fault is in red, dashed where uncertain, and with ticks pointing to the downthrown side. Main triangular facets are outlined in yellow based on Armijo et al. (1991) mapping. Field excursion stops are located by white dots (stop 1 is ~5 km north of map limit). Segmented purple lines labelled A and B correspond to topographic profiles displayed in Figure 4.

Benedetti et al. (2002) and bringing the figures from these articles with you in the field. The excursion presents the opportunity to review those seminal works about active faults in Greece. In the final section of this article (section 4) we summarizes the type of discussions that can be conducted in the field with the excursion participants, drawing on observations and published literature.

2 The Historical Record and Seismotectonic Context

The only historical record nearly contemporary with the 464 BCE earthquake was by Thucydides (~460-395 BCE) in the History of the Peloponnesian War (431-404 BCE). Thucydides very brief report[2] is focussed more on the important political consequences of the earthquake than on its effects on the landscape. Thucydides wrote that, taking advantage of the earthquake, the Helots (subjugated people often considered as slaves of the Spartans) and the Perioeci from Messenia[3] (Perioeci were free people but not full Spartan citizens living in secondary cities under the rule of Sparta) revolted against the Spartans. This rebellion was at the start of the so-called Third Messenian War marked by the siege of Ithome, a Messenian fortified mountain where rebelled Helots and Perioeci took refuge (e.g., *Cartledge*, 2001). Writing several centuries later, Diodorus of Sicily (1st century BCE) and Plutarch (46-119 CE) gave more details on the disaster of the city of Sparta than Thucydides. According to them, the earthquake devastated the ancient city of Sparta: *'A great and incredible catastrophe befell the Lacedaemonians; for great earthquakes occurred in Sparta, and as a result the houses collapsed from their foundations and more than twenty thousand Lacedaemonians 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 and no little household property was ruined by the quake'* [Diod. 11.63][4]. *'A greater earthquake than any before reported rent the land of the Lacedaemonians into many chasms, shook Taygetus so that sundry peaks were torn away, and demolished the entire city with the exception of five houses'* [Plut. Cim. 16][5]. Even if modern historians (e.g., *Cartledge*, 2001; *Ruzé and Christien*, 2007) consider these late reports, which are based on rather elusive sources, as exaggerated (the death toll of 20,000 victims seems particularly implausible), they confirm that the 464 BCE earthquake was indeed a very strong and destructive earthquake in Laconia. It temporarily greatly diminished the power of Sparta, prompting the Helots to rebel and the Messenians to fight against the Spartans for their freedom and independence (*French*, 1955; *Cartledge*, 2001; *Ruzé and Christien*, 2007). The siege of Mt. Ithome lasted up to 10 years (*Cartledge*, 2001) and ended with the resumption of Sparta's power and the exile of the rebelled Messenians to Nafpaktos in the western Corinth Gulf (*French*, 1955; *Cartledge*, 2001; *Luraghi*, 2002).

After briefly recalling this historical record, *Armijo et al.* (1991) inferred that *'the destruction caused by the earthquake was much less in the Pamisos valley* [W of the Taygetus range] *where the Messenians were settled, than in the Sparta and Eurotas valley* [E of Taygetus]*'*. From this observation, they concluded that the source of the earthquake must be a *'shallow crustal event located not far from Sparta'* rather than a deeper, more distant subduction event that would have produced more widespread regional destruction (*Armijo et al.*, 1991). This prompted them to target the prominent normal fault that separates the Taygetus range from the Sparta plain and Eurotas valley as the likely source.

The Taygetus range is a ~60 km long range that reaches an elevation of 2405 m at Profitis Ilias summit and extends southward into the Mani Peninsula (Figure 1). The Sparta fault follows the NE base of this mountain front. It is an east-dipping normal fault made of three main NNW-SSE striking segments. *Armijo et al.* (1991) focussed their analysis on the ~20 km long central fault segment facing the city of Sparta and extending southward in front of the Eurotas valley (Figure 1). They described a typical tectonically active mountain front characterized by triangular and trapezoidal facets and wineglass canyons, and marked at its base by a steep, up to 10m high limestone scarp. Interpreting this scarp as due to the accumulation of a few earthquakes, they suggested a most likely magnitude of M_s 7.2 for the 464 BCE earthquake (*Armijo et al.*, 1991). Following earlier observations by geomorphologists (e.g., *Dufaure*, 1977), *Armijo et al.* (1991, 1992) interpreted the Sparta fault scarp and similar scarps in the Mani peninsula and in Crete as offsetting erosional-depositional surfaces formed during glacial periods of the Pleistocene. It follows that such limestone scarps would be roughly Holocene in age, thus 10-15 ka old. From the sampling of the Sparta scarp at two sites (Anogia and Parori) and ^{36}Cl analyses, *Benedetti et al.* (2002) confirmed this post-glacial age, an interpretation that will later turn out to be true for most comparable calcareous scarps in the Mediterranean area (e.g., *Benedetti et al.*, 2013; *Palumbo et al.*, 2004; *Schlagenhauf et al.*, 2011). *Benedetti et al.* (2002) also confirmed that the scarp formed by the accumulation of offsets due to 4-5 earthquakes, with 500 to 4500 yrs time interval between those events. More recently, taking the destructive 464 BCE earthquake as a typical earthquake, *Papanikolaou et al.* (2013) estimated that a future event on the Sparta fault may result in seismic intensities IX in the Sparta area with a probability of occurrence up to 3.0±1.5 % over the next 30 years. This highlights a significant seismic hazard affecting the Laconia area and the fact that a reassessment of the building code might be necessary.

[2] Thuc. 1.101 – http://www.perseus.tufts.edu/hopper/text?doc=Thuc.+1.101

[3] The Sparta region to the east of Taygetus is called Laconia. Messenia is the region on the other (west) side of Taygetus. Today, the modern city of Kalamata is the largest city of Messenia.

[4] Diod. 11.63 – https://www.perseus.tufts.edu/hopper/text?doc=Diod.+11.63

[5] Plut. Cim. 16 – https://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:2008.01.0017:chapter=16

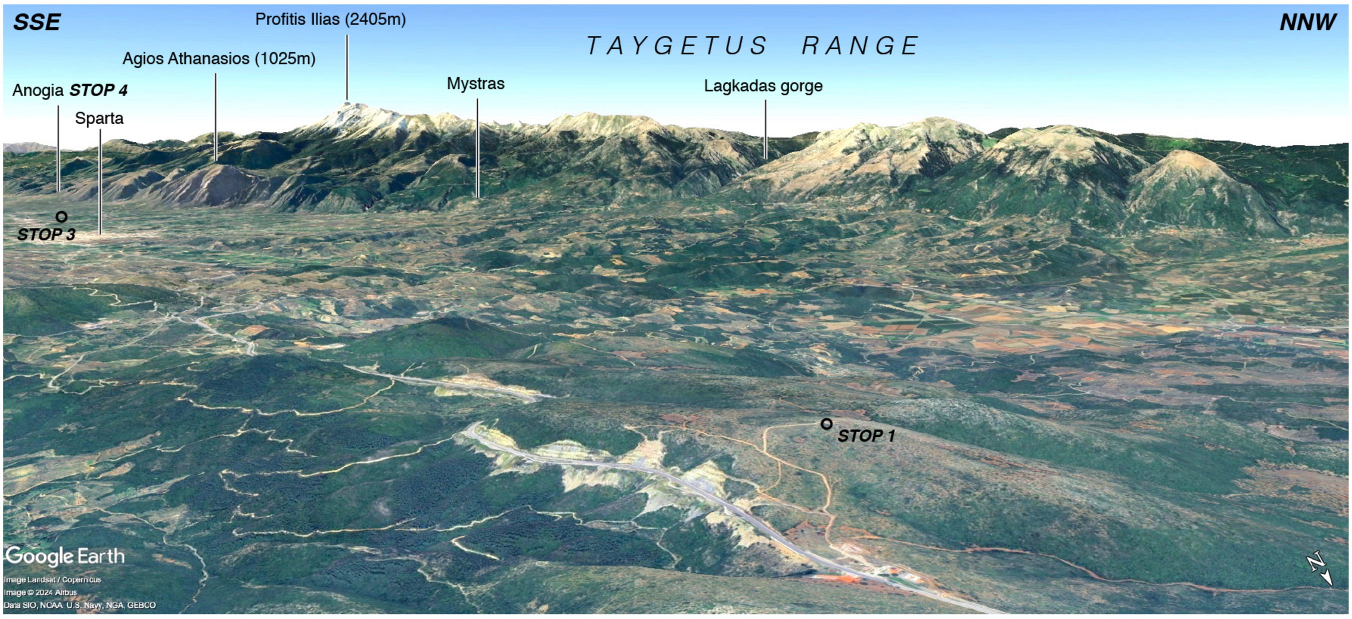

Figure 2 – Google Earth panoramic view (facing SW) of the Sparta region and Taygetus mountain range, as observed from above stop 1 (location marked on the image).

3 From Landscape View to the Earthquake Scarp, a Field Guide on the Sparta Fault

Following *Armijo et al.* (1991), we focus our excursion on the central segment of the Sparta fault. We start from landscape panoramic views to examine the general morphology of the Taygetus range and of the fault (Stops 1 and 2). Ideally, for the best lighting, these two stops should be visited quite early in the morning. Then we transfer closer to the mountain front to have a better view on the triangular facets and the fault scarp at their base (Stop 3). We end our excursion in Anogia village to closely examine the fault scarp itself where it has been dated with ^{36}Cl (Stop 4). We then briefly describe an optional complementary stop at the outlet of a deeply entrenched canyon (Stop 5). Below we provide brief practical information about the different stops. More details (routes and stop localisation in kml format, aerial views of the different sites) are given in the Supporting Information and can also be accessed from the Zenodo repository: https://doi.org/10.5281/zenodo.20050370.

3.1 Stops 1 and 2, General Morphology of the Taygetus Range and of the Sparta Fault

Stop 1 is along the old National road E961 from Tripolis to Sparta at 37°13.20'N - 22°25.44'E. Turn right then left on the dirt track between the buildings and park near a fence. Open the gate at the south end of this fence and walk ~1 km up the hill to the antennas (37°12.76'N - 22°25.08'E, 873 m elevation). You can also drive up to the top of the hill but the track is in pretty bad shape. From the hilltop you will have a general panorama of the Taygetus range. Duration: ~1.5 hour including observation and discussion time and the walk there and back. Note that the view from the top is spectacular but is only worth visiting if the atmosphere is clear and the light contrasting. Otherwise, you will have to settle for the clear view at stop 2.

The panorama from Stop 1 provides a general view of the Taygetus range which extends for about 60 km roughly north-south and reaches elevation above 2000 m (Figure 2). The Sparta Fault – an east-dipping normal fault made of several NNW-SSE striking segments – runs along the base of the eastern mountain front and separates it from the Eurotas plain where the modern city of Sparta is built. Note that the opposite western flank of Taygetus (not visible from viewpoint) is marked by less continuous and more segmented normal faults, some of which ruptured during the Kalamata earthquake (M_L 5.5) in 1986 (*Lyon-Caen et al.*, 1988). *Armijo et al.* (1991) identified two primary segments for the central part of the Sparta Fault, each approximatively 20 km long, one north and one south of the Lagkadas (Λαγκάδας) gorge. This gorge is the very distinct cut in the landscape clearly visible from stop 1 (Figures 1, 2). Like *Armijo et al.* (1991), we will focus on the southern segment, south of the gorge, which we hereafter call the Main Sparta Fault (Figure 1). Note that you may refer to *Cal et al.* (2024) for a geomorphic description of the northern segment. The Main Sparta Fault is facing the modern city of Sparta and the Eurotas plain east and prolongates south towards the Laconian gulf. From stop 1, looking south toward the Taygetus range, you start to see the characteristic morphology of an active mountain front with a convex and steeper shape near the base where the fault lies (Figure 1, 2). Stop 2, and more particularly Stop 3, will allow us to examine these characteristics more closely.

Exit stop 1 and follow the national road until you approach the modern city of Sparta. At the sign"Sparti 2km" turn left in the direction of Gytheio/Monemvasia, then at the roundabout turn right (direction Geraki,

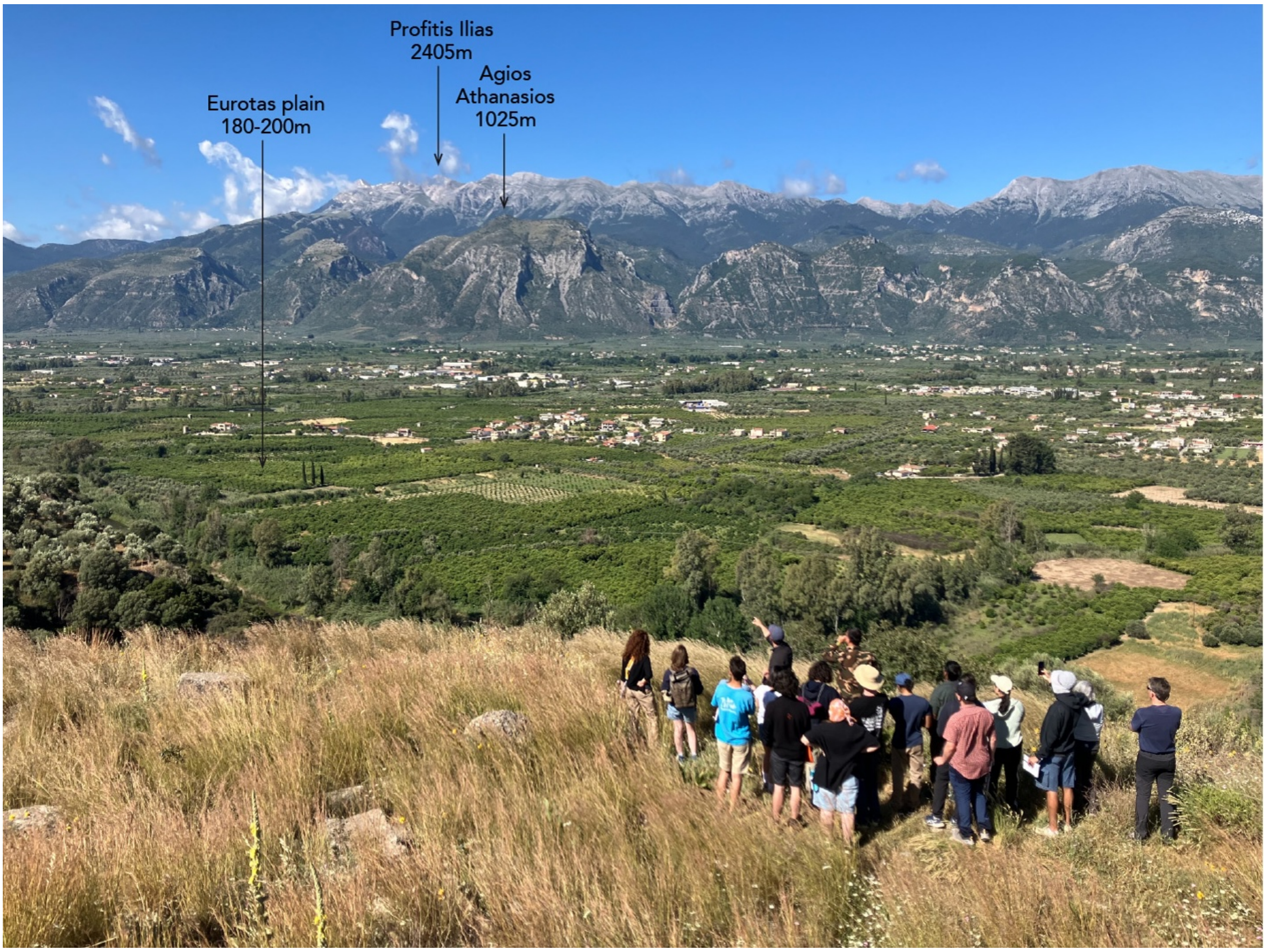

Figure 3 – View from Menelaion (Stop 2) with the Eurotas plain in front and the highest part of Taygetus mountain range in the background.

Gytheio, Monemvasia). Follow the Sparta outer deviation ring south for ~2.5 km until reaching a small crossroads (37°4.36'N - 22°27.03'E) with a dirt road on the left marked "Menelaia". Take it and park near the small church. Continue on foot ~1km to the archaeological remains to get a panoramic view toward the west (37°3.95'N - 22°27.21'E). Duration: ~1.5 hour including observation and discussion time and the walk there and back.

Stop 2 is at the Menelaion ($M\epsilon\nu\epsilon\lambda\acute{\alpha}\epsilon\iota o\nu$) archeological site (Figure 1, 3). From there, the modern Sparta town is visible to the northwest. The frontal panoramic view of the highest part of the Taygetus range and of the whole Main Sparta Fault—i.e. the fault segment studied by *Armijo et al.* (1991)—is spectacular (Figure 3). The total structural relief is about 2000 m on average, from the range crest, above 2000 m a.s.l., to the Eurotas plain at ~180 m a.s.l. Highest elevation is reached 2405 m at Profitis Ilias. The range topography is marked by two distinct steps with a flatter area in the middle at about 1000 m altitude (Figures 4a, 5a). The lower step, facing the Eurotas plain, is very steep. It has a convex shape in section, and is formed by composite triangular or trapezoidal facets separated by wineglass canyons (*Armijo et al.*, 1991). As already mentioned above these are typical indicators of an active mountain front whose morphology is regularly rejuvenated by active faulting and uplift events (e.g., *Wallace*, 1978). In contrast to the lower step's morphology, the topography from the flatter area at ~1000 m up to the summit crest of the range shows a more concave shape, resembling an erosive equilibrium profile (Figure 4a). This suggests that only the lower, steeper and convex step represents the structural relief recently acquired due to movement on the active Sparta Fault central segment. It reaches a maximum height of ~850 m between Agios Athanasios submit at 1025 m and the Eurotas plain at 200-160 m altitude (Figures 4, 5a). Agios Athanasios is at the top of the most prominent triangular facet in the center of the panorama (Figures 3, 5a). *Armijo et al.* (1991) subdivided the Main Sparta Fault segment into three sub-segments, each 6 to 7 km long: one from Mystras to the north of Agios Athanasios, a middle one with higher structural relief from Agios Athanasios to Anogia, a southern one from Anogia toward the south (Figure 1). Note that consideration of fault geometry and segmentation may have important consequences when evaluating potential seismic rupture length and

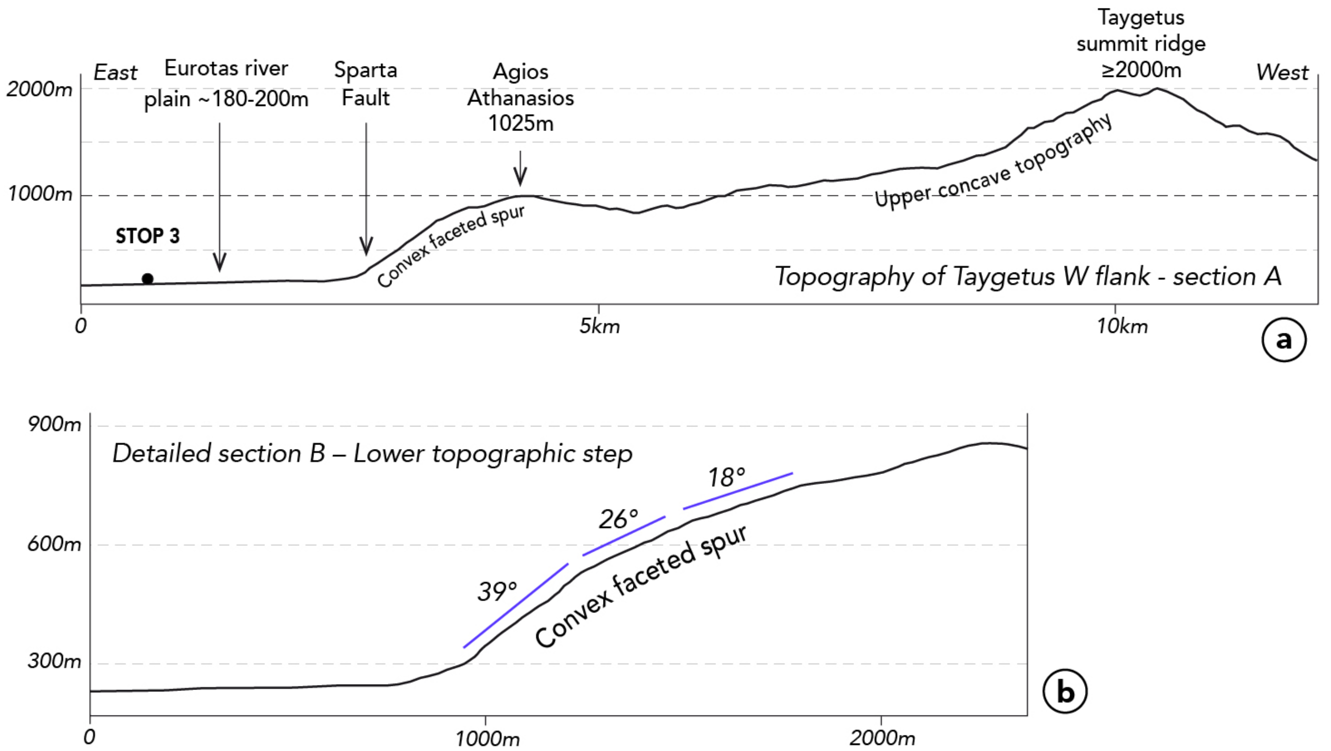

Figure 4 – Schematic topographic profiles across the western flank of the Taygetus mountains (profile traces shown in Figure 1 and labelled A and B). **a)** General topographic transect from the Eurotas plain to the summit crest. **b)** Detailed profile of the lower topographic step, illustrating its convex morphology and the estimated average facet slopes along this section.

earthquake magnitude[6]. Next stop will be a few km south of Sparta, closer to the range and just in front of the Agios Athanasios faceted spur.

3.2 Stop 3, a Mountain Front Shaped by Active Faulting

From Menelaion, return to the main road, drive back to the north ~1km, then turn left toward the modern city of Sparta. After crossing the town of Sparta, take the main road toward the south for ~2.5 km. Before crossing Amykles, take a small road to the right around the corner of a supermarket, cross the small hill and park along the road to stop 3 (37°2.79'N - 22°25.96'E). The best view is from the southern side of the olive grove on the left (south) of the road.

Stop 3, at ~200 m asl, is in front of the highest faceted spur topped by the Agios Athanasios summit (1025 m), roughly in the middle of the Main Sparta Fault (Figure 1). From there, the composite triangular/trapezoidal facets are clearly visible (Figure 5b). The valleys separating the faceted spurs are very narrow at the bottom and open more widely at the top forming a V profile, the whole resembling a wine glass. On Figure 6, hand-drawn sketches taken from our teaching field sketchbook illustrate the main characteristics of such faceted spurs. *Armijo et al.* (1991) have identified three sets of imbricated facets characterized by average slopes of ~40°, 30° and 20°, which collectively define the convex topography of the spur. A representative topographic profile across such a convex spur is illustrated in Figure 4b. The lowermost and most abrupt facet has an height of ~250 m. At its base, it is marked by an even steeper fault scarp, several meters high and laterally continuous, that cuts either the metamorphosed crystalline limestones of the fault footwall, or indurated Plio-Quaternary conglomerates constituting the top of an alluvial fan. From the viewpoint at Stop 3, the scarp is already visible from afar (Figures 5b, 6a, 7). At places, it is emphasized by small trees growing at its base, which gives an idea of its height (5-10 m). It was particularly visible a few decades ago when the vegetation was sparser as shown by a photograph taken in the 1990's (Figure 7), corresponding to the framed part of the scarp on Figure 5b. The fault scarp extends for kilometers along its strike, continuing southward to Anogia, where it is easily accessible to examine its details (Stop 4 below).

3.3 Stop 4, the Limestone Fault Scarp at Anogia

From stop 3 return to the main road and continue south for about 5 km. Turn right toward "The shelters of Taygetus" (as indicated on the sign), and reach the village of Anogia. Park on the square in the village centre, in front of the church of Agios Georgios. Walk half a kilometer westward to reach the fault scarp at

[6]Several studies have demonstrated that scaling-laws link earthquake magnitude to fault rupture length (e.g., *Wells and Coppersmith*, 1994).

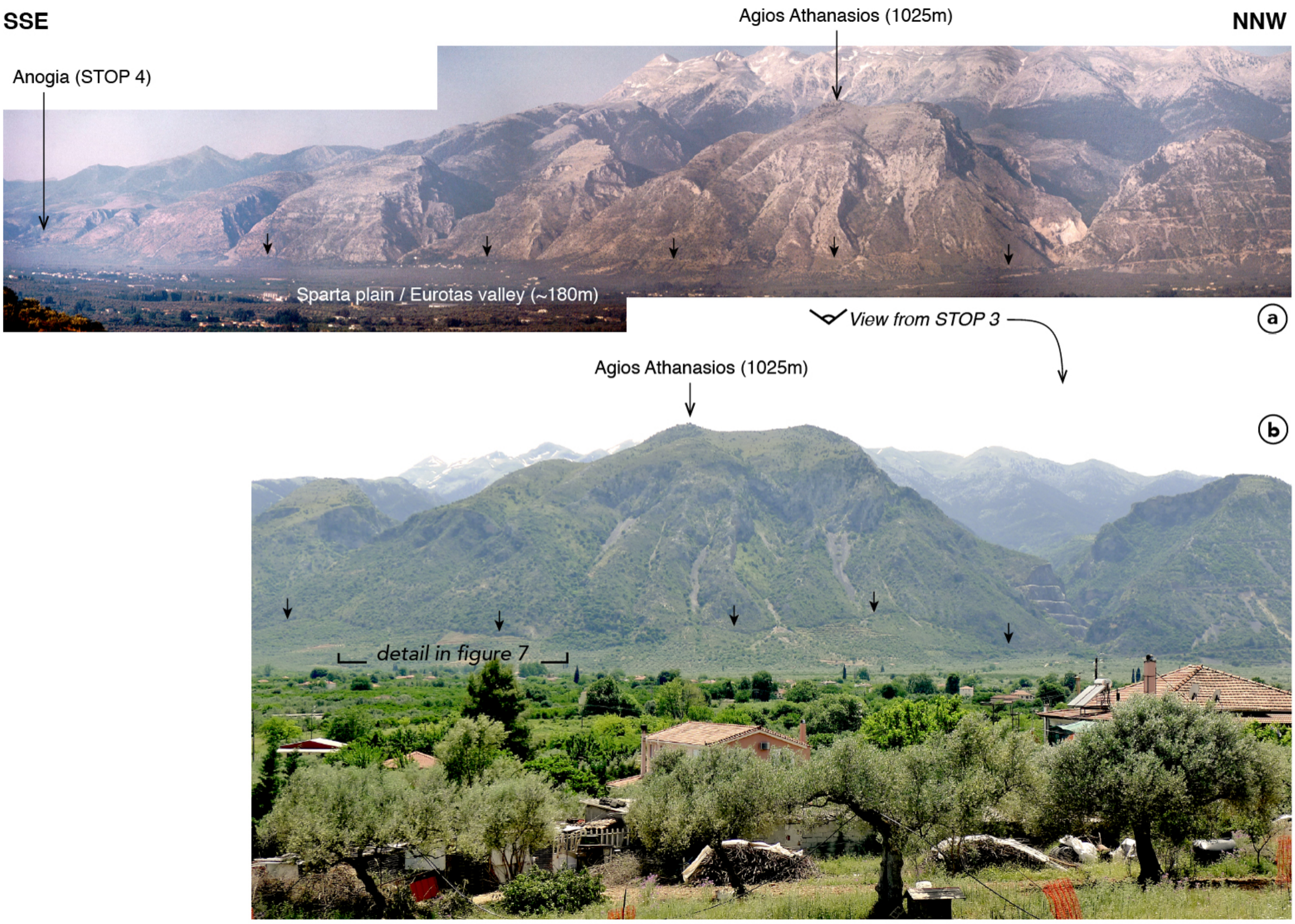

Figure 5 – **a)** Panoramic view (from Stop 2) of the prominent triangular facets at the base of the western flank of the Taygetus mountains. **b)** Closer view (from Stop 3) of the highest faceted spur topped by the Agios Athanasios summit. Arrows point to the steep scarp at the base of the facet. A hand-drawn sketch of this faceted spur is displayed on Figure 6.

a small cypress grove (36°59.38'N - 22°25.75'E), see detailed description of the route from the village square in Supporting Information.

Following the path from the village centre allows to reach a flatter area with a closer view on the steep fault scarp. From there the scarp resembles a wall built of limestone about 10 m high (Figure 8a). Above the scarp, the slope of the triangular facet is more degraded by erosion. According to *Armijo et al.* (1992), this slope is locally '*encrusted by lime-indurated conglomerates directly derived from erosion of the calcareous mountain front*'. Such conglomerates form the steep piedmont talus at the base (east) of the scarp. Crossing through the bushes by a barely visible path allows to reach a grove of cypress trees at the top of this piedmont talus and to touch the scarp itself (Figure 8b). Note the smoothness of the scarp surface which is only moderately degraded by karstification. The surface is locally marked by slickensides and corrugations indicating normal movement. Two parallel sampling transects are visible on the scarp (Figure 8c), as it has been sampled twice for cosmogenic ^{36}Cl exposure dating. Sampling was made by sawing the crystalline limestones from the scarp's base to its top, then cutting it in ~10 cm wide samples. The results of the first study, made by the end of the 1990's, has been published by *Benedetti et al.* (2002). We briefly discuss these results below. The more recent sampling, easily identified as it is less weathered, has been made ~20 years later and is published by *Goodfellow et al.* (2024). Their results confirm Benedetti et al's conclusions.

Few meters further north along the scarp, a wedge of conglomerate is stuck against the limestone scarp (Figure 9). That sort of geometry is observed at several places along the limestone scarp. *Armijo et al.* (1991, 1992) interpreted this feature as the result of the most recent faulting event, which did not follow the limestone scarp but instead locally reached the surface by cutting through and uplifting the piedmont conglomerate slope (Figure 9c). Same type of geometry has been observed elsewhere on more recent surface ruptures, like for the 1981 earthquakes in the eastern Gulf of Corinth (Jackson et al., 1982). Based on slope continuation between the top of the conglomerate wedge and the down-dropped piedmont talus we can estimate the displacement due to the last faulting event. As the conglomerate wedge overhangs the talus by ~2 m, the displacement would have been of this order of magnitude at Anogia (Figure 9c). This implies that the 10 m high scarp is not due to one single earthquake that would have been huge, but is cumulative and due to several events (*Armijo et al.*, 1991).

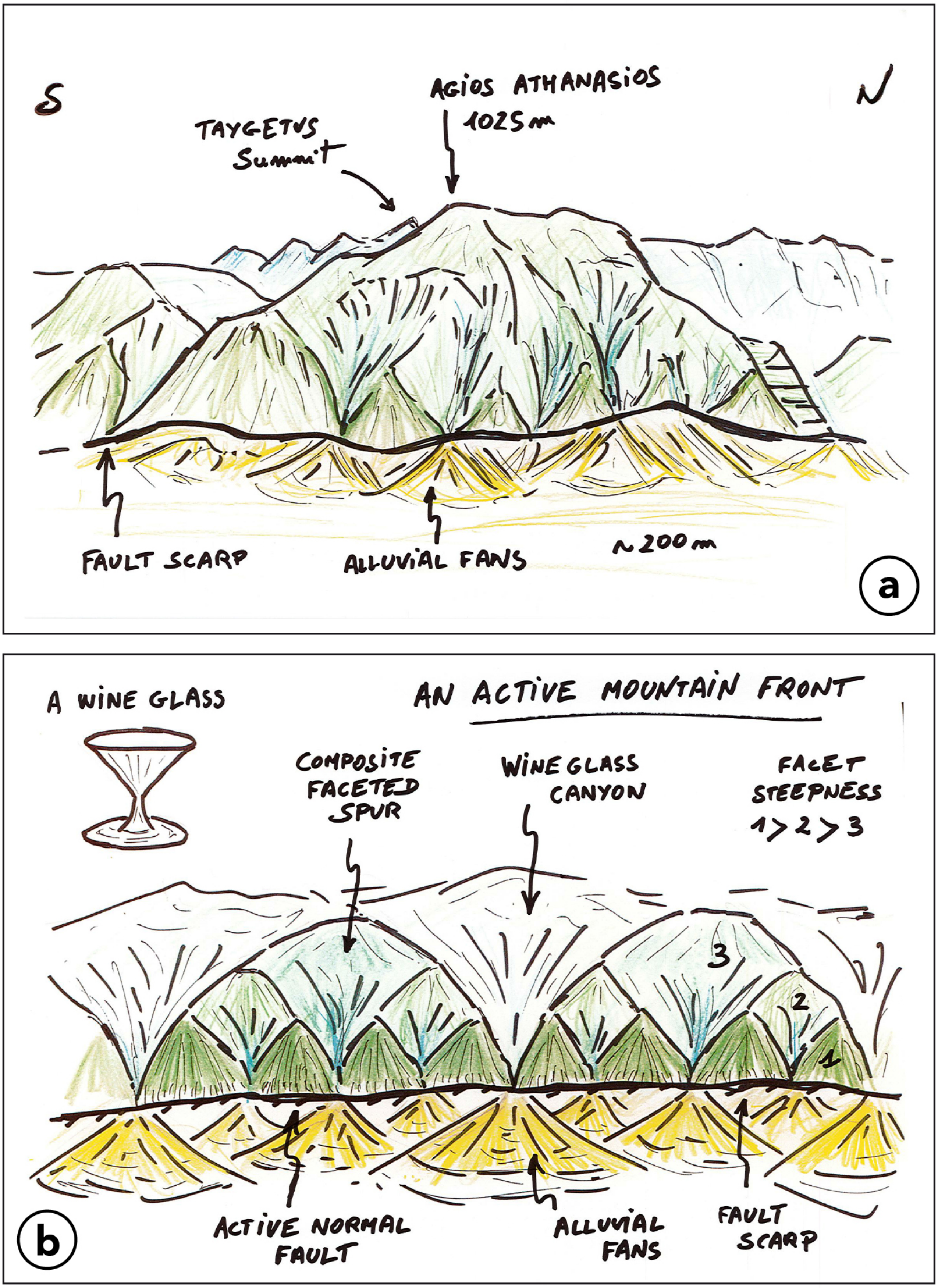

Figure 6 – Drawings taken from our teaching field sketchbook. **a)** the Agios Athanasios faceted spur as observed from Stop 3 (see also photo of the same panorama in Figure 5b); **b)** main characteristics of a mountain front shaped by active normal faulting at its base. These examples illustrate how hand-drawn notes can be usefully recorded during fieldwork.

Figure 7 – Detailed view of the Agios Athanasios facets (view located on Figure 5b). The steep limestone scarp (indicated by arrows) at the base of the facets is clearly visible in this 1990s photograph, when vegetation in the area was less dense. Photograph taken by R. Armijo.

3.4 Stop 5, an Antique Bridge on Top of the Fault and River Knickpoint

Optional stop. From the center of Anogia, drive south for ~4km on the old secondary road following the mountain front. Cross Paleopanagia, and reach the central square of Xirokambi. There turn right around the corner of a small café (a sign only in Greek indicates Koumousta and several other localities of Faridos Municipality) and then follow signs indicating "Hellenistic Bridge" and "Theater" in Greek. Park to the right before reaching the theater (36°57.38'N - 22°26.82'E) and follows the path to the antique bridge.

The antique bridge, built in Late Hellenistic-early Roman times (1st century BCE), is located at the exit of the very narrow Anakolou gorge deeply incised by the Erasinos river in the Mesozoic crystalline limestones. The bridge, which is located on the Sparta fault, is built on the Mesozoic limestones of the Taygetus range while Quaternary conglomerates with rounded pebbles are found immediately downstream of the fault. Those conglomerates may be observed along the path to the bridge. More precisely, the bridge sits just on top of a few meters high waterfall which marks a sharp knick-point on the river profile. This knick-point may have formed, or was amplified, by the 464 BCE earthquake, as a coseismic scarp, though we cannot exclude an additional effect of the lithological contrast between the limestones and the Quaternary deposits downstream. The ~2000-years-old bridge, postdating the 464 BCE event, has been constructed on top of the knickpoint /fault scarp and remained undisturbed since. Following the Anakolou gorge upstream leads to another knick point at some distance west of the frontal one.

4 Summary and Discussion

4.1 Magnitude and Recurrence Time of the 464 BCE Earthquake and Earlier Events

One key question following the discovery of the steep, decameter-scale scarp along the Sparta fault was to assess the possible magnitude of the 464 BCE earthquake. *Armijo et al.* (1991) noted that a rupture of the 20 km long Sparta fault with a slip of 10 m (i.e. the total height of the highest observed scarp) would imply a very high static stress drop. They considered it unlikely. This would also be at odd with the empirical earthquake scaling laws (e.g., *Wells and Coppersmith*, 1994). They considered a rupture with a displacement corresponding to approximately one-third of the scarp height as more credible, and suggested a magnitude of ~7.2 for the 464 BCE earthquake (*Armijo et al.*, 1991). The observation of conglomerate wedges perched against the fault and bordered by a secondary scarp like at Stop 4 (Figure 9) indeed supports this interpretation.

Ten years later, *Benedetti et al.* (2002) used cosmogenic dating to reconstruct the seismic history of the scarp at two locations: Anogia (Stop 4) and Parori, a site situated farther north near Mystras (Figure 1), which is now difficult to access[7]. By modeling of the ^{36}Cl concentrations, they estimated the number of recorded earthquakes, their displacements, ages, and recurrence intervals. The youngest event recorded at

[7] We present here a concise field excursion, progressing from landscape-scale observations to the analysis of the decametric scarp in Anogia. However, optional supplementary sites allowing observation of the fault scarp near Parori are included in the supplementary kml file.

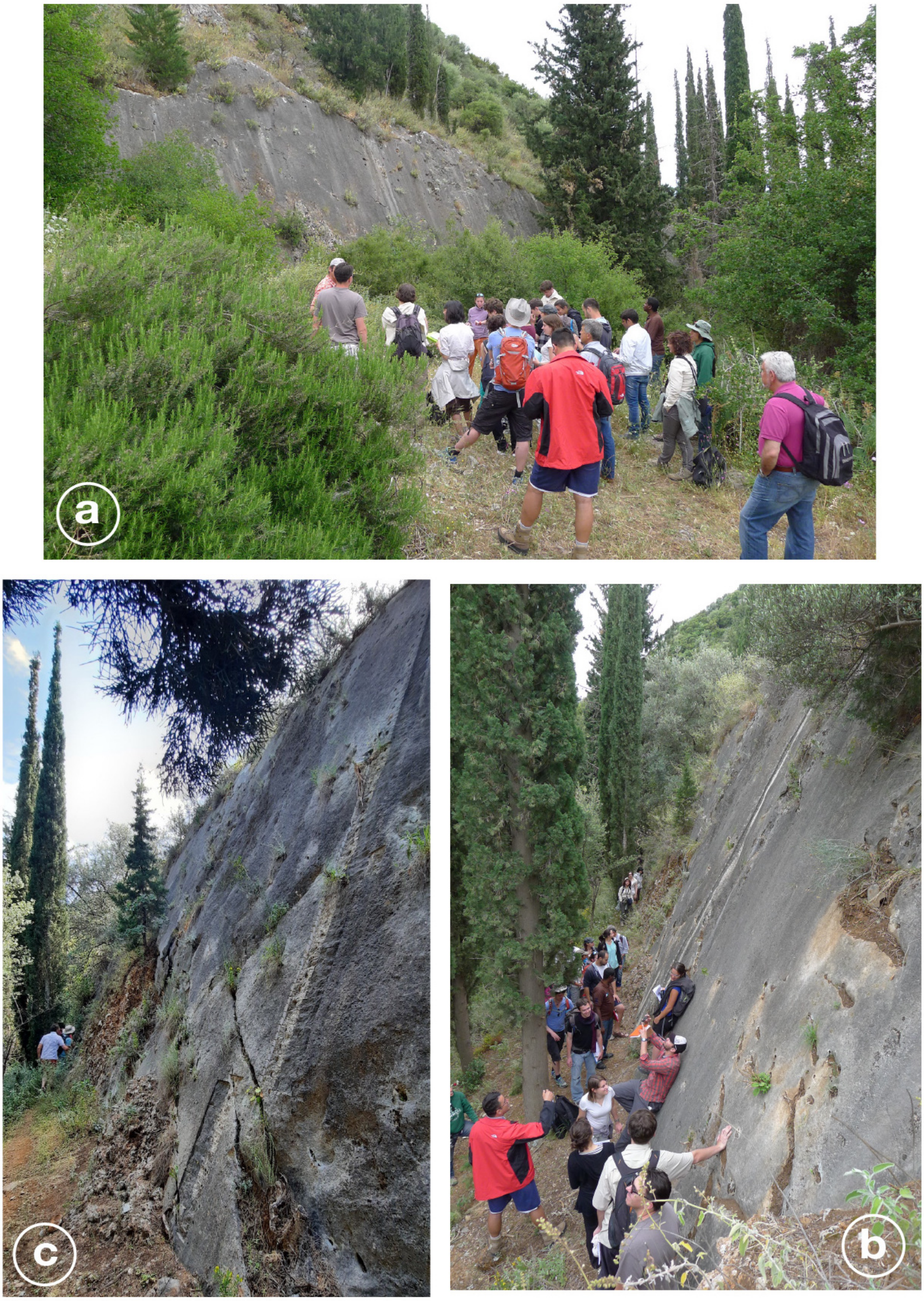

Figure 8 – Detailed views of the fault scarp at the Anogia site (Stop 4). **a)** Seen from some distance, the scarp resembles a smooth limestone wall, with the less steep facet slope above it locally overlain by encrusted red conglomerates. **b)** A closer view of the fault scarp (photograph taken from the top of the conglomerate wedge shown in 9a). The presence of people at its base provides a scale reference and allows to estimate its height, ~10 m. **c)** Detailed view of the fault scarp, illustrating the two ^{36}Cl sampling traces (ladder-like incisions in the limestone). Note the contrasting degrees of weathering between the two sampling sites, which were conducted approximately 20 years apart.

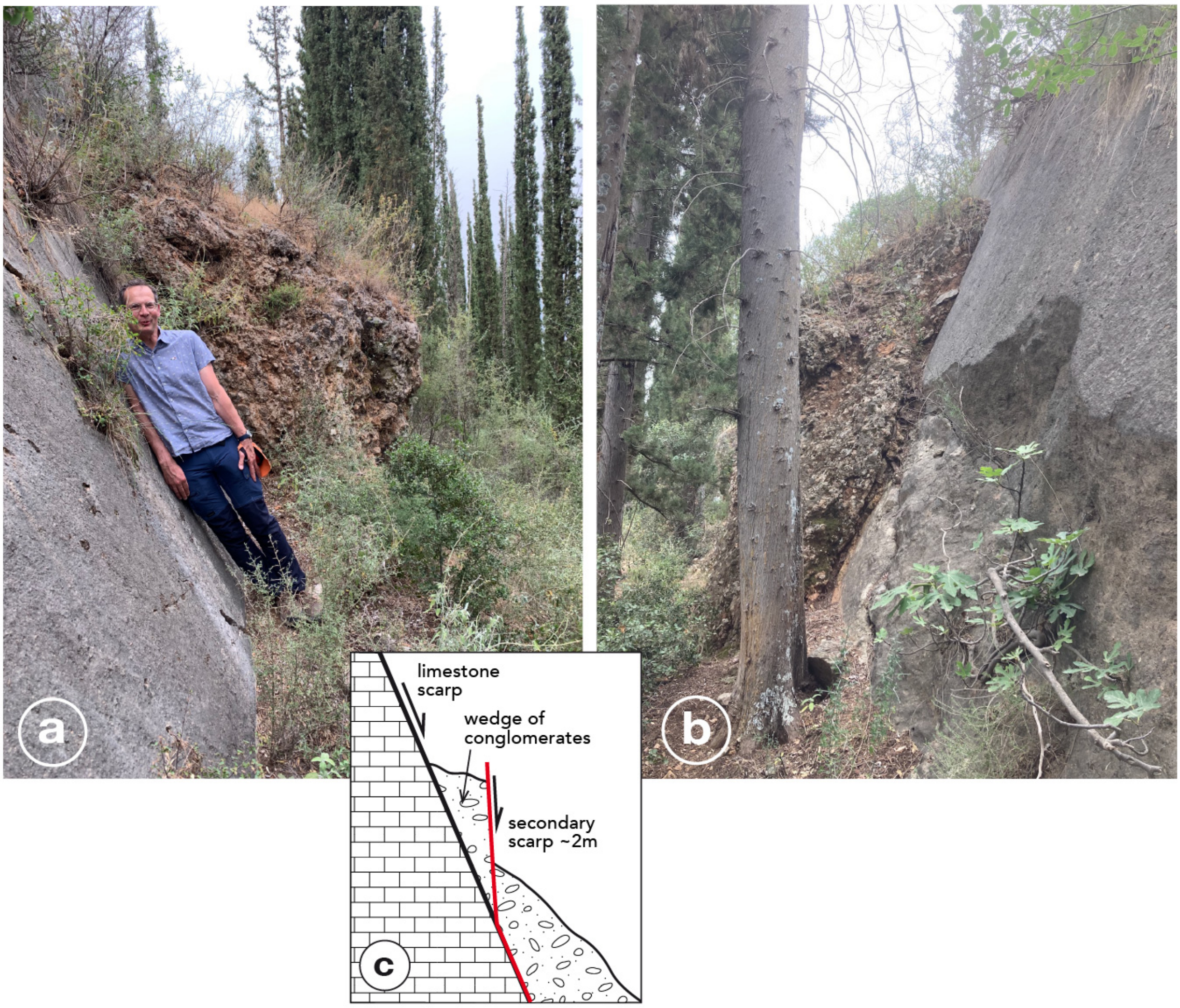

Figure 9 – two views of conglomerate wedges locally abutting the limestone scarp in Anogia. These wedges are delimited downslope by a secondary scarp approximately 2 meters in height (visible on the right in photo a, and on the left in photo b). An interpretative sketch is provided in 7c.

Parori dates to ~2.8 ka and is thus consistent with the 464 BCE earthquake. The associated displacement of 2 m supports the inference of a magnitude ~7 event for that earthquake. At least three additional events (at ~4 ka, 4.5 ka, and 5.9 ka) are documented at Parori by *Benedetti et al.* (2002), each also associated with a slip of ~2 m. In contrast, the most recent event they have identified at Anogia dates to ~4.5 ka, suggesting that the 464 BCE earthquake is absent from the scarp record here. The interpretation proposed by *Benedetti et al.* (2002) is that the Sparta earthquake bypassed the Anogia limestone scarp and ruptured few meters below as they found evidence for smaller scarps further down the slope. In hindsight, two alternative interpretations deserve consideration. We note that Anogia site is located at the southern tip of the central subsegment of the Main Sparta fault (Figure 1). There is a relay zone and the other subsegment that continues the fault further south is shifted to the east (Figure 1). This leaves the possibility that the 464 BCE earthquake branched on the southernmost subsegment bypassing the Anogia site more broadly than suggested by *Benedetti et al.* (2002), at least by hundreds of meters. Another possibility is that the rupture was limited to the northern portion of the main Sparta fault, terminating before reaching Anogia village. This would imply a shorter rupture and thus a slightly lower magnitude. Given the current uncertainties, none of these two options can be definitively ruled out.

While the repetition of ancient earthquakes with roughly consistent ~2 m displacements appears well demonstrated by Benedetti et al's study (*Benedetti et al.*, 2002), the recurrence intervals between these events exhibit significant variability, ranging from 500 to 4,500 years. Although large uncertainty remains, the estimated fault slip rate – on the order of 1 mm/yr (see below) – combined with the ~2,500-year elapsed time since the Sparta earthquake, suggests a high likelihood of another magnitude 6.5 to 7 event in the foreseeable future. An earthquake of such large magnitude would imply very strong shaking and destruction, with intensities IX, in the highly populated Sparta plain (see *Papanikolaou et al.*, 2013, for further discussion about the seismic hazard and time dependent probabilities in Sparta).

4.2 Limestone Fault Scarps, a Competition Between Tectonics and Surface Processes

Steep limestone scarps, such as the one observed in the field in Anogia, are also found along numerous active faults in Greece, Italy, and other Mediterranean countries (e.g., *Armijo et al.*, 1992; *Piccardi et al.*, 1999; *Mitchell et al.*, 2001; *Palumbo et al.*, 2004). This calls for a common explanation of their formation. It has been proposed that during colder Pleistocene periods, slope erosional processes were sufficiently intense to rapidly remove surface offset increments generated by past earthquakes (e.g., *Armijo et al.*, 1992; *Benedetti et al.*, 2002). As a result, cumulative scarp formation was inhibited. Subsequently, reduced erosional processes during the post-glacial period allowed slip increments to accumulate and the scarp to grow (e.g., *Armijo et al.*, 1992; *Benedetti et al.*, 2002; *Roberts and Michetti*, 2004). This reasoning suggests a shift in the balance between the tectonic and erosional rates. It assumes a roughly constant tectonic rate alongside significant variations in the erosional rate between glacial and post-glacial periods. For the sake of scientific debate, an alternative interpretation can be considered: maintaining a constant erosional rate while allowing the tectonic rate to vary. For example, the short-term tectonic rate could have increased due to recent earthquake clustering, allowing it to exceed the rate of scarp erosion or burial. If only the Spartan scarp were available for analysis, this interpretation could not be easily dismissed. However, the widespread presence of similar scarps across Greece and other Mediterranean regions makes this scenario highly improbable. While localized earthquake clustering cannot be ruled out for some of these faults, this cannot be the reason for the general scarp formation. Instead, as confirmed by some modeling results, scarp preservation reflects a dramatic decrease, of at least one order of magnitude, in the rate of hillslope erosion because of late Quaternary climate change (*Tucker et al.*, 2011). This implies that most of the limestone scarps observed in the field are post late glacial maximum (LGM), basically Holocene, in age. Cosmogenic dating results in Sparta (*Benedetti et al.*, 2002; *Goodfellow et al.*, 2024) support this interpretation, as the top of the scarp dates from the early Holocene. Similar conclusions have been reached for multiple limestone scarps in Italy and Greece (e.g., *Palumbo et al.*, 2004; *Roberts and Michetti*, 2004; *Benedetti et al.*, 2013; *Mechernich et al.*, 2018; *Goodall et al.*, 2021). We note however that some scarps at low altitudes or latitudes may, in certain cases, predate the Holocene, though they remain predominantly post-LGM in age (e.g., *Mechernich et al.*, 2023; *Mitchell et al.*, 2025).

Based of the observation that the steep ~10 m high scarp in Sparta is of Holocene age, *Armijo et al.* (1991) and *Benedetti et al.* (2002) proposed an average slip rate on the order of 1 mm/yr for the Sparta fault. Given that the scarp does not uniformly reach 10 m in height and may be slightly older than 10 kyr (Holocene starts at ~12 kyr) the inferred average slip rate on the Sparta fault likely ranges between ~0.7 and 1 mm/yr.

One implication of the above reasoning, and the observation that most scarps are Holocene in age, is that Greek active faults can be qualitatively compared. Specifically, one might hypothesize that a fault with a 1 m high scarp could exhibit a slip rate of ~0.1 mm/yr roughly one order of magnitude lower than one with a 10 m high scarp like in Sparta. Another implication is that, under two important assumptions, we can approximate the age of the active Sparta fault. First, we assume that the steep, convex frontal relief reaching a maximum height of 850 m at Agios Athanasios (Figures 4, 5) results exclusively from fault activity (As discussed at stops 1 and 2 and illustrated by Figure 5). Second, we need to account for the unquantified throw in the hanging wall of the fault. Combining these assumptions, and also assuming a constant slip rate since the initiation of the fault, its formation likely dates to ~1–2 million years ago. It has been discussed elsewhere (e.g., *Armijo et al.*, 1992; *de Gelder et al.*, 2022) that a newly developed set of N-S-trending faults, including the Sparta Fault, accommodating E-W extension, formed along the Aegean arc in response to recent changes in plate boundary conditions. These changes, such as increased coupling along the Hellenic subduction zone – potentially driven by, e.g., the incipient collision with the African continental margin or the westward propagation of the North Anatolian Fault into the Aegean system – may have triggered a transition from a N–S to an E–W extensional regime (see *de Gelder et al.*, 2022, for further discussion).

4.3 Final Remarks

The above discussion and deductions should not be viewed as definitive demonstrations, or proofs, but rather as illustrations of the reasoning processes we try to guide students through during the “Failles Vivantes” field course. Such exercises encourage them to critically consider the orders of magnitude of physical values in seismotectonics. This enables them to distinguish between plausible and implausible scenarios, thereby facilitating discussions about fault activity, regional geodynamical context and changes. The same progressive approach in the field, ranging from large-scale landscape analysis to metric-scale scarp investigation, coupled with a discussion of these observations and their implications, could very likely be applied to other geographical contexts, such as the numerous active normal faults of the Apennines in Italy.

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Author contributions

All authors contributed to teaching the Failles Vivantes field course and collaborated in designing its pedagogical framework. RL wrote the manuscript with help of the other authors.

Data availability

The TanDEM-X data used to generate the base-map of Figure 1 were acquired in the frame of a project (DEM_GEOL0584, PI R. Lacassin) supported by DLR (German space agency). These data are distributed under a restrictive licence and cannot be openly shared. Other data are included in the manuscript, the Supporting Information, or in the cited references.

Competing interests

The authors declare no competing interests.

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