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Along-Strike Discontinuity of Active Normal Faults and Its Influence on Quaternary Travertine Deposition; Examples From Western Turkey

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Abstract: Detail mapping of active fault zones bounding four travertine masses in the Gediz and Menderes grabens of western Turkey revealed that they are divided into geometric fault segments up to 13 km long. Fissures, supplying the carbonate-rich waters that give rise to the travertines are preferentially developed at the ends of the fault segments or in extensional step-over zones where the offset between the fault strands is about 1 km or more. The deposition of travertines in such structural settings is probably a consequence of the network of fissures supplying the carbonate-rich waters being highly interconnected where extensional strains were complex. It follows that during a neotectonic survey directed at finding active faults and identifying potentially hazardous segment boundaries it might be worthwhile searching for, and surveying, late Quaternary travertine bodies. Because the orientations of fissures and the long axes of fissure-ridges are related to local stresses in and around step-over zones, caution should be exercised when employing fissure orientations during regional palaeostress reconstructions. The main boundary faults penetrating down at depths probably act as the main deep conduits for the carbonate-rich thermal waters to ascend to the surface along the graben margins in the study area. However, at shallow depths in step-over zones and adjacent to fault tips, waters also probably flow through the complex fracture networks that commonly occur in these areas.

Key Words: Travertine, Active Tectonics

Aktif Normal Fayların Doğrultu Boyunca Gösterdikleri Süreksizlikler ve Bunların Kuaterner Yaşlı Traverten Depolanmasına Etkisi; Batı Anadolu'dan Örnekler

Özet: Gediz ve Büyük Menderes grabenlerindeki aktif normal fayların detay haritalanması bu fayların yekpare bir düzlem olmayıp, doğrultuları boyunca 13 km uzunluklara varan çeşitli geometrik segmentlere ayrıldıklarını ortaya çıkarmıştır. İçerisinden travertenlerin oluşmasına yol açan karbonatça zengin termal suların çıktığı açılma çatlakları bu fay segmentlerinin uç kısımlarında veya onların aralarındaki gerilmeli sıçrama (step-over) zonlarında bulunmaktadır. Tavertenlerin bu tür alanlarda depolanmasının sebebi kompleks ekstensiyonal deformasyonların var olduğu bu bölgedeki çatlakların büyük olasılıkla birbirine bağlı olmasıdır. Buradan aktif fay segmentlerinin uç kısımlarının belirlenmesinde Kuaterner yaşlı travertenlerin araştırılmasının yararlı olabileceği sonucu çıkmaktadır. Segment uçlarında ve segmentler arasındaki sıçrama zonlarında açılma çatlaklarının uzun eksenlerinin konumları lokal stres rejiminin etkisi altındadır. Dolayısı ile bölgesel stress alanını belirlemeye yönelik çalışmalarda bu bölgelerdeki çatlaklardan yararlanırken dikkatli olmak gerekir. Grabenlerin kuzey sınırını teşkil eden ana faylar muhtemelen karbonatca zengin yeraltı sularının yer yüzüne çıkmasında derin kanal görevi görmektedir. Ancak yeryüzüne yaklaştıkca sular genellikle, tavan bloku deformasyonu veya fay ucu deformasyonu olarak gelişen açılma ve diğer çatlak sistemleri boyunca yüzeye ulaşmaktadır.

Anahtar Sözcükler: Traverten, Aktif Tektonik

Introduction

Travertine is a type of fresh-water limestone deposited from cold or hot spring waters, or less commonly from percolating waters (Wyatt 1986). Travertines associated with thermal springs have been observed in many parts of the world and have been the subject of numerous investigations. These are mainly directed at understanding their hydrogeology, petrography, microbiology and palaeoclimatology (Dunn 1953, Scholl 1960, Irion and Muller 1968, Chafetz and Folk 1984, Pedly 1990, Ford and Pedley 1992, Altunel and Hancock 1993b, Pentecost 1994). It is also well known that many travertine deposits are related to neotectonic faults and other fracture systems, but this aspect of the subject has attracted relatively little attention with the exception of Altunel and Hancock (1993a, 1996) and Altunel (1994) who emphasised structural attributes of travertine-filled fissures in the Pamukkale area determining the present-day extension direction from them. The main aims of this paper are to describe and interpret the structural attributes of travertine deposits paying attention to the fault zone

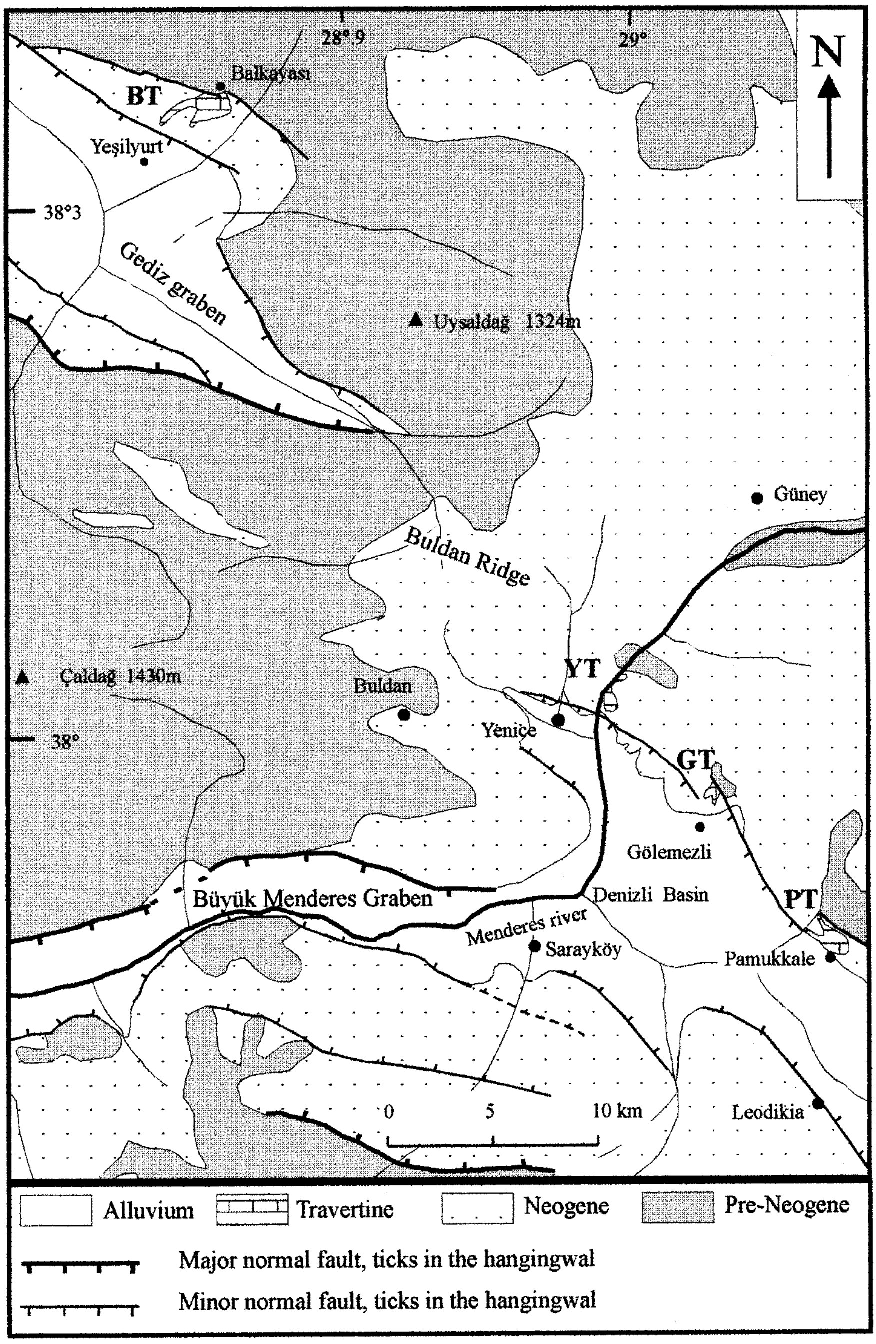

Figure 1. Simplified map showing the tectonic setting of western Turkey and the locations of the studied travertine bodies; the Balkayası (BT), Yenice (YT), Gölemezli (GT) and Pamukkale travertines (PT) (modified after Pamir and Erentöz, 1974).

geometry associated with the travertine masses. Four travertine masses were studied, namely the Balkayası, Yenice, Gölemezli and Pamukkale travertines (Figure 1). Although structural characteristics of the Pamukkale travertines were previously discussed by Altunel and Hancock (1993a) their tectonic significance re-evaluated in the lights of new observations. The remaining three masses have not been surveyed and discussed before.

Neotectonic and Geological Setting of the Study Area

The studied travertines are located towards the eastern ends of the Büyük Menderes and Gediz grabens, western Turkey. Western Turkey is a part of the Aegean extensional province where the extension rate is one of the fastest in the continental crust of the World (Jackson

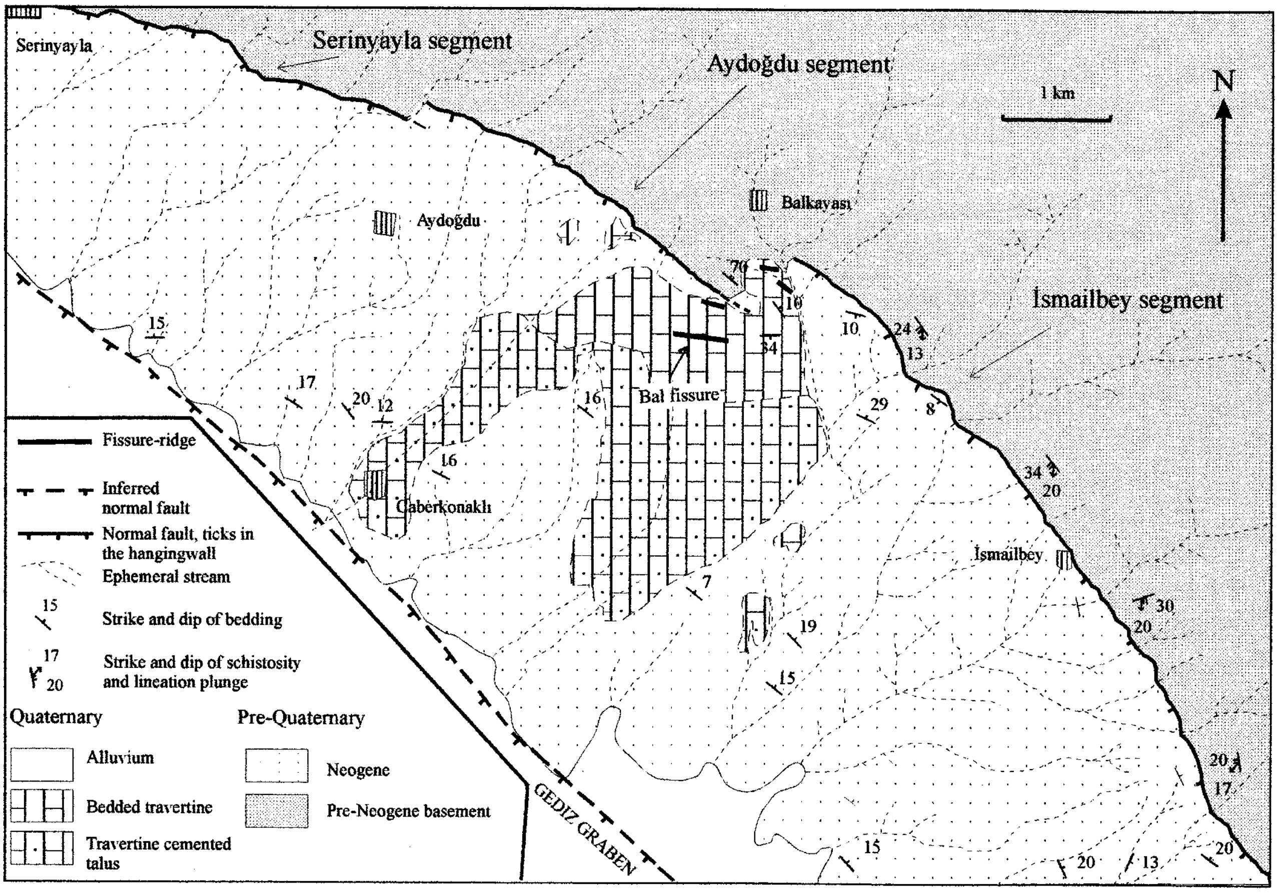

Figure 2. Geological map showing the Balkayası travertine mass and its surrounding area.

1994). Roughly north-south directed extension believed to have commenced some time between the Late Oligocene-Late Miocene is achieved mainly by E-W trending large normal faults that are thought to be planar through the brittle seismogenic layer (Eyidoğan and Jackson 1985, Roberts 1988, Westaway 1991, Cohen et al. 1995). The extensional regime is thought to be due to three factors; (1) westwards motion of the Anatolian block relative to Europe, following continental collision between the Turkish block and the Arabian plate in the Serravalian, which is achieved by two large strike-slip faults; dextral North Anatolian Fault and sinistral East Anatolian Fault (McKenzie 1972, Dewey and Şengör 1979, Şengör et al. 1985, Barka 1992, Jackson 1994), (2) roll-back of the Hellenic subduction zone (Le Pichon and Angelier 1979, Le Pichon 1982, Jackson and McKenzie 1984), and (3) spreading and thinning of the thickened crust (Seyitoğlu and Scott 1991, Seyitoğlu et al. 1992, Bozkurt and Park 1994, Hetzel et al. 1995, Seyitoğlu 1997).

Metamorphic rocks of the Menderes massif constitute the basement in the study area as well as most of central-western Turkey. Neogene sediments exposed as a result of normal fault uplift adjacent to the grabens floor are non-marine (Pamir and Erentöz 1964, Yılmaz 1986, Paton 1992, Cohen et al. 1995). The oldest sediments in the south of the Gediz graben contain a sporomorph association of Early Miocene age (Seyitoğlu and Scott 1996).

Structural Data

The Balkayası travertine mass

The Balkayası mass is located near the northeastern end of the Gediz graben (Figure 1) covering an area of approximately 9 km^2 (Figure 2). The Gediz graben locally trending NW-SE is bounded to the south by a major normal fault (Eyidoğan and Jackson 1985, Cohen et al. 1995). On the opposite side of the graben there are two normal fault zones that are antithetic to the main fault in the south; the Balkayası and Caber faults.

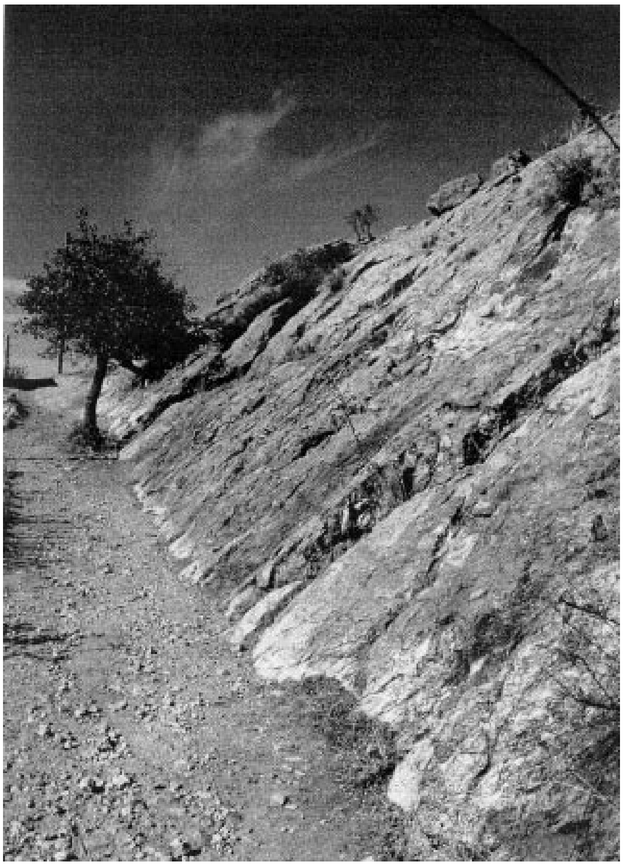

Figure 3. A 7-m high fault scarp at Serinyayla. Note that the scarp is relatively fresh and less degraded in its lower parts than in its upper parts, indicating that it has been subject to intermittent reactivation and uplift.

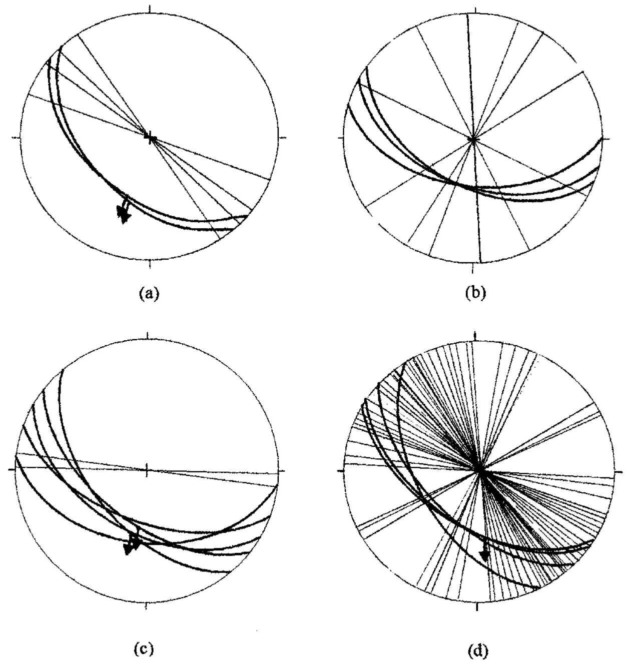

Figure 4. Stereoplots showing fault planes (bold lines) with striations (arrows) and travertine fissure-ridges in the Balkayası (a), Yenice (b), Gölemezli (c) and Pamukkale (d) areas. Note that although the strike of fissures is, in general, sub-parallel to the strike of nearby normal fault there are some fissures that trend highly oblique or orthogonal to the fa ults.

The main antithetic fault (ie. Balkayası fault) separates Neogene sediments from basement rocks (Figure 2). Towards the southeast, the fault changes its strike from WNW-ESE through NW-SE to NNW-SSE, each trend being represented by an individual left-stepping geometric fault segment (the Serinyayla, Aydoğdu and Ismailbey fault segments, respectively) which are continuous on a scale of a few kilometres. A well-preserved fault scarp, passing through the village of Serinyayla, is present in the Serinyayla segment (Figure 3). The scarp is about 350 m long, 1 to 7 m high, and trends from 083 to 118° and dips about 54° SW. Degradation of the fault scarp increases upwards, suggesting that the fault has been reactivated episodically. Lineations on fault scarp indicate dip-slip movement with a subordinate sinistral strike-slip component (Figure 4a). Towards the east near the village of Aydoğdu village, the Serinyayla and Aydoğdu segments overstep in a step-over zone of about 500m wide. Another step-over zone of about 1 km-wide is also present between the Aydoğdu and Ismailbey segments near the village of Balkayası. Compared to the Serinyayla segment, the fault scarps of the Aydoğdu and Ismailbey segments are highly degraded and, the original fault surface has been removed by erosion and generally covered by an alluvial apron. This is probably because the footwall blocks consist mainly of schists that are less resistant to erosion than metagranite that crops out along the Serinyayla segment.

The Caber fault is the present-day basin boundary fault. As it cuts unconsolidated or poorly consolidated alluvial deposits a fault scarp is not present but, its presence can be inferred from four observations: (1) in general, the elevation of Neogene sediments is higher than that of the present valley floor, probably expressing footwall uplift; (2) the contact between Neogene sediments and Quaternary alluvium along the basin is straight (200 m contour); (3) a surface break associated with the 1969 Alasehir earthquake was coincident with this boundary several kilometres further to the northwest (Arpat & Bingol, 1969); and (4) stream channels incise up to 30 m in the footwall (cf. Petersen 1985, Keller 1986).

Extensional fractures are mostly confined to the metamorphic basement as Neogene sediments are poorly

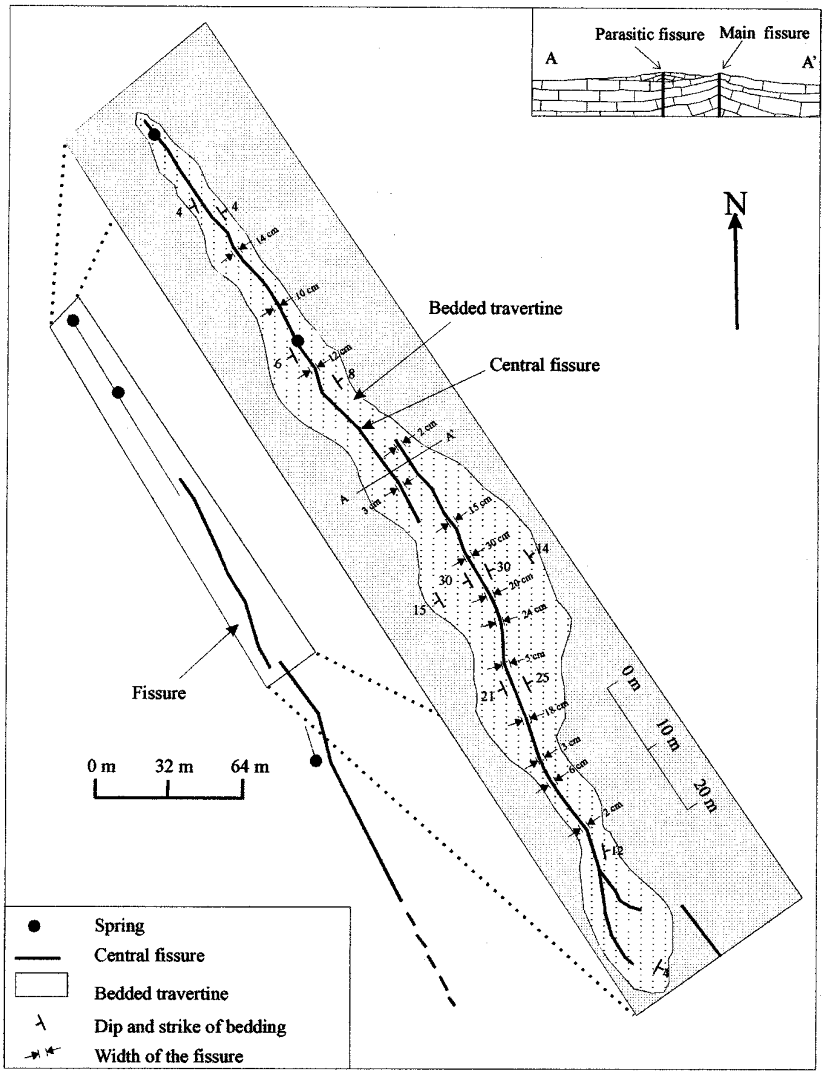

Figure 5. Plan of the Bal fissure-ridge in the Balkayası area (Figure 2). Note that fissure width increases towards the mid-point of both fissure segments. Bedding relationships, which are schematically illustrated in the inset box, indicate that the eastern segment is older than the western segment.

consolidated. In addition to extension joints, the rocks of the metamorphic basement are also cut by small shear fractures as a result of footwall deformation in the Balkayası fault zone. Shear fractures include closely spaced conjugate fractures and small-scale faults trending subparallel to the main fault.

An especially noteworthy observation is that fissures and dilated joints from which the carbonate-rich waters (and hence travertines) issue are located in the step-over zone between the Aydoğdu and Ismailbey segments of the Balkayası fault which trends oblique to them (Figure 4a). An example of an active fissure-ridge, namely the Bal fissure (Figure 2), is given in Figure 5. As seen in the figure the Bal fissure is about 350 m long and is divided into three left stepping segments, each segment having widths ranging from a few centimetres at it tips to a few tens of centimetres in the middle. From bedding relationships, as illustrated in the inset box, it was inferred that the middle segment is older than the other two segments. The fissure trends subparallel to oblique to the nearby Aydoğdu segments.

The Yenice travertine mass

The Yenice mass covering an area of about 1.5 km^2 on metamorphic basement and Neogene clastic deposits. It is located within the narrow valley occupied by the Menderes river immediately north of where it enters the Denizli basin (Figure 6), a 50-km-long and up to 24-km-wide sedimentary basin bounded by a NNE-dipping principal normal fault zone on its southern margin (Westaway 1990, 1993).

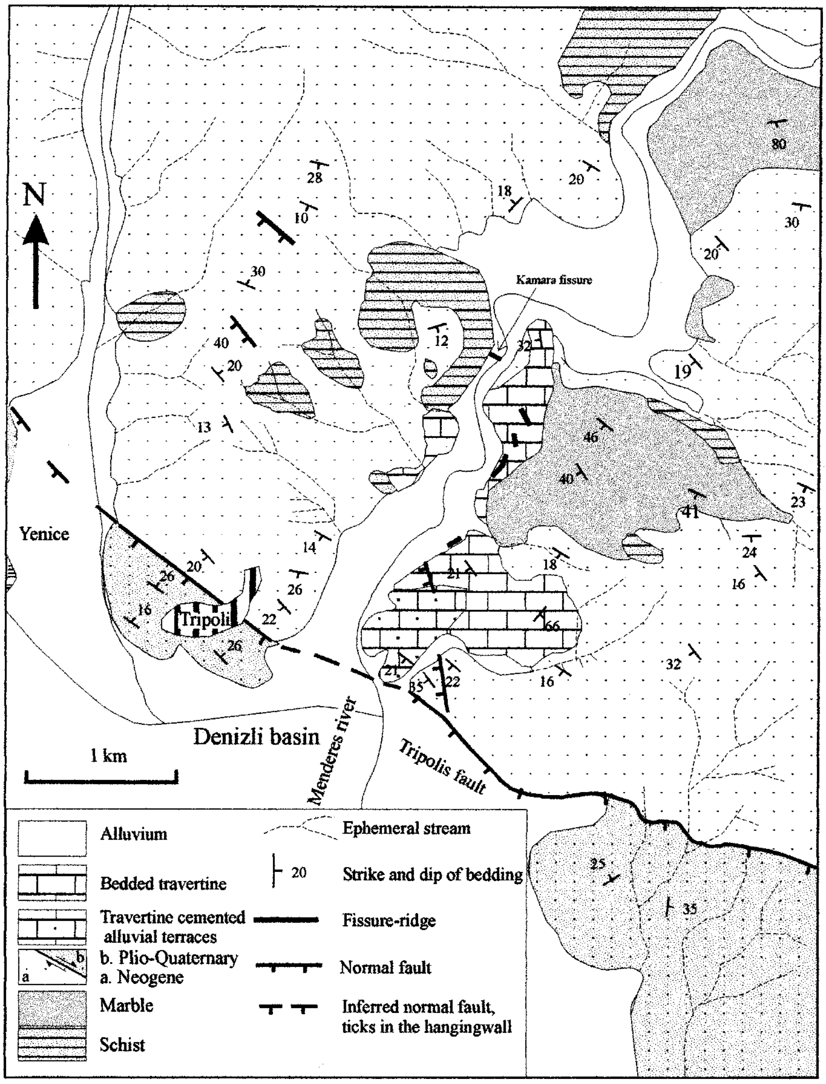

Figure 6. Geological map of the Yenice area (Çakır 1996, Turgay et al., 1985).

There are many small normal faults within the Neogene sedimentary cover. These faults trend NW-SE, in agreement with the present day direction of regional extension. The Tripolis fault forms the boundary of the Denizli basin to the northeast at Yenice. It is about 9 km long and expressed by the contact between Neogene sediments and Plio-Quaternary alluvial fan deposits. Previous studies (Turgay et al. 1985 and Çakır 1996). show that the latter sediments were probably derived from the uplifted Neogene sediments in the footwall of the Tripolis fault. As a result of normal faulting, sediments in the hangingwall, especially at Tripolis, have been tilted towards the fault (see Figure 6). Because the fault scarp is highly dissected, no fresh fault scarp is observed. According to Turgay et al. (1985) the fault dies out within Pliocene sediments several kilometres to the northwest. It continues about 8 km towards the southeast before stepping over to the left where the Gölemezli mass is located. It is also worth noting that many of the outcrops of schists and marbles of the basement complex are located externally to the travertines on the opposite sides of the valley, hinting at a possible Pre-Neogene fault zone along the Menderes river (Figure 6). The presence of such NNE-SSW trending structures in the Pre-Neogene basement has long been known (Kaya 1979, Koçyiğit 1984), and were thought by Şengör, (1987) to have influenced the present-day extensional regime in western Turkey by introducing cross-graben structures.

In the Yenice area, systematic joints trending NW-SE are well developed in consolidated rocks, particularly in limestones. There are six fissure-ridges within the Yenice

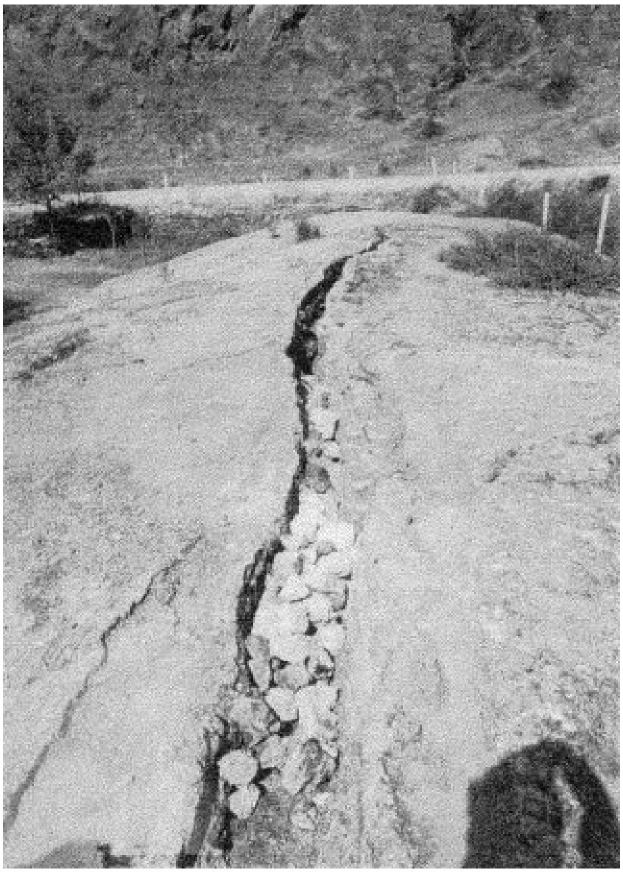

Figure 7. The active Kamara fissure-ridge. Note that the width of the central fissure decreases towards its tip. Note bedded travertines dipping away from the fissure. View towards the northwest.

travertine mass, travertine deposition currently taking place only along the Kamara fissure-ridge (Figure 7). With the exception of the Kamara ridge all fissure-ridges have trends that are oblique to the strike of the Tripolis fault (Figure 4b), the implications of which will be discussed later.

The Gölemezli travertine mass

The Gölemezli travertines occupying an area of less than 1 km^2 mainly on Neogene sediments (Figure 8) are located 5 km southeast of the Yenice mass. The NW-SE trending main fault is divided to two left-stepping geometric segments; the Tripolis segment which is the eastward extension of the Tripolis fault and the Akköy segment (See Figures 9 and 1 for eastern end of the Akköy segment). The relay ramp between the segments is about 1.5 km wide and dominated by small oblique faults and fissures that are typical in many relay ramps (Stewart and Hancock 1991, Peacock and Senderson 1991). Metamorphic rocks (mainly schists) of the Menderes massif are exposed mainly in the footwall of the Akköy fault segment. The fault scarp is in general highly dissected. Striations on a fault scarp dipping 50 to 58° to the southwest near the travertines indicate dip-slip movement with a subordinate sinistral strike-slip component. As in the Yenice area, the Tripolis fault segment separates the unconsolidated Neogene sediments from Plio-Quaternary alluvial fan deposits. Thus, a fresh fault scarp is not present along this segment.

No travertine is being currently deposited. There are two fissure-ridges trending slightly oblique to the nearby Akköy fault segment. The fissures are small (about 70 and 100 m long) and thus they are not shown to scale in Figure 8, but they are enlarge to illustrate their position and trend in relation to fault zone (Figure 4c). Field observations suggest that travertines were deposited from these fissure and partly along the fault plane of the Akköy segment. Again, it is noteworthy that the Gölemezli travertines are located in a step-over zone between fault segments (Figure 8).

The Pamukkale travertine mass

The Pamukkale mass occupies an area of 7.6 km^2 and mainly overlies Neogene sediments on the northern side of the Denizli basin (Figure 9), about 10 kilometres southeast of the Gölemezli mass (Figure 1). The Pamukkale range-front fault zone trending NW-SE and dipping 56-85° SW composes two left stepping fault segments, each up to 13 km long; the Hierapolis and Akköy segments. The former fault is expressed by the contact between Neogene sediments and metamorphic basement rocks in the hangingwall and footwall, respectively. Fault scarps are well-preserved, particularly where the Hierapolis fault cuts marbles. For example, a fresh fault scarp separating travertine-cemented scree and alluvium from basement marbles was described by Altunel and Hancock (1993a) in the neighbourhood of Yokuşyol. Striations on it indicate that there was a dominant normal dip-slip combined with a subordinate component of sinistral strike-slip (Altunel and Hancock 1993a). The fault is about 13 km long; to the northwest it dies out within Neogene sediments while, to the southeast, according to Altunel and Hancock (1993a, Figure 2) it continues for a few kilometres before stepping over to the left and extending for several kilometres further to the south. Altunel and Hancock (1996) have shown that the Hierapolis segment offsets a Roman water channel, and a Roman carving on a fresh scarp along this segment has been probably uplifted as a result of recent movements. These obsevations suggest that the Hierapolis and Akköy segments are both active faults and belong the same fault system controling the evolution of the Denizli basin.

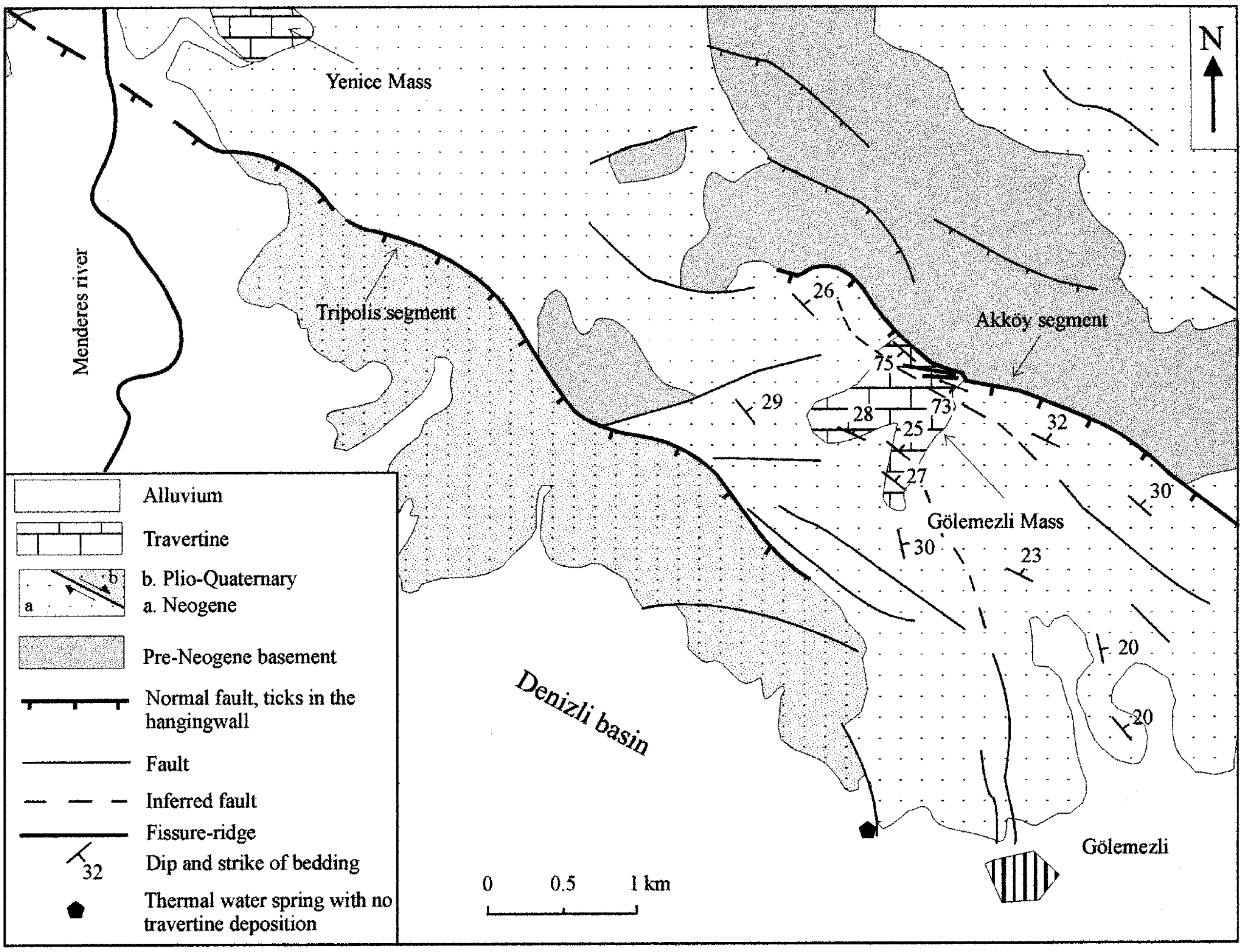

Figure 8. Geological map showing the Gölemezli travertine mass and its surrounding areas (modified from Turgay et al., 1985).

The Akköy fault segment to the northwest of the Hierapolis segment, emplaces Neogene sediments in the footwall against alluvial plain sediments in the hangingwall. Because it cuts poorly consolidated sediments, a well-preserved fault scarp is not present along this segment but, the presence of the fault can be inferred from three observations: (1) there are triangular facets truncating ridge spurs on the range front along its length (such facets are typical of fault-generated range-fronts [Stewart and Hancock 1990]); (2) the contact between Neogene and alluvial sediments along the basin margin is straight; and (3) the footwall block underlying Neogene sediments is significantly higher (>400 m) than the present valley floor. This segment is about 7-km long and dies out in the alluvial plain sediments towards both the southeast and northwest.

Some workers (eg. Westaway 1993) have interpreted that the Yeniköy and Akköy segments form a single continues fault segment. However, between Pamukkale and Akköy villages there is no topographic expression of a normal fault or other field evidence -such as those given above for the Akköy segment- which confirms this inference.

Near the village of Karahayıt the two fault segments overlap in a 2 km-wide step-over zone within which irregularly tilted Neogene sediments express the relay ramp (Figure 9). It is here that the Dumlupınar stream enters the Denizli basin, a characteristic of streams reported from other basins bounded by discontinuous normal fault segments (Paton 1992, Leeder and Jackson 1993). In addition, alluvial fan sedimentation is occurring at the foot of the northwestern part of the Hierapolis fault segment in the same area. Thus in this context, it is noteworthy that the fissures supplying travertine are located mostly in and close to the relay ramp, the number of fissures decreasing towards the southeast away from

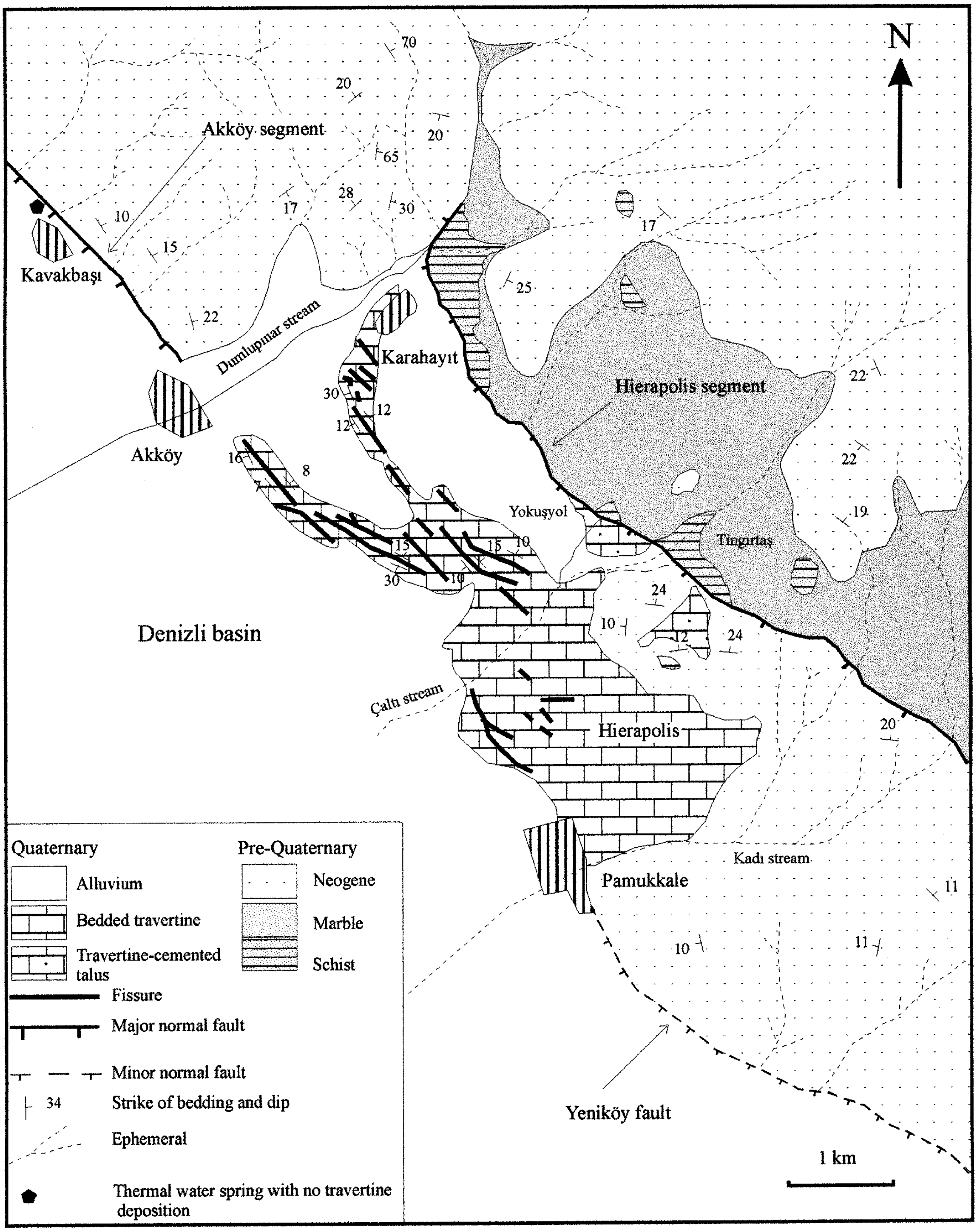

Figure 9. Geological map of the Pamukkale area (modified from Altunel & Hancock 1993a). Note that fissures from which carbonate rich-hot waters issue are located at the end of fault segments and near the step-over zone between the Hierapolis and Akköy fault segments.

the ramp. As Figure 9 shows the Pamukkale travertine mass extends further southeast away of the step-over zone and into an area where there are fewer fissures. These fissures are probably associated with the Yeniköy fault that terminates immediately to the south of them. Other older fissures might now be buried by the active

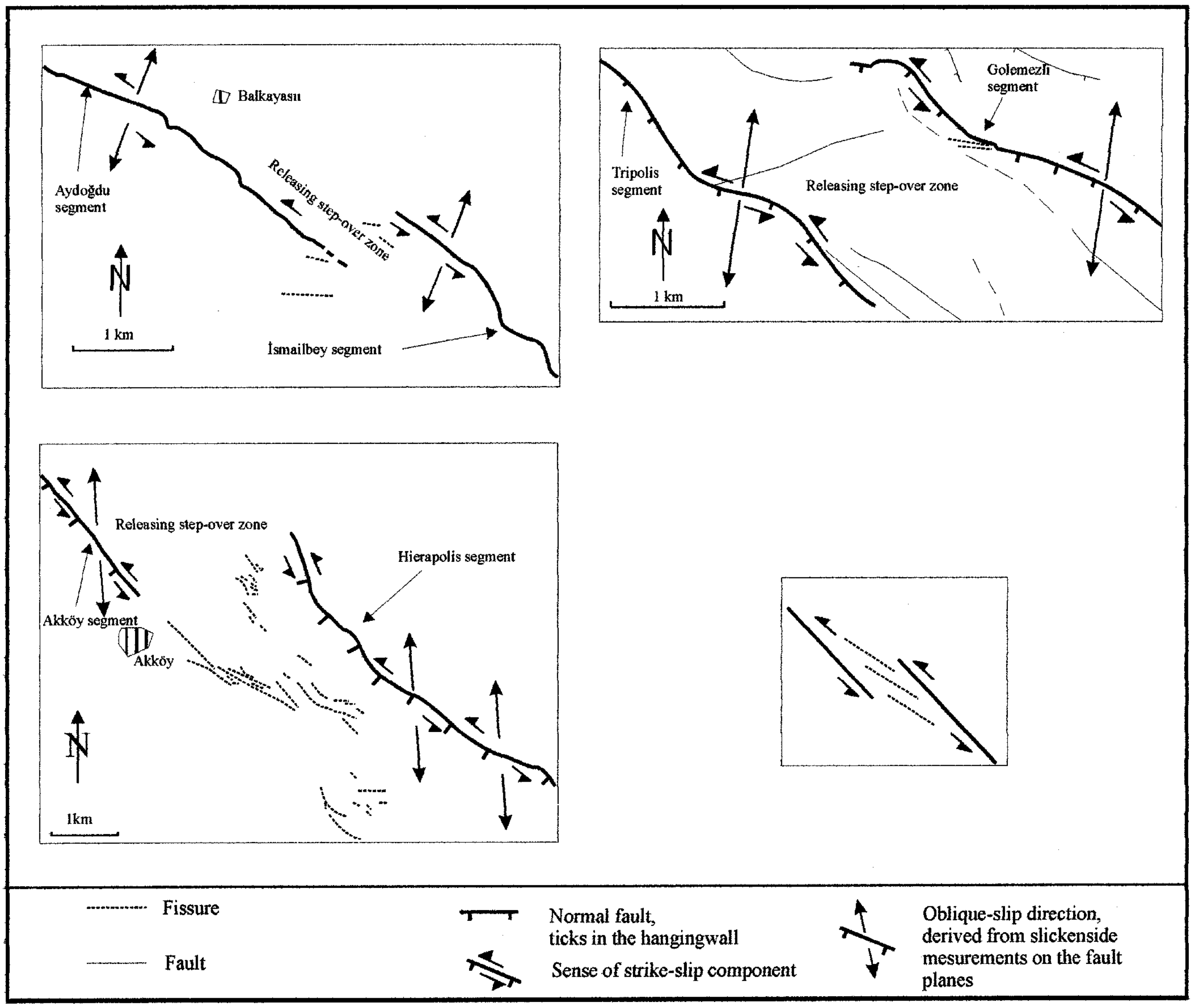

Figure 10. Maps showing the structural settings of the Balkayası (a), Gölemezli (b) and Pamukkale (c) areas. Long and short arrows indicate oblique-slip direction of opening and the sense of subordinate strike-slip on fault planes, respectively. The orientation of fissures in relation to the fault zone is shown idealised in box (d), which is consistent with the subordinate sinistral strike-slip. Note that, based on the minor strike-slip component, the step-over zones wherein travertine depositions occur are classified as releasing step-over zones.

terraced-mound travertines that underlie much of this area.

In the Pamukkale are some of the fissures, especially those away from the segment boundaries, might also be related to the hangingwall deformation of the Hierapolis segment, particularly backtilting and roll-over, which can give rise to the formation of extensional fractures (ie. fissures) on the surface.

The Yeniköy fault to the southeast of Pamukkale lacks most of the attributes that characterise the Akköy fault. Particularly significant is the observation that the average level of the footwall area underlain by Neogene sediments is only 200 m above that of the alluvial plain in the hangingwall of the fault. This suggests that the throw on the Yeniköy fault is probably small, perhaps no more than 40 m, that is, much less than (> 200 m) on the Akköy and Hierapolis faults.

Ridges cut by extensional fissures are up to 1.5 km long and 400 m wide with widths ranging from 2 cm to 5 m. Most fissure-ridges are cut by several sub-parallel parasitic fissures up to 200 m long on either side of a main central fissure (Altunel and Hancock 1996). Their long axes have trends mainly ranging from WNW-ESE to NNW-SSE, sub-parallel to the Pamukkale range-front fault (Figure 4d). Altunel and Hancock (1996) describe

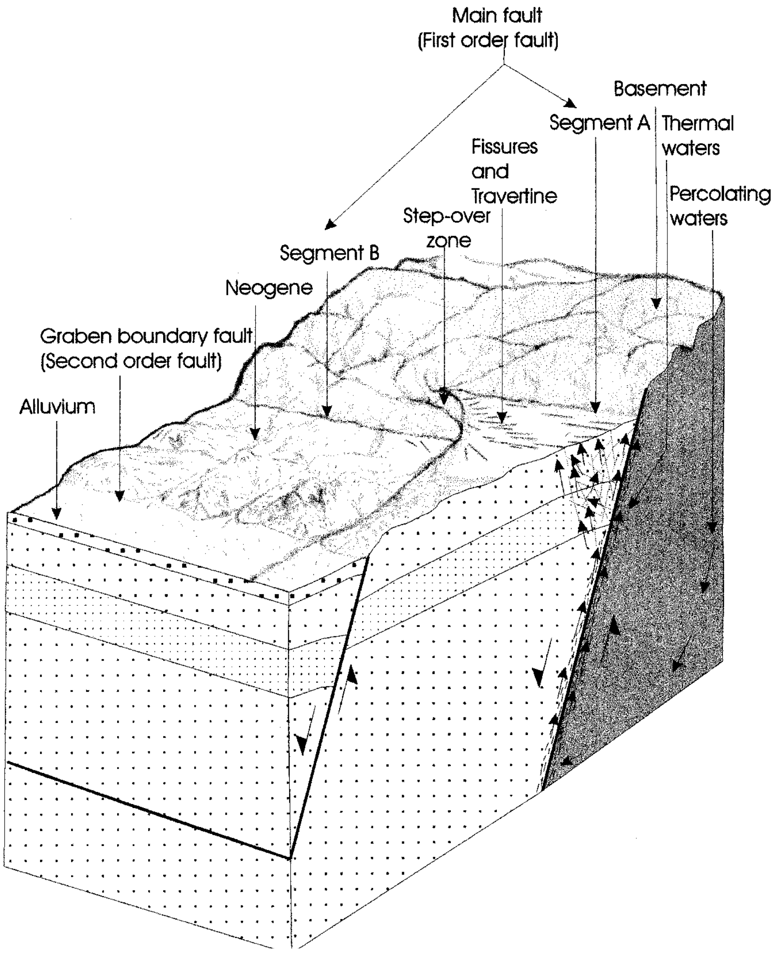

Figure 11. Block diagram illustrating a possible model for travertine deposition via fault planes and fissures in and around a step-over zone. Note that the first-order faults act as the main conduits for the carbonate-rich waters at depth, whereas at shallow depths, waters alsohlow through fracture networks resulting from complex extensional strains. Because waters coming from basement are caught by the principal faults and fractures adjacent to them they do not reach the second-order fault, and thus no travertine is deposited from it.

the geometry and architecture of the travertine filled fissures at Pamukkale in greater detail.

Discussion

As seen in Figures 2, 6, 8 and 9 the faults bounding the travertine masses are discontinuous along strike, that is, they are divided into individual fault segments. Segments are up to 13 km long and commonly display step-overs along strike. As reported earlier, the Balkayası, Pamukkale and Gölemezli masses are located at the ends of such fault segments or in the step-over zones between them. The deposition of travertines in such relay ramps is probably a result of the fracture network supplying carbonate-rich waters being highly interconnected where extensional strains are complex.

The Balkayası, Gölemezli and Pamukkale faults display a subordinate component of sinistral strike-slip in addition to a dominant component of normal dip-slip and both senses of step-over are left-handed. It follows that both step-over zones can be classified as releasing step-overs (Figure 10). Sibson (1987) has shown that releasing step-over zones between strike-slip fault segments also form loci for hydrothermal systems that act as pipe-like conduits for enhanced fluid flow. Thus, in this context, the occurrence of carbonate-rich springs (and hence travertines) in an around the releasing step-over zones between normal faults in the study area is especially noteworthy and consistent with the generally reported pattern. The width of the step-over zones where travertines are located range from 1 to 2 km. It is worthwhile to note that this range of width is believed to be the minimum required size for a step-over zone to act as a geometric barrier to an earthquake rupturing (Barka and Kadinsky-Cade 1988). The fact that these step-over zones are extensional and water-saturated is also of neotectonic importance, because according to Sibson (1981, 1987) such zones are the locations where aftershock swarms are located, that is, where earthquake rupturing is stopped or hampered. Consequently, the geometric fault segments around the travertines have the potential of being earthquake fault segments, which might be found out by paleoseismic investigations since there is no historical record of surface rupturing or reactivation of the studied faults.

It is known that at fault tips and in step-over zones regional stresses are locally perturbed (Segall and Pollard 1980, Burgmann and Pollard 1994). Thus, the strike of fissures will be influenced by local stress fields, thus explaining why some of them are highly oblique to the strikes of the faults adjacent to them. Therefore, care must be taken when using fissure orientations or ridge long axes to determine regional stress axes. For example, some of the stress axes inferred from fissures oblique to the Pamukkale range-front fault might reflect local stress axes, not regional axes as suggested by Altunel and Hancock (1993a). Although fissure-ridges in the Yenice area are not located at the ends of fault segments or in a step-over zone between them, they trend oblique to the Tripolis boundary fault, the only exception being the active Kamara fissure. The Yenice mass is located close to the northwestern end of the Tripolis fault close to where the Denizli basin is separated from the Gediz graben by the Buldan ridge, a topographic rise yet to be broken to connect the two grabens (Figure 1). Therefore, in such a structural setting regional stresses might also have been perturbed, with again the orientations of the fissure-ridges reflecting local stresses. As mentioned earlier, the valley along which Menderes river enters the Denizli basin might mark the trace of a possible Pre-Neogene fault. Such a fault might also account for some of the fissures-ridges being highly oblique to the main boundary fault.

One of the common characteristics of all travertine masses in the study area is that metamorphic basement rocks crop out adjacent to them in the footwall of a nearby graben boundary fault, and they overlie up to 2000-m thick Neogene-Quaternary fill in the grabens (Turgay et al. 1985, Paton 1992). This obsevertion suggests that CO_2 enrichment is probably associated with the dissolution of carbonate-riched metamorfic rocks which results from water-rock interactions at depth. Thus, principal boundary faults cutting metamorphic rocks are probably the main deep channelways for carbonate-riched thermal waters at depth (Figure 11). This may explain the absence of travertine deposits adjacent to subordinate faults cutting Neogene sediments. Channelways for thermal waters resulting in travertine deposition in the Yenice area are probably schistosity surfaces and minor fractures located in basement, thus explaining why the Yenice mass is located in the footwall of the Tripolis fault where metamorphic rocks crop out. In this context it should be recalled that although the mass is on the footwall side of the fault, the fissure-ridges are located only in the valley floor where its elevation is almost the same as that of present-day basin floor on the other side of the fault (Figure 6). This observation suggests that travertines now situated at up to 120 m above the valley floor were initially deposited on the valley floor and later elevated as a result of footwall uplift.

All the studied travertine masses are elongate parallel to nearby NW-trending fault traces along a distance of about 60 km from Pamukkale to Balkayası in the Menderes and Gediz grabens (Figure 1). This restriction to the northern sides of grabens might be related to all the areas of young volcanic activity being located to the north of the northern shoulders of these grabens. That is, the faults which act as channelways for carbonate-rich waters are located adjacent to areas where thermal, and especially CO_2 sources are abundant (cf. Pentecost 1994). For instance, the Balkayası mass is no more than 18 km away from the Kula area to the north where alkali-basalt magmatism took place as recently as 190 000 years ago (Richardson-Bunbury 1996).

Conclusions

The conclusion with the greatest prediction potential from the perspective of active fault studies is that late Quaternary travertine masses preferentially occur at the ends of fault segments or in the step-over zones between them. The deposition of travertines in such structural settings is probably a consequence of the network of fissures supplying the carbonate-rich waters being highly interconnected where extensional strains were complex. It follows that during a neotectonic survey directed at finding active faults and identifying potentially hazardous segment boundaries it is worthwhile searching for, and surveying, late Quaternary travertine bodies.

Because the orientations of fissures and the long axes of fissure-ridges are related to local stresses in step-over zones, caution should be exercised when employing fissure orientations to determine the regional stress axis.

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