The onset of the Dead Sea transform based on calcite age-strain analyses

P. Nuriel1*, R. Weinberger1,2, A.R.C. Kylander-Clark3, B.R. Hacker3, and J.P. Craddock4

1Geological Survey of Israel, 30 Malkhe Israel Street, Jerusalem 95501, Israel
2Department of Geological and Environmental Sciences, Ben-Gurion University, Beer-Sheva 84105, Israel
3Department of Earth Science, University of California, Santa Barbara, California 93106, USA
4Department of Geology, Macalester College, St. Paul, Minnesota 55105, USA

ABSTRACT
The onset and evolution of the Dead Sea transform are re-evaluated based on new in situ U-Pb dating and strain analyses of mechanically twinned calcites. Direct dating of 30 syn-faulting calcites from 10 different inactive fault strands of the transform indicates that the oceanic-to-continental plate boundary initiated between 20.8 and 18.5 Ma within an ~10-km-wide distributed deformation zone in southern Israel. Ages from the northern Dead Sea transform (17.1–12.7 Ma) suggest northward propagation and the establishment of a welldveloped >500-km-long plate-bounding fault in 3 m.y. The dominant horizontal shortening direction recorded in the dated twinned calcites marks the onset of left-lateral motion along the evolving plate boundary. The observed changes in the strain field within individual fault strands cannot be simply explained by local “weakening effects” along strands of the Dead Sea transform or by gradual changes in the Euler pole through time.

INTRODUCTION
Direct dating of brittle fault activity and deciphering the associated stress-strain field are key factors in tectonic reconstructions and paleoseismic studies. Yet, direct ages of fault activity coupled with robust strain directions along plate-bounding faults are rare. Here we focus on the Dead Sea transform (DST)—the plate boundary that accommodates the relative motion between the Africa (Sinai) and Arabia plates—and provide new insights into the onset and evolution of this seismically active system.

A host of stratigraphic and structural evidence paints a general picture of the evolution of the DST. There has been ~105 km of left-lateral offset across the boundary (Quennell, 1958; Freund et al., 1970; Garfunkel, 1981; Joffe and Garfunkel, 1987). The onset of this motion post-dates 22–20 Ma, based on offset magmatic dikes (Eyal et al., 1981), the ages of the oldest basinfill sediments along the transform (Garfunkel, 1981), and additional kinematic considerations related to the opening of the Red Sea (Joffe and Garfunkel, 1987). This strike-slip motion may have been preceded by normal faulting, suggesting that the present DST was localized within an old faulted terrane (Bosworth et al., 2005; Avni et al., 2012). Mesoscale analyses indicate regional NNW–SSE horizontal shortening associated with the left-lateral motion along the transform (Eyal and Reches, 1983). The trajectories of this strain field vary locally adjacent

© 2017 The Authors. Gold Open Access: This paper is published under the terms of the CC-BY license.

GSA Data Repository item 2017194, Figure DR1 (microstructural observations of fault-related calcites), Figure DR2 (methodology of calcite U-Pb geochronology with LA-ICPMS-MC), and Figure DR3 (calcite twin strain analysis methodology and results), is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.
DISCUSSION AND CONCLUSIONS

Combining the U-Pb ages with the shortening direction determined from calcite twins reveals a coherent picture for the onset and evolution of the DST. Left-lateral motion initiated by 20.8 ± 2.3 Ma in the southern, Elat part of the transform and reached the northern, Hermon region by 17.1 ± 0.3 Ma. These ages are compatible with northward propagation of fault activity to establish a well-developed, >500-km-long plate-bounding fault in 3 m.y., and provide further support to studies that show a northward progression of slip from the Gulf of Aqaba-Elat (Bar et al., 1974). These ages also support the chronological framework of the DST inferred by indirect methods (Eyal et al., 1981; Garfunkel, 1981) and exclude the possibility that the transform boundary initiated later at ca. 14 Ma (Bosworth et al., 2005). In the Elat shear zone, the oldest ages—20.8, 20.1, 19.0, 18.6, and 18.5 Ma—are from the westernmost and easternmost bounding faults (Gishron and Tsefahot fault previously dated by thermal ionization mass spectrometry (TIMS) (Mason et al., 2013; Vaks et al., 2013) and NIST-614 glass, respectively. Variation in the U-Pb ratios among individual spot analyses of single samples allows determination of a Tera-Wasserburg intercept age with 2σ errors better than 6% for most samples (see an example in Fig. 3 and in Fig. DR2). The ages of syntectonic calcite range from 21 to 6 Ma (n = 28; Fig. 4), and ages of 92 and 57 Ma (n = 2; Fig. DR2) were obtained for host-rock carbonate and an older generation of calcite veins, respectively.

Calcite twins mechanically at low differential stresses (~10 MPa) either during or shortly after calcite crystallizes in an active fault zone. While fault kinematics are susceptible to an instantaneous strain field during earthquake events (Fossen, 2010), calcite twin analyses can be used to infer the finite strain field. For calcite strain analyses, we used four-axis universal stage measurements of twin orientations and the crystallographic orientation of the host crystals to calculate the maximum shortening direction (ε1) using a least-squares technique (Groshong et al., 1984; see more in Fig. DR3). The dominant maximum shortening direction is horizontal, ranging from approximately NNW-SSW (11 samples) to approximately north-south (7 samples) and to approximately NNE-SSW (9 samples) directions (Fig. 4; Fig. DR3). Only two fault samples have oblique ε1 shortening directions that are plunging 56°–51° (samples GF51 and YG3). Host-rock carbonate with an age of 92 Ma next to the Roded fault (sample RD3a) has a subvertical ε1 shortening direction that is plunging 68°. An older vein generation (sample NAV2Vb, 57 Ma) that is offset by DST–related structure (sample NAV3Vb) has east-west ε1 directions. Sample TS2 is very different both in age (6 Ma) and ε1 direction (east-west) and is therefore considered as an outlier.
zones; Fig. 1C), and these faults have maximum horizontal shortening directions that are compatible with left-lateral motion. Hence, the Elat region preserves a record of the oldest known part of the DST system so far. The results further reveal that the transform initiated within an ~10-km-wide deformation zone (from the Gishron to the Tsefahot faults; Fig. 1C). The cessation of fault activity in the Elat shear zone at 12.7 Ma was followed by the formation of a flat erosion surface that truncates the structures (Fig. 1C).

The results do not support reactivation of preexisting normal faults, because calcite twins with subvertical maximum shortening directions are absent (see Fig. DR3). The dominant maximum horizontal shortening directions fluctuated between NNW-SSE and NNE-SSW during the period from 20.8 to 12.7 Ma. Such fluctuations in the strain field within individual segments cannot be simply explained by local “weakening effects” along fault strands of the DST (Garfunkel, 1981) or by gradual migration of the Euler pole through time (Gomez et al., 2007; Marco, 2007; Weinberger et al., 2009).

**ACKNOWLEDGMENTS**

This study was supported by grant 2012174 from the United States–Israel Binational Science Foundation (BSF). We are grateful to Atilla Aydin, Axel Gerdes, and an anonymous reviewer for thorough and helpful reviews, and to Amir Sagy and Michael Beyth for helpful suggestions during the course of this study.

**REFERENCES CITED**

Avni, Y., Segel, A., and Ginat, H., 2012, Oligocene regional denudation of the northern Afar dome: Pre- and syn-breakup stages of the Afro-Arabian plate: Geological Society of America Bulletin, v. 124, p. 1871–1897, doi: 10.1130/B30634.1.

Bar, M., Kolodny, Y., and Bentor, Y.K., 1974, Dating faults by fission track dating of epidotes—An attempt: Earth and Planetary Science Letters, v. 22, p. 157–162, doi: 10.1016/0012-821X (74)90076-4.

Ben-Avraham, Z., and Lyakhovsky, V., 1992, Faulting processes along the northern Dead Sea transform and the Levant margin: Geology, v. 20, p. 1139–1142, doi: 10.1130/0091-7613(1992)020<1139:FPATND>2.3.CO;2.

Beyth, M., Eyal, Y., and Garfunkel, Z., 2012, Geographical map of Israel, sheet 26-I, II: Elat: Jerusalem, Israel Geological Survey, scale 1:50,000.

Bosworth, W., Huchon, P., and McClay, K., 2005, The Red Sea and Gulf of Aden Basins: Journal of African Earth Sciences, v. 43, p. 334–378, doi: 10.1016/j.jafrearsci.2005.07.020.

Burkhard, M., 1993, Calcite twins, their geometry, appearance and significance as stress-strain markers and indicators of tectonic regime: A review: Journal of Structural Geology, v. 15, p. 351–368, doi: 10.1016/0191-8141(93)90132-T.

Coogan, L.A., Parrish, R.R., and Roberts, N.M., 2016, Early hydrothermal carbon uptake by the upper oceanic crust: Insight from in situ U-Pb dating: Geology, v. 44, p. 147–150, doi: 10.1130/G37212.1.

Eyal, M., Eyal, Y., Bartov, Y., and Steinitz, G., 1981, The tectonic development of the western margin of the Gulf of Elat (Aqaba) rift: Tectonophysics, v. 80, p. 39–66, doi: 10.1016/0040-1951(81)90141-4.

Eyal, Y., 1996, Stress field fluctuations along the Dead Sea rift since the middle Miocene: Tectonics, v. 15, p. 157–170, doi: 10.1029/95TC02619.

Figure 3. U-Pb Tera-Wasserburg concordia plots for samples SFN1 and SFN4 from Shelomo fault zone, Israel. Locations of laser ablation spot analyses (red circles) are indicated on cross-polarized microscopy images. Additional Tera-Wasserburg plots are given in Figure DR2 (see footnote 1). MSWD—mean square of weighted deviates.

Figure 4. Summary of U-Pb ages and calcite-twin strain analyses of fault-related calcite from Dead Sea transform (DST), Israel. Box heights represent 2σ errors. Lower-hemisphere stereoplots include contours of maximum shortening strain axis (ε1). Great circles represent fault orientations. Colored inset shows contours of all ε, with dominant NNW-SSE direction for all strain analyses (n = 28). Additional stereoplots are given in Figure DR3 (see footnote 1).
