Turkish Journal of Earth Sciences

Volume 17 | Number 2 Article 2

1-1-2008

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Recommended Citation

MESCİ, LEVENT; GÜRSOY, HALİL; and TATAR, ORHAN (2008) "The Evolution of Travertine Masses in the Sivas Area (Central Turkey) and Their Relationships to Active Tectonics," *Turkish Journal of Earth Sciences*: Vol. 17: No. 2, Article 2. Available at: https://journals.tubitak.gov.tr/earth/vol17/iss2/2

Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), **Vol. 17**, 2008, pp. 219–240. *Copyright ©TÜBİTAK*

The Evolution of Travertine Masses in the Sivas Area (Central Turkey) and Their Relationships to Active Tectonics

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Abstract: Sıcak Çermik, Delikkaya and Sarıkaya are important travertine fields with active hot springs located 31 km west of Sivas. Based on their morphology, most of the travertines are classified as fissure-ridge travertines. Eroded sheet-type, terraced, and self-built channel types of travertine are also present at a few locations.

Faults and fissures formed in the underlying İncesu Formation, and fissures developing in the fissure-ridge travertines are linked to one another. Tectonic deformation forming the fissure-ridge travertines resulted from NE–SW extension associated with a NW–SE compressional regime related to the Central Anatolian Thrust Belt and Sivas Backthrust.

U/Th series age dating results indicate that the travertine deposition extends back to 400 ka and yields ages of 11.400 (±500) to 364.000 ($^{+201.000}/_{-76.000}$) from the fissure-ridge travertines. Age data and fissure width observations indicate that a ~0.06 mm/year extension rate is associated with the compressional regime in the Sivas Basin. On average, fissure-ridge travertines formed over intervals of 56.000 years, and indicate that a major regional seismic event with a magnitude of 7.4 has occurred here with this order of frequency. The Pamukkale travertines in Western Turkey are one of the most spectacular natural heritage sites in the world, as well as a site of active tectonic studies, and are now protected for these reasons. As shown by this study, the Sıcak Çermik travertines are of comparable interest and should receive similar protection.

Key Words: active tectonics, earthquake, Sivas Basin, Sıcak Çermik, travertine, travitonics, U/Th age dating, Quaternary geology

Sivas (Orta Türkiye) ve Çevresindeki Travertenlerin Gelişimi ve Aktif Tektonikle İlişkileri

Özet: Sıcak Çermik, Delikkaya ve Sarıkaya Sivas'ın yaklaşık 31 km batısında yer alan önemli sıcak su çıkış merkezleri ve traverten oluşum alanlarıdır. Morfolojik sınıflamaya göre bölgedeki travertenlerin büyük bir kısmını çatlak sırtı tipi travertenler, az oranda aşınmış traverten tabakaları ve birkaç lokasyonda ise küçük yüzlekler biçiminde teras tipi ve kanal tipi travertenler oluşturmaktadır.

Travertenler için temel kaya niteliğinde bulunan İncesu Formasyonu kayaçlarında yer alan faylar ve çatlaklar ile sırt tipi travertenler içerisinde gelişmiş çatlaklaklar birlikte değerlendirilmiş, içerisinde sırt tipi travertenlerin geliştiği açılmaları sağlayan tektonik deformasyonun, Orta Anadolu Bindirme Kuşağı ile Sivas Geri Bindirmesinden kaynaklanan KB-GD doğrultulu sıkışmaya bağlı KD-GB yönlü açılma biçimde geliştiği sonucuna varılmıştır.

U/Th yaşlandırma bulguları, bu bölgedeki traverten oluşumunun yaklaşık 400.000 yıl önce başladığını ortaya koymuştur. Uranyum serisi yaş analizleri sonucunda inceleme alanlarında yer alan sırt tipi travertenlerin yaşlarının 364.000 ($^{+201.000}/_{-76.000}$) ile 11.400 (±500) yıl arasında değiştiği belirlenmiştir. Sırt tipi travertenlerin genişliklerini ve yaş sonuçlarını kullanarak Sivas Havzası içinde sıkışmaya bağlı açılma hızı 0.0633 mm/yıl olarak belirlenmiştir. Sırt tipi travertenlerdeki hidrotermal etkinliğin 56.000 yıllık bir periyotta aktifleşme ve pasifleşme dönemi geçirdiği gözlenmiştir. Bu bulgulara göre, Sivas ve yakın çevresindeki hidrotermal etkinliği tetikleyen büyük bir sismotektonik etkinliğin, 56.000 yıllık tekrarlanma periyodunda yaklaşık 7.4 büyüklüğünde bir depremin oluşmasını gerektirmektedir.

Aktif tektonik ile yakından ilişkisi, doğal güzelliği ve turistik çekiciliği nedeni ile Pamukkale'deki travertenler koruma altına alınmıştır. Ancak içerisinde gelişen yapıların özelliği gereği doğal jeolojik miras niteliğindeki Sıcak Çermik ve çevresindeki travertenlerin de koruma altına alınması gereklidir.

Anahtar Sözcükler: aktif tektonik, deprem, Sivas Havzası, Sıcak Çermik, traverten, traverten Tektoniği, U/Th yaş yöntemi

Introduction

The presence of active and inactive travertine deposits in the vicinity of Sivas (central Turkey) indicates that hydrothermal activity has occured extensively during the recent geological past. The studied travertine masses are located in Sıcak Çermik, Delikkaya and Sarıkaya, about 20 km west of the city of Sivas (Figure 1).

Previous work by several researchers in this region has focused mainly on geochemical and economic features of the travertines, including their value as structural and decorative stone (Ayaz 1998; Ayaz & Gökçe 1998; Ayaz & Karacan 2000; Tekin *et al.* 2000; Tekin & Ayyıldız 2001). Other studies have included the geothermal potential of the hot water (Ergin 1992; Erişen *et al.* 1996), geophysical investigations (Aydoğan 1991), and hydrotherapeutic applications of the spring waters (Kaçaroğlu *et al.* 1994).

Although there have been numerous studies on travertine deposits (Scholl 1960; Barnes *et al.* 1971, 1978; Martelli *et al.* 1989) only a few workers (Jones 1925; Scholl 1960; Martelli *et al.* 1989) discuss their relationship to tectonics.

Travertines have been widely used in studies of active tectonics since the 1990's (Altunel 1994; Çakır 1999), and most Turkish workers have concentrated on the classic occurrences at Pamukkale in Western Turkey (Altunel & Hancock 1993a, b, 1996; Altunel 1996; Hancock *et al.* 1999). This study is the first investigation of tectonic features of travertines in the Sıcak Çermik region (Sivas, Central Turkey).

Tectonic and Geological Setting of the Sivas Basin

The Sivas Basin of Tertiary age is bounded to the north by a tectonic contact represented by the İzmir-Ankara-Erzincan suture zone, which is composed mainly of ophiolitic rocks thrust upon basin fill sediments from north to south. The nappes of the ophiolitic mélange cap the Kırşehir metamorphic basement of the Sivas Basin. Most researchers (Cater *et al.* 1991; Guezou *et al.* 1996; Poisson *et al.* 1996) consider the Sivas Basin to be a foreland basin obducted from north to south at the southern margin of the Pontides during the closure of Neotethys. Since the studies undertaken by Koçyiğit (2003b), the Middle Anatolia region has been named the 'Central Anatolia Plains Region' following Şengör (1980), and the middle section of the Anatolian plate is named the 'Central Anatolia Neotectonic Region'.

Many secondary neotectonic structures have developed independently from the main neotectonic structures, such as North and East Anatolian fault zones. Koçyiğit (2003b) has divided the Central Neotectonic Region into two sub-neotectonic regions, comprising the Konya-Eskişehir neotectonic region and the Kayseri-Sivas neotectonic region. In these zones a contraction-extension type of neotectonic regime is present and is generally associated with strike-slip faulting. Gürsoy *et al.* (1992) noted the development of a large NNW-directed backthrust in the region, which they named the Sivas backthrust (Figure 2). The shear sense caused by thrusts in the Sivas Basin is southerly. Metamorphic, volcanic and sedimentary rocks, ranging from Palaeozoic to Quaternary in age, crop out in and around the region where the travertine outcrops are located. Following studies of Yılmaz (1983), Yılmaz *et al.* (1995), Ergin (1992), Özcan *et al.* (1980) and Ayaz (1988) in this region, the Akdağmadeni lithostratigraphic unit is recognised, which consists of gneiss, schist, amphibolite, quartzite and marble. This is succeeded unconformably by the Tokuş Formation consisting of alternating units of Nummulitic limestone, sandstone, claystone, and shale. The Kaletepe Volcanics consist of pillowed andesite and basaltic lava flows of Eocene age. The İncesu Formation consists of Upper Miocene–Pliocene terrestrial sediments. These are red and grey, loosely cemented, coarse- to fine-grained clastic rocks that are locally crossbedded, and quasi-horizontal. The İncesu Formation, which underlies the travertine deposits, lies with angular unconformity upon all the older units in the region (Figure 2).

Field Characteristic of Travertine Masses

Following their investigations of the Pamukkale (Denizli) travertine, Altunel & Hancock (1993a) noted that morphological criteria are the most useful for classifying travertine, and they added three new types to the morphological classification proposed by Chafetz & Folk (1984). One of these types, the fissure-ridge travertines, provides highly reliable tectonic data. In particular, the direction, length, and width of the axial crack of fissure-ridge travertines link the formation of the travertine ridge to the regional tectonic regime. The most important factor causing hydrothermal fluids to rise to the surface is the presence of tectonic discontinuity planes such as faults and major joints. Fissure-ridge travertines, which possess open fissures, are widely observed in regions

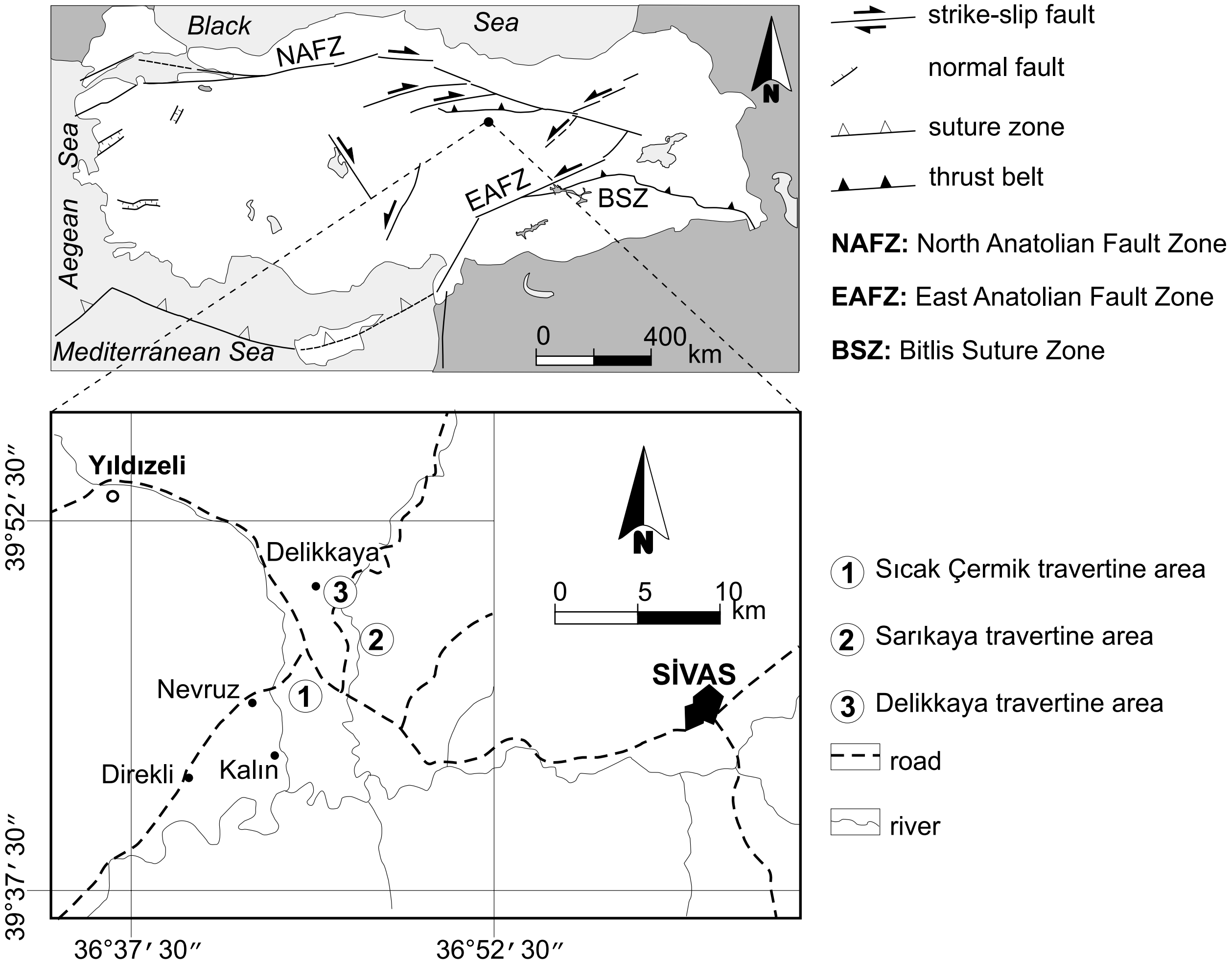


Figure 1. Map showing the location of the Sıcak Çermik, Sarıkaya and Delikkaya travertine areas.

subject to extensional tectonics. They form when calcium bicarbonate-rich hot water rises up from a crack or fissure and precipitates travertine, both in the crack and when it spills out on the surface. Water precipitates the generally nonporous 'banded travertine' in the open crack, commonly with bands of different colour depending on the minerals present and chemical impurities. Precipitation is generally symmetrical in both sides of the crack walls. As the crack continues to expand during regional extension, parallel-banded travertine is precipitated progressively on the crack walls. At the surface, due to changing physical conditions, porous and bedded travertines are formed as dipping layers perpendicular to fissure axis (Figures 3 & 4).

When the hydrothermal activity ceases, fissures may continue to expand due to the regional extension and an open cavity can form along the central axis of the main fissure ridge. Since the fissures in the fissure-ridge travertines are products of an extensional regime, they provide concrete information about the direction and rate of regional extension. Clearly the banded travertine lining the centre of the fissure is the youngest and the travertine bands at the fissure wall are the oldest. Thus, when the age of the oldest banded travertine furthest from the active fissure is compared with the age of the youngest banded travertine at the centre of the fissure, the extension rate can be calculated. Altunel & Hancock (1993a, b, 1996), Altunel (1994, 1996), and Çakır (1996) obtained important results for the travertine formations in the Denizli region using this method. They showed the uranium-thorium method to be the most suitable method for dating the age of travertine

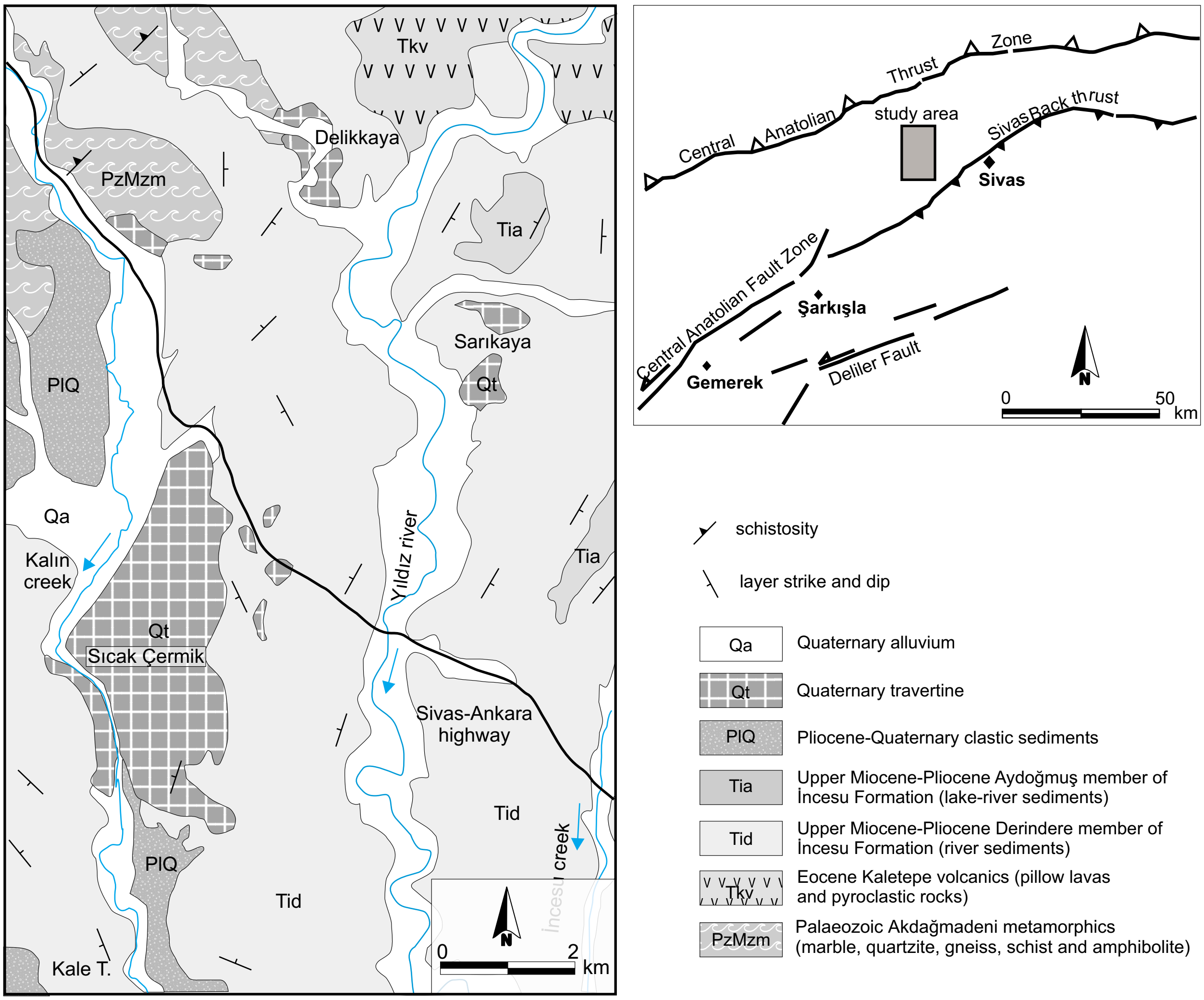


Figure 2. Geological map of the Sıcak Çermik region simplified from Yılmaz *et al.* (1997).

deposition since it can provide sensitive ages ranging from ~5.000 years to several hundreds of thousands of years. Recent studies concerning active tectonics and travertine formation have also provided important information. Çakır (1999), for example, stated that complex extensional deformation in the Gediz and Menderes grabens of Western Turkey caused hot waters to rise to the surface and form travertines that define when the normal fault movements occurred. Karabacak (2002) and Karabacak & Altunel (2003) examined the Ihlara Valley travertines from the perspective of their morphology and crustal deformation, and Koçyiğit (2003a) noted that active tensional orientations and the fissure-ridge travertine orientations within the Karakoçan fault zone are conformable and can be used in studies of active tectonics.

Based on the morphological classification, fissure-ridge travertines comprise 54% of the total travertine in the study region. Eroded sheet-type travertine comprises 24% of the Sıcak Çermik, Delikkaya and Sarıkaya travertine, while self-built channel and terraced types of travertines crop out only on a very small scale and cannot be mapped as discrete units. The travertine formations that are currently forming and have not completed their development account for 22% of the total (Figures 5, 6 & 7).

Accompanying the definition of each travertine type in each of the three travertine areas, the main and parasitic

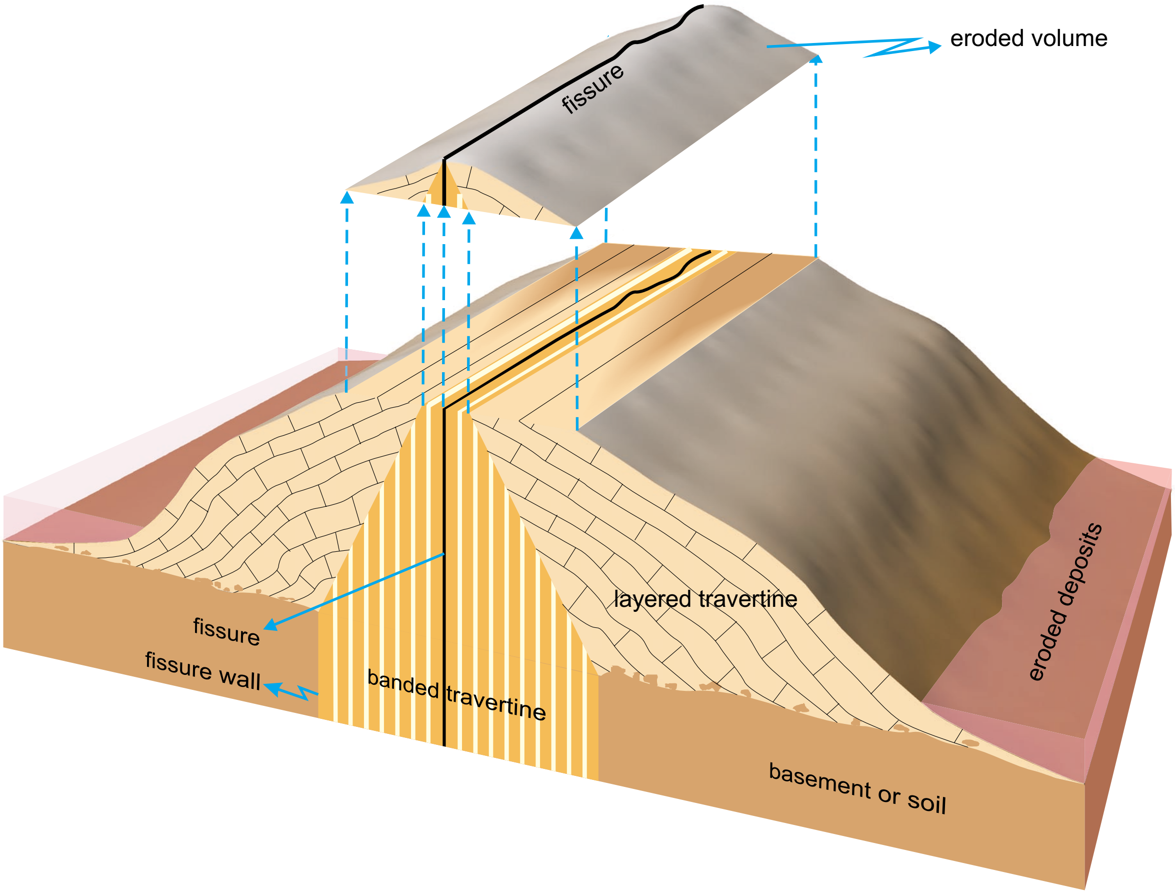


Figure 3. Three-dimensional oblique diagram showing arrangement of banded and layered travertine in a fissure-ridge deposit.

fissures of the fissure-ridge travertines have been mapped using GPS on a 1/5000 scale. At each location the width and height of the axis of the fissure, and the inclination values of the layered travertines have been recorded (Figures 5, 6 & 7).

Dating Results

The U/Th method of age determination has been used in most studies that have attempted to date travertine (e.g., Sturchio *et al*. 1994; Eikenberg *et al*. 2001; Semghouli *et al*. 2001; Mallick & Frank 2002; Soligo *et al*. 2002). It is applied here to resolve extension rates and to isolate episodes of travertine deposition. The most suitable material for dating is the banded travertine in the fissure system because these types are less porous and therefore less susceptible to diagenesis and contamination by superficial waters than the bedded travertines that form at the surface. Banded travertines that develop as fissure fills are therefore considered more favourable for the U/Th age dating method. As an example of this application, Altunel (1994) and Altunel & Karabacak (2005) used U/Th age dating to fissure-ridge travertines in the Pamukkale (Denizli) region. These results indicated regional extension rates in fissures with NE–SW orientation in the range 0.23–0.6 mm/year during the last 200,000 years.

Two samples were collected from each sampling location. One is the youngest and taken from the fissure axis and the other is the oldest and taken from the fissure wall. This approach aims to resolve opening rates from the age difference and the width of the fissure. Twelve samples from fissure-ridge travertines of the Sıcak Çermik travertine region and four samples from fissure-ridge travertines of Sarıkaya and Delikkaya were collected for age dating (Figure 5, 6 & 7). The results are summarized in Table 1.

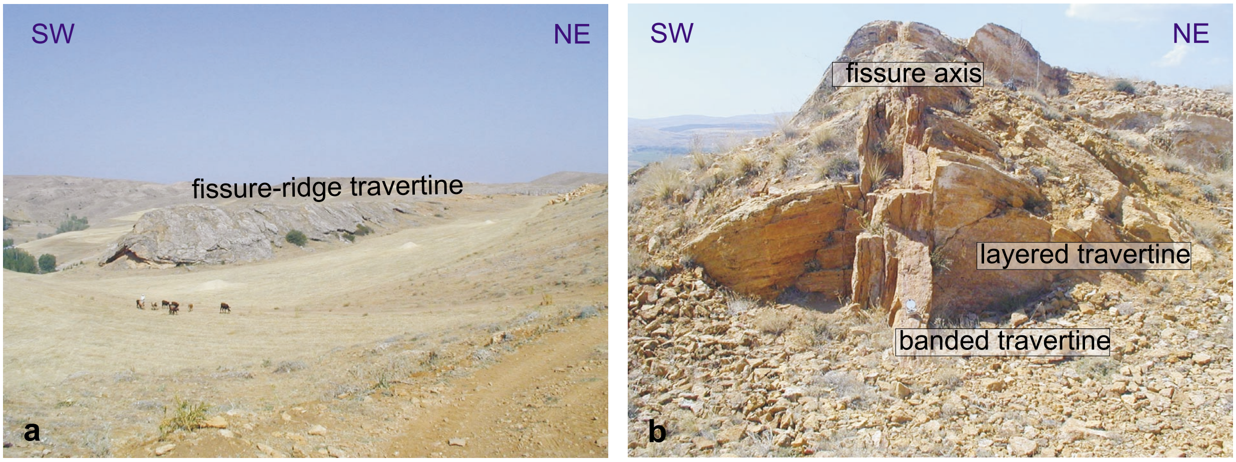


Figure 4. (a) View of a fissure-ridge travertine in the Delikkaya travertine area. (b) Cross section of fissure-ridge travertine at Sıcak Çermik.

These results indicate extension rates in the Sıcak Çermik travertine region between 0.14 and 0.028 mm/year, with an average rate of 0.068 mm/year. This average extension rate is highly variable across the region and was found to range from 0.007 mm/year for Sarıkaya to 0.110 mm/year for Delikkaya. The average extension rate based on the combined data from all three sites is 0.063 mm/year (Table 2).

Keller & Pinter (1996) termed the tectonic processes that create deformation in the crust and perceptible to humans as 'Active Tectonics'. Another point of view is that studies of 'active tectonics' should be viewed retrospectively with time period considered comprising the last several millions of years (Davis 1983). The hydrothermal activity that produced the structures forming the Sıcak Çermik, Sarıkaya and Delikkaya travertines spanned the last 500,000 years and the associated tectonic activity is therefore embraced by 'active tectonics' according to the definition of Davis (1993) but not that of Keller & Pinter (1996).

When age dating results obtained from the fissure-ridge travertines are presented graphically (Figure 8), it is observed that formation ages and the closing passive transition ages of some fissure-ridge travertines are remarkably concentrated within several intervals and regions. U/Th-2, 5, and 14 comprise a definite group; U/Th-4 and 11 another; and U/Th-1 and 8 comprise yet another. The average age obtained from U/Th-4 and 11 is 233,500 years, from U/Th-2, 5 and 24 is 178,300 years, and from U/Th-1 and 8 is 121,500 years.

The differences between these three groups are 55,200 and 56,800 years, respectively suggesting that new hydrothermal systems developed over an average period of about 56,000 years. At the end of the same intervals, hydrothermal activity and banded travertine formation at some fissure-ridge systems activity ceased, while new activity started elsewhere.

This relationship can be tested by adding 56,000 years to 233,500 years, which gives 289,500 years. The latter time coincides with the U/Th-12 passive transition, and also coincides with U/Th-7 when another 56,000 years are added (Figure 8). Using the same approach from the opposite direction, subtracting 56,000 years from 121,500 years gives a value of 65,500 years, which coincides with the U/Th-9 and U/Th-13 average value, and deducting a further 56,000 years gives 9,500 years, which coincides approximately with the age of U/Th-15 (Figure 8). Since travertine production stopped along some ridge axes and new ridges formed at intervals with an average period of 56,000 years, these repetitions can be assumed to have developed during periods in which major tectonic activity, such as major earthquakes, intensified.

When the data are compared with the Martinson *et al.* (1987) graphics showing climatic changes during last 300 ka (Figure 9) we observe that commencement and cessation times of fissure-ridges classified by this 56 ka interval are not apparently connected to climatic changes

Earthquakes that occur repeatedly along a fault zone with approximately the same time periods and similar magnitudes are defined as '*characteristic earthquakes*'. In these types of earthquakes, the slip rate on the fault, the magnitude of the earthquake, and the displacement taking place are assumed to be approximately constant

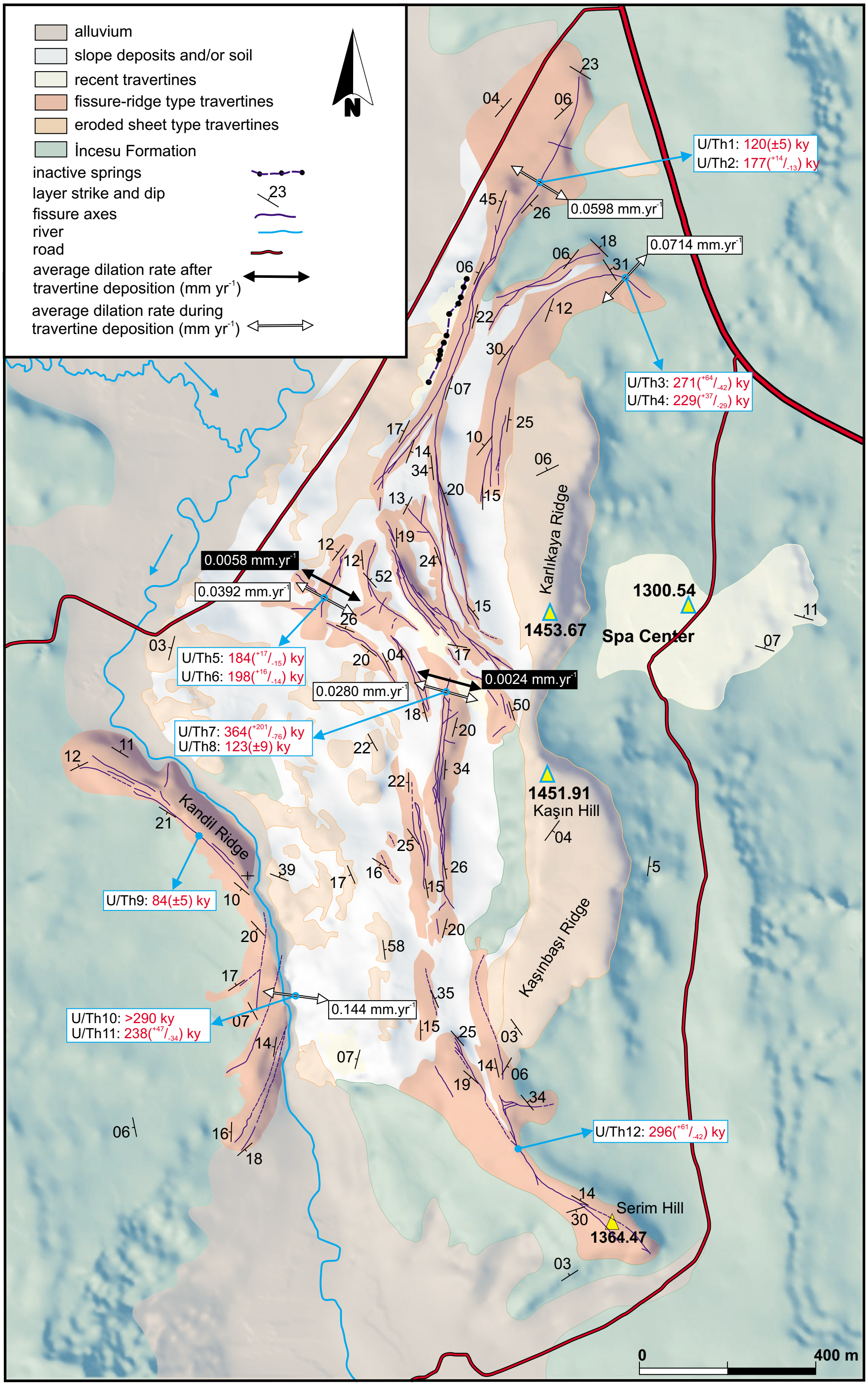


Figure 5. Travertine types, fissure axes, age dating results, and opening rates in the Sıcak Çermik travertine area.

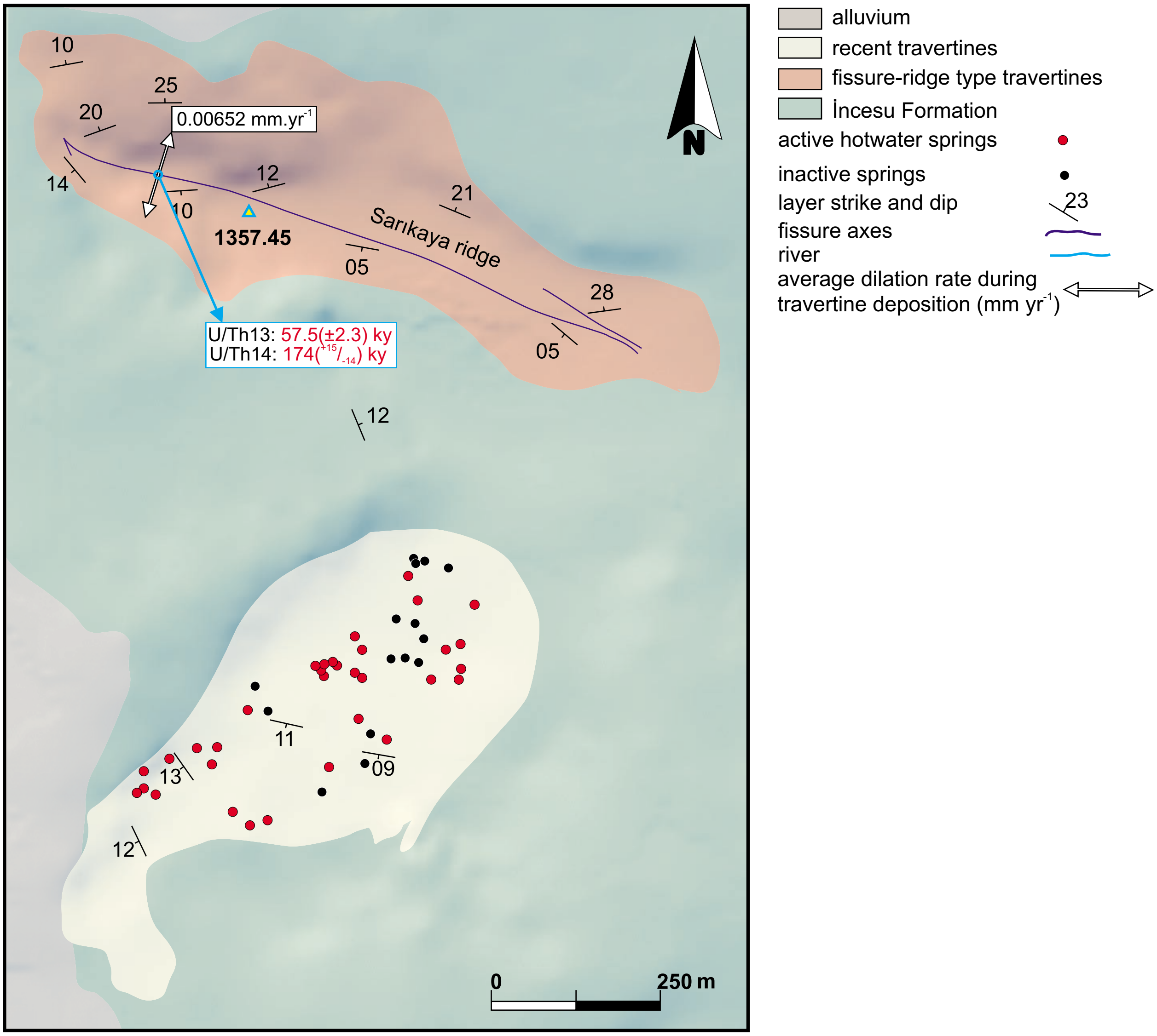


Figure 6. Travertine types, fissure axes, age dating results, and opening rates in the Sarıkaya travertine area.

for each event. Under such conditions, the average recurrence period is related in every case to the slip rate displacement. Slemmons & DePolo (1986) suggested that there is a relationship between the recurrence of earthquakes, and the slip rate and magnitude, which they showed graphically. The calculated extension rates, age dating results, and the time period between the beginning and end of hydrothermal activity on a fissure axis for this region have been applied to the Slemmons & DePolo (1986) graph (Figure 10). Based on the 56,000 years repetition period and an average extension rate of 0.0633 mm/year at Sıcak Çermik, Delikkaya and Sarıkaya, it can be inferred that earthquake(s) in and around the study area have been up to magnitude 7.4 and that the region falls in the "low activity" zone of the graph with respect to the frequency of earthquake activity (Figure 10).

Geological-Structural Relationships

One of the main aims of this study was to determine structural tectonic elements that led to the hydrothermal activity and caused the deposition of travertines. To this end, rose diagrams were constructed by taking measurements of the orientations of the main fissure

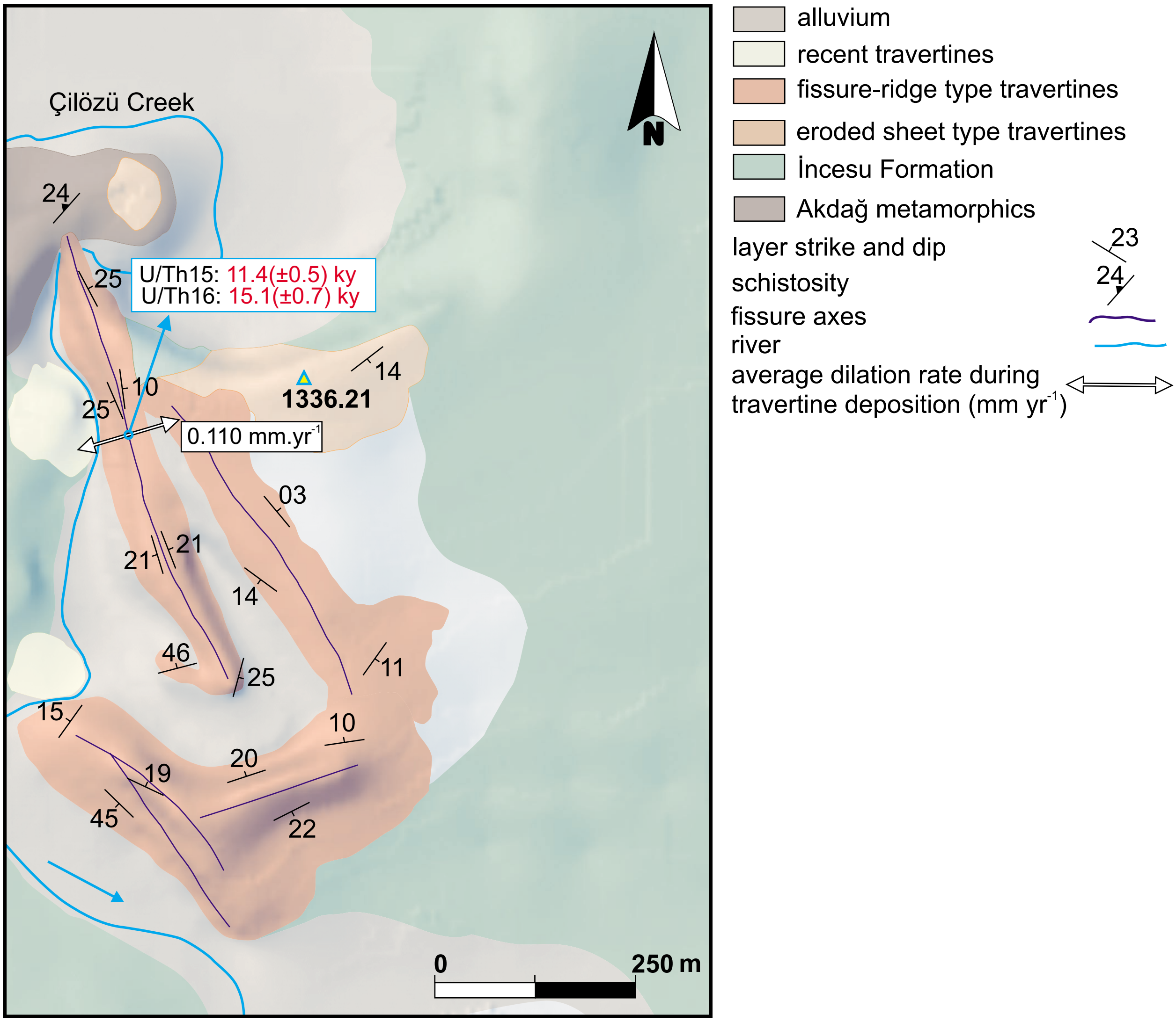


Figure 7. Travertine types, fissure axes, age dating results and opening rates in the Delikkaya travertine area.

axes of fissure-ridges at all three travertine sites; fault properties were also measured including data from the metamorphic rocks that crop out around the travertine sites and from the İncesu Formation, which is the substrate of the travertines. These data are essential for establishing the effective tectonic regime in the region and for determining whether trends conform to the axes of the fissure ridge travertines. Joint set data obtained from the quasi-horizontal İncesu Formation were also obtained to investigate the relationship between joint patterns and fissure systems at the travertine sites.

Analysis of Fissure Systems in The Travertines

Rose-diagrams were prepared from 599 strike measurements of fissure axes in the fissure ridge travertines of the Sıcak Çermik site. Similarly, 27 measurements from the Sarıkaya travertine site and 52 measurements from the Delikkaya travertine site were taken and evaluated. The fissure axis in the region is not uniform and therefore the measurement of each fissure axis were carried out in an approximately fifty metres successions where the trend of the fissure axis changed. Based on these results, concentrations are evident in the

Table 1. U/Th Age dating results of banded travertine from fissure-ridge travertines in the study area.

Sample	Location	U (ppm)	(^{234}U/^{238}U)	(^{230}Th/^{234}U)	Age (1.000 year)	U_i
U/Th1	Sıcak Çermik	0.73 (0.01)	1.98 (0.02)	0.718 (0.020)	120 (±5)	2.38 (0.03)
U/Th2	Sıcak Çermik	0.21 (0.01)	2.03 (0.06)	0.891 (0.032)	177 ($^{+14}/_{-13}$)	2.70 (0.09)
U/Th3	Sıcak Çermik	0.045 (0.002)	1.34 (0.06)	0.984 (0.049)	271 ($^{+64}/_{-42}$)	1.73 (0.14)
U/Th4	Sıcak Çermik	0.014 (0.001)	1.41 (0.07)	0.945 (0.046)	229 ($^{+37}/_{-29}$)	1.79 (0.13)
U/Th5	Sıcak Çermik	0.071 (0.002)	1.85 (0.07)	0.897 (0.036)	184 ($^{+17}/_{-15}$)	2.43 (0.11)
U/Th6	Sıcak Çermik	0.294 (0.008)	1.93 (0.03)	0.930 (0.030)	198 ($^{+16}/_{-14}$)	2.62 (0.06)
U/Th7	Sıcak Çermik	0.083 (0.004)	1.37 (0.06)	1.056 (0.050)	364 ($^{+201}/_{-76}$)	2.05 (0.17)
U/Th8	Sıcak Çermik	0.085 (0.002)	1.45 (0.42)	0.709 (0.030)	123 (±9)	1.64 (0.06)
U/Th9	Sıcak Çermik	0.420 (0.01)	2.53 (0.05)	0.575 (0.022)	84 (±5)	2.94 (0.06)
U/Th10	Sıcak Çermik	0.022 (0.001)	1.12 (0.10)	1.038 (0.077)	>290	1.60 (0.50)
U/Th11	Sıcak Çermik	0.034 (0.001)	1.17 (0.06)	0.921 (0.046)	238 ($^{+47}/_{-34}$)	1.33 (0.11)
U/Th12	Sıcak Çermik	0.025 (0.001)	1.59 (0.07	1.042 (0.044)	296 ($^{+61}/_{-42}$)	2.37 (0.17)
U/Th13	Sarıkaya	0.600 (0.01)	1.88 (0.03)	0.424 (0.014)	57.5 (±2.3)	2.04 (0.03)
U/Th14	Sarıkaya	0.269 (0.007)	1.60 (0.04)	0.859 (0.033)	174 ($^{+15}/_{-14}$)	1.98 (0.06)
U/Th15	Delikkaya	0.138 (0.004)	4.05 (0.10)	0.101 (0.004)	11.4 (±0.5)	4.26 (0.12)
U/Th16	Delikkaya	0.104 (0.004)	3.90 (0.14)	0.131 (0.006)	15.1 (±0.7)	4.03 (0.14)

Table 2. Opening rates of fissures deduced from U/Th age determinations.

Sample Number	Age (1.000 year)	Occurence Interval (1.000 year)	Maximum Width of Banded Travertines (cm)	Opening Rate mm.y^{-1}
U/Th-1	120(±5)	57	341	0.0598
U/Th-2	177($^{+14}/_{-13}$)			
U/Th-3	271($^{+64}/_{-42}$)	42	300	0.0714
U/Th-4	229($^{+37}/_{-29}$)			
U/Th-5	184($^{+17}/_{-15}$)	14	55	0.0392
U/Th-6	198($^{+16}/_{-14}$)			
U/Th-7	364($^{+201}/_{-76}$)	241	675	0.0280
U/Th-8	123(±9)			
U/Th-10	>290	52	750	0.144
U/Th-11	238($^{+47}/_{-34}$)			
U/Th-13	57.5(±2.3)	116.5	76	0.00652
U/Th-14	174($^{+15}/_{-14}$)			
U/Th-15	11.4(±0.5)	3.7	41	0.110
U/Th-16	15.1(±0.7)			

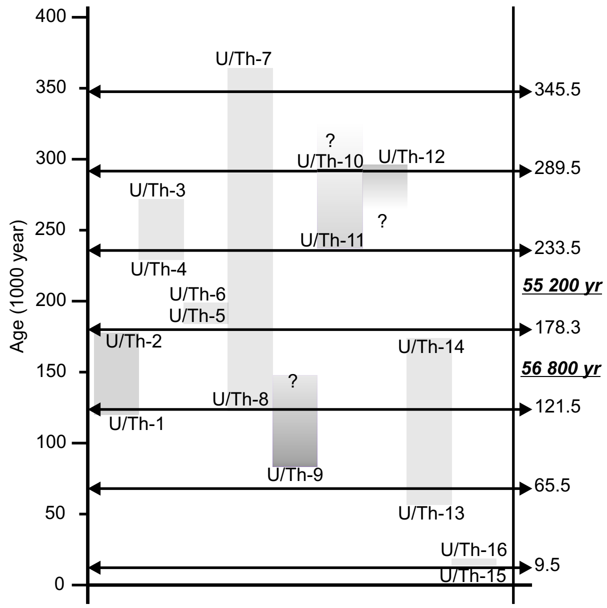
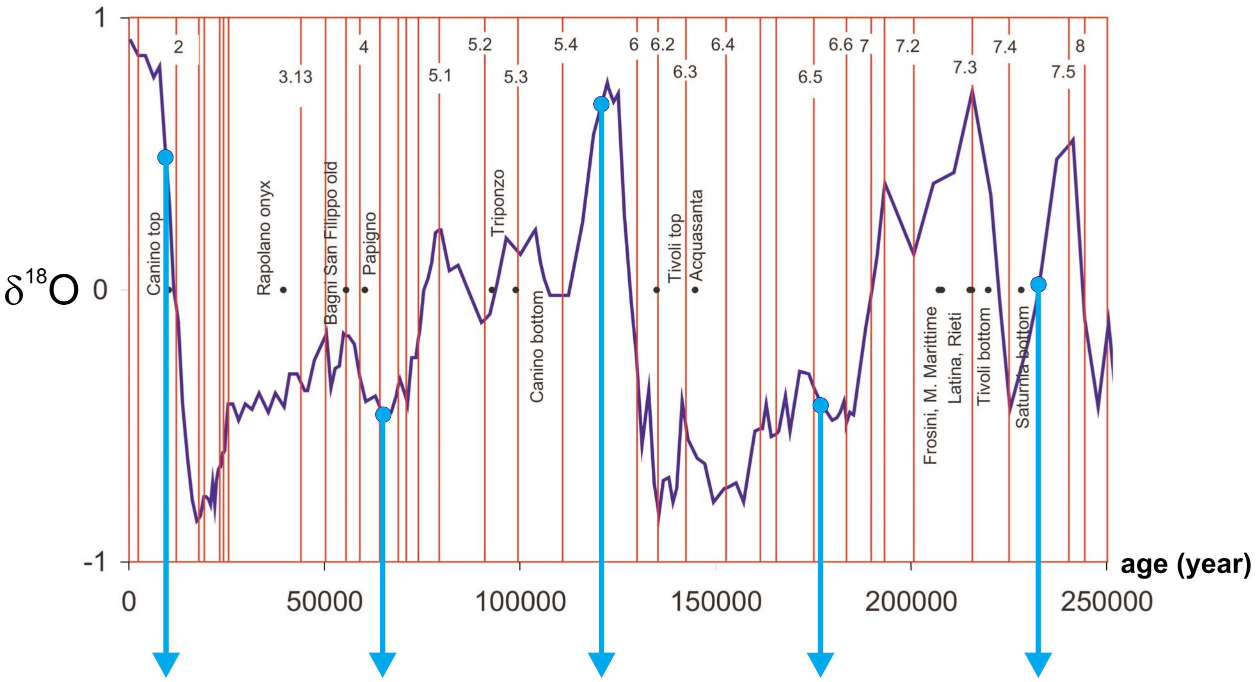


Figure 8. The relationship between U/Th ages and the opening and closure of travertine ridges in the study area.

Sıcak Çermik travertine site with N–S and N40°W orientations. In the Sarıkaya travertine site there is a concentration of N60°W orientations, whereas in the Delikkaya travertine site the concentration has N30°W orientation (Figure 11).

Kinematic Analysis of Fault Systems

Fourteen fault measurements from Palaeozoic metamorphic units that crop out around the travertine outcrops and 23 measurements from small scale faults in the İncesu Formation were measured and assessed using the Carey (1979) method for kinematic analysis. When data on fault kinematics of Palaeozoic marbles and the Upper Miocene–Pliocene İncesu Formation were evaluated, the resultant R value was found to be greater than 0.5, which indicates that these faults developed as a result of compressional tectonic deformation. The main compression that formed these faults was oriented NW–SE (343°N) in the Palaeozoic units while the maximum compression direction derived from fault



9500
ceasing of
fissure-ridges activity

65500
ceasing of
fissure-ridges activity

121500
ceasing of
fissure-ridges activity

178300
starting and
ceasing of
new fissure-ridges
activity

233500
ceasing of
fissure-ridges activity

Figure 9. Graph shows climatic changes during last 300 ka after Martinson *et al.* (1987). compared with the starting and ceasing periods of some fissure-ridges.

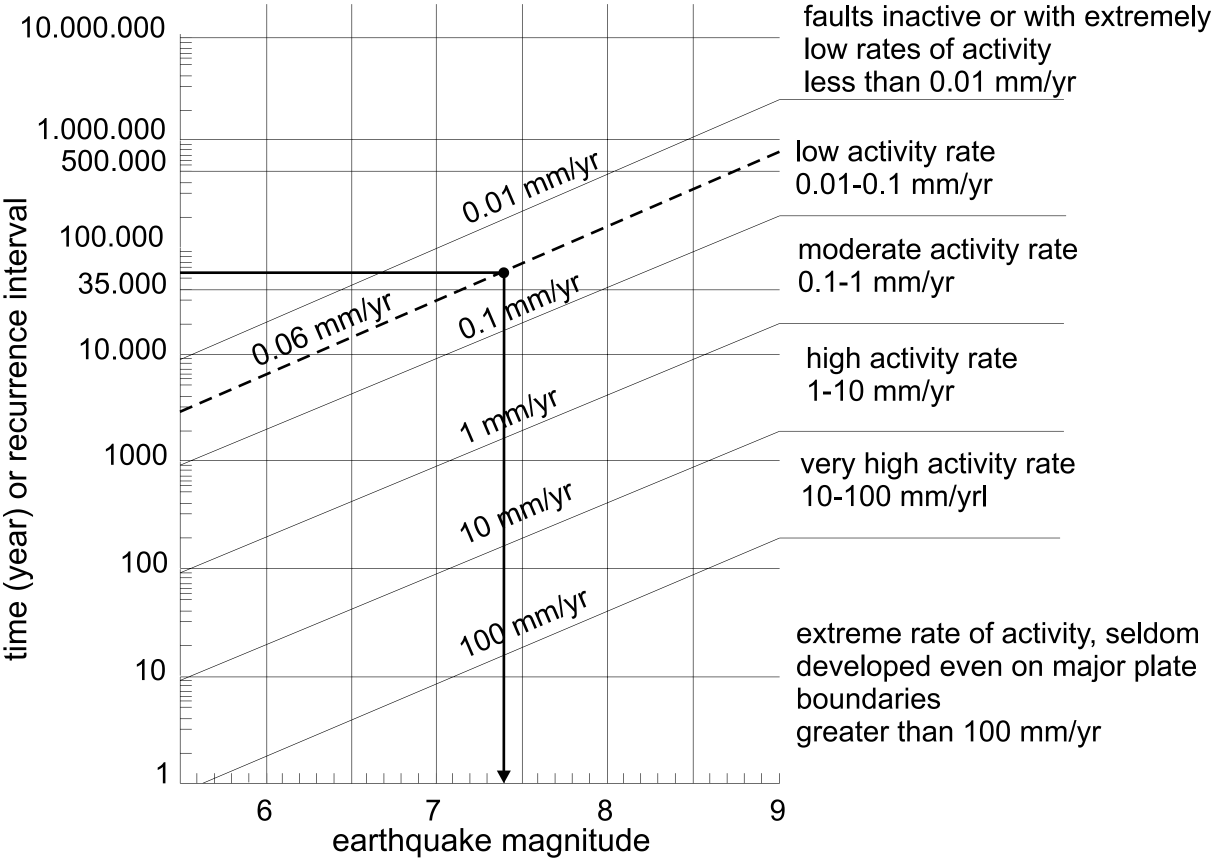


Figure 10. Graphical relationship between time-magnitude and motion for the ~56,000 year earthquake cycle (source graph from Slemmons & DePolo 1986, as reproduced in Keller & Pinter 1996).

kinematic analysis of the Upper Miocene–Pliocene İncesu Formation was determined to be NW–SE (308°N) (Figure 12).

This evidence shows that the force couple that produced the contractional tectonics in the region has changed its position during the neotectonic history. The angular difference between the compression directions is 035° counter-clockwise. Palaeomagnetic results obtained from the Miocene, Pliocene, and Quaternary rocks in the Sivas Basin also confirm that a rotation of this magnitude occurred during the Quaternary (Gürsoy *et al.* 1997). The agreement of rotation values derived from Miocene, Pliocene and Quaternary volcanic units in the Sivas Basin shows that the counter-clockwise rotations occurred mostly during last stage of neotectonic deformation during the Quaternary (Figure 13).

Analysis of Joint Systems

A contour diagram was prepared from 78 joint measurements collected from rock units of the İncesu Formation during the fieldwork and the dominant joint set was determined. A rose diagram, prepared using the measurements obtained from the fissure axes of fissure-ridge travertines at the Sıcak Çermik site, was compared with these joint set data (Figure 14). The dominant joints show two different strike orientations on the contour diagram: N35°W and N04°E. When the joints are considered in the context of the general inferred compression orientation of NW–SE (308°N), the first joint set (N35°W) is identified as an open (dilatory) system and the second joint set (N04°E) is identified as a shear joint system. The fissures in the fissure ridge travertines proved to be concordant with kinematic results obtained from both the fault measurements and

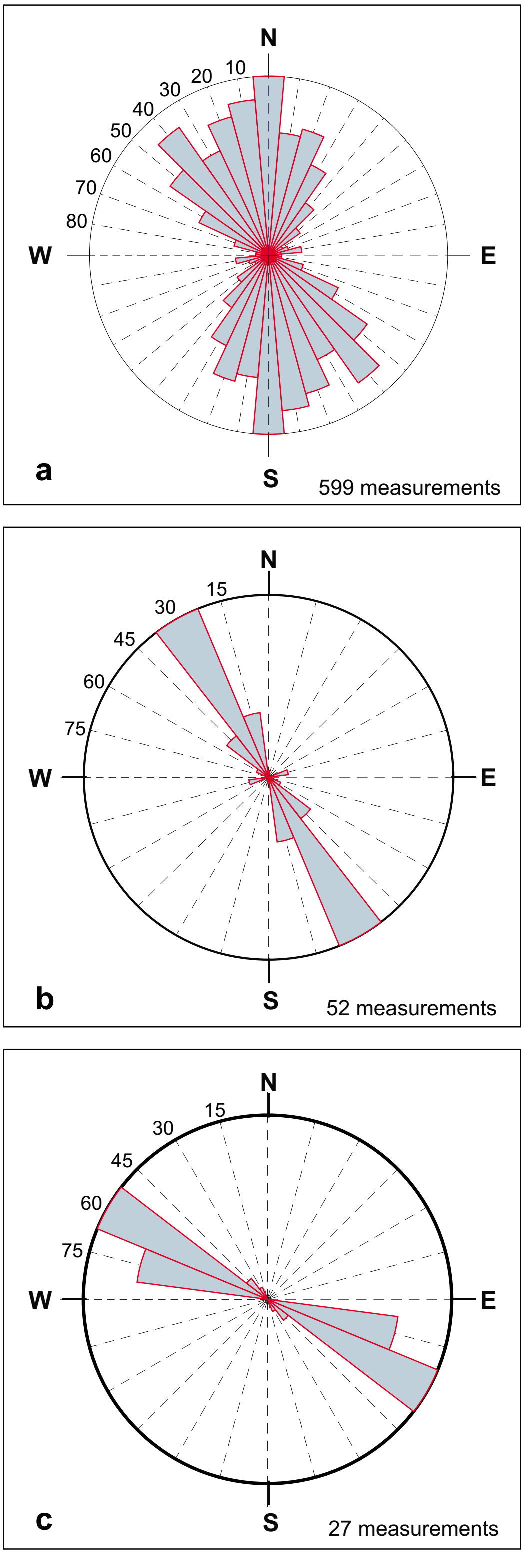


Figure 11. Rose diagrams of fissure axis orientations in the **(a)** Sıcak Çermik, **(b)** Delikkaya and **(c)** Sarıkaya fissure-ridge travertines.

the joint systems, although the fissure systems in the travertines are more compatible with the joint systems of İncesu Formation (Figure 14).

Lineament Analysis With Remotely Sensed Data

Lineation analysis on images obtained by remote sensing is a common method for investigating the quality and quantity of discontinuity planes such as fissures, faults, and joints, and also for studying their relationship to magmatic intrusion and volcanism. These methods can be used to locate the positions of the linear structures, and their general distribution can then be plotted on a rose-diagram. For lineation analysis, a framework covering the main study area and surrounding region was established initially on a Landsat TM image (Figure 15a). By applying 'Directional Gradient Enhancement' effects on the 5th spectral band of this framework, linear structures with different orientations are highlighted. To make the NE–SW-oriented linear structures become evident, a NW–SE-oriented enrichment method was applied and linear structures were drawn on the image (Figure 15b). The same method was used for enhancing the NW–SE-oriented linear structures (Figure 15c). While drawing linear structures on the image, comparison were made with the 1:25,000 scale topographic maps to resolve human-made cultural structures such as roads, water transportation channels, high voltage lines, etc. When the linear structures are plotted on rose-diagrams, the NE–SW and NNE–SSW orientations are evident (Figure 15d, e), and are compatible with the fault orientations obtained from the fault system analysis (Figure 12), and with the N04°E-oriented, dominant joint set (Figure 14).

Tectonic Model

The Sivas Tertiary Basin, which lies between ophiolites related to the closure of northern branch of Neotethyan ocean in the north and uplifted basement composed of metamorphic rocks of the Kırşehir Massif in the south, includes different rock units from Paleocene to Quaternary in age. The basin is tectonically limited by the Central Anatolian Thrust Zone in the north and by an unconformity from the Kangal Neogene sub-basin, which forms Uzunyayla Plateau in the south. The Sivas Backthrust is a thrust fault developed in the basin that extends through the left-lateral Central Anatolian Fault Zone to the southwest of Şarkışla (Figure 16).

The travertines and hot spring sites in the Sivas region extend from the northwest of Gemerek to Şarkışla in the southwest, and extend northwest of Sivas to a line

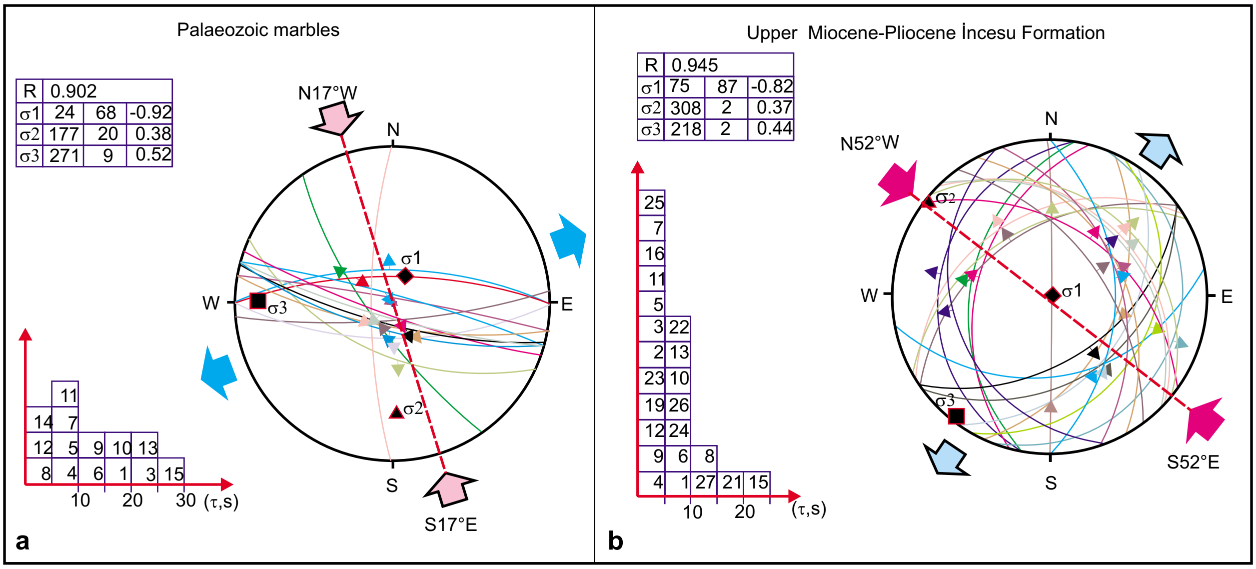


Figure 12. Lower hemisphere stereographic plots showing kinematic determination of fault planes in the (a) Palaeozoic marbles, and (b) Upper Miocene–Pliocene İncesu Formation.

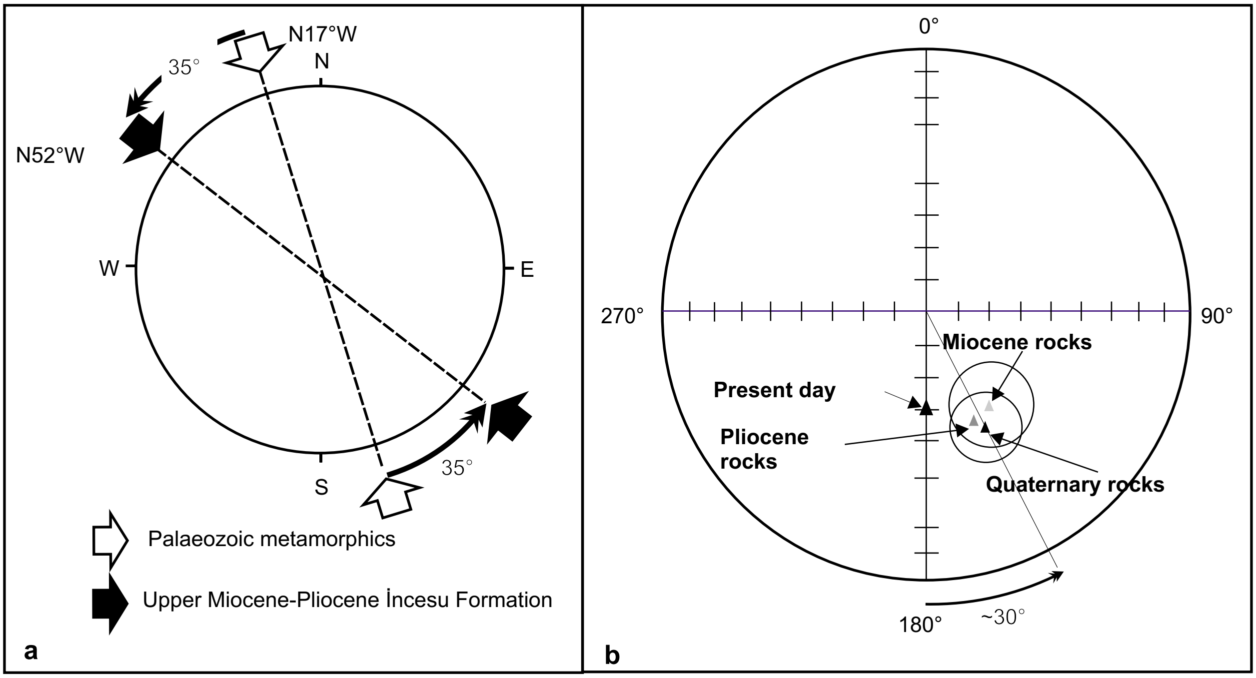


Figure 13. (a) Comparison of the 35° rotation derived from kinematic results from Palaeozoic marbles and the İncesu Formation and (b) stereographic projection of the regional palaeomagnetic results (Gürsoy *et al.* 1997).

oriented at approximately N40°E (Figure 17). The concentration of these features in a prominent NE–SW-trending linear zone can hardly be a coincidence and suggests deep control by a major tectonic structure.

When the main fissure axes of the travertines in the Sıcak Çermik region are carefully investigated as a whole, it is apparent that they are very similar to open structures formed in left lateral shear-zones (Figure 17). A possible

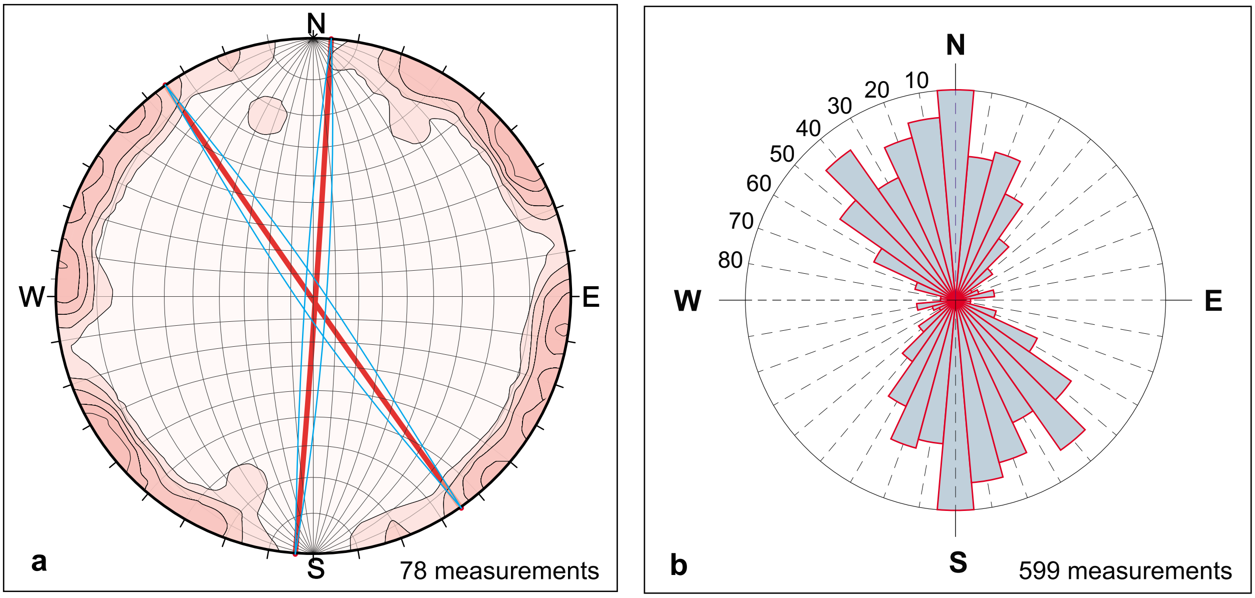


Figure 14. (**a**) Contour diagram and dominant joint planes in the İncesu Formation, (**b**) rose diagram of the fissure axes of the fissure-ridge travertines.

shear zone that would produce the fissure-ridge travertines in Sıcak Çermik should therefore be left lateral (Figure 18). The observation that the trend of the shear zone shown in Figure 18 is comparable with the linear trend given in Figure 17, which includes the hot springs and travertine sites in Sivas region, increases the significance of this interpretation.

The approach of Price (1966), which was applied to fissure systems formed in horizontal sedimentary rock units that have undergone compression and extension but without bending, has been applied to the Sıcak Çermik travertines. This method identifies a left lateral shear zone as the cause of a N52°W directed tensional force. It is then possible to interpret the fissures in this region as tensional and cutting fissures that are parallel and perpendicular to a regional compression (Figure 19). Also, the fact that some of the fissure axes are convex indicates that when the tension and fissures cross each other, or when the fissure axis development continues, this can force one fissure to change into the other type of fissure.

The data obtained from the fissure systems in the İncesu Formation, the rose-diagrams of the fissure locations in the Sıcak Çermik, Delikkaya and Sarıkaya travertine fields, and kinematic analysis of the fault planes measured in the İncesu Formation collectively identify the existence of a kinematically NW–SE-oriented compression linked to NE–SW extensional tectonics (Figure 20).

Results and Discussion

Travertines at the Sıcak Çermik, Sarıkaya and Delikkaya sites can be classified on their morphology into fissure-ridge travertines, eroded sheet-type travertines, and channel and terraced travertines. These travertine types and the fissure axes of the fissure-ridge travertines were mapped in detail on a 1:5,000 scale for the first time. Within the region, 54% of all the travertines that outcrop in this region are fissure ridge travertines, 24% are eroded sheet-type travertine, and 22% are actively forming travertines. The most widespread type is the fissure-ridge travertine, and because these types provide much information about tectonics, they were studied in detail and mapped on 1:5,000 scale with the help of GPS nineteen fissure-ridge travertines were mapped at Sıcak Çermik, three in Delikkaya, and one in Sarıkaya. The widths of the banded travertine that form as fissure fills in the fissure-ridges vary between 0.5 cm and 20.8 m.

To reveal the neotectonic properties of the region from the travertine, kinematic analysis of small-scale faults located in the Upper Miocene–Pliocene İncesu Formation, which is the substrate for the travertine sites, was carried out and rose and contour diagrams of the joint measurements were prepared. The rose-diagrams obtained from the fissure axes of the fissure-ridge travertines at Sıcak Çermik and the joint systems of the İncesu Formation are entirely compatible, and yield a compression direction oriented approximately at N20°W.

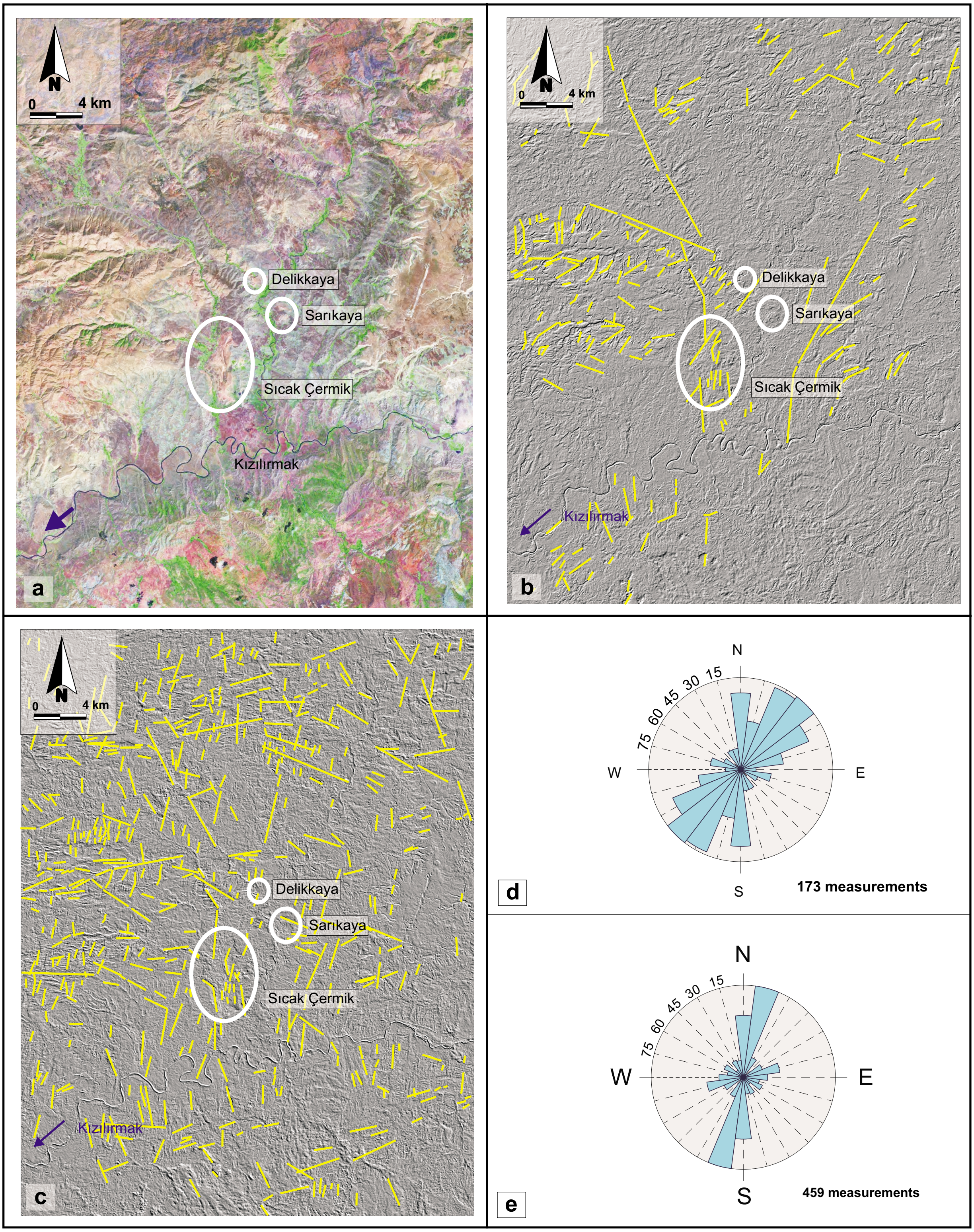


Figure 15. (a) Landsat TM satellite images comprising the study area (2, 4 and 7 bands, as RGB); (b) lineaments derived from NE and (c) NW. Filtering for the frame used *Directional Gradient Enhancement*. Rose diagrams of lineaments derived with (d) NW and (e) NE filtering.

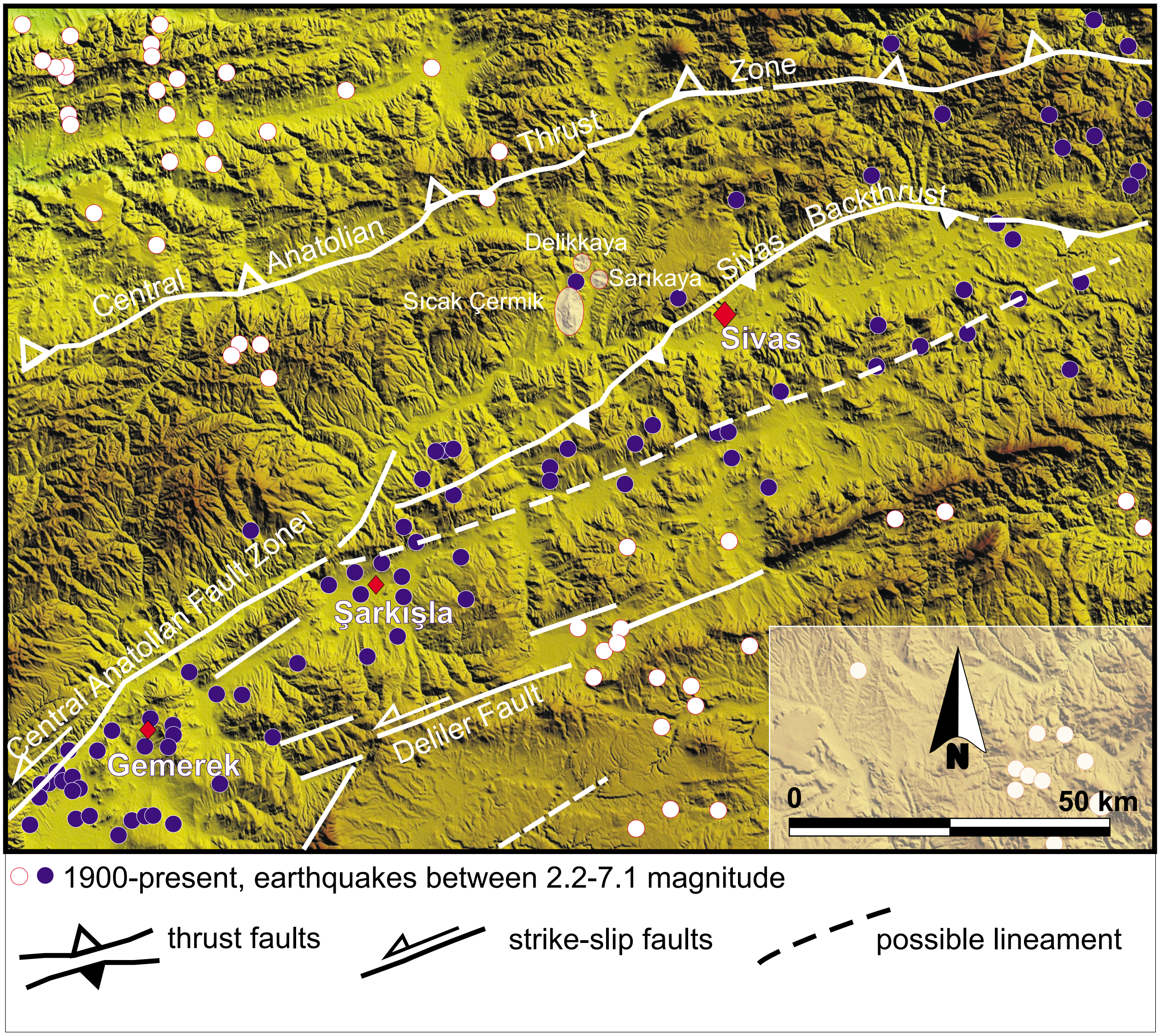


Figure 16. Digital elevation model, tectonic structures, and earthquake epicenters in the Tertiary Sivas Basin and surrounding area.

The fact that the tension joints developed in the İncesu Formation are conformable with the fissure systems in the travertines shows that hydrothermal solutions have been transported to the surface by these fissure systems and small faults located in the İncesu Formation.

Kinematic analysis of the faults located in the Palaeozoic Akdağmadeni metamorphic rocks and the Upper Miocene–Pliocene İncesu Formation yields a fundamental tension axis (σ_1) that is vertical or sub-vertical. The intermediate (σ_2) and the smallest fundamental tension axes (σ_3) were found to be horizontal and/or sub-horizontal, which together shows that a NE–SW opening tectonic regime is effective. A 35° counterclockwise difference was observed between the strikes of the kinematic results obtained from the Palaeozoic units and the kinematic results obtained from the Late Miocene–Pliocene units. This difference in the Sivas Basin conforms to the palaeomagnetic results of Gürsoy *et al.* (1997), who determined a counterclockwise vertical axis block rotation and identified rotation that has probably occurred entirely within the Quaternary. Remote sensing studies of satellite images has shown that lineations are concentrated in NE–SW and NNE–SSW directions.

The U/Th age dating method, which provides the main temporal framework of this study, was used to calculate

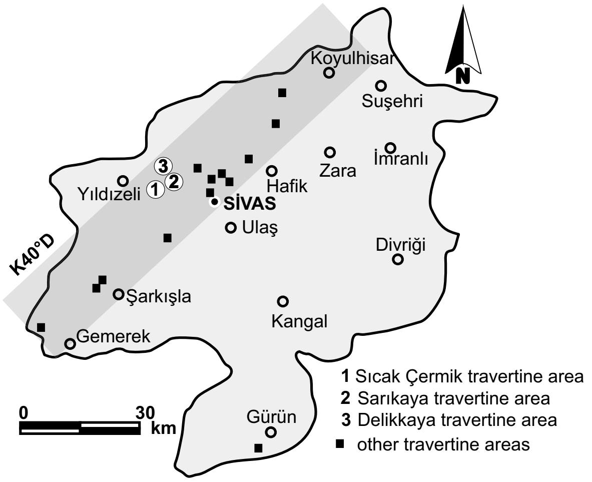


Figure 17. Distribution of travertine locations and spa centres in the Sivas region.

fissure opening rates and to identify the chronological progress of travertine formation using 20 core samples from the Sıcak Çermik, Delikkaya and Sarıkaya sites, and 26 other samples of which 21 were taken from Sıcak Çermik, three from Delikkaya and two from Sarıkaya. Analyses of 20 samples were completed, including 12 sample pairs, one of which was taken from the centre of the fissure and the other from the band near the outer wall of the fissure. In these six vertically-banded fissure-ridge travertines, the youngest was found to be 84,000 (±5,000) years old and the oldest was found to be 364,000 $(^{+201,000}/_{-76,000})$ years old. Two samples were taken from the only fissure-ridge travertine in Sarıkaya, which yielded ages of 57,500 (± 2,300) and 174,000 $(^{+15.000}/_{-14.000})$ years, respectively. The youngest fissure-ridge travertine deposit, based on the U/Th age dating results, is at Delikkaya, which yielded an age interval of 11,400 (±500) to 15,100 (±700) years.

According to age dating results from fissure-ridge travertines obtained from Sıcak Çermik, Sarıkaya and Delikkaya, a regional extension rate of 0.0633 mm/year is established. From the dating results, a grouping with a 56,000-year period is observed. However, this interval may be refined when further dating of the undated fissure-ridge travertines is carried out. According to the graph of Slemmons & DePolo (1986), which relates extension rate and recurrence period, this region falls in the low activity category and implies that a 7.4 magnitude major earthquake may have occurred in and around Sivas, with a recurrence interval of approximately 56,000 years. These findings suggest that the largest, most recent earthquake event may have occurred 9,500 years ago. No major destructive earthquake has been recorded historically in and around Sivas.

When earthquakes that have occurred in and around the Tertiary Sivas Basin in the period of instrumental observation are compared with tectonic lineaments, it is evident that the Central Anatolian Fault Zone extends from Kayseri to Şarkışla and is a fault zone with a low activity. The Sivas Backthrust extends from Şarkışla to the northeast; no earthquake focus has been observed on this fault line. Earthquake foci form a line from Şarkışla to the northeast to the south of Sivas Backthrust. This finding is probably related to the thrust fault geometry, which becomes listric at depth such that earthquake foci project onto the surface in the opposite direction to the thrust direction behind the fault line. These earthquakes show that the Sivas Backthrust is still an active fault.

The lineation formed by the travertine groupings located in the Sivas region shows a similarity between open fissure geometries and the 'S'-type geometry of *én echelon* fissures in the Sıcak Çermik. The evidence shows that these fissures have formed due to a NE–SW Sivas Backthrust activity, a left-lateral shear system that controlled NW–SE-oriented compression, and NE–SW-oriented extension tectonics.

Travertine sites have a special importance for studies of active tectonics and have been used intensively in these kinds of investigations, especially since 1990. Thus, the present research supplements a body of earlier studies that highlights the tectonic significance of travertine. Altunel & Hancock (1993a, b, 1996) and Altunel (1994, 1996) examined the relationship of Pamukkale (Denizli) travertines to the active tectonic regime. The travertines were found to have resulted from active faulting that originated in extensional tectonic regimes, and regional extension rates were obtained directly from studies of exposed fissure-ridge travertines. Çakır (1999) noted that in places where active normal fault segments jump in the Gediz and Menderes grabens and in the complex extensional regions, hot water rises to the surface and precipitates travertine. Karabacak (2002) and Karabacak & Altunel (2003) examined the Ihlara Valley travertines with respect to their morphology and crustal deformation, and Koçyiğit (2003a) stated that the effective tension orientations in the Karakoçan fault zone conform with the strikes of the fissure-ridge travertines and can be used in active tectonic studies.

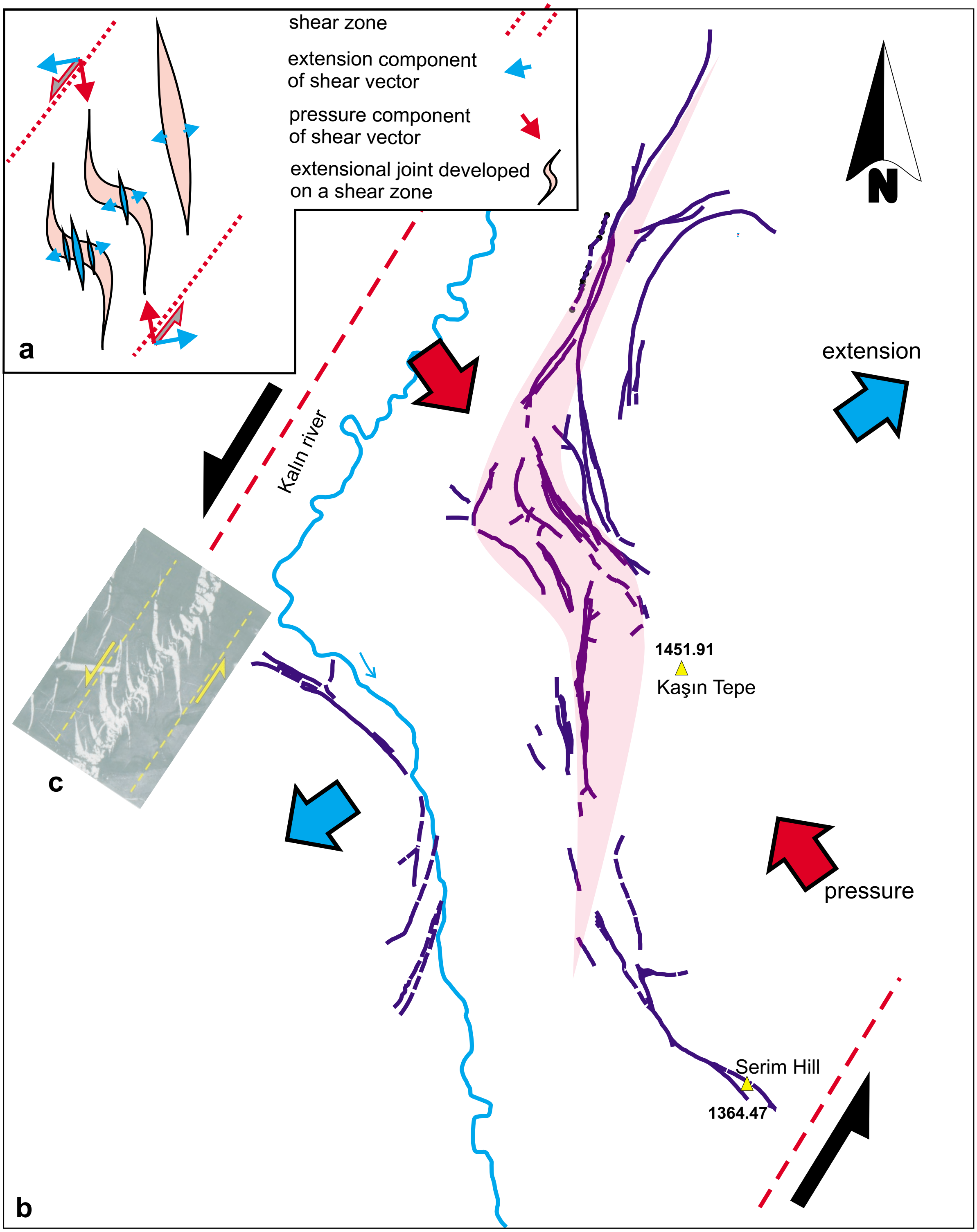


Figure 18. (a) Extension and pressure components in a shear zone (from Dunne & Hancock 1994), (b) General position of a shear zone geometry of fissures in the Sıcak Çermik travertine area, (c) view of S-shape rotation of én echelon fissures in a left-lateral shear zone (inverted image from figure 4 in Park 1989).

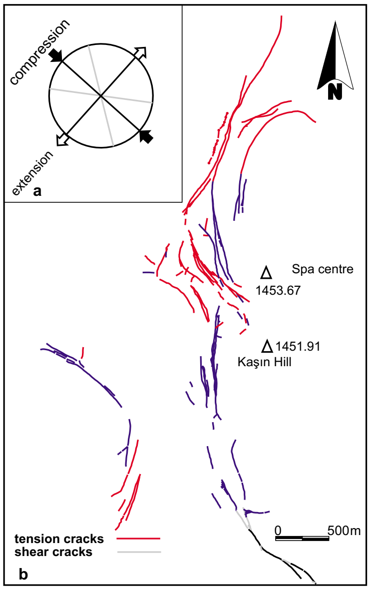


Figure 19. Inset (a) shows the similarity of the classification of fissures according to Price (1966) with (b) the fissures observed in Sıcak Çermik.

As pointed out in the earlier studies of Altunel & Hancock (1993a, b, 1996) and Altunel (1994, 1996), the morphology of the Pamukkale travertines and those in the Tertiary Sivas Basin are very similar. Although the tectonic regime in the Tertiary Sivas Basin and the tectonic regime in Pamukkale are now recognized as being different, the resultant travertine types and the tectonic environment are remarkably similar. Both this study and those undertaken by Altunel (1994, 1996) on the travertines of this study area show that travertine cropping out in different regions with different tectonic regimes can be evaluated and can make important contributions to the study of active tectonics.

Acknowledgements

This research is part of Levent Mesci's PhD work. U/Th analyses were performed by Dr. Neil Sturchio at the University of Illinois. We thank Dr. Sturchio for this contribution. The English was kindly reviewed by Dr. J.D.A. Piper. Financial support from CÜBAP (project no: M204) is gratefully acknowledged.

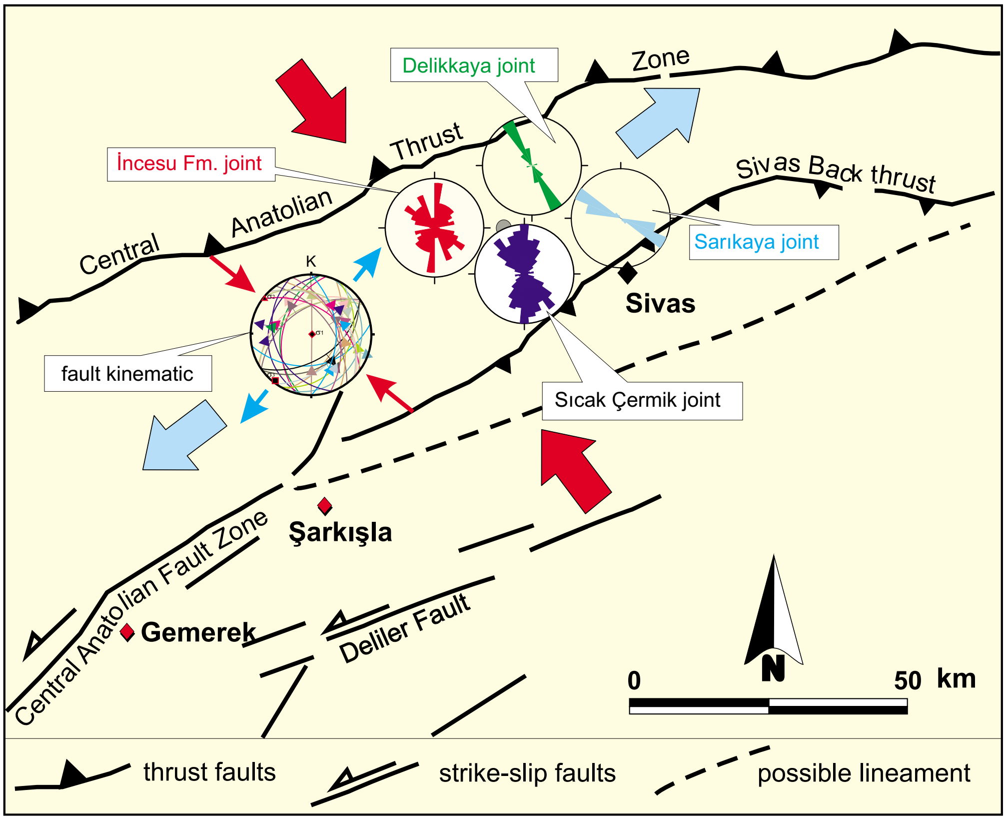


Figure 20. Regional pressure and extension directions based on rose diagrams of fissure systems in travertines, joint systems from the İncesu Formation, and kinematic results from fault analyses of the İncesu Formation within the Tertiary Sivas Basin.

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Received 08 January 2007; revised typescript received 01 November 2007; accepted 12 November 2007