PERGAMON

Journal of Structural Geology 21 (1999) 903–916

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Travitonics: using travertines in active fault studies☆

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Received 23 July 1998; accepted 22 February 1999

Abstract

Late Quaternary travertines deposited from hot springs can reveal much about the neotectonic attributes and histories of structures. On the basis of field studies in the Aegean region (Turkey and Greece), the northern Apennines (Italy) and the Basin and Range province (USA) we conclude that the following relationships are of predictive value: (i) travertine deposits are preferentially located along fracture traces, either immediately above extensional fissures or in the hanging walls of normal faults; (ii) the locations of many travertine fissure-ridge deposits coincide with step-over zones (relay ramps) between fault segments; networks of intersecting tensional fissures reflecting the complex strains experienced in such settings are probably responsible for enhancing hydrothermal flow; (iii) the morphology of travertine deposits overlying extensional fissures is controlled by the rheology of the underlying materials; tufa cones (towers, pinnacles) form on former and present lake floors where fissures underlie unconsolidated sediments, whereas fissure-ridges develop where fissures cut bedrocks at the surface; (iv) fissure-ridges comprise outwardly dipping bedded travertine flanking a central tensional fissure filled by vertically banded travertines; fissures can be used to infer local stretching directions; (v) where there are travertines datable by the U-series method it is possible to calculate time-averaged dilation and lateral propagation rates for individual fissures; (vi) most fissures cutting fissure-ridges comprise self-similar angular segments with fractal dimensions in the range 1.00–1.12, the properties of bedded travertine combined with stress perturbations at fissure tips probably being responsible for such similar fractal dimensions being inferred from such a wide range of locations. Fissures gradually increasing in width with depth are products of continuous fracture dilation in contrast to those that form during episodic dilation which display stepped increases of width with depth; (vii) travertine deposited from springs along fault zones accumulate in terraced-mounds sited down slope of the spring line; (viii) many post-depositional fractures cutting travertine deposits are locally oriented at right angles to deposit margins; and (ix) systematic joints in travertines are restricted to those parts of eroded sheet deposits that have been exhumed. © 1999 Published by Elsevier Science Ltd. All rights reserved.

☆ Professor Paul Hancock's initial research interests focused on understanding joints and faults in ancient rocks. Since then and specifically within the last 10 years he became more involved in neotectonics, especially palaeoseismology. One aspect of this neotectonic research included the study of the tectonics of late Quaternary travertine deposits within areas experiencing active earthquake faulting. Professor Hancock's motive for writing this review was to explain what he thought was possible, and what was not, to gain from studying and identifying tectonic attributes of travertines. He wished to elaborate on the more general thinking behind the subject and place on record some general principles that required explanation. This review is an amalgamation of his and his students' research, although it is predominately his views and particular focus on the potential of travertines as neotectonic indicators. Sadly Professor Paul Hancock died in December 1998, and thus this paper/review presents his last thoughts on the topic. Reviews by James Evans and David Wiltschko were addressed by the second author; however, some of the suggested changes were not made so as to preserve Professor Hancock's thoughts. This was done with the approval of the Chief Editor.

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PII: S0191-8141(99)00061-9

1. Preamble

This article reviews structural aspects of late Quaternary travertine deposits in order to appreciate how they can add to our understanding of neotectonic processes and histories. The topic has never been the subject of an article published in the Journal of Structural Geology (or an allied periodical), and, furthermore, it has not been addressed in books focusing on the geological aspects of earthquakes (e.g. Vita-Finzi, 1986; Yeats et al., 1997). We hope that this paper will remedy these omissions and place on record some general principles that require explanation.

We do not claim credit for introducing the neologism 'travitonics'. The idea of using the word to embrace all aspects of travertine tectonics was suggested to the senior author in 1992 by the carbonate sedimentologist Professor Robert Folk. We recommend those with a broader interest in these unusual rocks to read his now classic paper on travertines (Chafetz and Folk, 1984) together with Ford and Pedley's (1996) review of the World's travertine deposits.

The examples chosen to illustrate the general attributes of tectonically controlled travertines are taken from several actively extending terranes that we have investigated. They are: (i) the eastern ends of the Menderes and Gediz grabens in western Turkey; (ii) the island of Euboea in central Greece; (iii) Lakes Volvi and Lagada in northern Greece; (iv) Bridgeport in eastern California; (v) Searles Lake in southern California; (vi) Pyramid Lake in western Nevada; and (vii) Rapolano Terme area in southern Tuscany. The first three areas are within the Aegean extensional province (Jackson, 1994), the second three are in the Basin and Range province and Rapolano Terme is on the northern margin of the Tuscany (Italy) geothermal field (Chiarabba et al., 1995).

2. Travertine and tufa

Travertines and tufas are both 'freshwater' limestones deposited from spring and other waters that are saturated or supersaturated with calcium carbonate ($CaCO_3$). Although there are gradations between the two rock types, travertine and tufa are commonly distinguished from each other on the basis of their origins which are reflected in their textures. The name travertine is generally given to a compact white or pale hydrothermal hot-spring deposit. In contrast, tufa is a name that is usually used to describe a porous and bedded deposit originating from either cold springs or accumulating in veins or lakes (Muir-Wood, 1993; Ford and Pedley, 1996). Travertines and tufas have been much used as building and decorative stones from ancient Greek times onwards (Hancock et al., in press).

The origin of the term tufa is derived from the Roman word *tophus*, which was used by Pliny to describe crumbly whitish deposits which included calcareous tufa, petrified vegetable matter and volcanic tuff. According to *Challinor's Dictionary of Geology* (Wyatt, 1996) and Charles Lyell cited in Ford and Pedley (1996) the name travertine derives from *Lapis tiburtinus* (Tibur Stone), so called because of its association with the Tibur, the river on which Rome stands. By contrast, Julia (1983) has proposed an alternative derivation of the name, suggesting that it comes from Tivertino, the old Roman name for Tivoli in Italy, where extensive deposits of travertine are found.

The main reason travertine and tufa are deposited from carbonate-rich waters is the loss of carbon dioxide as a result of either or both: (a) degassing during the fluid pressure drop that accompanies the ascent of spring waters from depth and turbulent flow at the surface; or (b) bacterial and algal activity extracting carbon dioxide from the waters (Chafetz and Folk, 1984; Ford and Pedley, 1996). Six morphological varieties of travertine or tufa deposits accompany active normal faults:

1. Terraced-mound travertines are a result of deposition from thermal spring waters that issue from point sources within segments of active faults and then flow down a slope to build a mound of travertine that can be up to 60 m high. It is these travertine forms, and their associated hot waters pools that attract tourists to sites such as Mammoth Hot Springs, Wyoming (Bargar, 1978) and Pamukkale, western Turkey (Altunel and Hancock, 1993a,b). Nearly vertical or steeply dipping cascade deposits accumulate where terraced-mound slopes are steep.
2. Fissure-ridge travertines comprise vertical fissures occupied by banded travertine, and inclined bedded travertine flanking the fissures (Bargar, 1978; Chafetz and Folk, 1984). Ridges can be straight or curved in plan and range from about 100 to 2000 m long, 5 to 400 m wide and 1 to 20 m high. If the flow rate from a fissure is fast the waters from it spread out rapidly and a ridge with a low aspect ratio (0.1–0.2, height to width) develops. In contrast, where slow flow rates from a fissure occur the ridge formed is relatively high but narrow, with aspect ratios approaching 1.0. Younger parasitic fissures cut the sides of some ridges.
3. Range-front travertines deposited from springs in the immediate footwalls of faults, locally cement talus derived from fault scarps and range fronts. Field relationships suggest that they are mainly older travertines, a conclusion supported by a provi-

sional U-series date of 66 ± 9 ka for a sample from Pamukkale (Altunel and Hancock, 1993a,b).

4. Eroded-sheet travertines include all non-conglomeratic travertines that are bedded and have been eroded. Some of them are probably the edges of range-front or terraced-mound travertines. A sample of eroded-sheet travertine from Pamukkale was dated by U-series method as greater than 400 ka (Altunel and Hancock, 1993a).
5. Tufa cones, towers and pinnacles are characteristic deposits in present-day and former lakes into which carbonate-rich spring waters are or were being discharged into unconsolidated lake-bottom sediments. They range in height from a few tens of centimetres to a few tens of metres. Where cones are aligned they reflect an underlying control by a fracture.
6. The classical scholar Bean (1971) used the name self-built channel travertine to describe the narrow (0.5–3.0 m) up-to 10-m-high, wall-like masses of travertine that distribute carbonate-rich waters to lower ground within the Pamukkale area. The wall-like perched form of these petrified channels is a result of the continuous deposition of travertine from turbulently flowing water on their floors and sides.

3. Advantages and disadvantages of using travertine deposits in neotectonic investigations

A major advantage of investigating travertines is that they can be dated by the U-series method provided they are younger than 400 ka. Dates are of great value when wishing to determine rates of fissure dilation and lateral propagation. In a more general sense it should also be possible to use the dates to determine episodes when travertine deposition was at a maximum and thus consider whether such maxima are more likely to be controlled by tectonism or climate change.

Because travertines are terrestrial deposits of restricted lateral extent they can be easily removed by erosion, giving them a low preservation potential in the rock record. However, this low preservation potential has the advantage that we can be sure that where travertines are preserved they are young and thus potentially of neotectonic significance. Travertines, compared with most surficial rocks, are lithified and hence where they are preserved they are upstanding features. This combined with their pale colour makes them easy to spot in the landscape, a decided advantage when searching for them as guides to the locations of the subtle traces of active faults.

The observation that most travertine deposits are irregular in shape and are heterogeneous means that they contain few well-ordered tectonic structures, stresses being perturbed both at their edges and within the deposits. Different varieties of travertine morphology are often associated with different structural processes; for example, fissure deposits occupy extensional fractures whereas bedded deposits terraced-mound and range-front travertines are good indicators of the presence of a nearby fault trace. Petrified irrigation channels present the neotectonician with numerous archaeologically datable piercing points where a network of them is displaced by active faults.

4. Tectonic aspects of travertines associated with active normal faults

4.1. Locations of deposits

It has been known for a long time that hot springs are aligned along some active fault traces and that hydrogeological changes commonly accompany earthquakes. Muir-Wood (1993) has called the study of the fossil record of these changes ‘neohydrotectonics’. As Barnes et al. (1978) commented, there is a world-wide association of travertine and tufa deposits with tectonically active zones. This is because faulting plays a key role in the transport of hydrothermal fluids as pointed out by Sibson (1996). Although carbonate-rich hot springs are more abundant in the hanging walls of normal faults, where the highest fluid flows have been recorded (Muir-Wood, 1993), they can also occur in their footwalls. For this reason the site of a hot-spring travertine deposit can be used as an indicator of the approximate location of the trace of an active fault. Confidence in such an interpretation increases where several adjacent travertine deposits are aligned along a possible fault.

Many of the springs that are the sources of travertine of fissure-ridges are located in step-over zones (jogs) between adjacent fault segments. The Balkaysi travertine adjacent to the fault zone that bounds the northern side of the Gediz graben in western Turkey provides a good example of this relationship (Fig. 1; Çakir, 1996). Although the fissure-ridges from which the main deposit is derived occur within 500 m of the step-over zone between the Ismailbey and Serinyayla fault segments, the remainder of the deposit is in the hanging walls of the fault segments as a consequence of spring-waters having flowed down the gentle range-front slope. A comparable relationship holds about 50 km southeast along the same zone of NW-trending faults that frame the Gediz and Menderes grabens close to their confluence (Altunel, 1994; Çakir, 1996). The justly famous Pamukkale travertines occur in a 1- to 2-km-wide step-over zone between the Hierapolis and Akkoy segments of the Pamukkale range-front

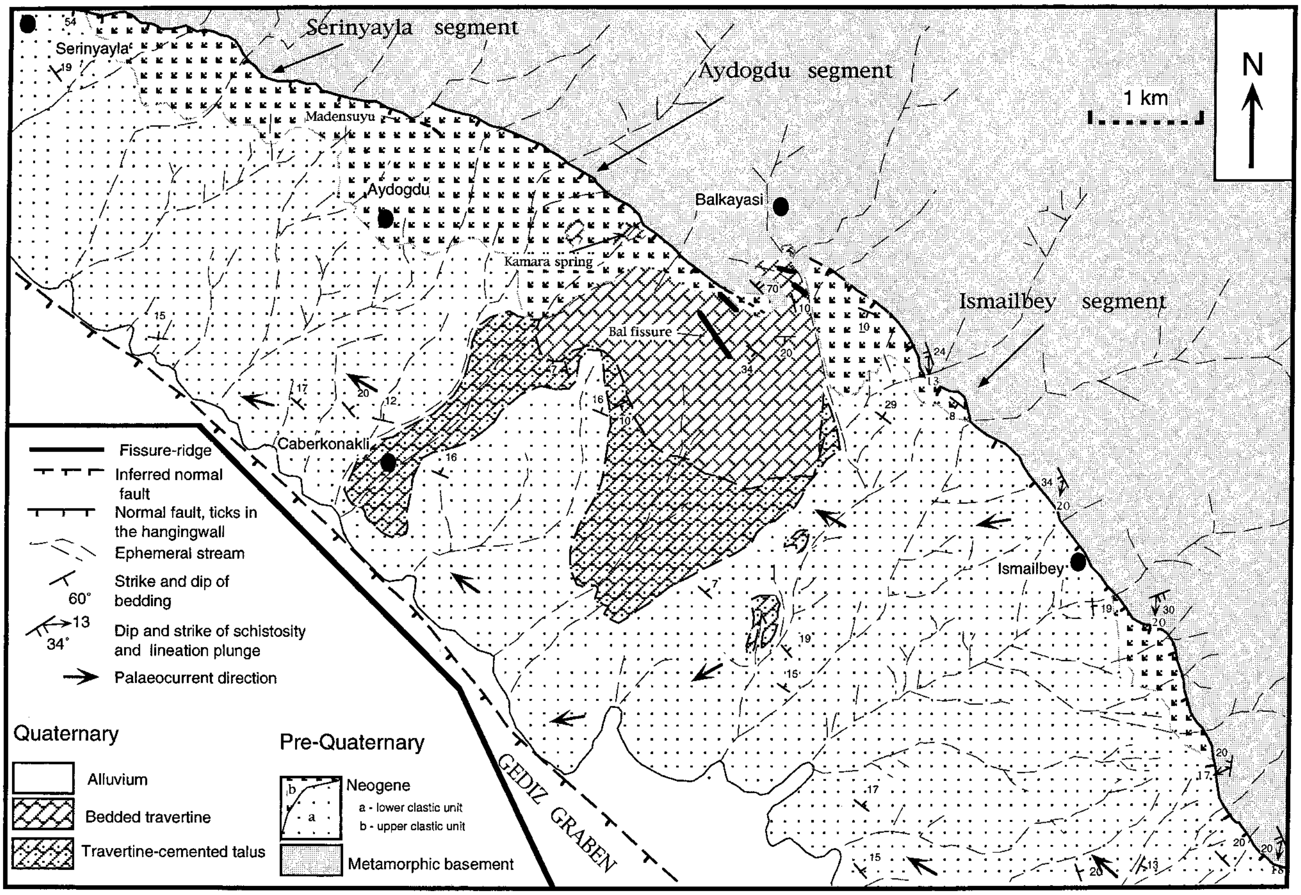

Fig. 1. Structural setting of the Balkayasi travertine deposit on the northeast margin of the Gediz graben, western Turkey. Note that the fissure-ridges from which the hydrothermal spring waters flowed are located in or close to a releasing step-over zone separating the Serinyayla and Ismeilbey fault segments. From Çakir (1996).

fault that locally forms the northeast margin of the Menderes graben (Fig. 2).

If this spatial relationship between step-over zones (relay ramps) and fissure-ridge travertine deposits is widespread it is one of great potential value to earthquake hazard reduction programmes because step-overs are common barriers to fault propagation (Yeats et al., 1997). A possible reason why fissure-ridges are features of normal fault step-overs is that in relay ramps complex strains are most likely to have been experienced (Jackson et al., 1982; Larsen, 1988; Fig. 3), the development of open Mode I cracks in such settings aiding sub-surface fluid flow. In some normal fault step-overs stretching related to the presence of a relay ramp is augmented by stretching related to the ramp also being the site of a releasing step-over. The Pamukkale travertine is a good example of this relationship; slickenlines on the Hierapolis segment of the fault indicating that dominantly normal motion was accompanied by a subsidiary component of sinistral strike-slip in a left-handed step-over.

Even where a step-over zone is not present other types of travertine deposits, such as terraced-mounds, are located at the lateral tips of major fault segments, perhaps where there are complex networks of small fractures in process zones (McGarth and Davison, 1995). The Edipsou Loutra travertine deposit is a possible example of such a setting. It occurs at the western end of the major NW-trending range-front fault where it locally turns to trend E–W (Fig. 4).

4.2. Travertine morphologies

The morphologies of travertine deposits are determined by both the local relief (itself probably of tectonic origin) and the structural setting of the springs supplying the carbonate-rich waters. For example, a line of springs situated along an extensional fracture (fissure) is expressed by a fissure-ridge if the springs are situated in bedrock exposed at the surface. The crestal fissures of ridges and the long axes of the ridges

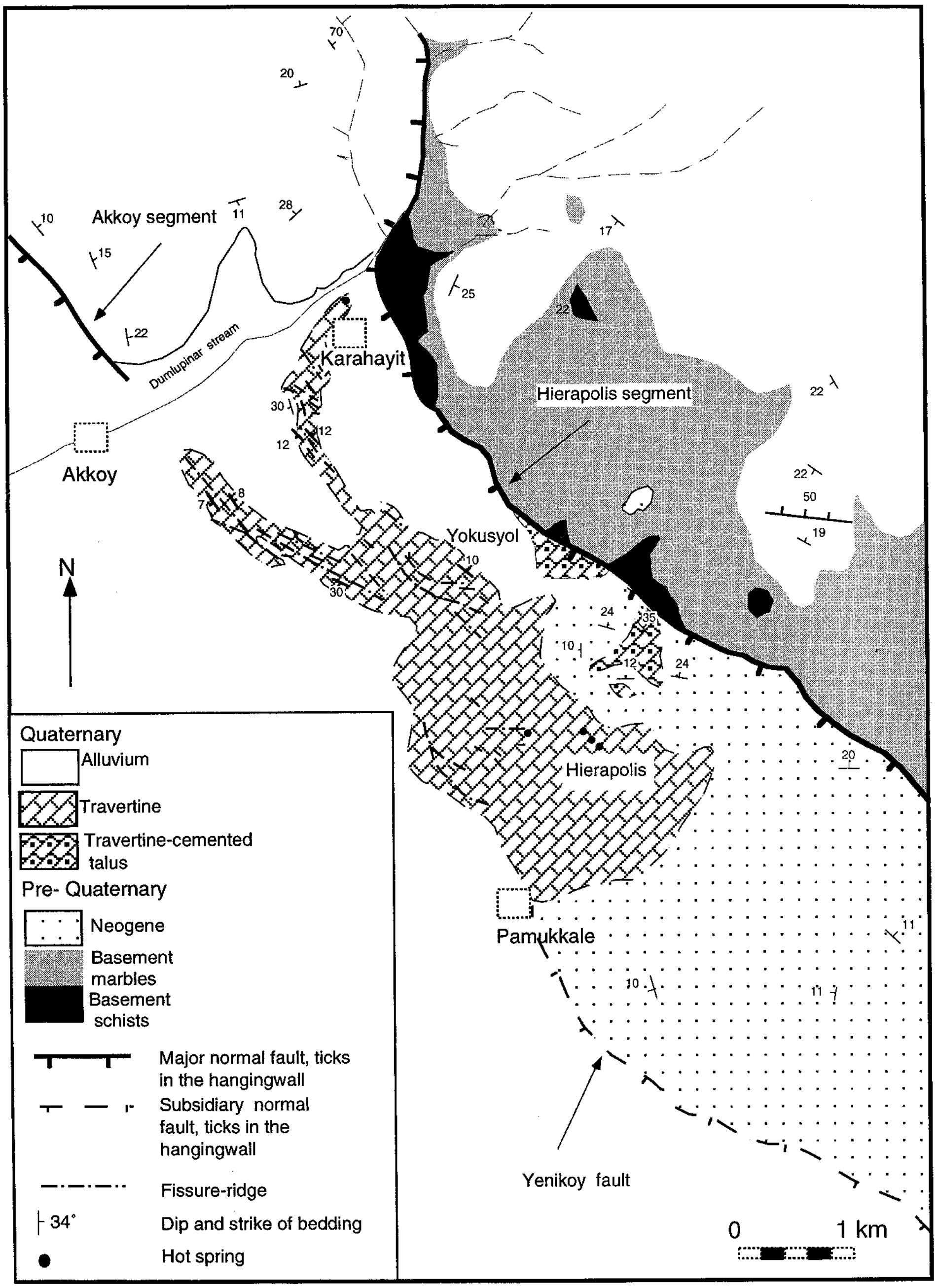

Fig. 2. Structural setting of the Pamukkale travertine deposit on the northeast margin of the Menderes graben, western Turkey. Note that the areal extent of the deposit is restricted to a releasing step-over zone between the Akkoy and Hierapolis segments of the Pamukkale range-front fault. Modified after Altunel (1994), Çakir (1996) and Chalmers (1998).

are both markedly elongate and parallel to each other, fissures developing normal to the local stretching direction (Figs. 5–7). By contrast, tufa cones (towers, pinnacles) form in and on the unconsolidated sediments of past and present lake floors where the sediments overlie fissures in bedrocks (Fig. 8). In these settings the spring waters reach or reached present or former lake floor via cylindrical orifices, rather than fissures. Some terraced-mound deposits, especially cascade deposits, are characteristic of travertines originating from springs situated in normal fault traces. An excellent example of a terraced-mound deposit is that at Pamukkale. As Fig. 9 shows, its irregular planform shape reveals little of its origin but its location immediately down-slope and in the hanging wall of the Hierapolis fault zone, within which there is a well-developed line of springs, can be confidently attributed to the presence of the fault.

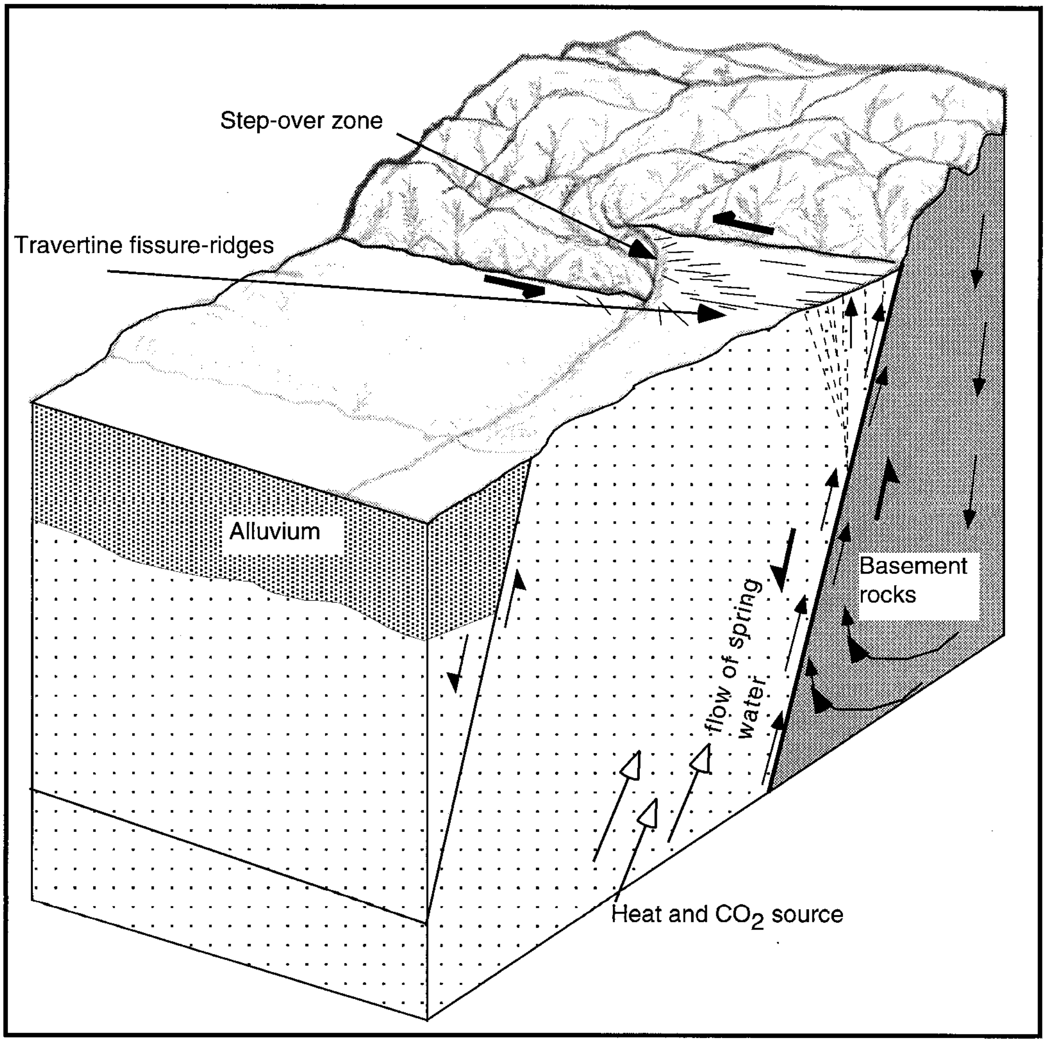

Fig. 3. A network of intersecting tensional fissures developed in response to a complex strain field in a releasing step-over zone between two fault segments on which motion is dominantly normal but also involves a subsidiary component of left-lateral strike-slip. The fissures act as pathways for ascending hydrothermal waters. Based on relationships observed in western Turkey. Modified from Çakir (1996).

4.3. Alignments of travertine morphologies

Within some travertine deposits the individual components define lineaments. Most spectacular of these are the tufa cones that rise above the sediments that accumulated on the floors of lakes or former lakes. Perhaps the best known example occurs at Searles Lake where at least two lines of towers, oriented roughly N–S parallel to nearby major normal faults, rise above the flat-floor of the former Quaternary lake that coincided with a structurally defined basin in this southern part of the Basin and Range province. Shorter parallel lines of tufa towers rise above Pleistocene sediments exposed at the northern end of Pyramid Lake in Nevada (Benson, 1994). These alignments are also oriented N–S, subparallel to nearby Basin and Range normal faults. The cluster of aligned and eroded towers (Fig. 8) in northern Greece between Lakes Volvi and Lagada is again situated in an area which was part of a lake. Despite many of the principal faults in this area striking either NW–SE or E–W the tower alignments trend NNW–SSE, possibly parallel to secondary tensional fissures in an area of complex faulting (Pavlides and Kilias, 1987). As Figs. 1 and 2 show, ridges in the Balkayasi and Pamukkale deposits are subparallel to both each other and the fault traces between step-overs. Their departure from perfect parallelism with the faults probably reflects the complex strains experienced in step-over zones.

4.4. Syndepositional structures in travertines

Fissure-ridges provide opportunities for examining (a) the attributes of tension fractures that have dilated

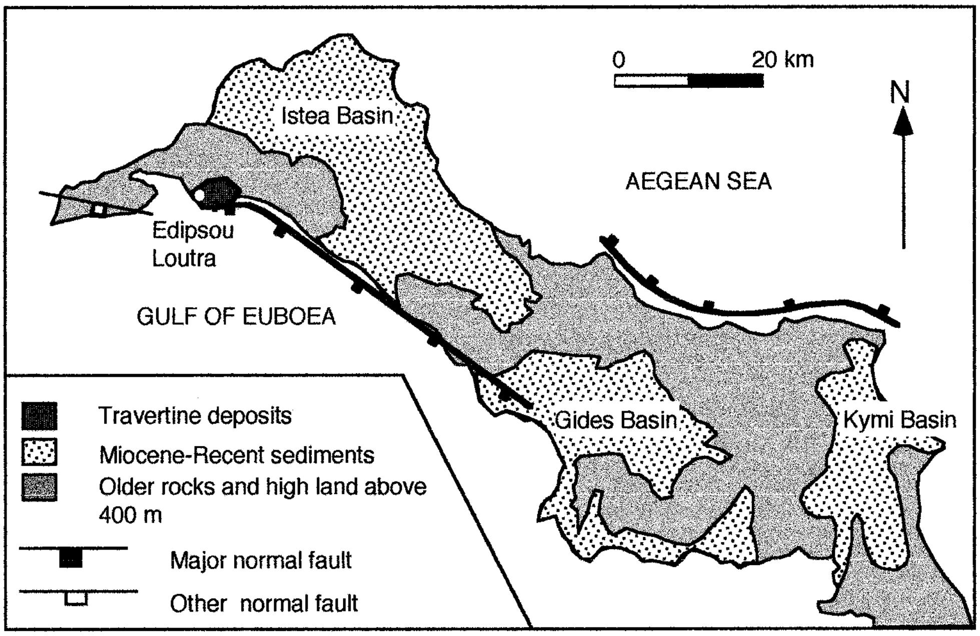

Fig. 4. Structural setting of the Edipsou Loutra travertine deposit on the island of Euboea, central Greece. Note that the travertines are being deposited at the western end of a range-front fault where its strike is locally E–W rather than NW–SE. Complex tensional strains might have been experienced in a process zone coinciding with this setting. Based on Roberts and Jackson (1991) and Chalmers (1998).

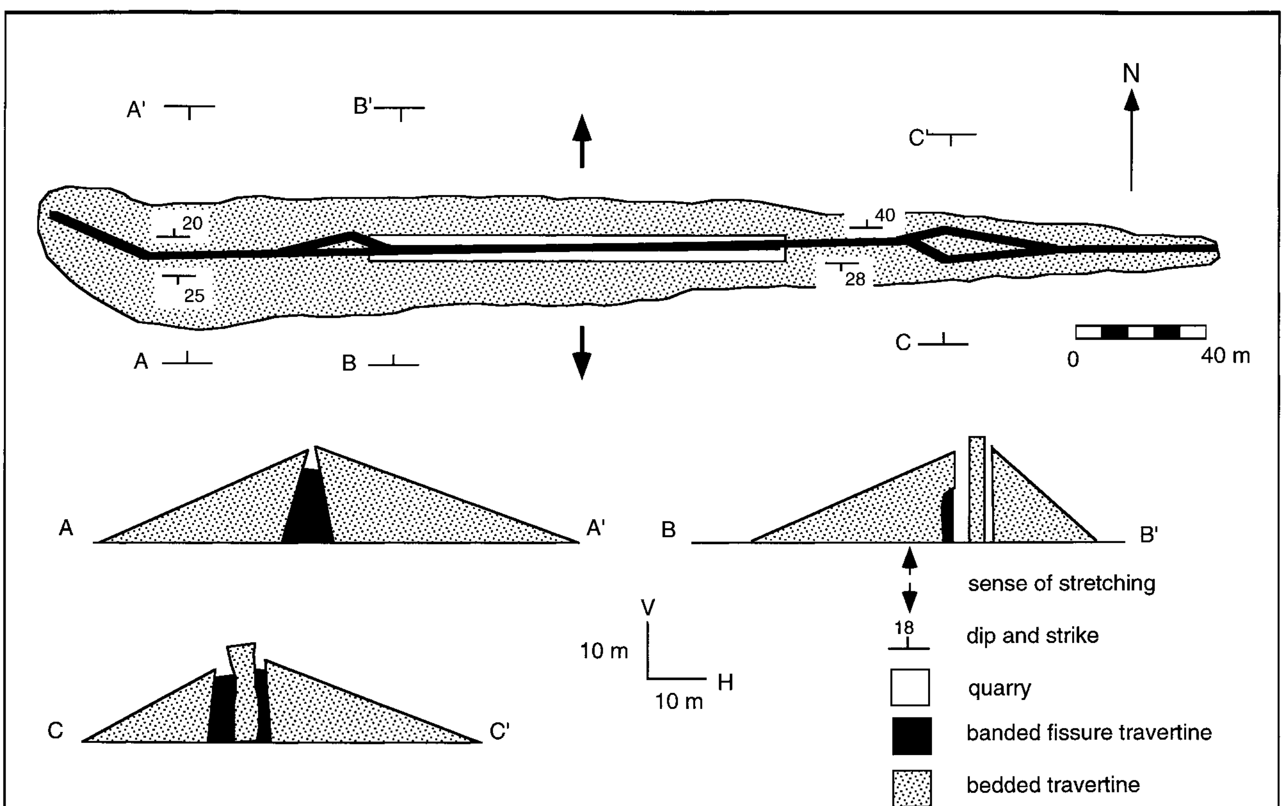

Fig. 5. Map and sections illustrating the morphology of a typical fissure-ridge. The Cukurbag fissure-ridge within the Pamukkale travertine deposit (western Turkey) comprises a central crestal fissure filled by banded travertine and flanked by bedded travertine forming the ridge. The E–W ridge is a product of a local N–S stretching direction. Based on Hancock et al., in press.

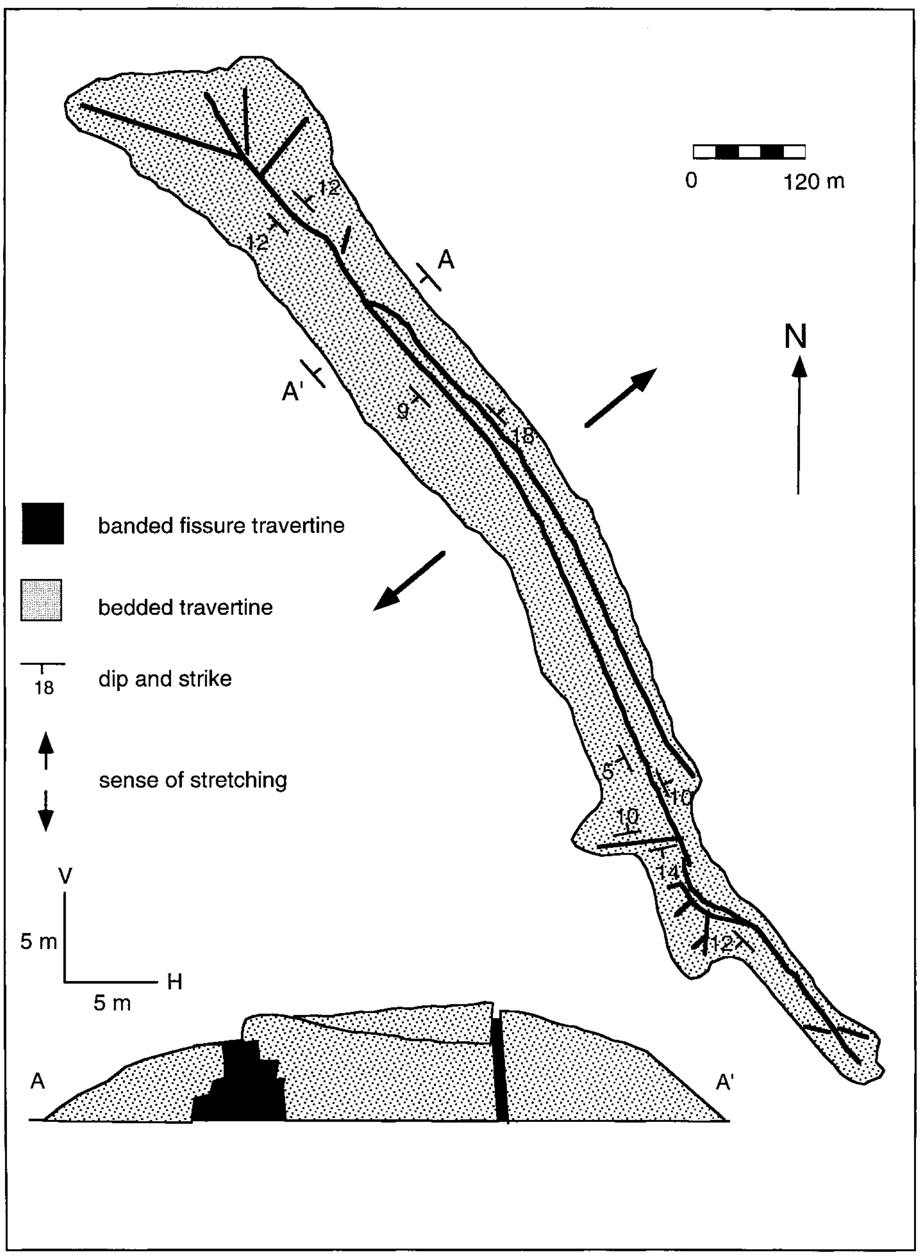

Fig. 6. Morphology of the Akkoy fissure-ridge within the Pamukkale travertine deposit. Note that the ridge is elongate parallel to the crestal fissure and that one of the fissures displays a stepped profile reflecting episodic dilation. The fissure maintaining a constant width with depth cuts the bedded deposits associated with the stepped-profile fissure and is thus younger than it. The location of splay fissures indicate the former ridge terminations. Modified from Altunel (1994).

at the Earth's surface; and (b) relationships between fracturing and travertine deposition. Because the dilation of fissures and the building of ridges are roughly synchronous events it is perhaps surprising that relatively few vertically banded fissure travertines pass sideways into dipping bedded travertines. The lateral propagation of fissure tips through bedded travertines that were deposited at the ends of ridges is probably responsible for the rarity of this relationship. Thus most fissure travertines cut adjacent bedded travertines although the time interval between the deposition of the two types of travertine is so short that they can be regarded as geologically synchronous.

Maximum fissure widths along ridge crests range from a few centimetres to five metres, the uppermost few tens of centimetres of most fissures being either gaping voids or filled by hot water. Most fissures are widest near their planform mid-points. Where quarrying has reached depths of a few metres the transverse profile shapes of fissures are revealed. Two transverse

Fig. 7. A typical fissure-ridge showing the whale-back like form of the ridge cut by a central tensional fissure from which the hot carbonate-rich waters flow. This fissure-ridge is part of the Bridgeport travertine deposit in California.

Fig. 8. An array of tufa towers rising above an area underlain by unconsolidated sediments between Lakes Volvi and Lagada, northern Greece. These towers are restricted to a small area within which a complex of small faults intersect and overlap each other. Tufa towers viewed at right-angles to a dominant alignment.

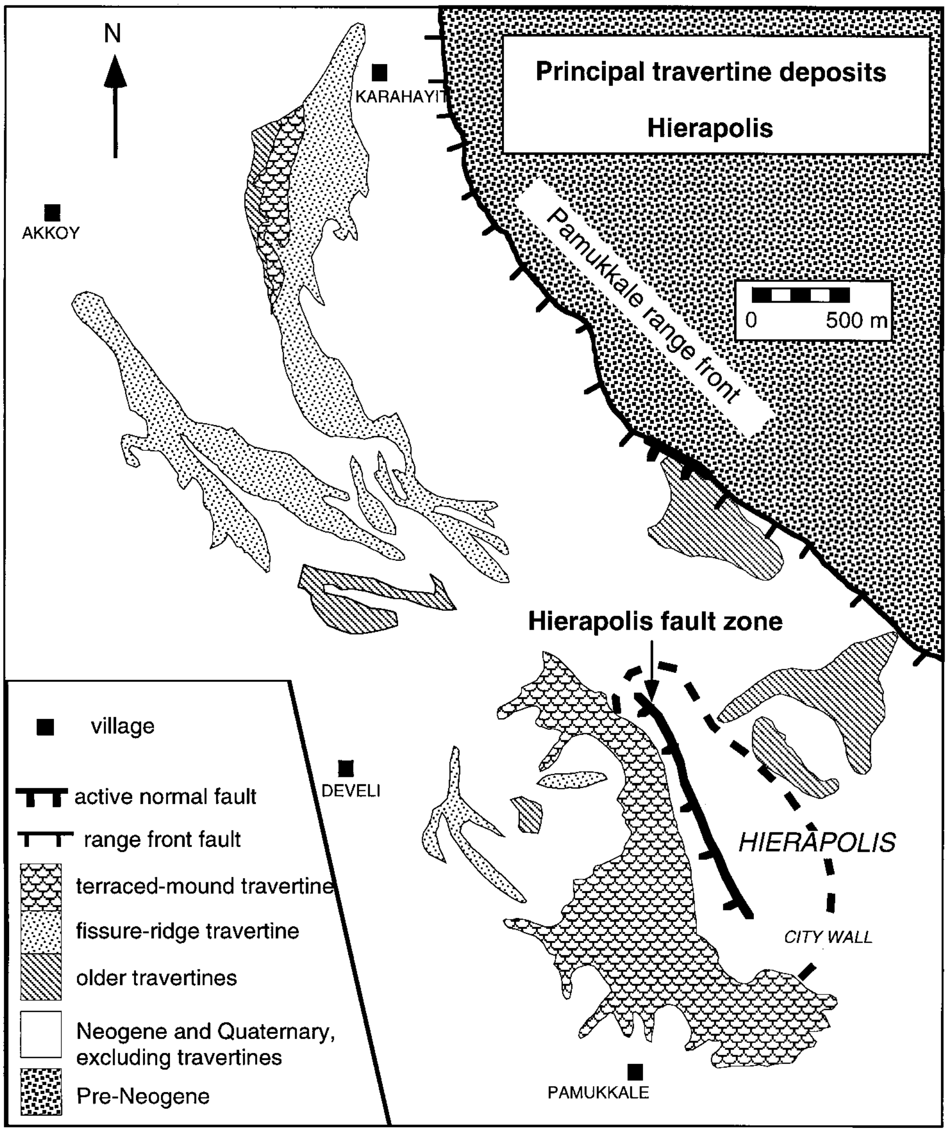

Fig. 9. Map of the distribution of travertine morphologies in the Pamukkale (western Turkey). Note that the major area of terraced-mound travertines occurs just down slope of and in the immediate hanging wall of the Hierapolis fault zone within which the springs are sited. After Hancock et al., in press.

fissure profile shapes are dominant: either fissure width increases gradually downwards, implying continuous fissure dilation, or there is a stepped increase of width with depth, reflecting episodic fissure dilation. Fissures maintaining a constant width with depth are generally younger than the ridges that they cut (Fig. 6). Few fissures cutting bedrocks have been observed but two examples containing banded travertine dated as $228+69$ ky in the Pamukkale range-front follow pre-existing joints (Altunel, 1994).

Although all ridges are cut by a crestal fissure occupied by banded travertines which are roughly contemporaneous with adjacent bedded travertines, some ridges at Pamukkale are also cut by subparallel parasitic younger fissures with associated ridge deposits. The planform irregularities of most fissure margins can be made to fit into each other if fissures are imagined to be closed at right angles to each other. An additional observation indicating that most fissures initiated and propagated as tension fractures, without either vertical or lateral shear, is that bedded travertines on the opposite sides of a crestal fissure are generally at the same height. Only across one major fissure at Pamukkale is there a significant difference in height of the uppermost flanking bedded travertines. Altunel and Hancock (1996) proposed that this fissure, across which there is a downthrow to the southwest of about 5 m, expresses the tip-line of a normal fault which is locally vertical within a few metres of the ground surface.

Some ridges contain subsidiary fissures splaying off principal fissures (Fig. 6). Because on many ridges splay fissures are common where travertine is actively accumulating at ridge ends, we interpret splays closer to ridge mid-points as marking the former lateral tips of fissures where long pauses were experienced between propagation episodes. This interpretation is supported by the observation that splay areas within ridges are commonly the sites of either metre-high culminations or steep slopes facing towards ridge ends. Splay zones probably form when differential stresses are low, whereas on-line, or nearly on-line, fissure segment boundaries probably express shorter pauses during lateral fracture propagation when relatively high differential stresses were maintained.

Most fissures comprise angular (up to 30°) self-similar segments on scales ranging in length from a few centimetres to several metres. Fractal analysis of these fissures indicates that they can be described as statistically scale-invariant, that is, shapes made of parts similar to the whole in some way. Table 1 sets out fractal dimensions for seven ridges in three of the study areas. The box-counting method was employed to determine the fractal dimension (D) using an equation taken from Turcotte (1993):

$$D = \frac{\ln(Nn + 1/Nn)}{\ln(rn/rn + 1)} \tag{1}$$

where ln is a logarithm to the base e, and Nn is the number of fragments with a characteristic linear dimension rn.

The close comparability of these fractal dimensions for fissures from different tectonic domains indicates that they share some common controls: probably the rheologically determined behaviour of tensionally rupturing travertine and failure in perturbed stress fields (Chalmers, 1998).

4.5. Post-depositional structures cutting travertines

At Pamukkale the network of sinuous self-built channel travertines in the Roman city of Hierapolis (modern Pamukkale) allows the kinematics of some faults to be appraised. This is because channels at a variety of angles to each other and a fault trace result in contrasting planform offsets depending on the sense of intersection where piercing points can be recognized (Fig. 10). Thus a small and poorly exposed fault which was originally interpreted as a strike-slip fault (Altunel and Hancock, 1993a,b) has been reinterpreted as a normal fault (Hancock and Altunel, 1997; Hancock et al., in press). As reported earlier, the knowledge that the Hierapolis fault zone

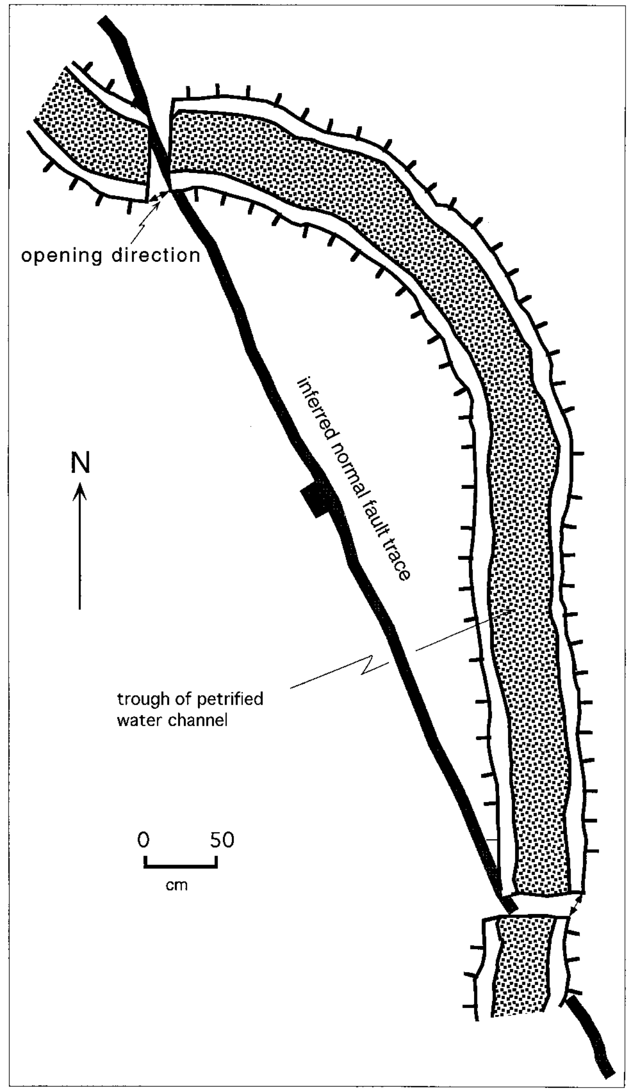

Fig. 10. Sketch plan of a petrified self-built channel that has been offset at two places by the Hierapolis Fault. Note that where the channel locally trends E–W the offset as determined from piercing points combines horizontal opening with sinistral motion, and where it locally trends N–S opening is 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. After Hancock and Altunel (1997).

Table 1
Fractal dimensions of selected crestal fissures cutting fissure-ridges

Pamukkale area (western Turkey)	
NW-trending Akkoy fissure-ridge (Pamukkale mass)	1.04
E–W-trending Cukurbag fissure-ridge (Pamukkale mass)	1.01
NW-trending Hanife fissure-ridge (Pamukkale mass)	1.00
NW-trending Bal fissure-ridge (Balkayasi mass)	1.12
Bridgeport area (eastern California, USA)	
NE-trending fissure-ridge A	1.04
NE-trending fissure-ridge B	1.12
Rapolano Terme area (southern Tuscany, Italy)	
E–W-trending Rapolano fissure-ridge	1.03

is a structure across which there is active stretching, and hence increased hydrothermal flow as reflected by the concentration of hot springs in the zone, helps to explain why the largest area of current travertine deposition is situated in its immediate hanging wall and just down-slope of the fault trace (Fig. 9). Furthermore, we can be sure that this fault is active because it displaces channels which have been dated as Roman or younger (D'Andria, in Peres, 1987).

As Fig. 10 shows, the cracks across which the petrified irrigation channel is broken are not parallel to the strike of the underlying normal fault; rather, they are roughly at right angles to the local direction of the channel long axis. Elsewhere, cracks at right angles to the margins of travertine bodies are also the commonest expression of post-depositional fractures, irrespective of the horizontal direction of local stretching. Local refraction of stresses at the margins of stiff elements such as travertine bodies is probably responsible for this lack of correlation between expected and realised fracture orientations.

Systematic joints cutting late Quaternary travertine deposits are rare. Two factors are probably responsible for this. Firstly, many travertine morphologies are both too externally irregular and internally heterogeneous to support well-ordered stresses and, secondly, most travertines have not been sufficiently buried and then exhumed (say, greater than a few tens of metres) to have experienced the level of confining pressure thought by Hancock (1991) to be a pre-requisite for the formation of systematic unloading joints. Only some of the lower parts of sequences of eroded-sheet travertines have been significantly buried and then exhumed, thus explaining why only they are cut by systematic joints. A notable example of such an unloading joint set occurs in the Kocabas travertine mass, about 20 km southeast of Pamukkale (Altunel, 1994). There, a well-developed WNW-striking set of multi-layer joints cuts the lower beds in a sequence of eroded-sheet travertines. The lack of evidence for shear on the fractures indicates that they are extension fractures or mode I cracks. Eroded-sheet travertines underlying the uppermost 200 m of the Kocabas sequence are not cut by systemic joints; presumably because they were not confined. The uniformity of strike of the Kocabas joints throughout a 200-m-thick sequence and an area of about 20 km^2 underlain by slopes of different trend indicates that local topography did not control joint orientation. Because the average WNW-strike of the Kocabas joints is roughly parallel to nearby neotectonic normal faults, the joints too are probably products of failure in the contemporary tectonic stress field.

4.6. Dilation and propagation of fissures cutting travertine ridges

Where there are travertines datable by the U-series method within fissures it is possible to determine dilation and lateral propagation rates for individual fissures. Time-averaged rates of dilation for individual fissures were determined using the ages of dated samples taken across the width of the travertine-filled fissures. Similarly, time-averaged rates of propagation were determined using the ages of dated samples taken along the lateral length of travertine-filled fissures. Time-averaged rates of dilation and propagation were determined for individual fissures at Pamukkale in western Turkey and at Bridgeport in California, USA. Fissure dilation rates at Pamukkale (Turkey) range from 0.03 mm y^{-1} to 0.09 mm y^{-1} and lateral propagation rates range from 2.8 mm y^{-1} to 22 mm y^{-1}. At Bridgeport the dilation rates range from 0.06 mm y^{-1} to 1 mm y^{-1} and lateral propagation rates range from 3 mm y^{-1} to 24 mm y^{-1} (Chalmers, 1998). The propagation rates are at least an order of magnitude faster than the dilation rates for both areas.

The ages determined for travertine samples taken along the lateral length of travertine-filled fissures indicate that the travertine is oldest towards the mid-point of the fissures, getting younger towards the lateral tips. This suggests that the growth of the fissures is a consequence of several rupture events and not one single event. Therefore, the ages indicate that propagation and dilation of fissures is episodic, although the period between episodes of propagation may be, geologically speaking, very short. The ages also confirm that the fissures propagate laterally away from a point of initiation. It is proposed that the growth of the fissures cutting the travertine ridges at Pamukkale and Bridgeport is related to earthquake activity within the areas in which they occur (Chalmers, 1998). However, it was not possible at this time to relate episodes of fissure growth to earthquake events.

5. Summary

Late Quaternary travertines can reveal much about the neotectonic processes and histories of areas that are experiencing active normal faulting. Most deposits accumulate close (within 1–2 km) to active fault traces and hence they can be used to find the fault traces. The sites of many travertine deposits, especially fissure-ridges, coincide with the locations of either step-over zones (relay ramps) or the lateral tips of fault zones. Both these settings are ones within which complex strains can lead to the development of networks of intersecting tensional fissures that enhance the subsurface flow of hydrothermal fluids. Because both step-over zones and lateral fault tips are potential barriers to earthquake fault ruptures this aspect of travitonics could be of great importance to earthquake hazard reduction.

The planform shapes of travertine bodies can reveal the orientations and locations of underlying faults or extensional fissures. The morphology of travertine deposits overlying tensional fissures is controlled by the character of the underlying materials; tufa cones (towers, pinnacles) forming where fissures underlie unconsolidated lake sediments and fissure-ridges developing where fissures cut bedrocks exposed at the surface. Fissure-ridges comprise outwardly dipping bedded travertines flanking a central tensional fissure filled by vertically banded travertines. Fissures gradually increasing in width with depth are products of continuous fracture dilation in contrast to those that form during episodic dilation which display stepped increases in width with depth. Fissures can be used to infer local stretching directions, those in step-over zones not necessarily being parallel to regional extension directions. Alignments of tufa towers also indicate the locations and orientations of underlying tensional fractures. In contrast to elongate fissure-ridges or aligned tufa cones, terraced-mound deposits are more equant and irregular in plan but they too can be used to locate fracture traces because they accumulate on slopes coinciding with the immediate hanging walls of faults.

The attributes of crestal fissures in fissure ridges indicates that they are tensional fractures. Most ridges grow by fissures extending laterally through the tips of older ones, the locations of some former tips being expressed by subsidiary fissures splaying towards the ends of ridges. Most fissures cutting fissure-ridges comprise self-similar angular segments with fractal dimensions in the range 1.00–1.12, irrespective of location. The most important controls on fissure geometry are the rheological properties of bedded travertine and the characteristics of locally perturbed stress fields.

Where a dated travertine body is displaced by a fault it is possible to attribute a bracketed date to the faulting event. For example, the offset of Roman and post-Roman self-built channel travertines at Hierapolis (ancient Pamukkale) in western Turkey indicates that the responsible fault is still active. Furthermore, because such channels are lines offset at a fault they permit opening directions to be determined from piercing points. At Hierapolis, where a network of curved channels intersects a poorly expressed rectilinear fault trace, analysis of piercing points has allowed a newly developing normal fault to be identified. Most cracks, including faults, intersect travertine bodies at right angles to their margins as a result of local stress refraction. Most travertine masses are not cut by systematic joints of tectonic origin. The only regional joints that we have observed cut eroded-sheet travertines which were buried by at least 200 m of overlying deposits, before being exhumed.

6. The future

When our investigation of travitonics started in the early 1990s we hoped to acquire sets of U-series ages which would enable not only the histories of individual structures to be tracked but also when peaks of hydrothermal flow occurred in the areas. Thus, knowing when episodes of enhanced fluid flow occurred it might be possible to relate these episodes to either increased earthquake faulting, following the suggestion of Muir-Wood (1993) that during earthquakes causing normal faulting coseismic strain will close cracks, thus expelling water to the surface, or during times of greater than normal amounts of ground water as, for example, during deglaciation. Unfortunately our dataset is still too small. In addition, the link between increased earthquake faulting and deglaciation is well known and thus in formerly glaciated areas it might not be possible to separate the two controls.

Another aspect of travertine deposits that requires systematic elaboration is whether they commonly accompany classes of active faults other than normal ones. Tutkun and Hancock (1990) showed that at the eastern end of the left-lateral North Anatolian fault, travertine deposits also occur in oblique extensional step-over zones, an observation supported by anecdotal evidence from elsewhere along this fault zone. We are unaware of reports of travertine associated with active thrusts, the class of faults least likely to be accompanied by nearly vertical fissures which act as pathways for hydrothermal fluids to rise to the surface (Sibson, 1990; Muir-Wood, 1993).

The reason travertines are not deposited from all hot springs in areas of active normal faulting remains a puzzle. For example, travertines are not a feature of the Cubukdagi geothermal field in the Menderes graben (western Turkey), despite the field being only 15 km west of the famous Pamukkale travertines. We note the close association between basaltic bedrocks and travertines; somewhat surprisingly the presence of limestone or dolomitic bedrocks may be a less important controlling factor. Indeed even in areas such as the Menderes and Gediz grabens which are not generally thought of as volcanic fields it is worth noting that the Balkayasi mass is only 18 km southeast of the Kula basalts which were erupted as recently as 190 ky (Richardson-Bunbury, 1996).

Acknowledgements

We are grateful to Claudio Vita-Finzi, Robert Folk, Robert Riding, and the University of Nevada Reno for their assistance and discussions. Financial support for our travitonic work has come from NERC, the Universities of Bristol, Osmangazi, Mersin and the Ministry of National Education of the Turkish Republic. U-series dating was carried out in Peter Smart's laboratory in the Geography Department at the University of Bristol. He also provided us with much good advice about investigating travertines. Anne Becher-Hancock was a great support, both in the field and while writing papers.

References

Altunel, E., 1994. Active Tectonics and the Evolution of Quaternary Travertines at Pamukkale, Western Turkey. Unpublished Ph.D. thesis, University of Bristol.

Altunel, E., Hancock, P.L., 1993a. Active fissuring and faulting in Quaternary travertines at Pamukkale, western Turkey. Zeitschrift Geomorphologie Supplementary 94, 285–302.

Altunel, E., Hancock, P.L., 1993b. Morphological features and tectonic setting of Quaternary travertines at Pamukkale, western Turkey. Geological Journal 28, 335–346.

Altunel, E., Hancock, P.L., 1996. Structural attributes of travertine-filled extensional fissures in the Pamukkale plateau, western Turkey. International Geology Review 38, 768–777.

Bargar, K.E., 1978. Geology and thermal history of Mammoth Hot Springs, Yellowstone National Park. Bulletin of the United States Geological Survey 1444, 1–55.

Barnes, I., Irwin, W.P., White, D.E., 1978. Global distribution of carbon-dioxide discharges and major zones of seismicity. United States Geological Survey, Water Resources Investigations 78–39, Open File report.

Bean, G.E., 1971. Turkey Beyond the Maeander. Ernest Benn, London.

Benson, L., 1994. Carbonate deposition, Pyramid Lake Subbasin, Nevada: 1. Sequence of formation and elevation distribution of carbonate deposits (Tufas). Palaeogeography, Palaeoclimatology, Palaeoecology 109, 55–87.

Çakir, Z., 1996. Tectonic Significance of Quaternary Travertine Deposits in the Gediz and Menderes Grabens, Western Turkey. M.Sc. thesis, University of Bristol.

Chafetz, H.S., Folk, R.L., 1984. Travertines: depositional morphology and the bacterially constructed constituents. Journal of Sedimentary Petrology 54, 289–316.

Chalmers, R.M.L., 1998. Neotectonic Fracturing Associated with Quaternary Travertines. Unpublished Ph.D. thesis, University of Bristol.

Chiarabba, C., Amato, A., Fiordelisi, A., 1995. Upper crustal tomographic images of the Amiata–Vulsini geothermal region, central Italy. Journal of Geophysical Research 100, 4053–4066.

Ford, T.D., Pedley, H.M., 1996. A review of tufa and travertine deposits of the world. Earth-Science Reviews 41, 117–175.

Hancock, P.L., 1991. Determining contemporary stress directions from neotectonic joint systems. Philosophical Transactions of the Royal Society of London A337, 29–40.

Hancock, P.L., Altunel, E., 1997. Faulted archaeological relics at Hierapolis (Pamukkale), Turkey. Journal of Geodynamics 24, 21–38.

Hancock, P.L., Chalmers, R.M.L., Altunel, E., Cakir, Z., Becher-Hancock, A., In press. Creation and destruction of travertine monumental stone by earthquake faulting at Hierapolis, Turkey. In: McGuire, W., Griffiths, D., Hancock, P.L. (Eds.), Volcanoes, Earthquakes and Archaeology. Geological Society Special Publication.

Jackson, J.A., 1994. Active tectonics of the Aegean region. Annual Review of Earth and Planetary Sciences 22, 239–271.

Jackson, J.A., King, G., Vita-Finzi, C., 1982. The neotectonics of the Aegean: an alternative view. Earth and Planetary Sciences Letters 61, 303–318.

Julia, R., 1983. Travertines. In: Scholle, P.A, Bebout, D.G, Moore, C.H (Eds.), Carbonate Depositional Environments. Memoir of the, 33. America Association of Petroleum Geologists, pp. 64–72.

Larsen, P.H., 1988. Relay structures in a Lower Permian basement-involved extension system, East Greenland. Journal of Structural Geology 10, 3–8.

McGarth, A.G., Davison, I., 1995. Damage zone geometry around fault tips. Journal of Structural Geology 17, 1011–1024.

Muir-Wood, R., 1993. Neohydrotectonics. Zeitschrift Geomorphologie Supplementary 94, 275–284.

Pavlides, S.B., Kilias, A.A., 1987. Neotectonic and active faults along the Serbomacedonian zone (SE Chalkidiki, northern Greece). Annales Tectonicae 1, 97–104.

Peres, A. (director), 1987. Hierapolis di Frigia 1957–1987. Settore Cataloghi D'Arte del Gruppo Editoriale Fabbri, Torino.

Richardson-Bunbury, J.M., 1996. The Kula volcanic field, western Turkey: the development of a Holocene alkali basalt province and the adjacent normal-faulting graben. Geology Magazine 133, 275–283.

Roberts, S., Jackson, J., 1991. Active normal faulting in central Greece: an overview. In: Roberts, A.M, Yielding, G, Freeman, B (Eds.), The Geometry of Normal Faults. Special Publication of the Geological Society, London 56, pp. 125–142.

Sibson, R.H., 1990. Conditions for fault-valve behaviour. In: Knipe, R.J, Rutter, E.H (Eds.), Deformation Mechanisms, Rheology and Tectonics. Special Publication of the Geological Society, London 54, pp. 15–28.

Sibson, R.H., 1996. Structural permeability of fluid-driven fault-fracture meshes. Journal of Structural Geology 18, 1031–1042.

Turcotte, D.L., 1993. Fractals and Chaos in Geology and Geophysics. Cambridge University Press, Cambridge.

Tutkun, S.Z., Hancock, P.L., 1990. Tectonic landforms expressing strain at the Kariova continental triple junction (E. Turkey). Annales Tectonicae 4, 182–195.

Vita-Finzi, C., 1986. Recent Earth Movement. Academic Press, London.

Wyatt, A, 1996. Challinor's Dictionary of Geology, 6th edition. University of Wales Press, Cardiff.

Yeats, R.S., Sieh, K., Allen, C.R., 1997. The Geology of Earthquakes. Oxford University Press, New York.