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Fracture networks and strike–slip deformation along reactivated normal faults in Quaternary travertine deposits, Denizli Basin, western Turkey

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ABSTRACT

The Denizli Basin in the West Anatolian Extensional Province in western Turkey is known for its numerous Quaternary travertine occurrences. Travertine morphology is often dependant on the relative position of the deposition with respect to basin-bounding faults. The travertine occurrences examined in this study are situated at the intersection of the locally E–W oriented Denizli Basin and the adjacent NE–SW oriented Baklan Graben in the NE. Based on an extensive field campaign, including LIDAR scanning, several high-resolution fault/fracture maps of five large quarries (>300 m in length and >60 m in height) are constructed in which this world-class travertine deposit is currently excavated. A structural analysis is performed in order to determine the tectonic overprinting of the travertine body and to derive the stress states of the basin after travertine deposition. The mostly open, non-stratabound joints are several tens of metres long and often bifurcate creating a dense fracture network. Minor infill of the joints resulted in the presence of a few colour-banded calcite veins. Based on the E–W, NE–SW and NW–SE orientation of three dominant joint sets it is concluded that the joint network is caused by local N-S extension, alternated by NW–SE and NE–SW extension exemplifying the presence of stress permutations in the Quaternary. High angle E–W to WNW–ESE faults cross-cut the quarries. Faults are filled with travertine debris and clastic infill of above lying sedimentary units indicative of the open nature of the faults. The specific E–W fault orientation in the locally E–W trending Denizli Basin indicates that they initiated as normal faults. A paleostress inversion analysis performed on kinematic indicators such as striations on the clayey fault infill and the sinistral displacement of paleosols shows that some of the normal faults were reactivated causing left-lateral deformation in a transient strike–slip stress field with a NE–SW oriented σ_1.

1. Introduction

Travertines have been studied in many places around the world, along which well-known examples in Yellowstone National Park (USA), Utah (USA), Central Apennines (Italy), New Zealand and western Turkey. In the last two decades numerous studies on recent Quaternary travertine deposits demonstrated the close relationship between neotectonic activity, hydrothermal circulation and travertine deposition (e.g. Altunel and Hancock, 1993a,b; Brogi and Capezzuoli, 2009; Brogi et al., 2010, 2012; Çakır, 1999; Hancock et al., 1999; Özkul et al., 2002, 2010). These studies particularly focus on understanding the hydrological, microbiological, palaeoclimatological, sedimentological and tectonic aspects that are related to travertine formation. Travertine deposits often have a complex internal sediment architecture frequently changing both in lateral and vertical directions over a short distance. Their complexity originates from many factors such as spring position, underlying topography, hill slope, chemical composition of travertine depositing waters, microbial activity and surficial waters (Guo and Riding, 1998; Özkul et al., 2002). In tectonic active regions, travertines have been described to develop in the hangingwall of normal faults (e.g. Brogi, 2004; Brogi and Capezzuoli, 2009; De Filippis and Billi, 2012), at the ends of fault segments (e.g. Çakır, 1999), in tensional fractures in shear zones (e.g. Faccenna, 1994; Faccenna et al., 2008) and in extensional step-over zones between the offset of normal faults (e.g Altunel and Hancock, 1993a; Brogi et al., 2012; Çakır, 1999; Hancock et al., 1999). With respect to these tectonic settings, the proposed term “travitonics” (Hancock et al., 1999) has become a very useful term to describe this active link between tectonic deformation and travertine development. Importantly, analysing the relationship between travertine build-up and intersecting faults and fractures is very useful for estimating the historical seismicity during basin development. Moreover, the results of paleostress analyses of structural features cutting through travertine deposits (e.g. Çakır, 1999; Kaymakçı, 2006) may be correlated to active tectonic regimes

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that are recorded by earthquake seismicity and GPS monitoring (e.g. Aktar et al., 2007).

A travertine fissure ridge is the most common example of a travertine deposit in which Ca-bicarbonate hydrothermal fluids are provided by a single hydrothermal feeder system. The ridge morphology has been described from well-known examples in western Turkey and in Central Italy (Altunel and Hancock, 1996; Altunel and Karabacak, 2005; Brogi and Capezzuoli, 2009; Çakır, 1999; De Filippis et al., 2012; Mesci et al., 2008). Although the formation of travertine has been studied in many tectonic settings, travertine is less investigated when it occurs at the complex intersection of several graben structures. At such intersections, however, a high groundwater permeability, which has been demonstrated by several hydrogeological investigations (e.g. Özer, 2000), is often present and allows the build-up of complex travertine bodies. At the intersection of several fault systems, the deposition of travertine is thus often a consequence of a complex fault- and fracture network in the subsurface, providing the necessary pathways for hydrothermal fluids to ascend.

In this study the geometry of a fault/fracture network developed in a large-scale, extremely well exposed 2 km-wide travertine body is documented. This travertine body is quarried in the southeastern part of the extensional Denizli Basin (western Anatolia, Turkey), at the intersection of three graben structures. Although the quarries exploit a large area of travertine (>10 km^2) this region has received little attention and has only been studied for its mammal fauna (Erten et al., 2005) and Homo Erectus founds (Kappelman et al., 2008). A brief sedimentological description of the travertine build-up is presented in Özkul et al. (2002) and technical geomechanical properties of construction stones are provided by Çobanoğlu and Çelik (2012) and Yagiz (2010). The quarry area, however, offers a unique possibility to study the complex sedimentological development of travertine and regional neotectonic Quaternary brittle deformation. Based on extensive fieldwork including LIDAR scanning, several high resolution fault/fracture quarry maps are presented. It is particularly focused on brittle structures such as joints, fractures and faults in order to reconstruct the Quaternary deformation history of the study area.

This structural analysis on post-travertine faults and fractures is performed to infer the different local paleostress directions that have been active after travertine deposition in order to understand the neotectonic activity in this area. This topic is of specific importance in the field of tectonics acting in geothermal environments in which travertine formed from tectonically controlled fluid flow. To be able to work out a good sedimentary model, which is beyond the scope of this study, first the effect of the tectonic overprinting needs to be addressed. This study can then be used to determine whether the complex sedimentological build-up of the travertine, which will be elaborated in parallel sedimentological and geochemical studies, fits in one of the deduced paleostress directions.

2. Geological and tectonic setting

The active continental extensional deformation of western Anatolia (West Turkey), one of the most seismically active tectonic regions on Earth, has been well described and numerously debated. The extensional basins in the West Anatolian Extensional Province in western Turkey result from a complex intraplate tectonism caused by both the northern migration of the Arabian microplate into the eastern Anatolian plate and the rollback subduction of the North African oceanic crust below the Anatolian plate in the Aegean region (Doutsos and Kokkalas, 2001; Westaway, 1993). On the one hand, the northward migration of Arabia forced the Anatolian block to wedge sideways between the Eurasian and African continent (Bozkurt, 2001; van Hinsbergen et al., 2010; Westaway et al., 2005). The resulting lateral motion causes lateral transpressional and transtensional deformation in the Anatolian Block such as exemplified by several intraplate strike–slip faults and the dominantly dextral and sinistral interplate strike–slip motions along the North Anatolian and East Anatolian fault zones respectively (Fig. 1a). The rollback subduction in the west, on the other hand, has caused an important N–S extension in the West Anatolian Extensional Province that is accompanied by normal faulting and the development of many E–W oriented basins in western Turkey (Demircioğlu et al., 2010; Koçyiğit, 2005; Koçyiğit and Deveci, 2007). Both previously mentioned geodynamic processes triggered the orogenic collapse of the Menderes Massif in the Miocene and caused the Pliocene to Quaternary development of the main E–W grabens and NW–SE or NE–SW cross-grabens in western Turkey (Westaway, 1993; Westaway et al., 2005). Different combinations of previous described geodynamic models have, however, been proposed and are summarised in Van Hinsbergen et al. (2010) and Gürbüz et al. (2012). As demonstrated by (current) seismic activity within the West Anatolian Extensional Province, many destructive earthquakes with a dominant normal fault activity have occurred within these E–W grabens (Aktar et al., 2007; Taymaz and Price, 1992). Only minor strike–slip faulting has been monitored at the intersection of some large-scale grabens (Aktar et al., 2007; Bozkurt and Sözbilir, 2006).

The currently still active Denizli Basin, located in the eastern part of the West Anatolian Extensional Province (Fig. 1b), developed in Cycladic blueschists, Cretaceous HP-LT nappes and Oligocene and Neogene sediments (van Hinsbergen et al., 2010). In the northern part of the basin, basement rocks dominantly consists of crystalline limestones (Westaway, 1993). A detailed stratigraphy of these pre-Neogene and Neogene deposits is described in Alçiçek et al. (2007). The Bouguer anomalie reflects the structure of a graben in which higher densities demonstrate the presence of metamorphic rocks below the Neogene deposits in the Denizli Basin (see Özgüler et al., 1984). The NE–SW oriented Denizli Basin is *c.* 50 km long and *c.* 24 km wide and is bounded by major NNE-dipping normal faults at its southwestern border and SSW-dipping normal faults at its northeastern border. According to Westaway (1993), extension in the Denizli Basin began in the Middle Miocene and has been active ever since.

The western part of the Denizli Basin is situated in a tectonic area at the intersection of three major E–W grabens. Laterally, it forms the continuation of the Büyük Menderes Graben and is separated by a topographic high from the Küçük Menderes and Gediz Grabens (Kaymakçı, 2006) (Fig. 1b). The central part of the Denizli Basin is characterised by a typical horst-graben structure and comprises two Quaternary sub-basins, namely the Laodikeia Graben in the south and the Çürüksu Graben in the north (Kaymakçı, 2006; Koçyiğit, 2005). This horst-graben morphology has been formed due to subsidence in the Denizli Basin, accompanied by several phases of tectonic uplift along the horsts (Westaway et al., 2005). The northern border of the Çürüksu Graben is the well-defined NW–SE Pamukkale Fault Zone that extends several tens of kilometres (Fig. 1c). Along this fault zone, travertine occurrences, among which the famous Pamukkale travertine (a UNESCO World Heritage Site), are precipitated in kilometre-wide left-lateral step-over zones that are developed between different NW–SE normal faults (Altunel and Hancock, 1993a; Çakır, 1999). The overall NW–SE orientation of the Denizli Basin curves towards an E–W orientation in its southwestern part, forming the lateral extend of the eastern NE–SW Baklan Graben and the E–W to NE–SW Acıgöl Graben (Fig. 1c) (Koçyiğit and Deveci, 2007). The eastern end of the Denizli Basin has a staircase geometry at the major Honaz and Kaklık faults, along which the Baklan, Acıgöl and Acıpayam basin-bounding faults interfere (Kaymakçı, 2006). In this region smaller antithetic faults trending N–S are intersected by the Honaz and Kaklık faults. Both the adjacent Baklan and Acıgöl Grabens are characterised by a halfgraben morphology due to greater subsidence rates at the southern basin-bounding faults (Price and Scott, 1994).