Proceedings of the Geologists' Association 128 (2017) 711–721

Contents lists available at ScienceDirect

Proceedings of the Geologists' Association

journal homepage: www.elsevier.com/locate/pgeola

Seismic faults and sacred sanctuaries in Aegean antiquity

Iain S. Stewart[a,*], Luigi Piccardi[b,*]

[a] School of Geography, Earth, & Environmental Sciences, University of Plymouth, Plymouth PL4 8AA, UK
[b] C.N.R., Institute of Geosciences and Earth Resources, Via G. La Pira 4, 50121 Firenze, Italy

ARTICLE INFO

Article history:
Received 6 November 2016
Received in revised form 27 July 2017
Accepted 28 July 2017
Available online 9 September 2017

Keywords:
Earthquakes
Archaeology
Tectonics
Greece
Turkey

ABSTRACT

The ancient destructive capability of earthquake faults is well chronicled by historians and their cultural impact widely uncovered by archaeologists. Archaeological and geological investigations at some of the most renowned sites in the ancient Greece world, however, suggest a more nuanced and intimate relationship between seismic faults and past human settlements. In the Aegean's karstic landscape earthquake fault scarps act as limestone ramparts on which fortifications, citadels and acropoli were constructed, and underlying fault lines were preferred pathways for groundwater movement and egress. The vital purifactory or therapeutic role of natural springs in the ritual practices of early settlements implies that the fault lines from which they leaked may have helped position the nascent hubs of Greek cities. Equally, the tendency for earthquakes to disrupt groundwater patterns and occasionally shut down persistent springs provides a hitherto unrecognized mechanism for the abrupt demise of those same settlements. Votive niches, carvings, reliefs and inscriptions on fault surfaces suggest important sacred sanctuaries, particularly those with oracular functions, may have been deliberately built astride active fault traces and venerated as direct connections to the chthonic realm ('the underworld'). Regionally, the Aegean's distributed network of tensional faulting, circulating geothermal waters and deep-seated de-gassing sets the tectonic framework for the springs and gases that infuse the ancient Greek netherworld of caves, chasms, chambers, and sacred grottos. The possibility that seismic faults may have constituted the fulcrum of prominent sacred places means that, for all their obvious destructiveness, earthquakes may have had an unacknowledged cultural significance in Greek antiquity.

1. Introduction

Throughout human history in the eastern Mediterranean region, urban settlements have co-existed with earthquakes (de Boer and Sanders, 2006). The destructive capability of seismic activity is well chronicled by historians (Ambraseys, 1971; Guidoboni et al., 1994), and its cultural wreckage widely uncovered by archaeologists (Karcz and Kafri, 1978; Rapp, 1986; Nikonov, 1988; Stiros and Jones, 1996; Sintubin et al., 2010; Jusseret and Sintubin, 2017). Accounts and observations of seismic damage to ancient constructions and relics offer partial information on the size, location and date of ancient earthquakes (Sintubin and Stewart, 2008). Buildings and structures damaged by shaking or offset across faults provide archaeological markers that can shed light on the slip history of possible seismogenic sources (e.g. Marco et al., 1997; Ellenblum et al., 1998; Galli and Galadini, 2003; Korjenkov et al., 2003; Sbeinati et al., 2010; Passchier et al., 2013) and can inform regional seismic hazard (Sintubin et al., 2008; Jusseret, 2014; Jusseret and Sintubin, 2012; Jusseret et al., 2013).

Any tendency for active faults to disrupt former urban settlements might seem to be an unfortunate situation that arose spuriously as a consequence of past populations, ignorant of seismic threats, being unwarily drawn to these invisible axes of destruction. The lure of these lethal corridors of land reflected the surprising advantages that tectonically active belts offer; active faults can create and sustain attractive conditions for human development, sustaining dynamic landscapes in which recent tectonics 'frame' patterns of human land use (Bailey et al., 1993; King et al., 1994; King and Bailey, 2010). Groundwater leakage and sediment build up along young fault lines provide well-watered corridors of land, leading some to conjecture that active tectonic zones seeded the earliest centres of Neolithic agriculture (Trifonov and Karakhanian, 2004) and even of early civilisations (Force, 2008; Force and McFadgen, 2010, 2012). Moreover, the tendency for active fault lines to provide persistent groundwater egress and fertile land over millennia lies at the root of the 'fatal attraction' that today finds many populous towns and cities across the eastern

* Corresponding authors.
E-mail addresses: istewart@plymouth.ac.uk (I.S. Stewart), luigi.piccardi@cnr.it (L. Piccardi).

http://dx.doi.org/10.1016/j.pgeola.2017.07.009

Mediterranean and Near East lying directly above seismically dangerous faults (Jackson, 2005).

In this paper, an association between active faults and ancient places is examined in the context of some of the most prominent sites of Greek antiquity. A close correspondence of active faults and ancient cities here is not unduly surprising – the Aegean region is riddled with seismic faults and littered with ruined settlements, so some casual correlation is to be expected. But the correlation is more than simply a contiguous association – across central Greece and western Turkey many seismic fault traces do not simply disrupt the palaeo-urban fabric of buildings and streets but rather they penetrate into the heart of ancient settlements to break or disrupt important sacred structures (Piccardi, 2001). At Priene on the Menderes graben in western Turkey, for example, a narrow corridor of seismic damage cuts the Hellenistic city centre, rupturing a series of public buildings that include the Sacred Stoa (Altunel, 1998; Altunel, 1999; Yonlu et al. 2010). Further south, the expansive Greco-Roman remains of Sagalassos sprawl in front of an active fault escarpment, with the most recent fault splay cutting the temple complex in the centre of the city (Sintubin et al., 2003; Similox-Tohon et al., 2006). In the following sections, the key relations between seismic faults and sacred sanctuaries in the wider Aegean region are set out, and the implications for earthquakes as a pervasive cultural influence in antiquity are discussed.

2. Scarps and springs: the example of Mycenae

In the Aegean sector of the Mediterranean, active normal faulting operates within a largely carbonate-dominated karstic landscape. Repeated vertical fault movements form limestone scarps, which in the physical landscape separate the rocky karstic uplands from the soil-rich plains (Stewart and Hancock, 1988; Stewart, 1993) (Fig. 1). These abrupt linear bluffs – metres to several tens of metres high and fronted by smooth surfaces polished by repeated seismic slip (Stewart, 1993, 1996a) – serve as natural ramparts on which fortifications, citadels and acropoli were constructed. In addition to forming advantageous topographic positions, across the limestone terrain of Greece and western Turkey, copious and persistent cold and hot mineral springs preferentially emerge along active faults (Higgins and Higgins 1996). In turn, because the waters harvested from them not only supplied a range of early water management practices but were also essential for purifactory or therapeutic purposes, it has been argued that early Greek settlements were purposefully centred on natural fountains and springs (Crouch, 1993).

Fig. 1. Repeated earthquake faulting in the limestone terrain of Greece and Western Turkey form distinctive fault scarps sllong the edges of many alluvial plains. These limstone fault scarps serve as natural ramparts on top of which fortifications, citadels and acropoli were constructe and are often lines of preferential spring egress.

An instructive example of the strategic benefits accrued from living on an active fault is found at Mycenae, in the eastern Peloponnese region of mainland Greece (Zangger, 1993). The famed Mycenean hillltop citadel is bounded by metre-high limestone fault scarps on its southwestern and northeastern sides, and its formidable 'Cyclopean Walls' partly built on top (Maroukian et al. 1996) (Fig. 2). The southwestern scarp is the more obvious, bordering the famed Lion's Gate entrance (Nur and Cline, 2000). The longer and more continuous northeastern strand, however, is arguably the more significant structure because it hosts the 'Sacred Spring' (Maroukian et al., 1993), one that although located just outside the citadel could be accessed from within the city walls via a subterranean passageway that tapped the fault zone. Maroukian et al. (1993) argue that it is this fault that ruptured during Mycenean times causing widespread destruction of the citadel (Kilian, 1996), a reminder that the strategic advantage of living atop an active fault could be negated by the ruinous effects of seismic reactivation directly below.

3. Earthquake hydrology and the curious case of Perachora Heraion

If natural springs are important for the functioning of Greek settlements then the loss of reliable groundwater sources might equally be a cause for the abandonment of those same sites (e.g. Gorokhovich, 2005). Large earthquakes are known to cause significant reorganisation of the pattern and rate of groundwater flow (Muir Wood and King, 1993; Rojstaczer et al., 1995; Yechieli and Bein, 2002; Manga and Wang, 2015). In the Aegean region, for example, the destructive 1894 earthquake along the shores of the Gulf of Atalanti caused freshwater springs to cease flowing, only to later return with their flow doubled, whilst coastal groundwater springs became muddy and brackish (Cundy et al., 2000). Such abrupt changes to groundwater can be transient and quickly recovered, but occasionally earthquakes cause the permanent termination of persistent springs and provoke new springs to burst forth elsewhere (Muir Wood and King, 1993). Finding archaeological evidence for settlements whose springs were lost to ancient earthquakes is difficult, but a possible candidate lies at the eastern end of the Gulf of Corinth, at Perachora Heraion.

The ruined Classical Greek sanctuary of Perachora Heraion occupies the westernmost tip of the Perachora Peninsula, a fault-bounded promontory projecting into the eastern Gulf of Corinth (Leeder et al., 2005). The sanctuary – a temple complex for the goddess Hera initiated around the 9th century BC – is an enigmatic Classical site (Tomlinson, 1976). It was largely unknown prior to its excavation in the 1930s by the British archaeologist Humphry

Fig. 2. The formidable 'Cyclopean Walls' of the hilltop citadel of Mycenae are built atop metre-high limestone fault scarps, with the southeastern one bordering the famed Lion's Gate entrance (a) and the northeastern one that lies along the line of the sacred Spring (b).

Payne, yet surprised all with a wealth of votives surpassed only by the famed Greek sanctuaries of Olympia, Delphi and the Athenian Acropolis (Parke, 1967).

The site's curious importance in antiquity has been attributed to its strategic position overlooking the dangerous maritime waters of the Gulf (Tomlinson, 1976), although Strabo in the late 1st century BC reported that it also had been an oracular sanctuary 'in early times'. That sanctuary had been highly frequented by the nearby Corinthians throughout the Archaic period, but subsequently fell into disuse around 300 BC. Although votive relics excavated from the temple by Payne (1940) confirmed its oracular status, it is uncertain how the oracle functioned (Tomlinson, 1976; Dunbabin, 1956). The most recent analysis (Menadier, 1995) identified a small, entirely walled room in the centre of the northern wall of the Hera Akraia temple as the most likely location of an oracular chamber. In that location, the chamber directly abuts a prominent active fault.

The steep E–W striking, S-dipping normal fault scarp forms the sheer backwall of the archaeological sanctuary (Fig. 3). The smooth limestone fault plane is etched by fine frictional striations, consistent with recent seismic slip. The scarp is part of a network of fault strands that coalesce eastwards into the South Alkonides Fault Zone (Roberts, 1996), a structure that ruptured in the 1981 Gulf of Corinth earthquake sequence, when two M 6 shocks produced metre-scale surface breaks east of Perachora village and created a corridor of ground fissuring west towards Heraion. Although no discernible surface ruptures occurred at the archaeological site (Jackson et al., 1982), there is geological evidence that the Heraion fault scarp has ruptured in recent millenia. The evidence comes from a series of marine notches cut into the limestone sea cliffs at Heraion, which record episodic late Holocene tectonic uplift of the headland (Boulton and Stewart, 2015). The highest and best defined notch level, dated at around 6.4 kyr BP, occurs at an elevation of +3.2 m above sea level in the sea cliff to the west of the harbour (Pirazzoli et al., 1994; Pirazzoli and Evelpidou, 2013), but occurs at +2 m within the harbour (Kershaw and Guo, 2001). The Heraion Fault separates the two, with the higher notch level cut into the uplifted footwall of the fault, indicating a 1.2 m vertical offset of this mid-Holocene marker and implying relative movement across the fault during the last few millenia.

There is also archaeological evidence for recent movement on the Heraion fault. The original site excavation – whilst not recognising the steep scarp as a fault plane – detected the effects of seismic disturbance in the 6th century BC temple, Hera Akraia (Fig. 4). According to Payne (1940), the northern wall of the temple of Hera Akraia is dislocated by a few tens of centimetres . . .

> " . . . because the western part of the building has slipped down to the south in the course of an earthquake. The easternmost stones of the western section have been tilted up by an earthquake and the whole eastern part, none of which is bedded on rock, may well have shifted slightly".

The geological and archaeological evidence suggests that the fault at Heraion experienced at least one seismic rupture in antiquity, but the extent to which the functioning of the settlement was fault-related is uncertain. There are no active springs at the site today – the western end of the peninsula is essentially waterless – though at Loutraki a few kilometres east the oldest Greek thermal springs (Dotsika et al., 2010) lies on the prominent Loutraki Fault (Roberts and Stewart, 1994). Moreover, much of the Heraion temple complex is constructed on late Pleistocene bioherms that attest to a prolific expulsion of carbonate-rich waters, indicating that the faulted headland is a former site of persistent CO_2 degassing from submarine springs (Portman et al., 2005). Although it remains entirely speculative, a viable alternative scenario for the demise of Perachora Heraion is of a fault-related oracular sanctuary abandoned as a result of a damaging seismic rupture disrupted the site, but more critically, permanently closed the groundwater springs that had secured its special status.

4. The sacred status of seismic faults: Ephesus and Cnidus

The rich mythology of water management practices in the Aegean karstlands supports the view that groundwater patterns may have influenced the founding and functioning of Greek cities in antiquity (Crouch, 1993; Clendenon, 2009; Robinson, 2017). Ephesus in western Turkey, for example, is widely held to have been established on the site of the famed Hypelaeus spring (Robinson, 2017), which Scherrer (2000) identifies with a source rising from a crevice in a limestone knoll located in the 8th century BC Ionian enclave to the north of the more extensive Roman city. Used as a sacred well from the Archaic period, the source was covered with a small shrine called the 'Crevice Temple', possibly a Temple of Athena, in the late Classical or early Hellenistic period. One of the earliest buildings in the original Greek settlement, it is believed to have served as an Apolline oracular sanctuary (Scherrer, 2000). Certainly the deep cleft is central to the temple

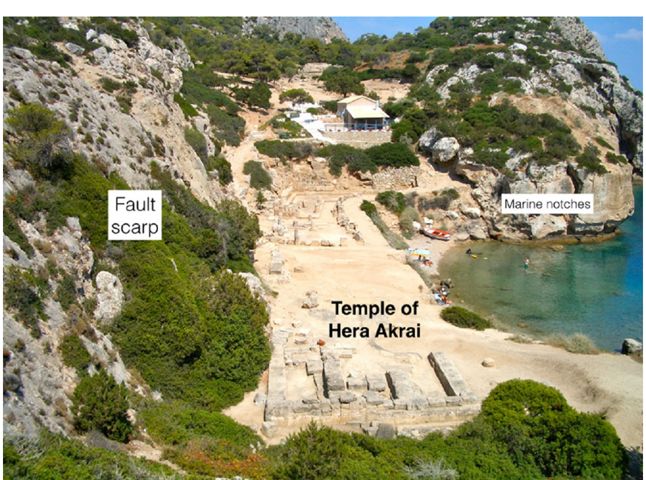

Fig. 3. The steep E–W striking, S-dipping normal fault scarp forms the sheer backwall of the sanctuary of Perachora Heraion, eastern Gulf of Corinth.

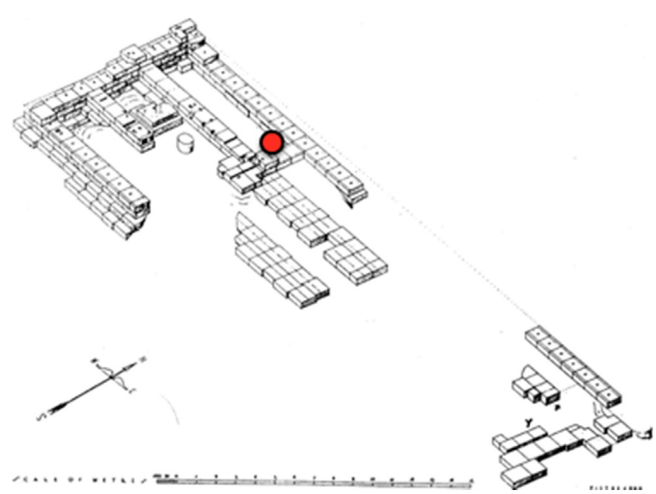

Fig. 4. Evidence of seismic disturbance at Perachora Heraion comes from the observation by Payne (1940) that the northern wall of the temple of Hera Akraia is dislocated by a few tens of centimetres ' . . . because the western part of the building has slipped down to the south in the course of an earthquake.

Fig. 5. **(a)** The Crevice Temple, at Ephesus straddles a deep natural fissure in the limestone bedrock. The fissure does not offset the temple walls or floor, indicating that it was already there when the 5th century BC Apolline sanctuary was hewn out of the bedrock. **(b)** The northern flank of the sanctuary is bounded by a prominent limestone fault scarp.

plan—the crevice fissure does not offset the temple walls or floor, indicating that that the fissure was already there when the temple was hewn out of the bedrock (Fig. 5a).

Although no faults displace the Crevice Temple, the northern edge of the sacred enclosure is bounded by a prominent limestone fault scarp (Fig. 5b). To the east, a similar scarp displays numerous upright, rectangular flat niches chiselled into the smooth rock face (Scherrer, 2000) (Fig. 6). These niches housed votive reliefs – the oldest of which date back to the 5th century BC – that reflect an important sanctuary, one which was at the peak of its renown in the late Classical-early Hellenistic period. Votive niches, carvings, reliefs and inscriptions are known to adorn other fault scarps elsewhere in the Aegean region (e.g. Hancock and Altunel, 1997), implying that they may have been a venerated part of the ritual landscape.

In the former Greco-Roman city of Cnidus, south-west Turkey, where a spectacular near-vertical fault surface forms the dramatic backwall to a sacred enclosure, rock-cut votive niches carved into the exhumed fault plane were interpreted by the archaeologist Charles Newton as signposts for a buried mid-4th century BC temple complex below (Altunel et al., 2003) (Fig. 7). Only sections of the enclosure's massive masonry retaining walls remained. Close to the fault scarp these walls are strongly tilted and bent. and excavation revealed that " . . . in one place near the centre of the escarp the strata of soil were curiously contorted, and among them was a layer of ashes, lamps and other human remains" (Newton, 1863), consistent with the description of a palaeoseismic ground rupture. The lamps and votive reliefs were dedicated to the underworld cult of Demeter and Kore (James, 1958), implying that the fault itself may have been considered a pathway to the underworld.

Fig. 6. At Ephesus in western Turkey, a limestone fault scarp displays numerous upright, rectangular flat niches chiselled into the smooth rock face.

5. Faults as connections to the underworld: Delphi and Hierapolis

It is an intriguing possibility that as physical conduits to the subsurface, faults themselves may have been regarded as direct connections to underworld—the chthonic realm. The geological aspects of the various gateways to the mythical underworld are reviewed elsewhere (Pfanz et al., 2014; Etiope, 2015) but here the key attributes of the two most prominent chthonic sanctuaries of

Fig. 7. The spectacular rock face that forms the backwall of the Temple of Demeter at Cnidus in south-west Turkey is a polished limestone fault plane decorated with rock-cut niches.

Greek antiquity are summarized. Those sites are Delphi and Hierapolis.

5.1. Delphi

For almost two thousand years Delphi was venerated as the principal oracular centre in the Aegean world. Here, ecstatic prophesy was achieved by a priestess who first purified herself by bathing in a sacred spring and then inhaled intoxicating vapours rising from groundwater issuing out of a natural chasm in the rock (Parke and Wormell, 1956; Parke, 1985). De Boer et al. (2001) proposed that the inhalation of the sweet-smelling ethylene, a mild narcotic, could be the reason for the mantic trance of the Pythia, while Etiope et al. (2006) speculated that if any gas-linked neurotoxic effect of the Pythia existed it could be related to oxygen depletion due to CO_2-CH_4 exhalation in the non-aerated inner sanctum ("adyton"). Geochemical studies disagree about the leakage of intoxicating gases from natural springs at Delphi (*cf.* de Boer et al., 2001; Spiller et al., 2002; Etiope et al., 2006), but Piccardi et al. (2008) contend that '. . . the mythological gas-exhaling chasm can plausibly be related to episodic seismic ruptures in the ancient past, which affected for a limited time gas pockets fed by a relatively deep confined hydrothermal system.'

Certainly the environs of Delphi are fault-controlled. The site occupies a distinct step-over in the trace of a major E–W trending active normal fault zone (de Boer et al., 2001), which forms a spectacular limestone fault escarpment at the foot of which are bedrock fault scarps and polished slip planes (Fig. 8a). In places, these fault surfaces exhibit rock-cut niches, although the function and significance of these is unclear (Fig. 8b and c). Within the site itself, two separate areas are considered to be affected by faults. The first is on a lower terrace where the original (Mycenean: 14th century BC) sanctuary was dedicated first to Ge, the female deity of Earth, and subsequently converted to Athena. The second is on an upper terrace where the more extensive sanctuary of Apollo was founded in the 8th century BC.

In the lower sanctuary, a recent splay from the main bedrock fault scarp cuts through the oldest temples and altars inside the shrine of Athena, faulting the archaeological relics therein (Piccardi, 2000). It is likely that much of this damage occurred

Fig. 8. (a) View looking west toward the the principal fault plane (F) at Delphi. (b) A close of up of the fault plane (F) showing the polished and grooved surface, adorned enigmatic rock-cut niches (c).

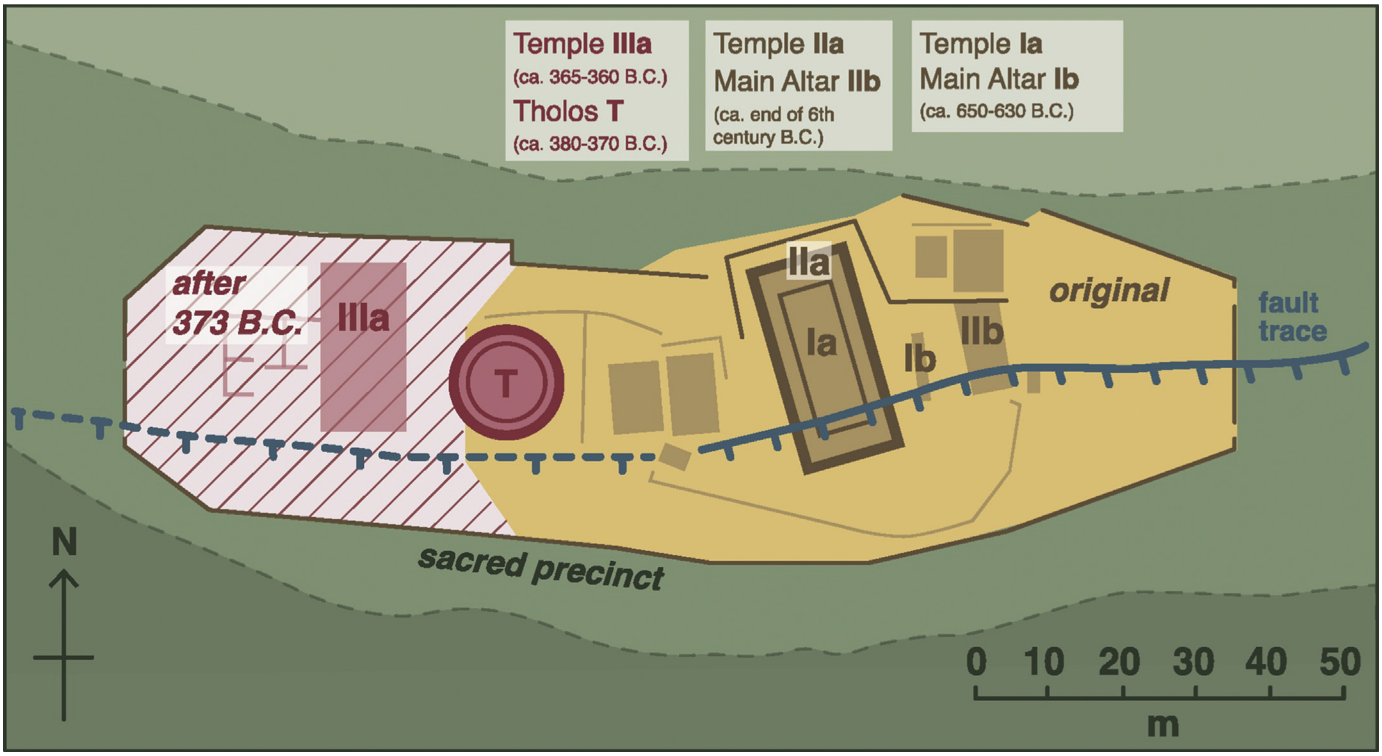

Fig. 9. Map of the lower sanctuary of Delphi, central Greece, where a recent fault break cuts through the oldest temples and altars inside the shrine of Athena. Much of this damage occurred in the earthquake of 373 BC, which caused widespread destruction at Delphi and which necessitated the reconstruction of the sanctuary. The new temple of Athena was relocated a few tens of metres further west along the fault trace. Redrawn from Piccardi (2000,Fig. 4).

in the earthquake of 373 BC, which caused widespread destruction at Delphi and which necessitated the reconstruction of the sanctuary; the new temple of Athena was relocated a few tens of metres further west but still directly straddling the fault trace (Fig. 9). Piccardi (2000) argues that because Mycenean remains are found at this site, it is this sanctuary that constitutes the original site and consequently is where the roots of the oracular activity ought to be found. However, for most workers the main functioning oracular site throughout the lifetime of the site was on the upper sanctuary.

Conventionally, archaeological sources place Delphi's oracular centrepiece – the site of the basement chamber (adyton) and the natural chasm – beneath the Temple of Apollo on the upper terrace (Parke and Wornell, 1956; Flaceliere, 1967; Parke, 1967). The higher sanctuary itself is cut by several NW–SE trending subsidiary faults, inferred mainly from spring lines, and one of these is taken to pass

Fig. 10. (a) General view of the Temple of Apollo at Delphi, and (b) a close-up showing its inner walls markedly bent at its intersection with the trace of the inferred cross-fault. The implication is that the oracular chamber below the temple complex lies on a line of minor fault movement.

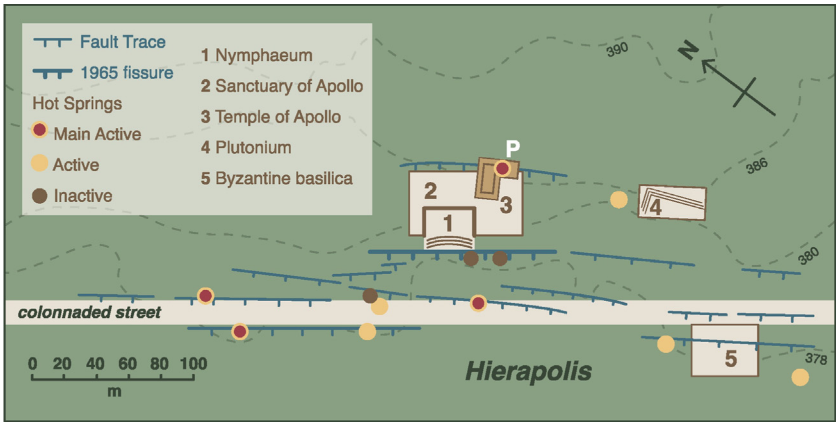

Fig. 11. Map of Hierapolis showing the trace of the active fault strands cutting through the heart of the Greco-Roman city. Active thermal springs at the site are coincident with prominent fault strands, one of which intersects the Temple of Apollo—long considered the location of the famed plutonium (P). The real Plutonium has been discovered to the south, and lies along the line of the same fault trace. Redrawn from (Piccardi 2007) and D'Andria (2016).

through the Temple of Apollo (de Boer and Hale, 2000; de Boer et al., 2001). Signs of this can be seen in the warping of its inner walls, which are markedly bent at its intersection with the proposed trace of the cross-fault (Fig. 10). This deformation is consistent with a minor (tens of cm) lateral shift on an underlying fault – either by gravitational slippage of the steep fractured terrain on which the sanctuary rests or by minor faulting – supporting the view of de Boer and colleagues that the adyton in which the oracular divination took place was above a discrete slip surface, directly below the temple.

5.2. Hierapolis

Ancient Hierapolis in the Denizli region of western Turkey was founded as a Greek colony at the end of the 3rd century BC on the site of the Charonion—a natural source of toxic vapour famed for prophetic qualities (Kreitzer, 1998; Piccardi, 2007). Carbonate-rich thermal waters cascading out from the Hierapolis Fault form travertine plateau that is today the famed world-heritage site of Pamukkale (Moller et al., 2004). The Greek city was destroyed and rebuilt after the 'Neronian' earthquake in 60 AD, and subsequently levelled again after an earthquake in Byzantine times, the line of which can be traced along the main street of the Roman city as a corridor of offset buildings and toppled walls (Hancock and Altunel, 1997; Kumsar et al., 2016). Along this seismic trace are a chain of hot mineral springs, and the opening of a hot spring in a fresh ground fissure formed during an earthquake in 1965 highlights how the springs are directly fed from the fault zone (Piccardi, 2007).

Built directly upon a strand of the Hierapolis Fault is the Temple of Apollo, the sanctuary of the Gods of the underworld, Hades and Kore. Historical sources recount how temple priests demonstrated their supernatural power and their equality to the gods by ushering animals into a basement chamber (Plutonium) where, after a few minutes, the creatures asphyxiated (Pfanz et al., 2014 and references therein). In 1963, Italian archaeological excavations beneath the Apollo temple found an inner chamber with a natural chasm in the limestone floor (Bean, 1971), as well as inscriptions confirming it was a seat of oracular activity (Parke, 1967). Very high levels of CO_2 concentrations in the chamber meant that for safety

Fig. 12. (a) The famed hot mineral pools of modern Pamukkale (ancient Hierapolis) cascade from an active fault, the Hierapolis Fault. (b) Archaeological excavations in recent years at Hierapolis have revealed the Plutonium, a subterranean grotto characterized by high CO2 concentrations. (c) The Temple of Apollo at Hierapolis, which was originally thought to been the location of the Plutonium.

reasons it became almost completely sealed. That both the temple and the associated chamber are cut by multiple strands of the Hierapolis fault is clear from topographic profiles (Piccardi, 2007) (Fig. 11), and geophysical imaging confirms that one of these fault splays passes directly beneath the chamber itself (Negri and Leucci, 2006). From these observations Piccardi (2007, p.103) concluded that, as at Delphi, the main cult-site at Hierapolis was deliberately directly above the active fault, making it ' . . . likely that, together with the natural gas emission from the fault inside the Plutonium, the fault itself was venerated and regarded as a material opening to the underworld.'

Unsurprisingly, this toxic chamber was widely interpreted as the famed Plutonium (e.g. Piccardi, 2007) and it is marked as such in touristic guides (D'Andria, 2003). However, recent excavations (2011–2015) have uncovered the real Plutonium immediately south of the Apollo Sanctuary, in the form of a hidden grotto dedicated to Pluto and Kore (D'Andria, 2013, 2016) (Fig. 12).

> 'Gas measurements inside the closed subterranean chamber revealed CO_2 concentrations of up to 91%. The entire basement of the grotto was totally dark but seemed to be highly humid, due to a warm, carbonate-rich creek flowing below it. Deadly CO_2 gas also exists in front of the actual grotto. Flooding out of the grotto's mouth, the escaping CO_2 forms a gas lake on the floor. The corpses of animals hint at the absence of oxygen and the presence of high CO_2 that builds up during the night.' (Pfanz et al., 2014, p. 111).

D'Andria (2016) reports that in the grotto there is a large crack caused by the seismic fault, which is filled with votive offerings to a female divinity linked to the natural world and powerful subsurface forces (Cybele and later Persephone). The new excavations strengthen the fault-related nature of the oracular sanctuary and its chthonic character, meaning that at Hierapolis two separate constructions appear to have been positioned purposefully on the same active fault trace.

6. The seismo-tectonic landscape of the Aegean

Delphi and Hierapolis not only lie at opposite ends of the Classical Greek world, but they also lie at the outer edges of the Aegean extensional province, a distributed belt of rapid N–S crustal tension that swings from the rifted marine gulfs of central Greece to link with E–W trending alluvial grabens in western Turkey (Jackson, 1994; Jolivet et al., 2013; Jolivet and Brun, 2010). Frequent moderate to strong seismicity along both the Greek and Turkish seaboards becomes more subdued into the Aegean Sea, where high heat flow and young magmatism feeds the volcanic islands of Santorini, Milos and Nisyros; landward these volcanic centres change to centres of hydrothermal and fumarolic activity and then to onshore geothermal fields (Ten Dam and Khrebtov, 1970; Ilkisik, 1995; Moller et al., 2004; Dotsika et al., 2009). Structural control on eruptive centres and hydrothermal activity in the southern Aegean indicates the significant role of active faults in directing fluid and magma pathways in the upper crust (Kokkalas and Aydin, 2013), and faults are the principal pathway by which CO_2 originating from deep thermo-metamorphism of carbonate rocks or mantle degassing reach the surface (Chiodini et al., 1999; Mörner and Etiope, 2002). An overview of how the current geodynamics of the Aegean region controls contemporary gas manifestations is covered in D'Alessandro and Kyriakopoulos (2013), but in this section the relationship to specific ancient Greek sites is briefly summarised.

In the Turkish sector – the Western Anatolian Extensional Province – the main bounding tensional (normal) faults of the Menderes and Gediz grabens act as priority pathways for carbonate-rich thermal waters to ascend slowly along the faults, emerging along the graben margins as hot CO_2-charged travertine springs (Hancock, 1999; Çakir, 1999; Kocyigit et al., 1999) or tapped near-surface by commercial geothermal plants (Karakuş and Şimşek, 2013). Many of the most active thermal waters emerge along the northern margin of the Buyuk Menderes graben, with low temperature springs associated with a low-angle detachment fault and high-temperature fields developed along higher angle border faults (Karakuş and Şimşek, 2013). At the eastern end of this seismically active geothermal corridor lies Hierapolis and its Plutonium but two other 'entrances to hell' (Charonion) are found along the trace of this major graben-bounding fault. One occured near Magnesia, where a cave sacred to Apollo exuded mildly euphoric vapours, whilst a second was a cave at Acharaca, where poisonous gases induced hallucinogenic experiences that were regarded as divinely inspired revelations (Ustinova, 2002, 2009a, 2009b). At Acharaca, the former road to the temple is vertically offset by about 1.5 m across a surface rupture that most likely slipped during an earthquake in the 2nd–3rd century AD (Altunel et al., 2008).

The opposing central Greek seaboard is similarly a complex multi-fractured domain of active normal faulting and geothermal activity (Goldsworthy et al., 2002). The principal hot springs discharge along the Gulf of Evia fault system, where young volcanic-charged waters, exploiting fault intersections, feed commercial geothermal fields (Sfetsos, 1988). Here, thermal and mineral springs derive from a mixing of shallow seawater influx and deeper mantle-sourced CO_2 rising up through deep-seated normal faults. Mariolakos et al. (2010) directly links the seismically active and heavily fractured terrain and copious thermal spring activity here with the proliferation of ancient oracular sites in this region. Most of these sites are only loosely located, forming part of the Homeric 'Hymn to Apollo' which charts the journey of Apollo from Mt Olympus founding a series of oracular places before ending up in Delphi. But some sites, however, are more confidently determined, such as the 'lost' Apolline oracle of Orovai which Mariolakos et al. (2010) locates on an active normal fault bounding the northern side of the Gulf of Evia.

To the south lies the Gulf of Corinth, stretching from Perachora Herion in the east to Delphi in the west. The former lies close to the thermal waters of Loutraki, a waning geothermal system that contrasts with volcanic fumarolic fields at Sousaki and Methana further south, which source from an active deep-seated geothermal reservoir below (Dotsika et al., 2009, 2010). At Sousaki, Pfanz et al. (2014) report a CO_2 gas creek that continually flows out of a cave mouth and pools downslope, killing small animals. In the west, at Delphi, the 373 BC earthquake that destroyed the city also destroyed the cities of Helike and Bura on the opposing southern shore (Mouyaris et al., 1992). Bura was the site of cave where a famed oracle of Heracles was located, and a few kilometres west, at Aegeira, was a famed oracle where a priestess descended into cave to utter prophesy. According to Parke and Wormell (1956) ' . . . by entering a cavern the servant of the goddess came into closer contact with the divine'. Both sites lie along the main Gulf of Corinth fault system (Soter and Katsounopoulou, 1993; Stewart, 1996b; Stewart and Vita-Finzi, 1996), occupying prominent step-over zones where CO_2-rich gases emerge from unusually deep (Pizzino et al., 2004; Pik and Marty, 2009). Gas expulsion was observed nearby during the 1995 Aegion earthquake (Soter, 1999), and offshore surveys reveal active natural gas seepage along the gulf coast (Christodoulou et al., 2003).

Overall, the volcano-tectonic framework of the central Aegean region is dominated by distributed seismic faulting accompanied by a pervasive expulsion of thermal waters and leakage of deep-seated volatiles. It is this geological framework that arguably sets the scene for the springs and gases that infuse the ancient Greek netherworld of caves, chasms, chambers, and sacred grottos (Pfanz et al., 2014).

7. Concluding remarks and wider cultural implications

Earthquake faulting is endemic to the Aegean world, present and past. The physical expressions of seismogenic faults are a prominent and distinctive part of the physical landscape, providing the bluffs for citadels and fortifications and the egress for subterranean springs. The tendency for deep-seated fault zones to be conduits for gas-infused groundwaters to move up from mantle depths provides a viable geological basis for the sacred landscape of Greek antiquity. Water was at the heart of many ritual practices and some persistent spring sources were the hubs of enduring settlements (Crouch, 1993), with the most revered being those whose mineral waters released euphoric, hallucinigenic or lethal vapours. In places, such fumes pooled in clefts and chasms along the fault lines or in natural caverns and grottoes, and artificial chambers were constructed in temple basements to concentrate their effects. The flow of prophetic vapours fluctuated with time, and Ustinova (2009a, 2009b) has proposed that at Delphi 'earthquakes could have been responsible for periods of renewed release of hydrocarbon gases', as well as for 'silencing springs' and closing fissures'. In such circumstances, it might be expected that sanctuaries that relied on sacred springs for rituals and prophetic activities might cease to be revered when disrupting earthquakes struck.

The contention that notable temple complexes appear to have been purposefully positioned astride active fault traces (e.g. Piccardi, 2001) raises the question about whether the faults themselves were venerated as natural passageways between the 'Upper' and 'Lower' worlds. Certainly the seismic terrain of Aegean antiquity is the backdrop to ancient tales of individuals who attained oracular status by descending into the subsurface or who dwelled in subterranean abodes. Trophonius, for example, vanished beneath a hill in Lebaeia (Boeotia) and subsequently lived in a cave, being widely consulted as an oracular god; those seeking divine consultation descended into a grotto and drank from natural springs. Another famous seer, Amphiaraus, was believed to have been swallowed up by a natural chasm as he fled from Thebes (modern Thiva), the fissure being opened by Zeus, who saved him from the imminent death in the hands of his foes and made him immorta1 (Ustinova, 2002). It has been suggested (Sineux, 2007, cited in Ustinova, 2002) that in the myth Amphiaraus disappeared at Thebes and emerged from the depths of the earth at Oropus, and that his cult moved to Oropus in the 5th century BC, which is where his oracular cult place resided; regardless of the detail, both Thebes and Oropus lie on prominent active faults (Mariolakos et al., 2010).

Ustinova (2002, p.108) argues that a common thread in these tales is that vanishing into a chasm was a divine blessing, implying that 'these tales look like explanations invented to account for the daemon's life in the depths of the earth: myths that give reasons for an ancient cult type' (Ustinova (2009, p.108). The association of many prominent Apolline cult centres with caves and subterranean grottoes – environments in which prophetic pronouncements were stimulated by isolation and sensory deprivation – means that these underground spaces may have exerted a formative influence across the ancient Greek world (Ustinova, 2009a, 2009b).

In geological terms, it is tempting to see in the stories of individuals achieving divinity through being swallowed up by the earth as literary metaphors for ground ruptures in large earthquakes. Over the last two centuries, the Aegean region has experienced earthquakes large enough to rupture the ground every few decades (Ambraseys and Jackson, 1990) and historical records indicate a comparable frequency and distribution of destructive earthquakes over recent millenia, many with contemporary or near-contemporary literary accounts of dramatic surface effects (Ambraseys, 1996; Ambraseys and White, 1996). Experiencing the sudden and dramatic renting of the ground during calamitous quakes would have been fairly commonplace in Greek antiquity and would have surely demanded enquiry and explanation from those affected. For all their obvious destructiveness, the possibility that seismic faults may have constituted the fulcrum of major sacred sanctuaries suggests that classical scholars ought to devote more consideration to social representation and cultural significance of earthquakes in Greek antiquity (Polimenakos, 1996). After all, even modern-day earthquakes ' . . . do strange things to our psyches, by shattering what may be our most widely held illusion, the inviolability of solid ground' (Ulin, 2004, p. 9).

References

Altunel, E., 1998. Evidence for damaging earthquakes at Priene: western Turkey. Turkish Journal of Earth Sciences 7, 25–35.

Altunel, E., 1999. Geological and geomorphological observations in relation to the 20 September 1899 Menderes earthquake, western Turkey. Journal of the Geological Society, London 156, 241–246.

Altunel, E., Stewart, I.S., Barka, A., 2003. Earthquake rupture at ancient Cnidus. Turkish Journal of Earth Sciences 12, 137–151.

Ambraseys, N.N., 1971. Value of historic records of earthquakes. Nature 232, 374–379.

Ambraseys, 1996. Seismicity of central Greece. In: Stiros, S., Jones, R.E. (Eds.), Archaeoseismology. Fitch Laboratory Occasional Paper Number 7. British School at Athens, Athens, pp. 23–36.

Ambraseys, N.N., Jackson, J.A., 1990. Seismicity and associated strain of central Greece between 1890 and 1988. Geophysical Journal International 101, 663–708.

Ambraseys, N.N., White, D.P., 1996. Seismicity of the East Mediterranean and Middle East-I. Engineering Seismology and Earthquake Engineering Research Report 96–103.

Bailey, G., King, G.C.P., Sturdy, D.A., 1993. Active tectonics and land-use strategies: a Palaeolithic example from northwest Greece. Antiquity 67, 292–312.

Bean, G., 1971. Turkey Beyond the Meander. E. Benn, London 236 p..

Boulton, S.J., Stewart, I.S., 2015. Holocene coastal notches in the Mediterranean region: indicators of palaeoseismic clustering? Geomorphology 237, 29–37.

Çakir, Z., 1999. Along-strike discontinuity of active normal faults and its influence on quaternary travertine deposition; examples from western Turkey. Turkish Journal of Earth Sciences 8, 67–80.

Chiodini, G., Frondini, F., Kerrick, D.M., Rogie, J., Parello, F., Peruzzi, L., Zanzari, A.R., 1999. Quantification of deep CO_2 fluxes from Central Italy. Examples of carbon balance for regional aquifers and of soil diffuse degassing. Chemical Geology 159, 205–222.

Christodoulou, D., Papatheodorou, G., Ferentinos, G., Masson, M., 2003. Active seepage in two contrasting pockmark fields in the Patras and Corinth gulfs, Greece. Geo-Marine Letters 23 (3–4), 194–199.

Clendenon, C., 2009. Karst hydrology in ancient myths from Arcadia and Argolis, Greece. Acta Carsologica 38/1, 145–154.

Crouch, D.P., 1993. Water Management in Ancient Greek Cities. Oxford University Press.

Cundy, A.B., Kortekaas, S., Dewez, T., Stewart, I.S., Collins, P.E.F., Croudace, I.W., Maroukian, H., Papanastassiou, D., Gaki-Papanastassiou, P., Pavlopoulos, K., Dawson, A., 2000. Coastal wetlands as recorders of earthquake subsidence in the Aegean: a case study of the 1894 Gulf of Atalanti earthquakes, central Greece. Marine Geology 170, 3–26.

de Boer, J.Z., Hale, J.R., 2000. In: McGuire, W.G., Griffiths, D.R., Hancock, P.L., Stewart, I.S. (Eds.), The Archaeology of Geological Catastrophes. Geological Society Special Publication, London, pp. 399–412.

de Boer, J.Z., Sanders, D.T., 2006. Earthquakes in Human History. Princeton.

de Boer, J.Z., Hale, J.R., Chanton, J., 2001. New evidence for the geological origins of the Ancient Delphic oracle (Greece). Geology 29, 707–711.

D'Andria, F., 2003. Hierapolis of Phrygia (Pamukkale). An Archaelogical Guide. Ege Yayinlari, Pamukkale.

D'Andria, F., 2013. Il Ploutonion a Hierapolis di Frigia. Istanbuler Mitteilungen 63, 157217.

D'Andria, F., 2016. Nature and cult in the Ploutonium of Hierapolis. Before and after the colony. In: Şimşek, C., D'Andra, F. (Eds.), Landscape and History in the Lykos Valley: Laodikeia and Hierapolis in Phrygia. Cambridge Scholar Publishing, pp. 189–218.

D'Alessandro, W., Kyriakopoulos, K., 2013. Preliminary gas hazard evaluation in Greece. Natural Hazards 69 (3), 1987–2004.

Dotsika, E., Poutoukis, D., Michelot, J.L., Raco, B., 2009. Natural tracers for identifying the origin of the thermal fluids emerging along the Aegean Volcanic arc (Greece): evidence of Arc-Type Magmatic Water (ATMW) participation. Journal of Volcanology and Geothermal Research 179 (1), 19–32.

Dotsika, E., Poutoukis, D., Raco, B., 2010. Fluid geochemistry of the Methana Peninsula and Loutraki geothermal area, Greece. Journal of Geochemical Exploration 104 (3), 97–104.
Dunbabin, T.J., 1956. The Oracle of Hera Akraia at Perachora. Annals of the British School at Athens 46, 61–71.
Etiope, G., 2015. Seeps in the ancient world: myths, religions, and social development. Natural Gas Seepage. Springer International Publishing, pp. 183–193.
Etiope, G., Papatheodorou, G., Christodoulou, D., Geraga, M., Favali, P., 2006. The geological links of the ancient Delphic Oracle (Greece): a reappraisal of natural gas occurrence and origin. Geology 34, 821–824.
Flaceliere, R., 1967. Greek Oracles. Elek Books, London.
Force, E.R., 2008. Tectonic environments of ancient civilisations in the Eastern Hemisphere. Geoarchaeology 23, 644–653.
Force, E.R., McFadgen, B.G., 2010. Tectonic environments of ancient civilizations: opportunities for archaeoseismological and anthropological studies. Geological Society of America Special Papers 471, 21–28.
Force, E.R., McFadgen, B.G., 2012. Influences of active tectonism on human development: a review and Neolithic example. Climates, Landscapes, and Civilizations 195–202.
Galli, P., Galadini, F., 2003. Disruptive earthquakes revealed by faulted archaeological relics in Samnium (Molise, southern Italy). Geophysical Research Letters 30, 1266.
Goldsworthy, M., Jackson, J., Haines, J., 2002. The continuity of active fault systems in Greece. Geophysical Journal International 148, 596–618.
Gorokhovich, Y., 2005. Abandonment of Minoan palaces on Crete in relation to the earthquake induced changes in groundwater supply. Journal of Archaeological Science 32 (2), 217–222.
Guidoboni, E., Comastri, A., Traina, G., 1994. Catalogue of Ancient Earthquakes in the Mediterranean Area up to 10th Century, ed. I ING, Rome.
Hancock, P.L., Altunel, E., 1997. Faulted archaeological relics at Hierapolis (Pamukkale), Turkey. Journal of Geodynamics 24, 21–36.
Higgins, M.D., Higgins, R.A., 1996. A Geological Companion to Greece and the Aegean. Cornell University Press, Ithaca.
Ilkisik, O.M., 1995. Regional heat flow in western Anatolia using silica temperature estimates from thermal springs. Tectonophysics 244, 175–184.
Jackson, J.A., Gagnepain, J., Houseman, G., King, G.C.P., Papadimitriou, P., Soufleris, C., Virieux, J., 1982. Seismicity, normal faulting, and the geomorphological development of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981. Earth Planetary Science Letters 57 (2), 377–397.
Jackson, J., 1994. Active tectonics of the Aegean region. Annual Review of Earth and Planetary Sciences 22, 239–271.
Jolivet, L., Brun, J.P., 2010. Cenozoic geodynamic evolution of the Aegean. International Journal of Earth Sciences 99, 109–138.
Jolivet, L., Faccenna, C., Huet, B., Labrousse, L., Le Pourhiet, L., Lacombe, O., Lecomte, E., Burov, E., Denele, Y., Brun, J.P., Philippon, M., 2013. Aegean tectonics: strain localisation, slab tearing and trench retreat. Tectonophysics 597, 1–33.
Jusseret, S., 2014. Earthquake archaeology. Journal of Contemporary Archaeology 1, 277–296.
Jusseret, S., Sintubin, M., 2012. All that rubble leads to trouble: reassessing the seismological value of archaeological destruction layers in Minoan Crete and beyond. Seismological Research Letters 83 (4), 736–742.
Jusseret, S., Langohr, C., Sintubin, M., 2013. Tracking earthquake archaeological evidence in late Minoan IIIB (~1300–1200 BC) Crete (Greece): a proof of concept. Bulletin of the Seismological Society of America 103 (6), 3026–3043.
Jusseret, S., Sintubin, M. (Eds.), 2017. Minoan Earthquakes: Breaking the Myth through Interdisciplinarity. Vol. 5. Leuven University Press.
Karakuş, H., Şimşek, Ş., 2013. Tracing deep thermal water circulation systems in the E–W trending Büyük Menderes Graben, western Turkey. Journal of Volcanology and Geothermal Research 252, 38–52.
Karcz, I., Kafri, U., 1978. Evaluation of supposed archaeoseismic damage in Israel. Journal of Archaeological Science 5, 237–253.
Kershaw, S., Guo, L., 2001. Marine notches in coastal cliffs: indicators of relative sea-level change Perachora Peninsula, central Greece. Marine Geology 179, 213–228.
Kilian, K., 1996. Earthquakes and archaeological context at 13th C BC Tiryns. In: Stiros, S., Jones, R. (Eds.), Archaeoseismology. Fitch Laboratory Occasional Paper 7. British School at Athens, Athens, Greece, pp. 63–68.
King, G., Bailey, G., Sturdy, D., 1994. Active tectonics and human survival strategies. Journal of Geophysical Research 99, 20063–20078.
King, G.C.P., Bailey, G.N., 2010. Dynamic landscapes and human evolution. In: Sintubin, M., Stewart, I.S., Niemi, T.M., Altunel, E. (Eds.), Ancient Earthquakes, 471. Geological Society of America Special Paper, pp. 1–19.
Kocyigit, A., Yusufoglu, H., Bozkurt, E., 1999. Evidence from the Gediz graben for episodic two-stage extension in western Turkey. Journal of the Geological Society, London 156, 605–616.
Kokkalas, S., Aydin, A., 2013. Is there a link between faulting and magmatism in the south-central Aegean Sea? Geological Magazine 150 (02), 193–224.
Korjenkov, A., Baipakov, K., Chang, C., Peshov, Y., Savelieva, T., 2003. Traces of ancient earthquakes in Medieval cities along the Silk Road: northern Tien Shan and Dzungaria. Turkish Journal of Earth Sciences 12, 241–261.
Kreitzer, L.J., 1998. The Plutonium of Hierapolis and the descent of Christ into the lowermost parts of the earth in Ephesians-IV,9 (Ancient Roman numismatics as a hermeneutical key for understanding incorporated references to Christ in the mythologies of Asia-Minor). Biblica 79, 381–393.
Kumsar, H., Aydan, Ö., Şimşek, C., D'Andria, F., 2016. Historical earthquakes that damaged Hierapolis and Laodikeia antique cities and their implications for earthquake potential of Denizli basin in western Turkey. Bulletin of Engineering Geology and the Environment 75 (2), 519–536.
Leeder, M.R., Portman, C., Andrews, J.E., Collier, R.E., Ll Finch, E., Gawthorpe, R.L., McNeill, L.C., Pérez-Arlucea, M., Rowe, P., 2005. Normal faulting and crustal deformation, Alkyonides Gulf and Perachora peninsula, eastern Gulf of Corinth rift, Greece. Journal of the Geological Society 162, 549–561.
Manga, M., Wang, C.Y., 2015. 4.12. Earthquake hydrology, Treatise on Geophysics. Second edition Elsevier, Oxford, pp. 305–328.
Mariolakos, I., Nikolopoulos, V., Bantekas, I., Palyvos, N., 2010. Oracles on faults: a probable location of a 'lost' oracle of Apollo near Oroviai (northern Euboea island, Greece) viewed in its geological and geomorphological context. Bulletin of the Geological Society of Greece XLIII, 829–844.
Maroukian, H., Gaki-Papanastassiou, K., Papanastassiou, D., 1996. Geomorphologic-seismotectonic observations in relation to the catastrophes at Mycenae. In: Stiros, S., Jones, R.E. (Eds.), Archaeoseismology. Fitch Laboratory Occasional Paper No. 7, Athens, pp. 189–194.
Menadier, B., 1995. The Sixth Century BC Temple and Sanctuary of Hera Akraia, Perachora. MSc Dissertation. University of Cincinnati.
Moller, P., Dulski, P., Savascin, Y., Conrad, M., 2004. Rare earth elements, yttrium and Pb isotope ratios in thermal spring and well waters of West Anatolia, Turkey: a hydrochemical study of their origin. Chemical Geology 206, 97–118.
Mörner, N.A., Etiope, G., 2002. Carbon degassing from the lithosphere. Global Planetary Change 33, 185203.
Mouyaris, N., Papastamatiou, D., Vita-Finzi, C., 1992. The Helice fault? Terra Nova 4, 124–129.
Muir Wood, R., King, G.C.P., 1993. Hydrological signatures of earthquake strain. Journal of Geophysical Research 2, 22035–22068.
Negri, S., Leucci, G., 2006. Geophysical investigation of the Temple of Apollo (Hierapolis, Turkey). Journal of Archaeological Science 33, 1505–1513.
Nikonov, A.A., 1988. On the methodology of archaeoseismic research into historical monuments. In: Marinos, P.G., Koukis, G.C. (Eds.), Proceedings of an International Symposium Organised by the Greek National Group of IAEG, Balkema, Athens, pp. 1315–1332.
Nur, A., Cline, E.H., 2000. Poseidon's horses: plate tectonics and earthquake storms in the late Bronze Age Aegean and Eastern Mediterranean. Journal of Archaeological Science 27, 43–63.
Parke, H.W., 1967. Greek Oracles. Hutchinson, London.
Parke, H.W., 1985. The Oracles of Apollo in Asia Minor. Croom Helm, London.
Parke, H.W., Wormell, D.E.W., 1956. The Delphic Oracle. Blackwell, Oxford.
Passchier, C.W., Wiplinger, G., Gungor, T., Kessener, P., Surmelihind, G., 2013. Normal fault displacement dislocating a Roman aqueduct of Ephesos, western Turkey. Terra Nova 292–297.
Payne, H., 1940. Perachora: The Sanctuaries of Hera Akraia and Limenia. Clarendon Press, Oxford.
Pfanz, H., Yüce, G., D'Andria, F., D'Alessandro, W., Pfanz, B., Manetas, Y., Papatheodorou, G., 2014. The ancient gates to hell and their relevance to geogenic CO_2. History of toxicology and environmental health. Toxicology in Antiquity 1.
Piccardi, L., 2000. Active faulting at Delphi, Greece: seismotectonic remarks and a hypothesis for the geologic environment of a myth. Geology 28, 651–654.
Piccardi, L., 2001. Fault-related sanctuaries. In: AGU Fall Meeting Abstracts, #U52B-03, http://adsabs.harvard.edu/abs/2001AGUFM.U52B..03P 001AGUFM. U52B..03P.
Piccardi, L., 2007. The AD 60 Denizli Basin earthquake and, G. the apparition of Archangel Michael at Colossae (Aegean Turkey). In: Piccardi, L., Masse, B. (Eds.), Myth and Geology, 273. Special Publication of the Geological Society, pp. 95–105.
Piccardi, L., Monti, C., Vaselli, O., Tassi, F., Gaki-Papanastassiou, K., Papanastassiou, D., 2008. Scent of a myth: tectonics, geochemistry and geomythology at Delphi (Greece). Journal of the Geological Society, London 165, 5–18.
Pik, R., Marty, B., 2009. Helium isotopic signature of modern and fossil fluids associated with the Corinth rift fault zone (Greece): implication for fault connectivity in the lower crust. Chemical Geology 266, 67–75.
Pirazzoli, P.A., Stiros, S.C., Arnold, M., Laborel, J., Laborel-Deguen, F., Papageorgiou, S., 1994. Episodic uplift deduced from Holocene shorelines in the Perachora Peninsula Corinth area, Greece. Tectonophysics 229, 201–209.
Pirazzoli, P.A., Evelpidou, N., 2013. Tidal notches: a sea-level indicator of uncertain archival trustworthiness. Palaeogeography, Palaeoclimatology, Palaeoecology 369, 377–384.
Pizzino, L., Quattrocchi, F., Cinti, D., Galli, G., 2004. Fluid geochemistry along the Eliki and Aigion seismogenic segments (Gulf of Corinth, Greece). Comptes Rendus Geoscience 336, 367–374.
Polimenakos, L.C., 1996. Thoughts on the perception of the earthquake in Greek antiquity. In: Stiros, S.C., Jones, R.E. (Eds.), Archaeoseismology. British School of Athens Occasional Paper, pp. 253–257.
Portman, C., Andrews, J.E., Rowe, P.J., Leeder, M.R., Hoogewerff, J., 2005. Submarine-spring controlled calcification and growth of large Rivularia bioherms, Late Pleistocene (MIS 5e), Gulf of Corinth, Greece. Sedimentology 52.
Rapp, G., 1986. Assessing archaeological evidence for seismic catastrophies. Geoarchaeology: An International Journal 1 (4), 365–379.
Robinson, B.A., 2017. Fountains as reservoirs of myth and memory. Myths on the Map: The Storied Landscapes of Ancient Greece, p.178.
Roberts, G.P., 1996. Non-characteristic normal faulting surface ruptures from the Gulf of Corinth, Greece. Journal of Geophysical Research 101, 25255–25267.

Roberts, G., Stewart, I., 1994. Uplift, deformation and fluid involvement within an active normal fault zone in the Gulf of Corinth, Greece. Journal of the Geological Society 151 (3), 531–541.

Scherrer, P. (Ed.), 2000. Ephesus—The New Guide. Ege Yayinlari.

Sfetsos, C.S., 1988. Inventory of thermal and mineral springs of Greece (III Continental Greece). Hydrological and Hydrogeological Investigations, 39. IGME, Athens.

Similox-Tohon, D., Sintubin, M., Muchez, P., Verhaert, G., Vanneste, K., Fernandez-Alonso, M., Vandycke, S., Vanhaverbeke, H., Waelkens, M., 2006. The identification of an active fault by a multidisciplinary study at the archaeological site of Sagalassos (SW Turkey). Tectonophysics 420, 371–387.

Sintubin, M., Muchez, P., Similox-Tohon, D., Verhaert, G., Paulissen, E., Waelkens, M., 2003. Seismic catastrophes at the ancient city of Sagalassos (SW Turkey) and their implications for the seismotectonics in the Burdur-Isparta area. Geological Journal 38, 359–374.

Sintubin, M., Stewart, I., 2008. A 'logical' methodology for archaeoseismology. A proof of concept at the archaeological site of Sagalassos (SW Turkey). Bulletin of the Seismological Society of America 98 (5) .

Sintubin, M., Stewart, I., Niemi, T., Altunel, E., 2008. Earthquake archaeology—just a good story? Seismological Research Letters 79, 767–768.

Sintubin, M., Stewart, I., Niemi, T., Altunel, E., 2010. Ancient Earthquakes. Geological Society of America Special Paper 471 280 p..

Soter, S., 1999. Macroscopic seismic anomalies and submarine pockmarks in the Corinth–Patras rift, Greece. Tectonophysics 308 (1), 275–290.

Spiller, H.A., Hale, J.R., De Boer, J.Z., 2002. The Delphic oracle: a multidisciplinary defense of the gaseous vent theory. Journal of Toxicology: Clinical Toxicology 40 (2), 189–196.

Stewart, I.S., 1993. Sensitivity of fault-generated scarps as indicators of active tectonism: some constraints from the Aegean region. In: Thomas, D.S.G., Allison, R.J. (Eds.), Landscape Sensitivity. British Geomorphological Research Group Symposium Series, John Wiley and Sons, 129-147.

Stewart, I., 1996a. A rough guide to limestone fault scarps. Journal of Structural Geology 18, 1259–1264.

Stewart, I., 1996b. Holocene uplift and palaeoseismicity on the Eliki Fault western Gulf of Corinth, Greece. Annali di Geofisica 39, 575–588.

Stewart, I.S., Hancock, P.L., 1988. Normal fault zone evolution and fault-scarp degradation in the Aegean region. Basin Research 1, 139–153.

Stewart, I., Vita-Finzi, C., 1996. Coastal uplift on active normal faults: the Eliki Fault, Greece. Geophysical Research Letters 23, 1853–1856.

Stiros, S.C., Jones, R.E. (Eds.), 1996. Archaeoseismology. British School of Athens Occasional Paper.

Ten Dam, A., Khrebtov, A.I., 1970. The Menderes Massif geothermal province. Geothermics 2, 1117–1123.

Trifonov, V.G., Karakhanian, A.S., 2004. Active faulting and the human environment. Tectonophysics 380, 287–294.

Tomlinson, R.A., 1976. Greek Sanctuaries. St. Martin's Press, New York.

Ulin, D.L., 2004. The Myth of Solid Ground: Earthquakes, Prediction and the Fault Line Between Reason and Faith. Penguin, London.

Ustinova, Y., 2002. Either a daimon or a hero, or perhaps a god: mythical residents of Subterranean Chambers. Kemos 15, 267–288.

Ustinova, Y., 2009a. Cave experiences and ancient Greek oracles. Time and Mind 2, 265–286.

Ustinova, Y., 2009b. Caves and the Ancient Greek Mind. Oxford University Press.

Yechieli, Y., Bein, A., 2002. Response of groundwater systems in the Dead Sea Rift Valley to the Nuweiba earthquake: changes in head, water chemistry, and near-surface effects. Journal of Geophysical Research: Solid Earth 107 (B12) .

Zangger, E., 1993. The Geoarchaeology of the Argolid. Gebr. Mann Verlag, Berlin.