Dating and geochemical tracing of paleoseismic events.

I. Tonguç Uysal
University of Queensland
Brisbane QLD 4072
t.uysal@earth.uq.edu.au

Jian-xin Zhao
University of Queensland
Brisbane QLD 4072
j.zhao@uq.edu.au

Suzanne D. Golding
University of Queensland
Brisbane QLD 4072
s.golding@earth.uq.edu.au

Yuexing Feng
University of Queensland
Brisbane QLD 4072
uqyfeng@newmailbox.uq.edu.au

Dion Weatherley
University of Queensland
Brisbane QLD 4072
uqdweath@uq.edu.au

Erhan Altunel
Osmangazi University
Eskisehir, Turkey
ealtunel@ogu.edu.tr

Halim Mutlu
Osmangazi University
Eskisehir, Turkey
hmutlu@ogu.edu.tr

Volkan Karabacak
Osmangazi University
Eskisehir, Turkey
karabacak@ogu.edu.tr

SUMMARY

Dating of shallow faults is crucial to understanding of the mechanism of earthquake generation and future seismic risk. However, radiometric dating of low temperature authigenic minerals in shallow fault zones has been a major challenge because of the contamination of fault rocks by older mineral phases and the overprinting of the syn-tectonic isotopic signature by post-tectonic re-crystallisation events. We present a technique for a reliable dating of fault movements using a combined application of low temperature geochronology, mineralogy and isotope-trace element geochemistry. Such combined studies further allow constraining the origin and migration of seismically mobilised fluids along active fault zones.

We investigated illitic clay minerals from fault gouges and late Quaternary carbonate deposits in co-seismic fissures along currently active fault zones in Turkey. Our results indicate that the North Anatolian Fault Zone has been active since the Late Paleocene – Early Eocene that followed immediately the continental collision related to the closure of the Neotethys Ocean. Fault movement is considered to have driven deeply sourced fluids, with metamorphic fluids being supplied by the compression along the Neotethyan orogenic suture zone. Precise dating of the late Quaternary carbonate deposits by U-series geochronology provide important constraints on the late Quaternary fissure generation related to the neotectonic processes and active faulting. Isotopic and trace element data indicate that the fissure carbonate deposits precipitated from deeply hydrothermal fluids. Mobilisation of deep fluids and their surface effusion is attributed to tectonic processes such as seismic pumping. K-Ar and U-series dating of clay and carbonate minerals respectively in seismically active areas is very promising for further studies for dating of major earthquake events and their recurrent intervals, with significant implications for the Australian active fault systems.

Key words: Fault dating, K-Ar, U-series, stable isotope, trace elements.

INTRODUCTION

Dating of shallow faults is crucial to understanding of the mechanism of earthquake generation and future seismic risk. Faulting events can be dated using syn-tectonic metamorphic minerals from ductile deformation zones where complete isotopic homogenisation is achieved due to high temperatures (e.g., Blisniuk et al., 2001). However, in young or recent tectonic regimes where ductile deformation zones are not exposed, dating of faulting events is a major challenge (Kralik et al., 1987). In such environments, only low temperature authigenic minerals can be used, which precipitate during surface or near-surface faulting in the crust's brittle regime. The low temperatures in shallow environments may prevent the complete syntectonic crystallisation leading to a mixture of authigenic and detrital mineral populations. In some other cases, the original syn-tectonic isotopic signature may be overprinted due to post-tectonic open system conditions. Nevertheless, a combined application of geochronology and isotope-trace element geochemistry allows a reliable dating of mineral deposits in shallow fault zones and fault-related fissures. Further, such combined studies help to constrain the source of seismically driven fluids and ultimately the evolution of seismic events. In the present study, we conducted geochronological and geochemical investigations of clay and carbonate mineral deposits from some of the most seismically active areas in the world. Our studies focussed on the North Anatolian Fault Zone (NAFZ), which is one of the largest currently active continental transform fault in the world, and the West Anatolian extensional province, which is characterised by a substantial extension rate (Bozkurt, 2001; Sengör et al., 2005). The aim is to show that K-Ar isotopic studies of clay fractions from fault gouges and U-series dating of carbonate deposits in co-seismic fissures are important geochronological techniques to establish timing of near surface faulting events. We also show that stable isotope and trace element studies of the syn-tectonic clay and carbonate minerals are useful in tracing of mineral precipitating fluids mobilised during seismic events.

METHOD AND RESULTS

Methods for the K-Ar and trace element analyses were described in Uysal et al. (2005). U-series dating technique followed Zhao et al. (2001).

K-Ar dating of fault gouges

Reliable age dating requires a detailed petrographic-mineralogic investigation to assess the effect of any contamination in the fault rock samples by older inherited clay phases. For example, clays from a fault gouge sample in one location along the NAFZ are composed of a mixture of phyllosilicate minerals characterised by 1M and 2M polytypes typical for authigenic illite and detrital mica, respectively (see More and Reynolds, 1989 for polytype definition). K–Ar dates of clays of different size fractions are plotted against the percentage detrital 2M illite (Figure 1a). Such plots allow extrapolation to apparent ages for detrital and authigenic end members. The lower intercept of the regression line at 0% detrital mica extrapolates to an age of 57.4 ± 2.7 Ma for authigenic illite formation during the faulting (Figure 1a). Age constrains of previous studies, which were based only on the terrestrial fossils in pull-apart basins along the NAFZ, suggest that the initiation of the NAFZ took place in the Middle Miocene or later (see Uysal et al., 2006 for discussion and references). In contrast, our study, which is the first attempt to constrain the evolution of the NAFZ by radiometric age dating show that this fault system has been active since the cessation of continental collision between the African and Eurasian plates in the Paleocene-Eocene.

Some clay samples from some other locations were formed through hydrothermal alteration of pseudotachylytes with no detrital contaminations. The K–Ar dates for one of those samples range from 26.6 ± 1.4 Ma (>4 µm) to 8.3 ± 0.9 Ma (<0.2 µm), with continuously lower K–Ar values obtained from the finer size fractions (Figure 1b). Such a relationship indicates diffusive radiogenic ^{40}Ar loss of an early generation illite, rather than a mechanical mixing of different clay generations because the composition of the illitic clays, which are mixed-layered illite smectite (R ≥ 3) (Uysal et al., 2006), remains unchanged with particle size changes (Figure 1b). The >4 µm and 4-2 µm fractions exhibit nearly flat K–Ar ages spectrum in Figure 1b that may approximate the timing of the initiation of illite formation at ~26 Ma, which is considered as a reactivation age of the NAFZ. The younger event or events related to fault movements responsible for ^{40}Ar loss from the fine-grained clays in this sample seems to have occurred earliest at 8.3 ± 0.9 Ma.

U-series dating of carbonate deposits

Although we can provide some age constrains on the initiation and reactivation of fault movements along the NAFZ based on K-Ar isotopic studies, it is not possible to determine the age for the individual seismic events precisely for the more ancient systems older than late Quaternary. A precise dating of late Quaternary seismic event is possible by U-series dating of syn-tectonic carbonate deposits. There are significant travertine deposits in seismically active areas in Turkey, and these travertines precipitated in co-seismic extensional fissures. Previous studies have shown that the travertine-filled fissures are related to late Quaternary earthquake faulting along active major fault zones (Hancock et al., 1999). The fissures are located in close proximity (within 500 - 2000 m) and subparallel to the active fault systems and occur in step-over zones or at lateral tips of fault zones as subsidiary structures. Such locations are common sites for vein networks, increased fluid migration that occurs during and after rupture events and leads to significant mineral deposits (Micklethwaite and Cox, 2004).

Thin section and XRD analyses show that the travertine samples consist of pure aragonite or calcite having no sign of any re-crystallisaton and detrital input, which is the most important prerequisite for successful U/Th dating of carbonate samples.
Two samples collected in location K (Figure 2a) near the midpoint and on the margin of the fissure yield U/Th ages of 188.5±2.1 ka and 195.2±5 ka respectively, which are close within the analytical errors. Samples PI-1, PI-2 and PI-3 dispersed along the whole width of the vein in another location yield much younger and more precise ages of 24.7±0.2, 24.5±0.2 and 24.8±0.4 ka respectively (Figure 2b), which are identical within analytical uncertainties indicating a rapid vein growth within 0.21±0.83 ka.
Samples from location PII were collected from a fracture zone with a thickness of 43 cm (Figure 2c). Thin section analysis shows the presence of small veinlets, which are not recognisable in macroscopic scale (Figure 2d-e). Microscopic observations provide evidence of repeated fracturing of a previously sealed crack system followed in each case by sealing by a new increment of veining. Each sample we used for the U/Th age determination represents an individual vein, and the ages range from 94.6±0.9 to 121±2 ka (Figure 2b). The age of 121±2 ka may represent the minimum age of the initial fissure generation and vein filling, upon which new cracks formed again and again.

Geochemical tracing

Although it is evident from the structural geological context that the deposition sites of the clay and carbonate deposits are located in areas of active tectonism, supporting geochemical data are necessary to verify that the clay and carbonate deposition was a result of seismically induced hydrothermal process. Oxygen isotope compositions of the illitic clays from different locations along the NAFZ are characterised by narrow ranges in δ^{18}O values indicating clay precipitation from fluids with similar oxygen isotope compositions and crystallisation temperatures. The δ^{18}O and δD values of the calculated fluid isotopic composition (δ^{18}O = 5.9 ‰ to 11.2 ‰, δD = –59 to –73 ‰) are consistent with metamorphic and magmatic origin of fluids mobilised during active tectonism (Fig 3a).

The rare earth element (REE) composition of the fissure travertines in Western Anatolian Extensional Province is indicative of involvement of fluids from deep sources. The carbonates are characterised by significant positive Eu anomalies and substantially elevated Y/Ho ratios (Figure 3b). Unless extremely reducing conditions, Eu anomalies can develop only at high temperatures (>250 ºC) under hydrothermal conditions (Bau and Moller, 1992). Y and Ho are twin elements and behave coherently in condrites and all terrestrial rocks. In natural waters, Y is fractionated leading to somewhat elevated Y/Ho ratios (~50). Mobilisation and concentration of Y in hot hydrothermal fluids is much more intense with substantially elevated Y/Ho ratios up to >200 (Bau and Moller, 1992), as is the case for the Y/Ho ratios of the fissure travertine in the study area. These geochemical data suggest that the fissure travertine precipitated from extraneous hydrothermal solution, which received its rare earth element (REE) signature at temperatures of above 250ºC (Bau and Moller, 1992).

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CONCLUSIONS

This paper presents two different techniques for dating of paleoseismic events. The first example focussed on K-Ar age constraints on the ancient evolution of a fault system, the North Anatolian Fault Zone, which is still active and produce significant earthquakes. The second example dealt with high resolution and precise dating of much younger, late Quaternary seismic events.

Radiometric dating of near-surface faulting is possible by combined petrographic and K-Ar analyses of illitic clay minerals from fault gouge and pseudotachylytes. Stable isotope data can provide information on fluid sources mobilised during faulting events. Along the North Anatolian Fault Zone, deeply sourced metamorphic and/or mantle fluids were involved in syn-tectonic mineral authigenesis that occurs near-surface conditions. Precise dating of late Quaternary carbonate deposits in co-seismic fractures can be done by U-series geochronology. Our U-series dating results combined with the trace element data show that fracturing and circulation of carbonate-rich hydrothermal fluids with vein mineralization were initiated during and immediately after seismic events. In areas lacking volcanic activities, as is the case in the study area, mobilization of deeply sourced extraneous hydrothermal fluids and their surface effusion can be related to tectonic processes such as seismic pumping.

The results of our study have some important implications for further studies of other currently active fault systems in the world. Since there are a number active continental fault systems in central and western Australia and earthquakes involving surface fault rupture have occurred in the past 25 years, the approach presented in this study is relevant to the Australian fault systems. Particularly, U-Th dating carbonate deposits in co-seismic fissures can be very useful for precise dating of prehistoric major earthquake events and their recurrent intervals, augmenting historical and instrumental records. This new technique may offer the possibility to examine the recurrence statistics of large earthquakes over intervals two or three orders of magnitude larger than previously feasible.

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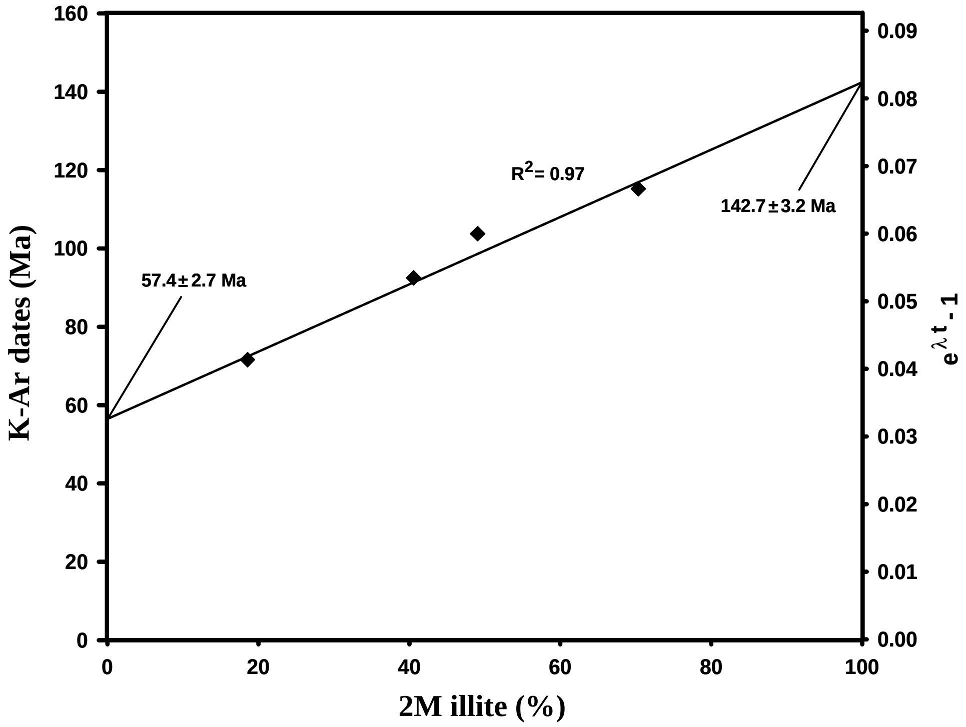

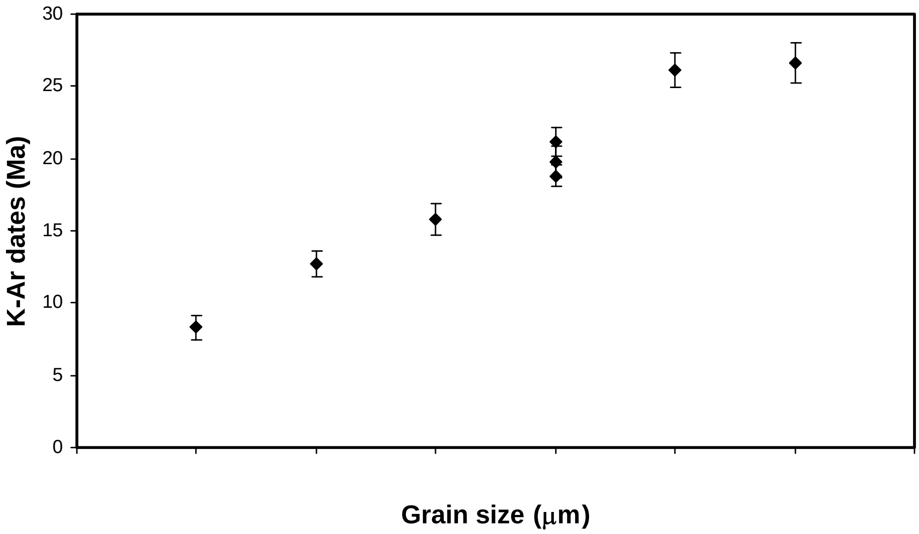

Figure 1. (A) Extrapolation of authigenic illite and metamorphic mica (2M) K–Ar age of different size fractions of sample GRD; (λ is decay constant, *t* is apparent age). (B) Relationship between the K–Ar dates and grain size for the clay fractions from sample KSL.

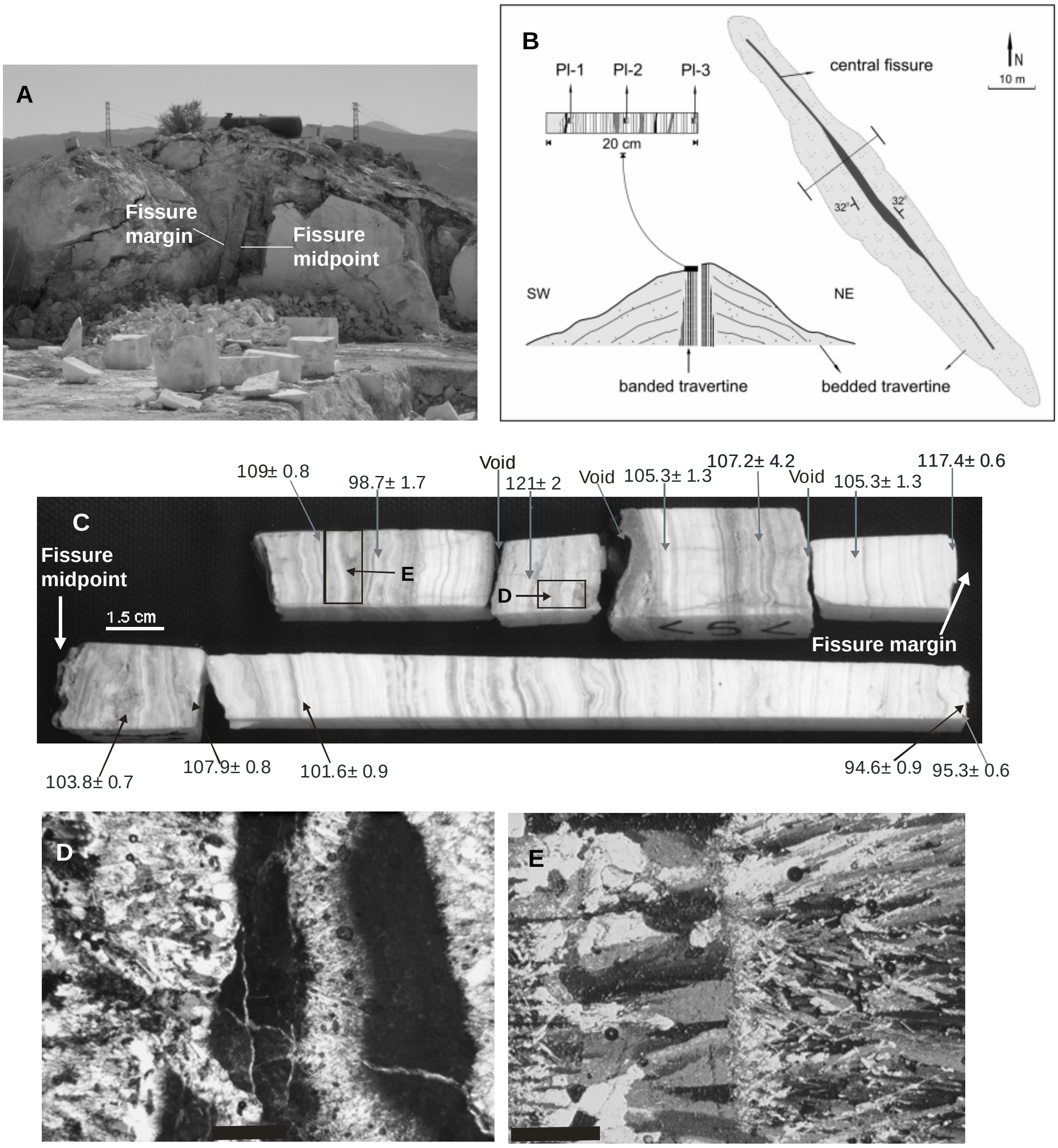

Figure 2. Images of U-Th dated fissure travertine samples. A: Outcrop picture of the fissure travertine sampled in a quarry. B: Map and section illustrating the location of samples PI. C: Block cuts from an outcrop near Village Pamukkale (sample PII). The initial travertine growth occurred from the fissure margin to the right of the upper cuts towards the midpoint to the left of the bottom cuts. D: Photomicrograph showing younger veinlets consisting of carbonate fibres and blocky crystals (white) within a micritic carbonate material (black) of an earlier vein generation. Sample PII-7 (121±2 ka) represents the micritic carbonate. Scale bar = 1 mm. E: Photomicrograph illustrating different carbonate vein generations. Note sharp contacts with abrupt termination of crystal growth and the radial alignment of new carbonate fibres on walls of earlier vein generations. Sample PII-6 (98.7±1.7 ka) represents the new carbonate generation on the right. Scale bar = 0.5 mm.

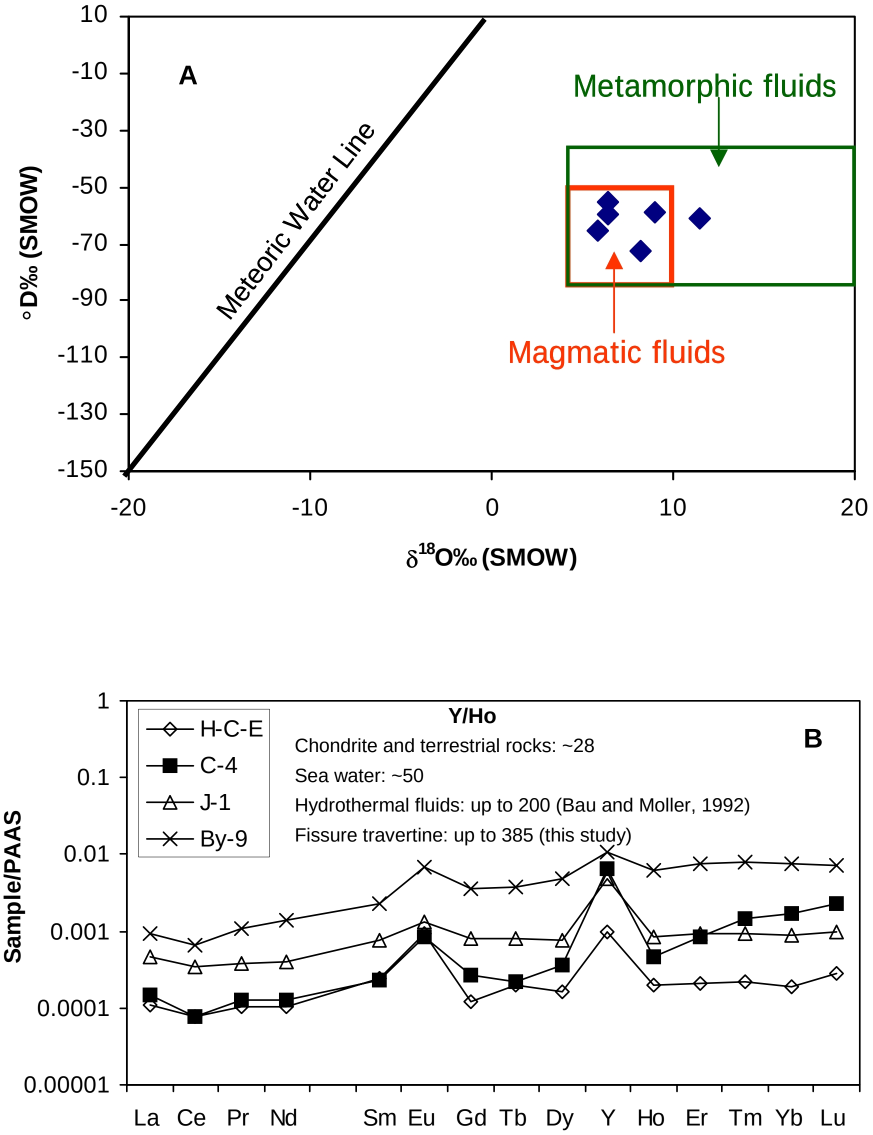

Figure 3. A: Calculated fluid stable isotopic compositions in equilibrium with clays from the fault gouges. B: REE pattern of the fissure travertine in the West Anatolian extensional province.