Creation and destruction of travertine monumental stone by earthquake faulting at Hierapolis, Turkey

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Abstract: The presence of travertines adjacent to the city and their value for construction was well known to the Greek, Roman and Byzantine residents of Hierapolis (modern Pamukkale). The travertines were mainly extracted from quarries on the outer slopes of a low plateau below the city. The distinctive attribute of most of the quarries is that they are narrow but deep vertical-sided trenches. Each trench is the site of a nearly vertical fissure that was filled by banded fissure travertine, one type of so-called *Phrygian marble*. Trench walls, formerly the contacts between vertical banded travertines and outward dipping bedded travertines, bear a well-defined herringbone pattern of tool marks identical to those on many of the stone blocks that were used for building Hierapolis. Deposition of the travertines in 21 major fissure–ridges was a consequence of precipitation following degassing of carbonate-rich hot waters emerging from springs aligned along active faults and associated fissures. Whereas the dense and attractively banded travertine in fissures was principally used as an ornamental stone, the bedded travertines of ridge sides were mainly employed as a dimension stone and for making columns. After many of the monuments at Hierapolis had been constructed from travertine, itself a faulting-related material, some of them were subsequently destroyed or damaged by earthquake fault reactivation, which caused them to be either shaken or displaced. The zone of greatest seismic damage coincides with the trace of the Hierapolis fault zone, whose location was detected from an alignment of offsets of walls and petrified irrigation channels. The kinematic class of this fault zone could be deduced because offsets of the linear archaeological features permitted opening directions to be determined, thus allowing the fault zone to be reinterpreted as a normal fault zone achieving a small downthrow to the southwest. The knowledge that the Hierapolis fault zone is a structure across which there is active stretching and increased hydrothermal flow helps to explain why the present-day area of hot pools and travertine deposition is situated immediately downslope of the fault trace. If this relationship between displaced features and recent travertine deposits occurs elsewhere it might be employed for finding the locations of earthquake faults.

The purpose of this paper is to explain how earthquake faulting in the city of Hierapolis is associated with the deposition of a large body of travertine that was quarried for stone in Greek and Roman times, and how subsequent reactivation of faults in the same area during these periods and later was responsible for damaging the city. The site of Hierapolis, one of several Greek and Roman cities in the Maeander River valley (the present Menderes River) (Fig. 1), is roughly coincident with the present tourist village of Pamukkale, a settlement that in the last 50 years has served the needs of visitors not only to Hierapolis but also to the famous white travertine deposits that give Pamukkale its name, 'cotton castle'. Excluding the extensive northern necropolis and smaller southern necropolis, much of Hierapolis lies within its late Roman city wall (Peres 1987) (Fig. 2).

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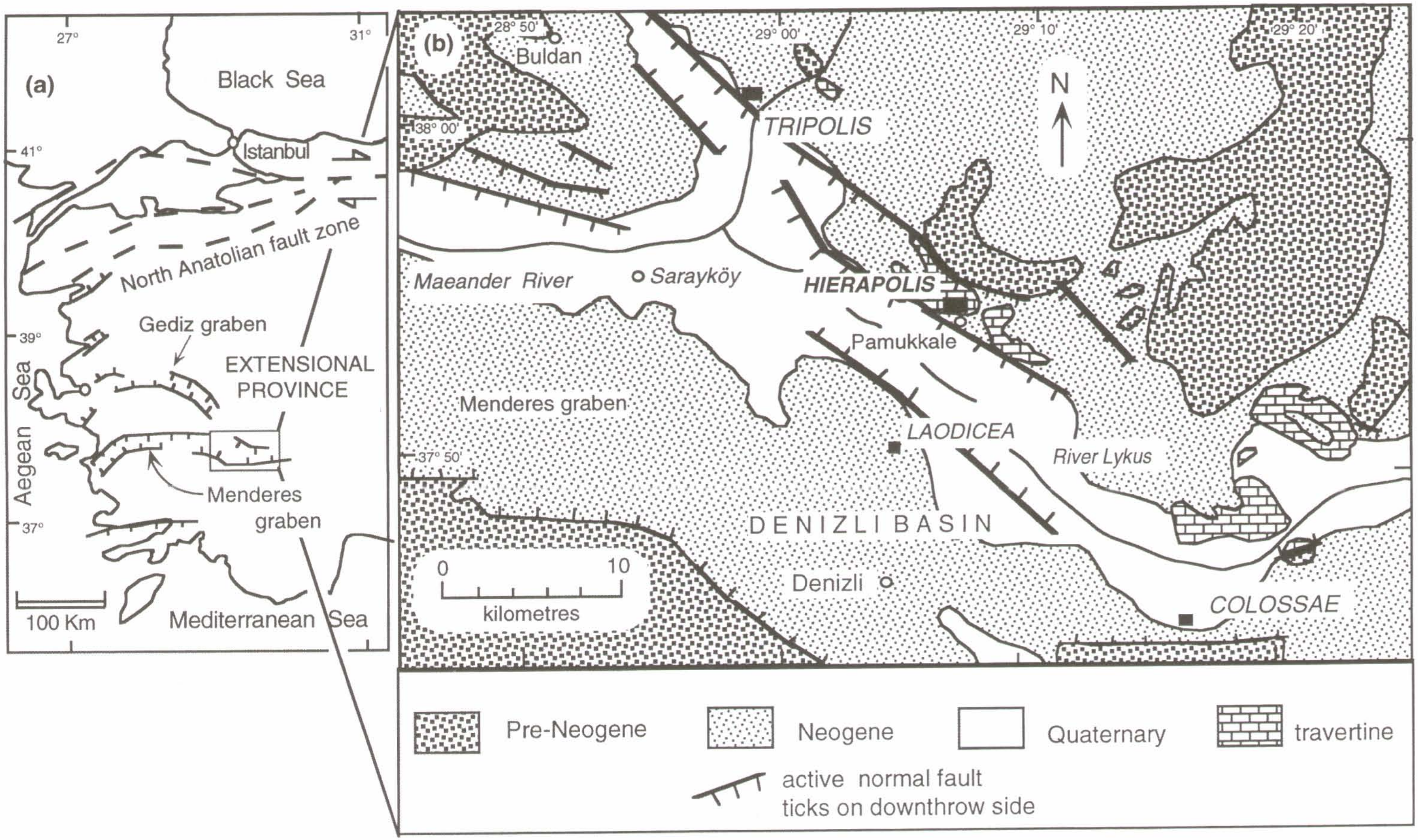

Fig. 1. (**a**) Turkish sector of the Aegean extensional province. (**b**) Geological, topographic and historical setting of Hierapolis within the Denizli basin (modified after Altunel & Hancock 1993*a*).

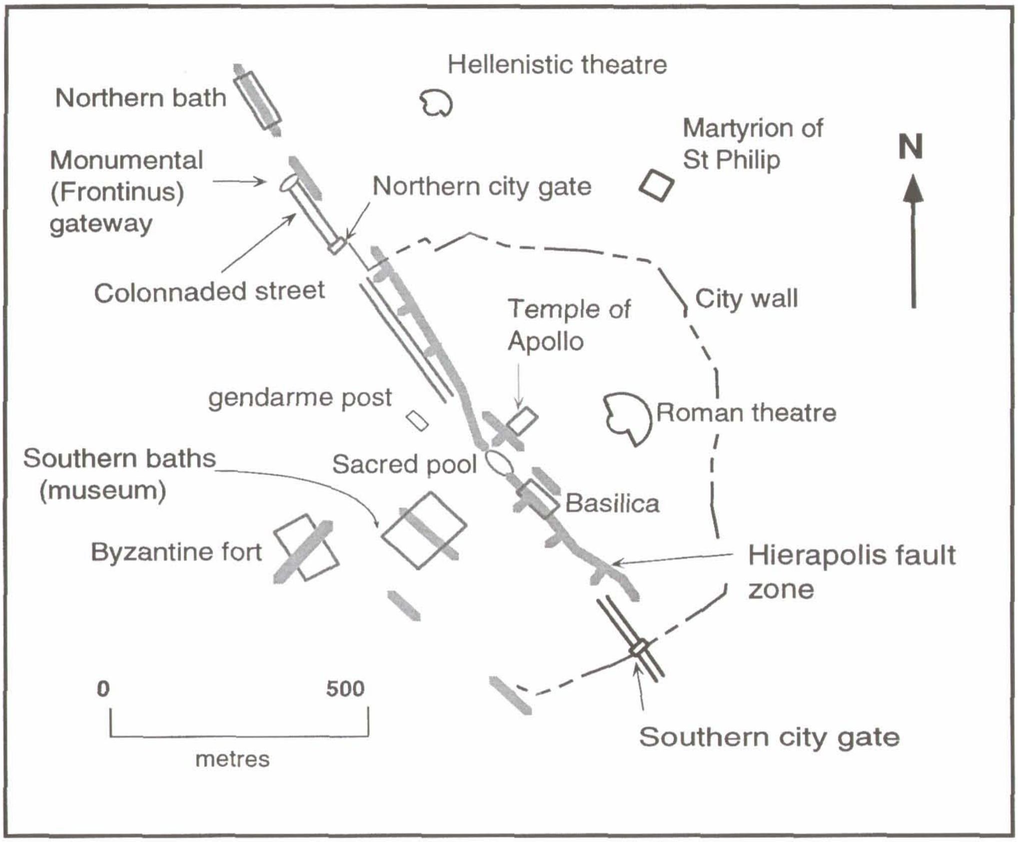

Fig. 2. Sketch map of selected principal monuments within Hierapolis.

Neotectonic, topographic and historical setting

Many landforms in regions of active extensional tectonics directly reflect recent earth movements and hence they can have a great influence on routeways and settlements. This is especially true of western Anatolia, which is situated in the east of the Aegean extensional province (Fig. 1a), a region currently experiencing normal faulting and the formation of rift valleys (grabens) and intervening horst-block mountains as a consequence of roughly NNE–SSW stretching (Jackson 1994).

Hierapolis is sited on the northeastern edge of the Denizli basin, a structure within the Menderes graben but close to its confluence with the Gediz graben. The Denizli basin has been subsiding since Miocene time (Westaway 1993). It is framed to the south by a major E–W trending normal fault, which is part of the Menderes system, but to the northeast the principal faults trend NW–SE, that is, they follow the Gediz graben trend. The Denizli basin and the Gediz graben are separated by a zone, to the northwest of Buldan (Fig. 1b), that does not contain large normal faults and hence is not expressed by a graben or basin.

The floor of the Denizli basin is mainly underlain by Neogene and Quaternary clastic sediments. The Quaternary travertine masses of the basin, of which the Pamukkale mass is only one, rest on these clastic sediments. External to the Denizli basin there are outcrops of metamorphic and igneous basement rocks unconformably overlain by Neogene clastic deposits. The Pamukkale range-front fault separates the sediments of the Denizli basin from the basement rocks to the northeast, with a downthrow southwest of at least 450 m (Altunel & Hancock 1993*a*).

The large-scale topography of the region is a direct expression of Neogene and Quaternary tectonic activity. For example, the Denizli basin is an area of low relief, the nearly level Quaternary flood plains of the Maeander and Lykus (modern Çuruksu) rivers being at about 280 m above sea level and about 60 m lower than the surrounding incised plateau underlain by Neogene sediments. The mountain massif of Küçük Çökelezdag to the northeast of the basin rises to a maximum of 1739 m, whereas to the south of Denizli the higher mountain of Babadag reaches 2300 m and the even higher peak of Honazdag, south of Colossae, achieves 2571 m. Between the Denizli basin and the Alasehir valley of the Gediz graben is an area of high but not rugged ground, rising to about 1324 m.

The Pamukkale travertines, which were used for building Hierapolis, are situated within what we call the Pamukkale plateau but some parts of northeastern Hierapolis are sited on the

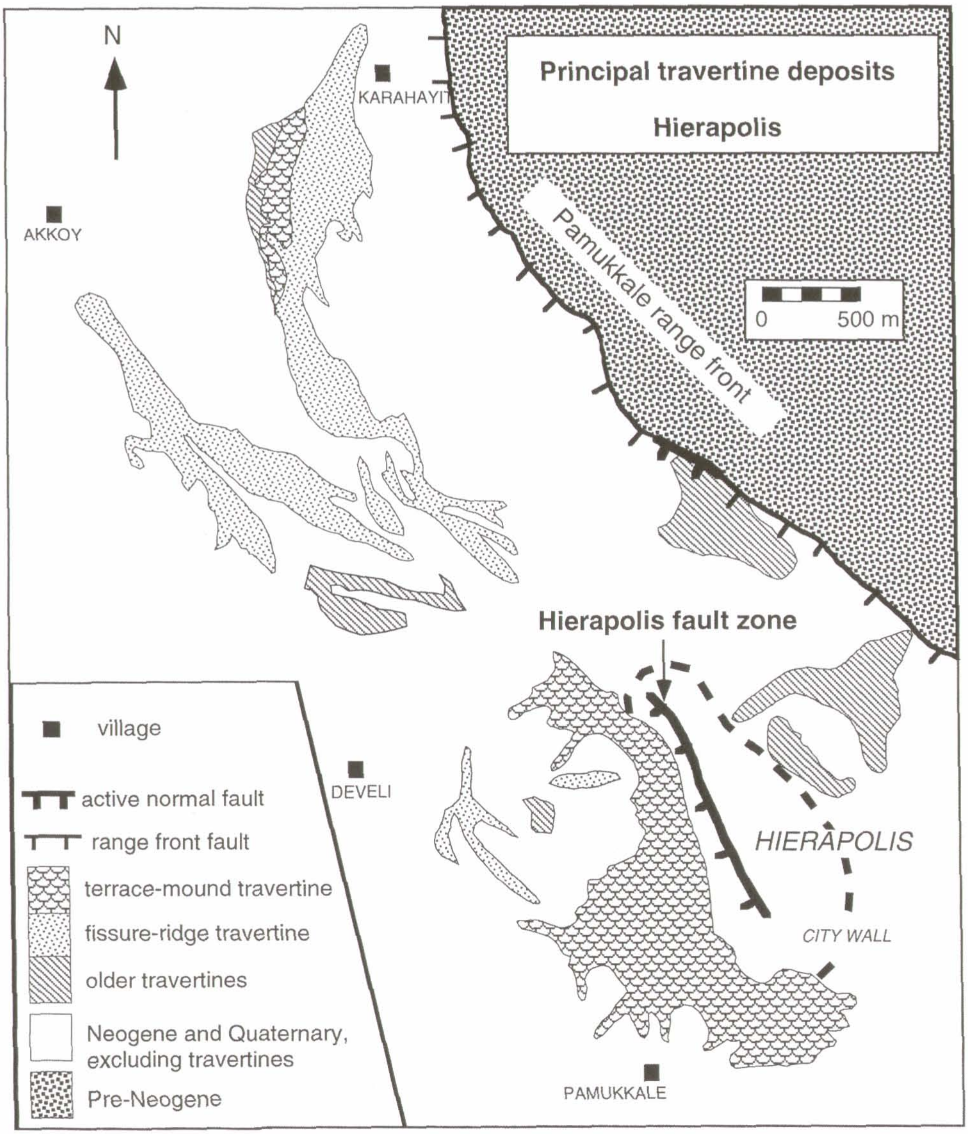

Fig. 3. Map of the distribution of morphological varieties of travertine and active faults in the Hierapolis area (based on Altunel & Hancock 1993*a*). It should be noted that the large outcrop of actively depositing terraced-mound travertine near Pamukkale is sited in the hanging wall of the Hierapolis fault zone.

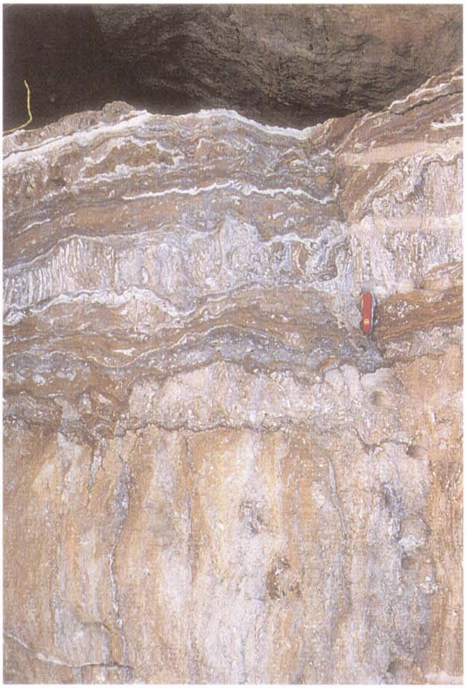

Fig. 4. Vertically banded fissure travertine cutting horizontal bedded travertine in the Yarikkaya fissure–ridge, about 1400 m north of Develi.

lower slopes of the Pamukkale range front. The plateau is bounded to the northeast by the 300 m-high Pamukkale range front that defines the southwest edge of the Küçük Çökelezdag massif. There are, except in the south, two levels within the Pamukkale plateau. Hierapolis is situated on the upper level, adjacent to the Pamukkale range front, and about 30 m above the lower level, which contains most of the travertine deposits (Fig. 3). The southern segment of the slope between the two terraces of this divided plateau is the site of the most spectacularly white of the actively depositing travertines.

The major valleys, which coincide with the Menderes and Gediz grabens, were important routeways for peoples and armies travelling either west or east between the Aegean coastlands and the central Anatolian plateau, a region that gave access to the upper Euphrates valley and from there to Persia and further east (see Ramsay's (1890) map of routes in ancient Asia Minor). Although the Menderes graben provided the easiest pathway from the Aegean coast via Tralles (modern Aydin) and Nyssa to the interior, the Gediz graben was also a vital route connecting Magnesia (modern Manisa), King Croesus' city of Sardis and Philadelphia (modern Alasehir) in the Gediz graben to the cities of Tripolis, Hierapolis, Laodicea and Colossae in the Denizli basin.

Because the Denizli basin lies at the confluence of two major routes from the coast to the interior and because it is a large area of relatively level and well-watered ground close to the Anatolian plateau it is no surprise that cities developed within it in ancient times. In addition to Hierapolis (of Greek foundation, although mainly Roman and Byzantine monuments remain), there were Tripolis, Laodicea and Colossae (Fig. 1b). Hierapolis was probably occupied before Classical times, its hot springs, both then and later, being a great attraction. Furthermore, the presence of a holy spring (the Plutonium next to the Temple of Apollo; see later discussion) in Hierapolis was critical to

Fig. 5. A vertical crestal fissure of approximately 5 m width within an inactive NW-trending fissure–ridge about 1500 m north of Develi. (Note the gentle dip of the bedded ridge travertines away from the fissure, which is the site of a Roman quarry from which Phrygian marble was obtained.)

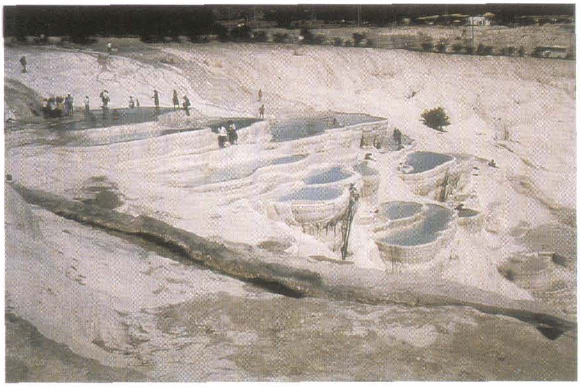

Fig. 6. Terraced-mound travertine with metre-scale pools, 800 m NE of Pamukkale village. Water supplying these pools issues from springs sited on the Hierapolis fault zone. (Note the palisades of stalactites fringing each pool.)

Fig. 7. A perched self-built and petrified water channel of approximately 10 m height that is now ruptured, possibly as a result of earthquake ground shaking; about 1600 m east of Develi.

maintaining the city's continuing importance throughout Classical times. It is also noteworthy that Herodotus (484–420 BC), who in Book 7 writes about this area, refers to a city in the present neighbourhood of Hierapolis as Cydrara, and later mention is also made by him to Hydrela, both places possibly being the city that we now think of as Hierapolis.

Laodicea was a Greek city, mainly built of travertine, but with important Roman modifications in the form of aqueduct pipes bringing water from a spring in Denizli, 8 km away, across a valley and into a water tower within the city centre. The pipes of this damaged water tower are now furred-up with calcareous deposits, testifying to the widespread presence of dissolved calcium carbonate in the ground waters of the entire Denizli basin. Colossae, which is much less well preserved than Hierapolis or Laodicea, was, again, both a Greek and Roman city. Tripolis, a mainly Greek city in the extreme northwest of the Denizli basin, is also built of travertine quarried from a small mass within the footwall block of the range-front fault. Until excavated, the city was largely covered by slope deposits derived from the range front. Herodotus (1954), in Book 7 states that this is the route taken by Xerxes, who is reputed to have discovered, near what was probably Tripolis, a plane tree so beautiful that he decorated it with golden ornaments.

Travertine deposits

In this paper we use the term 'travertine' to embrace all 'freshwater' limestone products of deposition from hot carbonate-rich spring waters irrespective of whether they are compact (i.e. travertine as often defined) or whether they are

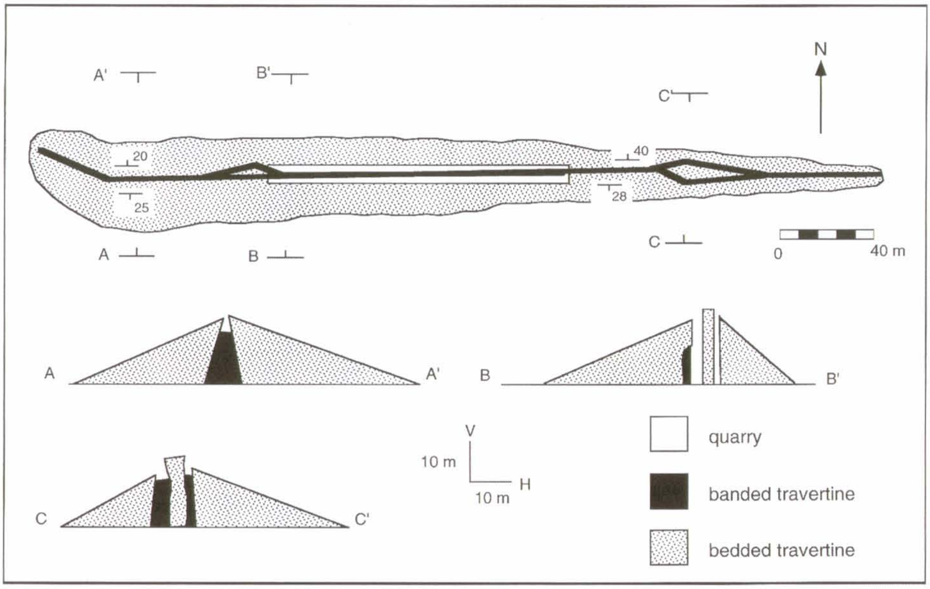

Fig. 8. Plan and profiles of the Çukurbag ridge (900 m east of Develi), the profiles emphasizing that Roman (and possibly later) quarrying has given rise to trench-like excavations where vertically banded fissure–ridge travertine has been selectively extracted.

porous, and might be called 'tufa' (Ford & Pedley 1996). Neogene clastic sediments are the most abundant materials underlying the Pamukkale plateau but the most distinctive rocks are travertines of Quaternary age, mainly less than 400 ka (Altunel & Hancock 1993*a*). Although the older travertines are of middle Pleistocene age (>400 ka), travertines are still being deposited, testifying to the continued action of hydrothermal flow in this area of active faulting. All the travertines are products of the degassing and consequential precipitation from hot carbonate-rich waters that emerge from springs aligned along fissures and faults that opened during the late Quaternary stretching of the Denizli basin. Stretching was also responsible for the increments of slip on the normal faults that frame the basin. The Pamukkale range-front fault is the closest of these faults to the travertines of the Pamukkale plateau.

Of the five types of landform constructed of travertine (Altunel & Hancock 1993*a*, *b*, 1996),

Fig. 9. A well-defined trench-like quarry corresponding to the central fissure of a ridge 900 m NNW of Pamukkale (visible in the background). The bedded travertines of the ridge are higher on the east side of the fissure because it expresses the location of an underlying normal fault downthrowing west.

Fig. 10. Part of an abandoned Roman column cut from bedded travertine in the Çukurbag ridge, about 900 m east of Develi.

Fig. 11. A toppled wall constructed of travertine blocks quarried from bedded travertine. Toppling of this wall to the northeastern side of the Colonnaded Street probably occurred during an earthquake. (Note that a small petrified water channel (arrows) formed on the upstanding edges of one row of fallen blocks.)

three are especially important from the perspective of the construction and destruction of Hierapolis (Fig. 3):

(1) The 21 fissure–ridges, mainly younger than 80 ka, each comprise a crestal fissure filled by vertical colour-banded travertine cutting white- to yellow-bedded travertine dipping away from ridge crests (Figs 4 and 5). Ridges range in length from about 100 to 1500 m in width from about 5 to 500 m, and in height they rise up to 25 m above the surrounding nearly flat land of the lower level of the Pamukkale plateau.

(2) Terraced-mound travertines, many of which are still accumulating, mantle the hillslopes between the upper and lower levels of the Pamukkale plateau down which the carbonate-rich waters have flowed and cascaded. Where they are being actively deposited these travertines are snow-white but where they are dry they have weathered to an unattractive dark brown to black colour. Numerous hot pools encircled by palisades of travertine stalactites characterize the southern slopes of the main mass of terraced-mound deposits near Pamukkale village (Figs 3 and 6).

(3) Self-built channel travertines, the sites of most of which were artificially determined, are wall-like features of 1–2 m width developed where carbonate-rich, hot spring waters flow in a confined channel used for irrigation or other purposes. Degassing during turbulent flow leads to the precipitation of travertine on the floors and walls of these channels, which grow in height until the channel becomes perched far above its original level. Some of these petrified water channels date from Roman times because: (a) Vitruvius described them at the time of Augustus (27 BC–AD 14) (D'Adria, in Peres

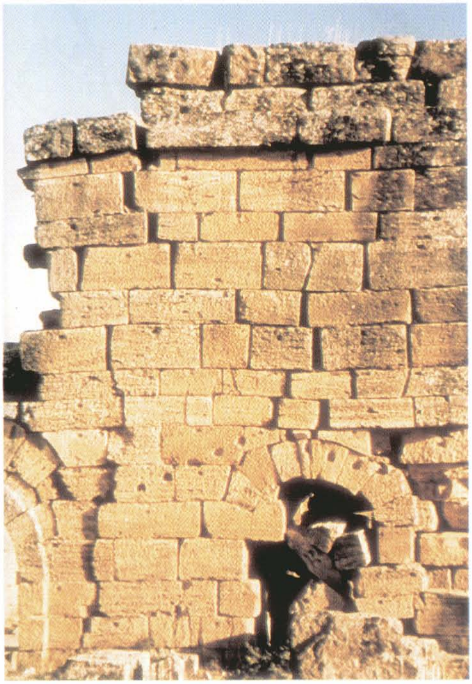

Fig. 12. Fissures cutting the walls of part of the Northern Baths, a monument built of bedded travertine blocks. Fissuring is a characteristic form of damage in dry masonry walls shaken during an earthquake.

1987), and (b) Hierapolis is the centre of the network they define. Some channels, such as those passing through the Northern City Gate or the Byzantine Basilica, are clearly younger; indeed, some of them are still in use. On the outer and steeper slopes of the Pamukkale plateau some petrified irrigation channels have grown as high as 10 m (Fig. 7).

The genetic connection between travertine deposition and earthquake faulting is that the stretching responsible for normal faulting also opened associated vertical fissures striking parallel to the faults (Altunel & Hancock 1993*a*). It is mainly these fissures that have allowed the carbonate-rich hydrothermal waters to rise to the surface. In addition, some waters ascend via the steeply inclined fault zones, some of which curve to become nearly vertical fissures close to the ground surface. The Pamukkale area and surrounding region are characterized by abnormally high heat-flow values. This is vividly reflected in the geothermal field near Cubukdagi, about 15 km to the west of Pamukkale (Simsek & Okandan 1990). Whether individual slip increments on faults are accompanied by changes in subsurface water flow, as Muir Wood (1993) has suggested happens elsewhere in the world, is not known. Thus whether travertine deposition at Hierapolis was greater or less at such times is a major question requiring an answer.

Travertine as an ancient building material

Much of Roman and Byzantine Hierapolis is built of travertine extracted from quarries in the fissure–ridge deposits situated below the city. The distinctive attribute of these quarries is that many of them are narrow (2–10 m) but deep (5–20 m) vertical-sided trenches. Each trench is the site of a nearly vertical fissure that was filled by banded fissure travertine, one type of the so-called *Phrygian marble* (Figs 5, 8 and 9). Trench walls, formerly the contacts between vertical banded travertines and outward dipping bedded travertines, display scaffolding holes and many are decorated by a herringbone pattern of tool marks identical to those on sarcophagi and many of the blocks that were used for constructing buildings at Hierapolis. The dense and attractively banded travertine from fissures was principally used as an ornamental stone, whereas the bedded travertine from ridge sides was mainly employed as a dimension stone and for making columns (Fig. 10). Bean's (1971) remark that local marble was not widely used in Hierapolis does not accord with our experience, unless he was referring only to the banded travertine from fissures.

Notable buildings constructed of bedded travertine blocks include, from north to south (Fig. 2): (1) the Northern Roman Baths dating from the second–third centuries and including a Byzantine (fifth-century) Basilica built within it; (2) the Hellenistic Theatre, which was largely demolished in the first century AD when the Roman Theatre was built; (3) the Monumental (Frontinus) Gateway dedicated to Domitian, dating from the end of the first century AD; a structure that was rebuilt after a devastating earthquake; (4) the Nymphaeum adjacent to the Monumental Gateway; (5) the early Christian Martyrion in honour of St Philip from the end of the fourth or beginning of the fifth century; (6) the Northern Gate through the city wall; (7) the Temple of Apollo; (8) the Roman Theatre; (9) the Southern Baths (now a museum); (10) a Byzantine Basilica of the sixth century; (10) a 12th–13th century Byzantine fort; (11) the sixth-century Southern City Gate. In addition, most tombs in both the Northern and Southern Necropolis, beyond the city walls, are built of travertine blocks, as is the city wall itself. According to D'Adria (in Peres 1987)

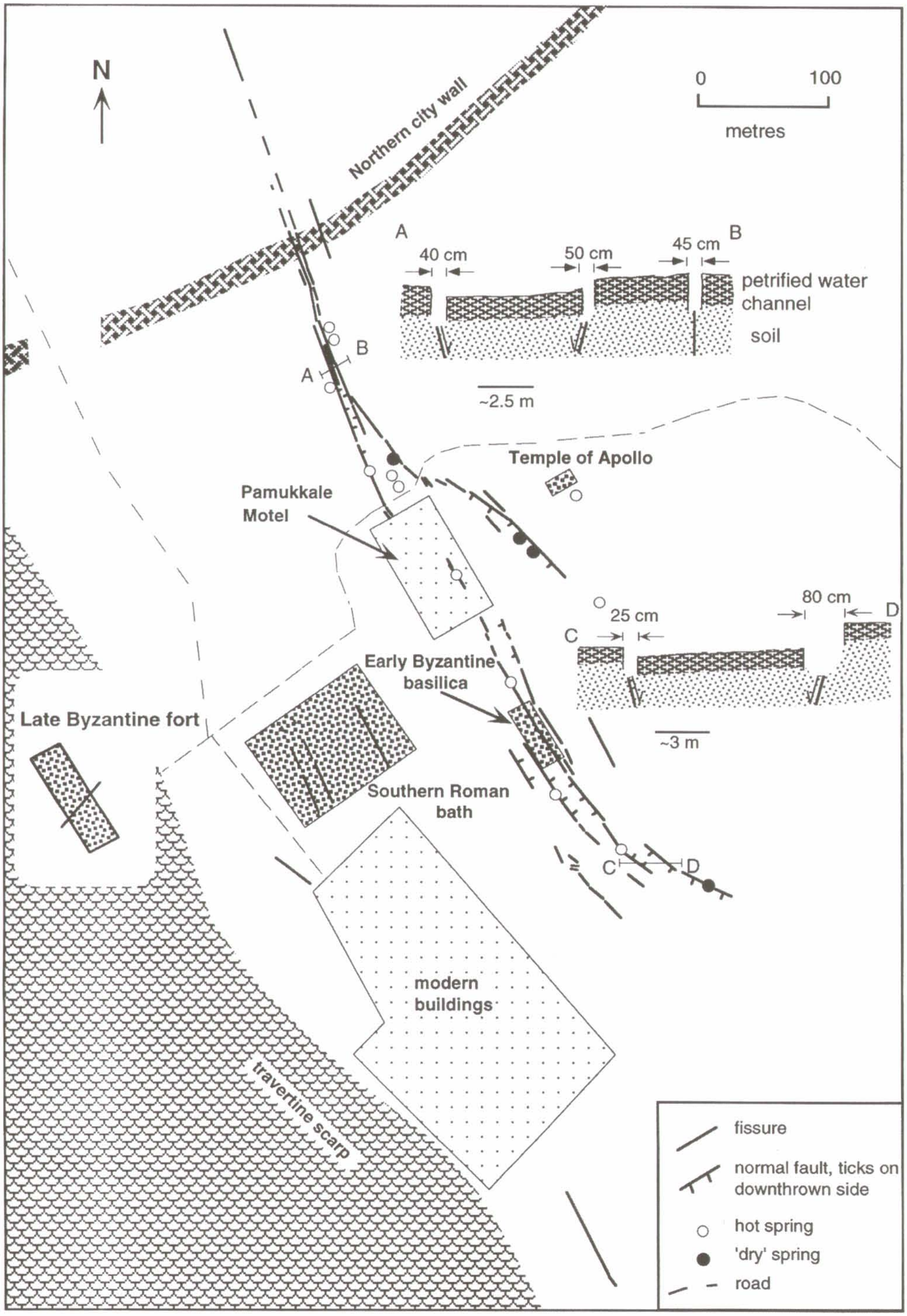

Fig. 13. Plan of the Hierapolis fault zone. The shapes of buildings are schematic and not all modern buildings are shown (after Hancock & Altunel 1997). It should be noted that in section A–B the petrified water channel is downfaulted in a mini-graben where it has been stretched over two normal faults that are oriented roughly at right angles to the line of the channel; the appearance of this mini-graben is illustrated in Fig. 15.

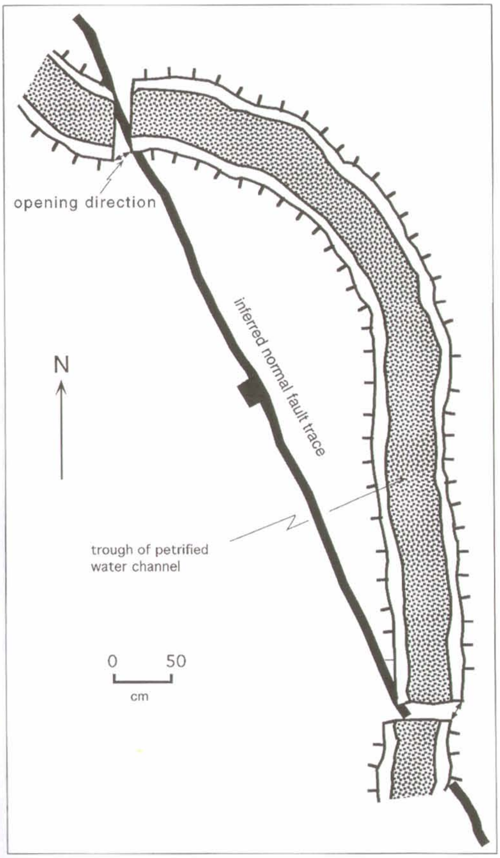

Fig. 14. Sketch plan of a petrified irrigation channel that has been offset at two places by the Hierapolis fault about 90 m SSE of the northern city wall. It should be noted that where the channel locally trends E–W the offset as determined from piercing points combines horizontal opening with sinistral motion, and where it locally trends N–S opening is combined with a dextral sense of motion. These apparently contradictory senses of horizontal offset have arisen because the observed 'strike-slip' sense is controlled by the angle between a channel long axis and the opening direction across the trace of the fault. There is also an overall downthrow of about 7 cm to the west across the fault (after Hancock & Altunel 1997).

blocks from many buildings were cannibalized to construct the city wall, which was built as a result of a law introduced in AD 396, that is, at a time late in the Roman Empire. Furthermore, many of the Doric columns lining the sides of the Colonnaded Street (Via Domizianea) are of travertine and directly comparable with the stone of the abandoned column at the Çukurbag quarry (Fig. 10).

Earthquake history of Hierapolis

Although faulted archaeological features are readily analysed indicators of deformation patterns associated with earthquakes they may be more difficult to employ as guides to their timing. Historical earthquake catalogues are needed for this aspect of their analysis. The scholarly catalogue of pre-tenth century AD earthquakes by Guidoboni *et al.* (1994) indicates that the following earthquakes after the birth of Christ but before the 10th century were destructive at Hierapolis: 47, 60, an unknown date in the third century, an unknown date in the fourth century, 494, and early in the seventh century. It is also possible that an earthquake recorded by Guidoboni *et al.* (1994) as having occurred in about 27 BC, which was responsible for rebuilding work at Laodicea, might have also damaged Hierapolis, less than 10 km from Laodicea. Soysal *et al.* (1981) also reported the AD 60 earthquake in their catalogue, and added to it events of MSK intensities VIII and VII in 65 and 20 BC, respectively. Most archaeological and historical writers focus on the AD 60 earthquake; for example, Peres (1987) recorded that Hierapolis was rebuilt after it, as did Bean (1971), and McDonagh (1989) also reported that Laodicea was rebuilt after the event.

Earthquakes of MSK intensity VII or more that affected the Hierapolis area between the 10th and 20th centuries include those of 1354, 1651, 1703, 1887 and 1899, according to Soysal *et al.* (1981), Ates & Bayülke (1982) and Ambraseys (1988). In the 20th century, the only event of M_s greater than 6.0 to have affected the Hierapolis area is that of 1900 reported by Ergin *et al.* (1967) and Gencòglu *et al.* (1990).

Earthquake damage at Hierapolis

Many of the monuments that had been constructed of travertine related to older Quaternary episodes of faulting were then destroyed or damaged by reactivation of the faults, which caused continued earthquake shaking or ground displacement. For example, the toppled wall (Fig. 11), part of the Colonnaded Street, collapsed without losing its essential form and then became the foundation of a later petrified water channel, which follows part of its length. Vertical fissures, which elsewhere are regarded as a characteristic form of earthquake shaking damage (Stiros 1996), rupture the walls of the third-century Northern Baths (Fig. 12). Examples of buildings reported by D'Adria (in Peres 1987) as having been reconstructed after the

Fig. 15. A slightly raised petrified irrigation channel cut by two fissure-faults (arrows) reflecting the locations of underlying normal faults that dip towards each other. The nearer of the faults, which achieves the greater displacement, downthrows west; the further but subordinate fault downthrows east. A section along the channel close to the gendarme post is shown in section A–B in Fig. 13.

Fig. 16. The so-called 'sacred pool' containing a submerged section of the Roman Colonnaded Street and fallen columns. The pool is sited on the trace of the Hierapolis fault zone; the flooding of the hollow possibly is a result of the subsidence of a small graben within the fault zone. A thin veneer of travertine is being unconformably deposited on the columns, which, being aligned, might have toppled during an earthquake.

AD 60 earthquake in Nero's reign include the Temple of Apollo and the Roman Theatre. In the southeastern Necropolis a sarcophagus made of travertine was overturned by earthquake shaking (presumed here to be the AD 60 event because Ronchetta (in Peres 1987) described it as 'the' earthquake).

The zone of greatest earthquake damage coincides with the trace of the Hierapolis fault zone, whose location was detected from an alignment of offset walls and petrified irrigation channels (Fig. 13) (Hancock & Altunel 1997). The kinematic class of this fault zone could be determined precisely from the many offsets of the linear archaeological features, which are cut by vertical fissures expressing faults that are steeply inclined a few metres below the surface (Hancock & Altunel 1997) (Fig. 13). The offset archaeological features permitted piercing points, and hence opening directions, to be determined, thus allowing the fault zone, previously thought by Altunel & Hancock (1993*a*) to be a sinistral strike-slip, to be reinterpreted as a normal fault zone achieving a small downthrow to the southwest. In plan, the sense of the angle between a channel and the trace of a fault determines whether a channel is offset horizontally in a dextral or sinistral sense (Fig. 14). Where the line of a channel is subparallel to the opening direction there will be horizontal opening and a normal component of displacement of the channel. This gives rise to a mini-graben, where a subsidiary normal fault that is antithetic to the main one also cuts the channel (Figs 13 (section A–B) and 15). The knowledge that the rapolis fault zone is a structure across which re is active stretching and increased hydro-rmal flow, as reflected by the concentration of t springs in the zone, helps to explain why the rea of greatest present-day travertine deposition is situated in its immediate hanging wall and just downslope of the fault trace (Fig. 3).

In the once-beautiful 'sacred pool' (now within the Pamukkale Motel and not be confused with the holy cavern of the Plutomium) a thin veneer of travertine is being unconformably deposited on columns that have fallen alongside a submerged paved area, possibly a continuation of the Colonnaded Street. The pool, possibly sited on a small graben within the Hierapolis fault zone, is being fed from a hot spring within the fault zone. The nearly uniform direction of toppling of the fallen columns might be a reflection of earthquake shaking (Fig. 16) (Nur & Ron 1996), and, if this is so, the deposition of travertine on the columns testifies to the intimate relationship between faulting, ground rupture, earthquake shaking and travertine deposition.

Hierapolis, like Delphi (Greece), possesses a holy cavern about which legends have grown up. At Delphi the Oracle's mantic sessions might have been a result of the Oracle inhaling light hydrocarbon gases arising from buried limestones rich in bitumens (De Boer 1999). At Hierapolis, the legend that animals and men, other than certain priests, who entered the holy cavern, known as the Plutomium (adjacent to the Temple of Apollo) died in the so-called strong-smelling 'steams' we think is likely to be a consequence of the concentration of carbon dioxide in addition to other gases in such a small subsurface chamber into which hot waters flowed. The Plutomium's proximity to the eastern branch of the Hierapolis fault zone means that beneath it there is likely to be a higher than normal concentration of vertical fissures that are the conduits for such waters (Fig. 13).

Summary

(1) The travertine deposits at Hierapolis are secondary products of the area having been stretched during earthquake normal faulting for at least 400 000 years.

(2) The bedded travertines of fissure–ridges have been quarried since before Roman times for dimension stone and were the principal building materials used by Greeks, Romans and Byzantines in the construction of monuments. Finely banded travertines quarried from the vertical fissures cutting ridges were mainly used for ornamental purposes.

(3) Many of the monuments and other features built of travertine have been damaged by earthquake shaking or faulting during the period since at least AD 60. Damage is concentrated along a narrow corridor coincident with the Hierapolis fault zone.

(4) Opening directions determined from piercing points defined by displaced features allow the Hierapolis fault zone to be reinterpreted as a normal fault zone. The area of contemporary greatest travertine deposition is just downslope and in the immediate hanging wall of the fault zone. If this relationship occurs elsewhere it might be employed for finding the locations of earthquake faults.

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