Author/s:
Kohn, B;Weissbrod, T;Chung, L;Farley, K;Bodorkos, S

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PROFESSOR BARRY KOHN (Orcid ID : 0000-0001-5064-5454)

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Correspondence to:
Professor Barry Kohn

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Short Title: Francolite thermochronology - Dead Sea Transform motion

Barry Kohn[1], Tuvia Weissbrod[2], Ling Chung[3], Ken Farley[4], Simon Bodorkos[5]

[1] Address: School of Earth Sciences, University of Melbourne, Victoria, Australia 3010
email: b.kohn@unimelb.edu.au
phone: +61 3 8344 7217
fax: +61 383 447 761
ORCID: 0000-0001-5064-5454

[2] Address: The Geological Survey of Israel, Jerusalem 95501, Israel
email: tuviaweissbrod@hotmail.com
phone: +972 2 6423 104
fax:
ORCID:

[3] Address: School of Earth Sciences, University of Melbourne, Victoria, Australia 3010

email: lchung1@unimelb.edu.au
phone: +61 3 8344 9669
fax: +61 383 447 761
ORCID:

[4]Address: Division of Geological and Planetary Sciences, California Institute of Technology, CA 91125, USA
email: farley@gps.caltech.edu
phone: +1 626 395 6005
fax: +1 626 395 0935
ORCID: 0000-0002-7846-7546

[5]Address: Geoscience Australia, Canberra, ACT 2601, Australia
email: Simon.Bodorkos@ga.gov.au
phone: +61 262 495 869
fax: +61 262 499 111
ORCID: 0000-0001-8605-0276

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ABSTRACT

Cambrian siliciclastic sequences along the Dead Sea Transform (DST) margin in southern Israel and southern Jordan host both detrital fluorapatite [D-apatite] and U-rich authigenic carbonate-fluorapatite (francolite) [A-apatite]. D-apatite and underlying Neoproterozoic basement apatite yield fission track (FT) data reflecting Paleozoic-Mesozoic sedimentary cycles and epeirogenic events, and dispersed (U-Th-Sm)/He (AHe) ages. A-apatite, which may partially or completely replace D-apatite, yields an early Miocene FT age suggesting formation by fracturing, hydrothermal fluid ascent and intra-strata recrystallisation, linked to early DST motion. The DST, separating the African and Arabian plates, records ~105 km of sinistral strike-slip displacement, but became more transtensional post-5 Ma. Helium diffusion measurements on A-apatite are consistent with thermally activated volume diffusion, indicating Tc ~52-56±10°C (cooling rate 10°C/Myr). A-apatite AHe data record Pliocene cooling (~35-40°C) during the transtensional phase of movement. This suggests that timing of important milestones in DST motion can be discerned using A-apatite low-temperature thermochronology data alone.

1 INTRODUCTION

Authigenic apatite (francolite or carbonate-fluorapatite) (A-apatite) has been reported from Cambrian strata from areas neighbouring the DST in southern Israel, Jordan and Sinai (e.g. Weissbrod, 1980; Weissbrod & Nachmias, 1986). A-apatite, which may form euhedral overgrowths on detrital apatite (D-apatite) (e.g. Fig. 6 in Vermeesch et al., 2009), is clearly post-depositional, yet the age of authigenesis remains unclear. A late Devonian-early Carboniferous thermal event in southern Israel, and Egypt (Sinai and Eastern Desert) is recorded in zircon fission track data (Kohn et al., 1992; Bojar et al., 2002; Vermeesch et al., 2009) and geochronological data from other mineral systems in southern Israel (e.g. Segev et al., 1995, Heimann et al., 1995, Golan et al., 2018). A-apatites do not appear in strata younger than Devonian (Weissbrod & Nachmias, 1986), so Vermeesch et al. (2009) and Weissbrod et al. (1987) proposed that its growth resulted from a pulse of U-rich hydrothermal fluid circulation related to the Paleozoic thermal event. On the other hand, Segev (1992) suggested a Neogene age for abundant U-mineralisation and A-apatite in Cambrian strata in southern Israel.

Low-temperature thermochronology (LTT) is a powerful tool for quantitatively constraining the timing and rates of processes that disrupt the thermal regime of the upper crust over geological time scales (e.g. Reiners, 2005). Within the LTT toolbox, various thermochronometric systems have different temperature sensitivities. For zircon (U-Th)/He (ZHe), typically ~110-180°C (e.g. Wolfe & Stockli, 2010; Guenthner et al., 2013), but lower in highly radiation damaged grains, for apatite fission track (AFT), typically ~60–110°C (e.g. Gleadow et al., 2002) and for apatite (U-Th)/He (AHe), ~–35 to >120°C [covering a range of radiation damaged grains and Cl content] (e.g. Shuster et al., 2006, Flowers et al., 2009; Gautheron et al., 2009; Djimbi et al., 2015). Tzifas et al. (2017) flagged the potential for fission-track dating of francolite, but to date no LTT data have been reported. This study investigates A-apatite genesis and thermal history using AFT, AHe and ZHe dating from Cambrian strata and underlying crystalline basement in the Nahal Shehoret and Eilat area, southern Israel, bordering the DST (Figure 1).

2 GEOLOGICAL SETTING AND SAMPLES

Following the Pan-African Orogeny, a thick sequence of shelf sediments accumulated over the northern margin of the Arabian-Nubian Shield through several depositional cycles. From Cambrian to Paleogene, recurrent eustatic oscillations caused minor hiatuses, whereas epeirogenic doming and subsequent truncation resulted in wide stratigraphic gaps. The most significant movement, in the Late Paleozoic, removed ≥2.5 km of Carboniferous to Ordovician strata from large areas in the Levant, and was accompanied by anomalously high geothermal gradients (e.g. Gvirtzman and Weissbrod, 1984; Kohn et al., 1992; Vermeesch et al., 2009). In southern Israel and southern Jordan, along the Dead Sea Rift margin marked by the DST, the sub-Cretaceous unconformity has superseded the Late Paleozoic (sub-Permian) unconformity, so that Lower Cretaceous siliciclastic rocks directly overlie Cambrian strata (Figures 1 and 2).

The DST separates the African (Sinai sub-plate) and the Arabian plates over a distance of ~1000 km, and relates the Red Sea spreading centre in the south to the Bitlis-Zagros zone of plate convergence in southern Turkey to the north. The matching of offsets of Precambrian to Paleogene stratigraphic markers, depositional patterns and tectonic elements on both sides of the DST indicate left-lateral displacement of ~105 km (e.g. Quennell, 1958; Freund et al., 1970; Garfunkel, 1981). Different timetables have been proposed for the initiation and stages of DST movement (e.g. Quennell, 1958; Freund et al. 1970; Freund and Garfunkel, 1976; Bartov et al., 1980). However, Garfunkel (2014) summarised the evidence supporting early Miocene commencement of lateral motion along the DST (between 20 Ma and ~17–16 Ma). The slip history is strongly constrained by plate kinematics related to the opening of the Red Sea and the Gulf of Aden (e.g. Freund et al., 1970; Cochran, 1983; Joffe & Garfunkel, 1987). Further details of the geological history and stratigraphy of the study area are presented in several works (e.g. Weissbrod, 1980; Weissbrod, 2005; Vermeesch et al., 2009).

Studies of heavy minerals in the Paleozoic-Mesozoic clastic sequence (‘Nubian Sandstone’) on both sides of the DST were reported by Bender (1968), Weissbrod & Nachmias (1986) and Weissbrod & Bogoch (2007). Apatite is a common accessory in Cambrian siliciclastics, but is absent in the overlying series. D-apatite (fluorapatite) generally appears as subangular to rounded grains (typically up to 200 μm in size) and more rarely, as prisms with rounded edges. D-apatites have euhedral overgrowths, some of which are A-apatite, which may contain opaque inclusions and may be coated with limonite. A-apatite (francolite) usually

occurs as basal hexagonal platelets (Figure 3). A-apatites are often associated with authigenic kaolinite, which may also be abundant in overlying Cretaceous strata, where no apatite is recorded.

3 SAMPLES AND METHODS

The Cambrian sequence in southern Israel is divided into four formations (Weissbrod, 2005). For this study, five samples of D-apatite from the Shehoret Formation and three from the overlying Netafim Formation (where A-apatite is common), were analysed for AFT, AHe and ZHe thermochronometry (Figure 1). Apatite, forming mm-size crystals in a pegmatite from underlying Neoproterozic crystalline basement near Eilat (Figure 1) was also included for AFT and AHe analysis.

Mineral separations and analyses followed Gleadow et al. (2015), except that for ZHe analysis ^{233}U and ^{229}Th spikes were used. AFT measurements were made only on prismatic faces parallel to the c-axis (determined by orientation of track openings under reflected light). For A-AFT analysis, hexagonal plates were mounted 'vertically', so that measurements could also be made on prismatic faces, which ranged in width from ~80–125 μm.

4 RESULTS

A- and D-AFT data, as well as AFT basement data, are presented in Table 1, with single grain radial plots and confined track-length histograms shown in Figure SI 1 (see also Tables SI 1 and SI 2 for further AFT and chemical data). D-AFT and basement fission-track parameters span a limited range and clearly indicate total thermal resetting post-crystallisation/deposition. A-AFT data are markedly younger, yielding a central age of 17.2±1.3 Ma (1σ), with longer mean track lengths (MTL) (Table 1). D-AHe ages on subrounded-rounded grains, ranging from ~11-207 Ma are younger than D-AFT ages, whereas A-AHe ages are Pliocene (weighted mean 3.2±0.4 Ma at 95% CI) (Tables 2 and 3). The slight spread in AHe-A-apatite ages may indicate heterogeneity in U and Th content as reflected in the concentric growth pattern, affecting the α-ejection correction. ZHe data predominantly yield Paleozoic ages from both D- and A-apatite bearing strata, with a negative age versus eU ppm correlation reflecting increased He diffusion in heavily radiation damaged grains (e.g. Guenthner et al., 2013) (Figure 4 and Table 4). However, one grain in sample TW650 (in A-apatite-bearing strata), with exceptionally high eU

(>9000 ppm) yielded a ZHe age of 17.3±1.1 Ma, concordant with the coexisting A-AFT age.

5 DISCUSSION

Our D-AFT and D-AHe ages show similar trends to those of Vermeesch et al. (2009), although D-AFT MTL in that study were markedly lower. The wide dispersion of D-AHe ages probably reflects a range of factors (e.g. Table 4 in Wildman et al., 2016) and in this case may specifically include the influence of U-rich A-apatite overgrowths (either present or removed) on the age calculation. Time-temperature models for D-AFT using the HeFTy software (Ketcham, 2005) show a similar thermal history (Figure 5, see also Table SI 1 for model input data), including overprinting related to the late Devonian-early Carboniferous thermal event, constrained by the ZFT age in the Nahal Shehoret section reported by Vermeesch et al. (2009).

The A-AFT age data indicates that A-apatite growth was not directly linked to the late Devonian-early Carboniferous thermotectonic event. Rather, we suggest it resulted from intra-strata recrystallisation from low temperature, U-rich hydrothermal solutions, associated with early DST activity (e.g. Garfunkel, 2014). Further, a highly radiation-damaged zircon in sample TW650 yielded a ZHe age concordant with the co-existing A-AFT age. This suggests that highly-damaged zircons have the potential to record low-temperature thermal events driven by hydrothermal fluids (e.g. Mackintosh et al., 2017; Johnson et al., 2017).

Apatite is sensitive to a range of chemical and textural changes induced by fluids, over a broad range of pressures and temperatures (e.g. Harlov, 2015). The temperature of the fluids facilitating A-apatite growth was presumably relatively low with respect to the AFT temperature sensitivity range, because the D-AFT system in strata (and basement) proximal to predominantly A-apatite-bearing strata was not thermally overprinted to any extent in early Miocene time, although the widely dispersed D-AHe data do include some Miocene ages.

Cu-Mn-U mineralisation is associated with marine Cambrian phosphorite-bearing strata (Timna Formation) in the Timna Valley, southern Israel (Figure 1), where A-apatite-rich beds are also located (e.g. Bar-Matthews, 1987; Bar-Matthews & Matthews, 1990; Segev, 1992; Harlavan et al., 2017). Considerable debate has arisen over interpretation of field, petrographic and geochemical data related to mineralisation processes and their timing.

However, there is clear evidence for epigenetic dissolution (karstification) and mineralisation (including U-mobilisation and reprecipitation), also affecting crystalline basement, over a broad time span (e.g. Bar-Matthews, 1987; Segev et al., 1995, Beyth et al., 1997). Some mineralisation has been linked to the pattern of dense faulting and jointing, accompanied by the circulation of brines, associated with DST development (e.g. Beyth, 1987; Segev et al., 1995). Furthermore, altered Neoproterozoic gabbros in the Mt Timna Igneous Complex (Figure 1) acquired a chemical remanent magnetisation in the middle Miocene, which Marco et al. (1993) attributed to early DST-induced hydrothermal activity. The normal polarity suggests that alteration took place within a short time interval (<~1 m.y.), while the basement still resided under a sedimentary cover.

Approximately two-thirds of total DST offset occurred by pure strike-slip movement until the end of the Miocene. Then, due to changes in regional plate kinematics, an additional minor transtensional or transpressional component resulted in some southern areas developing a more rift-like morphology (e.g. Garfunkel & Ben-Avraham, 2001; Smit et al., 2010), in part manifested as pull-apart basins, (e.g. Gulf of Eilat [Aqaba] and the Dead Sea). During this phase ~1 km of Tertiary to Senonian section was removed from rift flanks bordering the DST and deposited in developing adjacent rift basins, as the prevailing drainage system was deepened (e.g. Avni et al., 2012). We therefore interpret Pliocene A-AHe ages as a cooling response related to removal of overburden along the southern rift margins, leading to exposure of the Cambrian section and underlying basement.

In order to discern the temperature sensitivity of the A-AHe system, we carried out preliminary diffusion measurements on southern Israel A-apatite, supplemented by more detailed data from Yucca Mountain, USA A-apatite. The data indicate closure temperatures covering the two measurements of 52°C and 56°C, respectively (with a conservative uncertainty estimated at ~10°C), at a cooling rate of 10°C/Myr (Figure 6), which is lower than for typical igneous apatites (e.g. Farley, 2000). Considering this closure temperature range and a mean annual surface temperature of ~25°C, a time-temperature model for LTT A-apatite data indicates that A-apatites have undergone ~35-40°C of cooling in Pliocene time (Figure 5). Assuming a present-day geothermal gradient of ~20°C/km in southern Israel (Eckstein & Simmons, 1977) would suggest that ~1.5-2 km have been removed. However, any calculation of the thickness of cover removed based on these figures may be an overestimate, because deep faults associated with the rift system acted as conduits for hot

241 water ascending from deep aquifers, resulting in anomalously high heat flow (Eckstein &
242 Simmons, 1977). The upper limit on the amount of Pliocene cooling must honor the co-
243 existing early Miocene A-AFT age and MTL parameters; however, the temperature
244 sensitivity of fission-track annealing for francolite is unknown and only nine track lengths
245 were located for measurement. Assuming it is similar to fluorapatite, A-apatite would have
246 resided under thermal conditions that preserved the A-AFT record from the early Miocene
247 until Pliocene cooling.
248
249 Our A-AFT and A-AHe dates are similar to ages recorded from 'Mottled Zone' outcrops to
250 the north, in Israel and Jordan (Figure 1). This unique sequence of high temperature, low-
251 pressure metamorphic rocks has a complex mineralogy (Gross, 1977) reflecting near-surface
252 combustion metamorphism of late Cretaceous-early Tertiary bituminous chalk and marl (e.g.
253 Kolodny & Gross, 1974; Burg et al., 1999). Combustion is linked to exposure and contact of
254 these rocks with atmospheric oxygen, following uplift and erosion at the DST margins.
255 Absolute dating indicates that combustion occurred in different areas at different times:
256 gehlenite $^{40}Ar/^{39}Ar$ at ~16.0±0.2 Ma and anorthite-sanidine fels $^{40}Ar/^{39}Ar$ at ~2.3–4.0 Ma,
257 (Gur et al., 1995), AFT age at 13.6±2.0 Ma (Kolodny et al., 1971). Gur et al. (1995) linked
258 the early event to initial exposure of host rocks in the Miocene, and interpreted the Pliocene
259 ages as a later combustion event related to removal of Neogene sediments and renewed
260 exposure of bituminous rocks following initiation of the Dead Sea depression. 'Mottled
261 Zone' geochronology therefore provides independent evidence for the timing of important
262 DST-related events, and these events can be linked to those discerned in southern Israel (see
263 Figure 7).
264

265 6 CONCLUSIONS

266
267 Detrital (D) and authigenic (A) apatites (francolite) are found in Cambrian strata in southern
268 Israel. D-apatites preserve a similar low-temperature thermochronological history to
269 underlying Neoproterozic basement, reflecting Paleozoic-Mesozoic sedimentary cycles,
270 marked by a distinct late Devonian-early Carbonifeous thermal event. A-apatites, which may
271 partially or totally replace D-apatite, record more recent geological events. A-AFT and ZHe
272 (from a highly radiation-damaged zircon) data yield early Miocene ages (~17 Ma), while
273 coexisting AHe ages are distinctly younger (~3-4 Ma). A-AFT and ZHe ages are interpreted

to reflect intra-strata recrystallisation driven by low-temperature hydrothermal solutions ascending through fractures created during early DST activity. We link our A-AHe ages to uplift and erosion of overlying cover during a transtensional DST phase, recording cooling due to removal of overburden during the Pliocene. The timing of two important milestones in DST movement is therefore recorded by A-apatite data in isolation. This timetable is also supported by independent chemical remanent magnetisation overprinting and mineralisation data in southern Israel and geochronology of the "Mottled Zone" to the north. This study invites further (U-Th)/He investigation of highly radiation-damaged zircons in southern Israel and other areas to evaluate the extent of early Miocene fluid-flow related to DST activity.

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FIGURE CAPTIONS

Figure 1. Locality map. Mt TIC = Mt Timna Igneous Complex. A stratigraphic section at Nahal Shehoret, showing positions of samples analysed and types of low temperature thermochronology methods carried out on them. Numbers following formation names can be keyed into those indicated in the section photo in Figure 2. Stars next to sample numbers indicate those that contain A-apatite.

Figure 2. Cambrian sedimentary type locality in Nahal Shehoret valley (see also Figure 1). Foreground shows the Multicolored Member (1) of the Shehoret Formation, consisting of alternating beds of coarse- to fine-grained, cross-bedded subarkose and laminated clays displaying a range of colors. Background shows the cliff-forming White (2) and Variegated (3) (red-brown) members of the Shehoret Formation, comprising uniformly fine-grained and thinly cross-bedded subarkose. These strata are overlain by red-brown fine- to medium-grained and cross-bedded quartz-arenite of the Netafim Formation (4), which in turn is overlain unconformably by the Lower Cretaceous Amir Formation (5) at top. Note recent gravel beds on the valley floor between units (1) and (2).

Figure 3. a) Scanning electron microscope image showing hexagonal A-apatite with small particles of kaolinite in sample TW650. Grains typically range from ~50-400 μm in diameter, though well-developed prisms and twin crystals also occur. A-apatites are typically U-rich, display undulatory extinction when observed down the c-axis, sometimes show concentric lamellae and effervesce upon dissolution in weak HNO_3. These are all characteristics of carbonate-rich fluorapatite (francolite). b) Spontaneous fission tracks in A-apatite sample TW650. c) Spontaneous fission tracks in D-apatite sample TW558.

Figure 4. a) Plot of single grain AHe age versus effective uranium content (eU) ppm from Cambrian sedimentary samples, which are predominantly either D- or A-apatite-bearing (see

Tables 2-3). The general negative relationship, with younger ages generally related to increased eU content, reflects the effect of radiation damage on He diffusion (e.g. Shuster et al., 2006; Flowers et al., 2009 and Gautheron et al., 2009). b) Plot of single grain ZHe age versus effective uranium content (eU) ppm from Cambrian sedimentary samples, which are predominantly either D- or A-apatite-bearing (see Table 4). Oldest zircon ages at low eU (ppm) may reflect primary Neoproterozoic Pan African Orogeny cooling ages, but a negative relationship between single grain age and increased eU content (which is a proxy for radiation-damage), shown more clearly in the upper panel, is the product of increased He diffusivity. Note that for one grain with very high eU, the ZHe age of 17.3±1.1 Ma is concordant with an A-AFT age from the same sample (see text for further discussion).

Figure 5. Thermal history reconstructions of representative samples analysed using HeFTy software (Ketcham, 2005 and fission-track annealing model of Ketcham et al., 2007 and where applicable for sample TW650 using the He diffusion model of Flowers et al., 2009). Measured and model ages are compared, together with GOF = Goodness of Fit for best-fit time-temperature paths, which are represented by a dark solid line within the statistical good-fit envelope (magenta), which represents good models that fall within a probability >50% (a weighted mean path for this envelope is also shown). Also displayed is an outer envelope (green), which represents accepted models that fall within a probability of 5%. The right-hand panels show measured and model MTL (n = number of length measurements) and c-axis projected confined track lengths illustrated as histograms and the smoothed probability distributions representing the model track lengths from the “best-fit” models. Broad time-temperature constraints used were as follows. Cambrian stratigraphic age or nominal Pan-African age for basement, partial annealing of zircon fission tracks for Nahal Shehoret section during late Devonian-early Carboniferous time (see text). Following that constraints are related to the amount of erosion estimated in accordance with the thickness of the various formations in Israel and adjacent regions. Since Pan-African orogeny the sedimentary column of southern Israel has been affected by four main epeirogenic events, which are expressed by notable unconformities with conspicuous rate of truncation (beside numerous disconformities). The rate of truncation of each event was calculated according to the thickness of the missing sequence (formations) from the bounding flanks of the DST while they are still preserved in close or remote areas in southern Israel (Permian to Miocene) and adjacent countries such as southern Jordan, northwestern Saudi Arabia and Sinai (also Ordovician to Carboniferous), which in keeping with their sedimentary shelf characteristics

584 and the paleogeography should have been deposited over the whole Near East, but have been
585 removed from large areas in the Levant including the DST rift shoulders. Present day mean
586 surface temperature is assumed to be ~20-25°C. Note no ZFT data are available from
587 basement sample (EP2), located ~10 km south of Nahal Shehoret and in this case modelling
588 indicates only partial Paleozoic overprinting of the AFT system to ~80±5°C (Figure 6). Note
589 for sample TW650 only nine track lengths were available for measurement.
590
591 **Figure 6.** Results of He step-heating diffusion experiments carried out on hexagonal
592 francolite in the Cambrian Netafim Formation, southern Israel (at the University of
593 Melbourne) and from Tertiary ash-flow tuffs, Yucca Mountain, Nevada (at Caltech). Initial
594 diffusivities are lower than the extrapolation of values at higher temperatures. This is
595 commonly observed in apatites and is attributed to rounding of the initial concentration
596 profile by α-ejection and possibly by diffusion (e.g. Fechtig & Kalbitzer, 1996; Farley,
597 2000). Between ~200–300°C the diffusivity lies on a linear array (independent of any
598 temperature cycling), which is consistent with thermally activated volume diffusion implying
599 a closure temperature for the two measurements of 52°C and 56°C (with a conservative
600 uncertainty of ~10°C) at a cooling rate of 10°C/Myr. Step heating data and calculations of
601 parameters arising from the diffusion experiments are presented in Table SI 3.
602
603 **Figure 7.** Schematic summary timetable relating the proposed time-temperature history of A-
604 apatite (and one ZHe measurement) in southern Israel, deduced from low-temperature
605 thermochronology data, to major phases of DST motion and other independent geological
606 information (see text). Phase I relates to initial early-late Miocene strike-slip DST
607 movement, resulting in about two-thirds of the total ~105 km displacement. Phase II relates
608 to the onset of a more transtensional environment along the DST resulting in more of a rift
609 morphology, with erosion of the rift flanks filling adjacent pull-apart basins, leading to
610 cooling and exposure of Cambrian sediments and underlying crystalline basement. D-AHe
611 ages are widely dispersed. CRM = chemical remanent magnetisation and M-Zone = timing of
612 combustion events dated from the "Mottled Zone" (see text for further discussion).

Table 1. Apatite fission track data.

Sample No.	Lithology/Formation	Location (Long E/Lat N)	No. of grains	N_s	ρ_s [10^5 cm^{-2}]	^{238}U [ppm ± 1σ]*	Pooled age [Ma ± 1σ]	Central age [Ma ± 1σ]	N_{length}	Mean track length [µm ± se]	St.Dev. [µm]	D_{par} [µm]*
Authigenic (Cambrian)												
TW650	Netafim Fm	34°57' / 29°38'	46	463	4.36E+05	50.99 ± 18.57	17.0 ± 1.7 Ma	17.2 ± 1.3 Ma	9	13.82 ± 0.48	1.45	1.80 ± 0.46
Detrital (Cambrian)												
TW558	Shehoret Fm (White Mbr)	34°56' / 29°38'	24	2819	3.605E+06	23.39 ± 13.57	299.8 ± 15.5	313.4 ± 14.2	147	11.68 ± 0.12	1.47	1.59 ± 0.24
TW560	Shehoret Fm (White Mbr)	34°56' / 29°38'	36	3044	3.242E+06	22.50 ± 12.98	282.0 ± 11.3	289.0 ± 11.8	112	11.34 ± 0.13	1.41	1.54 ± 0.17
TW670	Shehoret Fm (White Mbr)	34°56' / 29°38'	30	1484	2.997E+06	21.57 ± 15.17	274.3 ± 12.3	279.1 ± 12.2	60	11.31 ± 0.19	1.48	1.95 ± 0.57
TW683	Shehoret Fm (White Mbr)	34°56' / 29°38'	27	1524	3.782E+06	28.97 ± 20.20	259.1 ± 16.8	266.9 ± 15.5	45	11.16 ± 0.25	1.71	1.56 ± 0.15
TW836	Shehoret Fm (Multicolored Mbr)	34°56' / 29°38'	10	321	1.802E+06	10.64 ± 7.04	328.1 ± 36.1	337.4 ± 32.4	51	11.29 ± 0.20	1.43	1.47 ± 0.16
Basement (Neoproterozoic)												
EP-2	Elat pegmatite	34°56' / 29°34'	13	2718	1.127E+07	59.38 ± 23.58	364.4 ± 12.4	366.3 ± 11.0	119	11.78 ± 0.13	1.46	1.63 ± 0.10

Ns = number of spontaneous tracks counted; ρs = spontaneous track density; N_{length} = number of confined lengths measured; se = standard error; Dpar = long axis of track etch pit;

*Uncertainty is standard deviation of mean

Notes: Apatite grains were mounted and polished, and fission tracks analysed using the LA-ICP-MS technique following procedures described in Gleadow et al. [2015].

Analyses were performed on image sets captured by the software *TrackWorks*. Spontaneous track densities were measured on prismatic internal apatite surfaces after etching with 5M HNO3 for 20 sec at 20ºC.

Track counts were obtained by automated counting using the software *FastTracks* employing the 'coincidence mapping' technique of Gleadow et al. (2009) followed by manual inspection.

Uranium concentrations of each grain were determined by LA-ICP-MS single spot analysis using a New Wave Nd:YAG Laser (λ= 213nm with 5Hz @ 50% power, spot size = 30µm) connected to an Agilent 7700 mass spectrometer.

NIST612 was used as the primary LA-ICP-MS standard, together with a sintered Mud Tank Carbonatite apatite as an in-house secondary reference material.

Data reduction of LA-ICP-MS results was performed using the TraceElement_IS data reduction scheme in software package Iolite [Paton et al., 2011]. Single grain and pooled ages were calculated according to Hasebe et al. (2004).

Central ages were estimated from single grain ages and errors according to the formulas given by Galbraith (2005, p.100) using the Newton-Raphson method. All ages are 'model' ages obtained using a range factor (Rs) of 7.50 µm.

Confined track lengths (TINTS) were measured as true 3D lengths using FastTracks and are corrected for a refractive index of 1.634 for apatite.

Table 2. Single grain apatite (U-Th-Sm)/He data for detrital and crystalline basement apatite.

Sample No.	Lab. No.	He#	[4]He (ncc)	Mass (mg)	[a]Mean F_T	U ppm	Th ppm	Sm ppm	Th/U	[b][eU] ppm	Corrected age (Ma)	Error (±1σ)	Grain length (μm)	Grain half width (μm)	[c]*Rs*	[d]Grain morphology
Detrital (Cambrian)																
TW558	14392	46447	0.573	0.0068	0.76	23.2	40.6	54.1	1.75	32.7	**27.6**	**1.7**	213.1	56.3	66.8	0T
TW558	14393	46450	2.037	0.0106	0.81	7.9	5.2	94.2	0.66	9.1	**206.9**	**12.8**	220.0	69.3	79.1	0T
TW558	14394	46453	0.724	0.0064	0.78	11.9	8.3	314.6	0.69	13.9	**83.1**	**5.2**	168.9	61.6	67.7	0T
TW558	14395	46456	0.435	0.0042	0.73	8.0	11.3	34.2	1.42	10.7	**108.1**	**6.7**	176.6	48.9	57.4	0T
TW558	14396	46459	0.056	0.0078	0.78	3.1	4.1	95.2	1.33	4.1	**18.0**	**1.1**	192.5	63.6	71.7	0T
TW560	14413	46462	1.350	0.0105	0.82	106.7	15.3	63.9	0.14	110.3	**11.7**	**0.7**	136.3	87.6	80.0	0T
TW560	14415	46468	0.650	0.0077	0.79	49.6	5.7	94.7	0.11	50.9	**17.2**	**1.1**	99.7	87.5	69.9	0T
TW560	14416	46471	0.147	0.0037	0.72	23.8	17.5	226.4	0.73	27.9	**15.8**	**1.0**	171.2	46.6	54.9	0T
TW560	14417	46474	0.080	0.0113	0.81	5.5	5.1	36.6	0.94	6.7	**10.6**	**0.7**	199.7	75.0	81.8	0T
TW560	14418	46477	0.911	0.0072	0.78	8.8	7.8	20.4	0.89	10.6	**125.1**	**7.8**	192.2	60.8	69.3	0T
TW670	18757	62411	0.068	0.00264	0.70	15.2	16.0	227.3	1.05	19.0	**15.8**	**1.0**	114.0	48.0	50.6	0T
TW670	18758	62414	0.680	0.00193	0.65	37.5	59.2	441.1	1.58	51.4	**85.1**	**5.3**	114.2	41.0	45.2	0T
TW670	18759	62417	0.133	0.00133	0.59	9.4	41.4	220.6	4.39	19.1	**71.4**	**4.4**	109.1	34.8	39.6	0T
TW670	18760	62420	0.121	0.00171	0.63	14.1	43.8	169.3	3.10	24.4	**37.2**	**2.3**	104.0	40.5	43.7	0T
TW670	18761	62423	0.974	0.00226	0.69	52.2	20.0	294.8	0.38	56.9	**88.9**	**5.5**	83.2	52.0	48.0	0T
TW670	18762	62426	0.091	0.00280	0.70	21.1	15.1	201.7	0.72	24.6	**15.3**	**0.9**	80.9	58.6	51.0	0T
TW670	18763	62429	0.700	0.01311	0.82	5.5	5.9	57.9	1.06	6.9	**76.1**	**4.7**	185.1	83.9	86.6	0T
TW670	18764	62432	2.475	0.00482	0.76	33.1	17.6	282.5	0.53	37.2	**146.9**	**9.1**	150.3	56.5	61.6	0T
Basement (Neoproterozoic)																
EP-2	18750	62393	92.569	-	1.00	-	-	-	0.78	-	**390.1**	**24.2**	-	-	-	-
EP-2	18751	62396	54.245	-	1.00	-	-	-	0.74	-	**458.2**	**28.4**	-	-	-	-
EP-2	18752	62399	35.246	-	1.00	-	-	-	0.38	-	**327.3**	**20.3**	-	-	-	-
EP-2	18753	62402	37.197	-	1.00	-	-	-	0.76	-	**289.4**	**17.9**	-	-	-	-
EP-2	18754	62405	22.686	-	1.00	-	-	-	0.27	-	**205.3**	**12.7**	-	-	-	-
EP-2	18755	62408	113.722	-	1.00	-	-	-	0.41	-	**442.5**	**27.4**	-	-	-	-
Durango apatite																
Durango	14466	46390	6.379	-	1.00	-	-	-	22.86		**31.7**	**2.0**	-	-	-	-
Durango	14467	46519	2.452	-	1.00	-	-	-	20.81		**31.0**	**1.9**	-	-	-	-
Durango	14527	46554	6.289	-	1.00	-	-	-	21.16		**31.3**	**1.9**	-	-	-	-
Durango	18756	62380	4.628	-	1.00	-	-	-	16.31	-	**31.5**	**2.0**	-	-	-	-
Durango	18793	62489	3.895	-	1.00	-	-	-	21.34		**31.8**	**2.0**	-	-	-	-

Table 2. Single grain apatite (U-Th-Sm)/He data for detrital and crystalline basement apatite.

[a] F_T is the α-ejection correction after Farley et al. (1996).

[b] Effective uranium content [U ppm + 0.235*Th ppm].

[c] Radius of the equivalent sphere of the crystal.

[d] Grain morphology - 0T = no crystal terminations, 1T = one crystal termination and 2T = 2 crystal terminations.

***Note**:* Durango apatite reference material (31.02±1.01 Ma - McDowell et al., 2005) was run as an internal check with each batch of apatites analysed.

Table 3. Single grain authigenic apatite (U-Th-Sm)/He data.

Sample	Lab. No.	He#	^{4}He (ncc)	Mass (mg)	[a]Mean F_T	U ppm	Th ppm	Sm ppm	Th/U	[b][eU] ppm	Corrected age (Ma)	Error (±1σ)	Grain plate thickness parallel c-axis (μm)	Grain plate width perpendicular c-axis (μm)
TW650	14420	46483	0.164	0.0216	0.82	17.0	25.3	41.4	1.49	22.9	**3.3**	**0.2**	92.8	304.7
TW650	14421	46486	0.355	0.0282	0.83	20.9	82.0	36.9	3.92	40.2	**3.1**	**0.2**	107.0	324.0
TW650	14422	46489	0.206	0.0220	0.82	23.5	32.5	53.6	1.38	31.1	**3.0**	**0.2**	89.5	312.6
TW650	14423	46492	0.157	0.0142	0.79	26.2	25.1	49.8	0.96	32.1	**3.6**	**0.2**	73.8	277.1
TW650	14424	46495	0.156	0.0240	0.82	16.9	20.7	40.3	1.22	21.8	**3.0**	**0.2**	92.7	321.2
TW650	14425	46498	0.166	0.0285	0.83	19.4	18.1	38.9	0.94	23.7	**2.5**	**0.2**	94.8	345.8
TW651	14432	46501	0.108	0.0068	0.74	28.7	46.4	155.2	1.62	39.6	**4.4**	**0.3**	66.0	203.1
TW651	14433	46504	0.134	0.0082	0.75	32.8	147.6	150.1	4.50	67.5	**2.7**	**0.2**	70.0	215.4
TW651	14434	46507	0.128	0.0087	0.76	27.3	53.1	115.6	1.94	39.8	**4.0**	**0.2**	76.2	213.3
TW651	14435	46510	0.086	0.0105	0.78	24.0	33.8	128.4	1.41	31.9	**2.7**	**0.2**	84.2	223.1

[a]F_T is the α-ejection correction after Farley et al. (1996).

[b]Effective uranium content [U ppm + 0.235*Th ppm], which can be used as a proxy for radiation damage.

Note: Durango apatite reference material was also analysed with these samples (refer to lab nos. 14466, 14467 and 14257 in Table 2).

Table 4. Single grain zircon (U-Th)/He analytical data for D- and A-apatite-bearing Cambrian siliciclastic sediments.

Sample	Lab. No.	He#	[a]He (ncc)	Mass (mg)	[a]F_T	U ppm	Th ppm	Th/U ratio	[b][eU] ppm	Corrected age (Ma)	Error (±1σ)	Grain length (μm)	Grain half width (μm)	[c]*Rs*	[d]Crystal morphology
Authigenic apatite-bearing strata															
TW650	14426	46129	149.064	0.0155	0.85	116.4	65.2	0.56	131.8	**559.1**	**34.7**	274.1	69.5	83.2	2T
TW650	14427	46132	128.801	0.0103	0.82	128.8	105.5	0.82	153.6	**631.2**	**39.1**	218.6	67.9	77.7	2T
TW650	14428	46135	153.018	0.0141	0.83	137.3	110.2	0.80	163.2	**519.1**	**32.2**	284.3	62.8	77.1	2T
TW650	14429	46138	46.662	0.0077	0.78	99.4	73.1	0.74	116.6	**412.8**	**25.6**	265.3	45.5	58.3	2T
TW650	14430	46141	165.026	0.0086	0.80	9050.9	295.9	0.03	9120.4	**17.3**	**1.1**	243.5	52.7	64.9	2T
TW650	14431	46144	190.250	0.0183	0.82	157.1	93.5	0.60	179.0	**457.5**	**28.4**	265.1	60.9	74.3	0T
TW651	14437	46147	321.108	0.0139	0.83	507.4	147.5	0.29	542.0	**339.1**	**21.0**	302.6	58.6	73.7	2T
TW651	14438	46150	28.870	0.0077	0.78	53.3	30.9	0.58	60.6	**485.1**	**30.1**	260.4	46.3	59.0	2T
TW651	14439	46153	56.155	0.0088	0.80	64.4	48.0	0.75	75.7	**653.2**	**40.5**	234.6	55.2	67.1	2T
TW660	18800	62557	59.033	0.0031	0.73	278.3	219.8	0.79	330.0	**453.4**	**28.1**	165.2	39.4	47.7	2T
TW660	18801	62560	57.277	0.0040	0.70	359.4	137.1	0.38	391.6	**291.4**	**18.1**	248.0	30.9	41.3	1T
TW660	18802	62563	8.615	0.0024	0.70	47.1	4.3	0.09	48.1	**583.1**	**36.1**	164.0	33.2	41.4	2T
Detrital apatite-bearing strata															
TW558	14397	46059	83.910	0.0052	0.76	205.7	368.7	1.79	292.3	**438.2**	**27.2**	200.5	45.6	55.8	2T
TW558	14398	46062	77.620	0.0050	0.77	213.9	196.9	0.92	260.2	**466.9**	**29.0**	183.8	49.1	58.1	2T
TW558	14399	46065	129.691	0.0066	0.76	288.0	292.3	1.01	356.7	**436.0**	**27.0**	274.3	40.6	53.0	2T
TW558	14400	46068	104.735	0.0049	0.76	312.3	284.3	0.91	379.1	**447.4**	**27.7**	199.7	43.9	54.0	2T
TW558	14401	46071	169.558	0.0108	0.79	193.8	163.6	0.84	232.3	**528.3**	**32.8**	327.6	47.4	62.1	2T
TW558	14402	46074	89.185	0.0090	0.79	120.0	219.1	1.83	171.5	**458.2**	**28.4**	279.1	48.1	61.5	2T
TW560	14403	46077	129.181	0.0060	0.74	526.5	302.8	0.58	597.6	**288.6**	**17.9**	286.2	37.3	49.5	2T
TW560	14404	46080	79.011	0.0069	0.78	137.1	113.4	0.83	163.8	**544.5**	**33.8**	250.7	44.8	57.0	2T
TW560	14405	46083	52.619	0.0052	0.75	136.8	139.5	1.02	169.6	**473.1**	**29.3**	233.1	39.8	51.0	2T
TW560	14407	46089	43.335	0.0066	0.77	97.3	40.6	0.42	106.9	**481.2**	**29.8**	268.8	41.2	53.6	2T
TW560	14408	46092	48.156	0.0040	0.72	150.3	100.2	0.67	173.8	**537.9**	**33.3**	230.9	34.6	45.1	2T
TW639	18794	62539	134.302	0.0058	0.76	458.0	212.0	0.46	507.9	**360.7**	**22.4**	255.7	39.8	51.7	2T
TW639	18795	62542	93.332	0.0103	0.77	124.4	137.6	1.11	156.7	**454.5**	**28.2**	387.8	41.2	55.8	2T
TW639	18796	62545	88.372	0.0087	0.77	154.7	165.3	1.07	193.5	**416.4**	**25.8**	288.6	45.9	59.4	2T
TW639	18797	62548	15.356	0.0148	0.85	13.6	2.8	0.20	14.3	**561.9**	**34.8**	272.5	67.6	81.3	2T
TW639	18798	62551	131.069	0.0054	0.73	851.7	971.3	1.14	1080.0	**180.9**	**11.2**	274.0	36.3	48.1	2T
TW639	18799	62554	138.749	0.0119	0.81	1451.7	918.7	0.63	1667.6	**57.0**	**3.5**	257.4	54.3	67.2	1T
TW670	18804	62569	27.848	0.0048	0.75	83.5	56.0	0.67	96.6	**469.3**	**29.1**	220.3	40.0	50.8	2T
TW670	18805	62572	103.816	0.0084	0.78	166.8	152.1	0.91	202.5	**479.6**	**29.7**	262.2	48.6	61.5	2T
TW670	18806	62575	45.957	0.0064	0.79	94.7	72.3	0.76	111.7	**503.1**	**31.2**	185.8	58.5	66.7	2T
TW670	19807	62578	52.272	0.0049	0.78	196.3	124.7	0.64	225.6	**375.5**	**23.3**	173.0	52.1	60.0	2T
TW670	18808	62581	87.979	0.0045	0.76	287.3	123.5	0.43	316.3	**479.6**	**29.7**	196.3	42.7	52.6	2T
TW670	18809	62584	28.191	0.0043	0.74	90.3	34.5	0.38	98.4	**521.2**	**32.3**	195.8	41.2	51.0	2T
TW683	18810	62587	335.341	0.0156	0.83	572.2	352.4	0.62	655.0	**263.3**	**16.3**	321.9	59.8	75.6	2T
TW683	18811	62620	68.930	0.0058	0.76	160.0	114.2	0.71	186.8	**495.7**	**30.7**	239.0	42.0	53.6	2T
TW683	18812	62623	49.175	0.0062	0.76	116.4	64.5	0.55	131.6	**471.0**	**29.2**	258.0	41.1	53.2	2T
TW683	18813	62626	78.002	0.0068	0.75	199.5	142.5	0.71	233.0	**392.8**	**24.4**	245.9	41.0	52.7	1T
TW683	18814	62629	74.966	0.0055	0.77	250.7	143.9	0.57	284.6	**379.9**	**23.6**	202.1	47.1	57.2	2T
TW683	18815	62632	95.837	0.0081	0.79	154.8	95.5	0.62	177.2	**521.5**	**32.3**	202.8	51.3	61.4	1T
Fish Canyon Tuff															
FCT	14410	46098	9.250	0.0074	0.78	324.4	173.0	0.53	365.0	**28.2**	**1.7**	248.3	46.9	59.2	2T
FCT	14411	46123	9.774	0.0079	0.79	344.9	167.7	0.49	384.3	**26.3**	**1.6**	250.5	48.7	61.2	2T
FCT	14412	46126	5.908	0.0045	0.74	333.7	197.8	0.59	380.2	**28.6**	**1.8**	188.2	43.9	53.4	2T
FCT	18689	62536	8.730	0.0060	0.77	366.9	181.4	0.49	409.6	**29.3**	**1.8**	236.9	42.8	54.4	2T
FCT	18691	62747	6.499	0.0037	0.75	456.7	226.8	0.50	510.0	**28.3**	**1.8**	175.3	41.6	50.4	2T

[a]F_T is the α-ejection correction after Farley *et al*. (1996).

[b]Effective uranium concentration (U ppm+0.235 Th ppm).

[c]Equivalent spherical radius

[d]Grain morphology - 0T = no terminations, 1T = one termination, 2T = 2 terminations.

Notes: Samples TW651 and TW660 are from different beds of the Netafim Formation at the same locality as sample TW650 in Nahal Shehoret (see Table 1).

Fish Canyon Tuff zircon reference material (28.3±0.4 Ma - Gleadow et al., 2015) was analysed as an internal check with each batch of zircons analysed.