Temporal and spatial relations between large-scale fault systems: Evidence from the Sinai-Negev shear zone and the Dead Sea Fault

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ABSTRACT

In the major zones of crustal deformation within the Arabia-Sinai-Nubia plates, the interactions between the Sinai-Negev Shear Zone (SNSZ) and the Dead Sea Fault system (DSF) shed light on the interplay between neighboring, large-scale fault systems. The SNSZ is composed of several \textit{E-W} to ENE–WSW trending, mainly normal and dextral, strike-slip faults that are tens to hundreds of kilometers long. These faults form a \textit{120 km} wide shear zone in the Sinai sub-plate. On reaching the plate-bounding Dead Sea Fault system (DSF), individual lineaments of the SNSZ are observed in the Arabian plate offset left-laterally by 105 km, which is the total estimated offset of the DSF. In this contribution, we review the geologic setting of the SNSZ and its complex relations with the DSF in light of newly obtained age-strain analyses. For this we use \textit{in-situ} U–Pb geochronology in conjunction with twin analysis of syn-faulting calcite from both systems. The results indicate that the deformation along the SNSZ initiated in the Campanian–Maastrichtian or earlier, as the oldest dates are 73–71 Ma. The main phase of fault activity began in the late Oligocene – early Miocene (27–22 Ma) as documented by numerous dates that were obtained along several lineaments of the SNSZ. The activity continued until \textasciitilde10 Ma, after which no direct ages have been obtained. The dominant phase of activity along the SNSZ at 27–22 Ma preceded the timing of initiation of lateral faulting along the DSF at \textasciitilde20–18 Ma by a few Myr. For the overlapping period of activity between 20 and 10 Ma, episodes of fault activity along the SNSZ followed by episodes of fault activity along the DSF. Moreover, dominant episodes of activity along one fault system were associated with a decrease in activity along the other system. The temporal relations between the SNSZ and DSF highlight the possibility that these fault systems are mechanically interrelated, but the exact mechanism for this fault interaction needs further study.

We consider the paleo-strain (or paleo-stress) that control the evolution and style of the SNSZ and assess them at the central Sinai-Negev region during the Cenozoic. We show that the formation of new plate boundaries at the region, i.e., the Red Sea - Suez rift and the DSF, affected the strain field within the SNSZ. The proximity of the two systems indicates that the DSF-related stress originated within the SNSZ and possibly caused structural and style changes in the latter system. Syn-faulting calcite-twin analyses within the SNSZ show pronounced spatial and temporal variations of the principal strain directions between and along individual faults. This observation demonstrates that the imposed stress within the central Sinai-Negev were not uniform over time. The high angle (> 70°) between the traces of the SNSZ and the direction of the DSF-related maximum shortening likely suppressed the dextral motion along the SNSZ post-20 Ma. Field evidence, U-Pb dates, and recent seismicity shows that the current SNSZ is a long-lived structure that has been active during the Miocene alongside the dominantly DSF and may still be sporadically active today.

1. Introduction

Large-scale shear zones commonly accommodate displacement along a wide zone of deformation, which includes a variety of structures (e.g., faults, folds, joints, veins), styles (extensional, contractional, strike-slip) and orientations. Among these structures, a set of sub-parallel faults are generally the most abundant, accompanying the principal shear zone (e.g., Reidel structures; Katz et al., 2004). The resulting
architecture is a complex pattern of deformation that may evolve due to fault interactions, branching, termination, and possibly, reactivation of pre-existing structures. Although fault evolution has been the focus of many structural studies (Fossen, 2016 and references therein), the spatial and temporal association among the different sets of faults, as well as the level of heterogeneity of the strain field along the shear zones are not well understood. Much progress has been achieved by studying the interactions between large-scale, plate-bounding fault systems such as the San Andreas Fault (SAF) and the East California Shear Zone (ECSZ) in USA (e.g., Dolan et al., 2007; Nuriel et al., 2019b); or the North Anatolian Fault Zone (NAFZ) and East Anatolian Fault Zone (EAFZ) in Turkey (e.g., Dewey et al., 1986). In the major zones of crustal deformation within the Arabia-Sinai-Nubia plates, only a few studies have been dedicated to study the interactions between the Sinai-Negev Shear Zone (SNSZ) and the Dead Sea Fault system (DSF). This is of major concern because the SNSZ is considered to be displaced
by the total amount of the sinistral movement along the DSF (~105 km), but, on the other hand, coeval activity along the two systems during the Neogene is suggested by stratigraphic evidence (Zilberman, 1983). While the span of activity along the DSF is relatively well-constrained to the last 20 m.y. (Eyal et al., 1981; Nuriel et al., 2017; Oren et al., 2020), fault activity along the SNSZ is poorly constrained. Hence, the spatial-temporal relation between the SNSZ and the DSF should be better documented based on robust dating of the fault activity and auxiliary structural data. Several important questions remain open and cannot be answered by field evidence alone: What is the spatial and temporal activity along the SNSZ? How does the activity along the SNSZ relate to that of the DSF? How does the paleo-strain (stress) within the SNSZ vary during the CenozoicMiocene as new plate boundaries (Red Sea - Suez rift, DSF) evolved in the surrounding region? What is the geometrical and kinematic relations between the SNSZ and the DSF?

U-Th and U-Pb geochronology of syn-faulting calcite has been used to constrain the timing of fault activity, with recent application to the Central Alps (Ring and Gerdes, 2016), the Atlantic margin (Roberts and Walker, 2016), the DSF (Nuriel et al., 2012a, 2017; Oren et al., 2020) and the North Anatolian Fault Zone (Nuriel et al., 2019a). Constraining the timing of fault initiation and reactivation is challenging because early kinematic indicators are commonly obliterated by later deformation. Within an active fault system, calcite can mechanically twin at low differential stress (~10 MPa), and twin analyses can then be used to infer stress and strain directions (Groshong Jr, 1972). Using absolute dating by laser-ablation U-Pb methods in conjunction with measurements of the mechanical calcite twins in the same grains is a new avenue for determining how the strain field (either regional or local) and the style of deformation evolve over time. In previous studies, we obtained a set of calcite U-Pb age-strain data (n = 30) from fault-related precipitates that unravel the initiation time and early phase of activity along the DSF (Nuriel et al., 2017). In this study, a larger set of data (n = 77) from the SNSZ has been obtained and analyzed, shedding light mainly on the Cenozoic activity of the SNSZ, and the concurrent activity and deformation history of the SNSZ and the DSF during the Miocene. We first review the geologic setting of the SNSZ and its individual faults. This review is essential because no integration of previous and new data on the SNSZ has been published since the seminal works of Bartov (1974; in Hebrew) and Zilberman (1981, 1983, 1985). We then discuss the new U-Pb dating and strain direction results of the samples from the SNSZ sites. Finally, we discuss the kinematics and the temporal and spatial variations of the strain (stress) field within the SNSZ and between the SNSZ and the DSF systems.

2. Geologic setting

2.1. General

The SNSZ is composed of several, ~E-W to ENE–WSW trending, mainly normal and dextral strike-slip faults that are tens to hundreds of kilometers long, forming ~120 km wide shear zone in the Sinai subplate (Fig. 1). The SNSZ is truncated by the Suez rift, which is the northern continuation of the Red Sea rift, forming a plate boundary between Africa (Nubia) plate and Sinai subplate. To the east, the SNSZ is bounded by the DSF, which is the ~1000 km long, ~N-S trending plate boundary between the Arabia plate and Sinai subplate (Fig. 1). On reaching the DSF, the individual lineaments of the SNSZ do not continue eastward along strike, but they can be matched with lineaments that occur further north and extend a few hundred kilometers eastward in Jordan (Quennell, 1959; Bender, 1974). Matching of these lineaments constrains the total sinistral offset of the DSF to about 105 km. The ~E-W Cairo-Suez shear zone in the Africa (Nubia) plate seems to be the westward extension of the SNSZ (Bartov, 1974; Guiraud and Bosworth, 1997), suggesting that the SNSZ and the DSF are of comparable length. Nevertheless, the entire dextral offset of individual faults of the SNSZ (< 3 km; Bartov, 1974) is two orders of magnitude smaller than the sinistral displacement along the DSF (~105 km). The paleo-stresses attributed to the sinistral DSF are known as the Dead Sea stress field (DS; Eyal and Reches, 1983) and associated with maximum horizontal shortening trending NNW-SSE (SHmax). Because of the high angle (> 70°) between the traces of the SNSZ and the direction of the SHmax, the dextral motion along the SNSZ was certainly suppressed in the past 20 m.y., suggesting that both systems could hardly be activated concurrently under the DSS. These relationships led Bartov (1974) to exclude the possibility that SNSZ is part of a conjugate set or a secondary feature of the sinistral movement along the DSF.

The central and southern Negev (Israel) are traversed by six fault systems (Bartov, 1974 and Fig. 1): the Zin line, the Sa‘ad-Nafha–Halal line, the Ramon–Minshara line, the Arif–Batur line, the Paran–Aref en Naaq–Buruq line, and the Thamad–Wadi Sudr line. Excluding the Zin line, all these shear zones extend into central Sinai, Egypt (Fig. 1a). Each of these lines exhibits one or more of the following (Bartov, 1974; Zilberman, 1981, 1983, 1985; Moustafa and Khalil, 1994; Flexer, 2001): variations in the direction of stratigraphic throw in various segments of the shear zone; changes of inclinations of the fault plane; offset (usually dextral) of cross-cutting structural elements (e.g., migmatic dikes); oblique to horizontal slickensides on the fault plane; development of small-scale folds (anticlines and synclines, domes and half domes) and extensional features (e.g., rhomb-shaped grabens), with their axes being subparallel to, or at a low angle with, the trace of the shear zone.

Based on these features, it has been concluded that the faults of the SNSZ have a strike-slip component (Bentor and Vroman, 1954; Bartov, 1974; Moustafa and Khalil, 1994) that cannot exceed a few kilometers (Freund, 1965; Bartov, 1974; Baer, 1981; Zilberman, 1983). Conclusive evidence for the earliest activity along the SNSZ during the Upper Cretaceous were found in sporadic anticlinal structures along these lines (Bentor and Vroman, 1951). The main tectonic phase, which formed the present structural pattern of the system, post-dated the deposition of the Hazeva continental sequence, as it was demonstrated that the Hazeva sediments along the Sa‘ad-Nafha, Paran, Arif–Batur are deformed relics, preserved due to downfaulting (Bartov, 1974; Zilberman, 1983; Zilberman and Galvo, 2013). The Hazeva Formation was deposited during the Neogene or even earlier (Avni et al., 2012) in an extensive fluvial system, covering all the central Negev and Sinai. In general, the fluvial system shows no relationship to the present structural pattern of the SNSZ, and the contact between the Hazeva Formation and the underlying Eocene Avedat Group exhibits only slight erosional unconformity in all the relics (Bartov, 1974; Zilberman, 1977, 1981; Eidelman, 1979; Bartov et al., 1980). Evidence of dextral motion along these faults post-dates the early Miocene intrusive phase in Sinai (K–Ar ages of 20–22 Ma dikes; Steinitz et al., 1978). The overlying clastic sediments of the Plio-Pleistocene Arava Formation are almost undisturbed along these lines such as the Karkom graben along the Paran line (Fig. 1c; Bartov, 1974, Avni, 1993). Late-Pleistocene faulting activity was detected at certain segments of the Zin fault system (see below).

The SNSZ in the Israeli Negev consists (from north to south; Figs. 1, 2) of the Zin, Sa‘ad-Nafha, Ramon, Arif-Batur, Paran, and Thamad fault systems. Numerous folds, domes and pull-aparts are superimposed on these main lineaments. In using the term ‘lineament’, we refer to the line feature on the surface of the Earth that represents all of these superimposed structures.

2.2. Geologic setting of individual fault systems

Below we present the setting of individual fault systems including the stratigraphic framework of the faulted blocks that are relevant to the sampling sites for the present analyses (Table 1). A general chronostatigraphic and lithological chart of the exposed rocks in the study area is presented in Table 2.
2.2.1. Zin Fault system

The Zin Fault system is a broad (10–15 km) faulted zone with surface expression of ~25 km in the Negev (Bentor and Vroman, 1951). The system is composed of many short (0.1–3 km) fault segments trending between WNW-ESE and WSW-ENE (Avni and Weiler, 2013). The deformation pattern associated with the fault system suggests a dextral strike slip component (Bentor and Vroman, 1954; De Sitter, 1962; Shamir, 1983). The Zin lineament does not extend eastward to the Arava Valley and westward to central Sinai as the other SNSZ features. Nevertheless, in spite of these differences, the Zin lineament is considered a major structural feature that is probably associated with a basement fault (De Sitter, 1962; Folkman and Klang, 1985). The earliest tectonic activity inferred along this line is of pre-Campanian age (Bartov et al., 1976). Evidence for Pleistocene tectonic activity is demonstrated in the Sede Boqer area (Fig. 2; Avni and Zilberman, 2006 and references therein).

2.2.2. Sa`ad-Nafha Fault system

The Sa`ad-Nafha Fault system extends ~100 km from Gebel Hallal in Sinai to Wadi Marzeva on the western margins of the Arava. This lineament consists of an E-W trending system of small-scale, ~2 km wide folds and domes in its western segment, and fault-controlled depressions in its eastern segment (Zilberman, 1981). The character of these structures and frequent changes in the throw indicate strike-slip movement along the fault (Zilberman, 1993). Evidence for folding activity extends from the Santonian to late Eocene. The main faulting phase post-dated the deposition of the Hazeva Formation (Bartov, 1974; Zilberman, 1977; Zilberman, 1981). In the Wadi Hawwa fault-controlled depression, the top conglomerate of the Hazeva Formation is downfaulted against the middle-upper Eocene rocks. The latest age of activity along this fault cannot be constrained because of the absence of post-Hazeva sediments. The maximum measured vertical throw is on the order of 100 m, and the amount of lateral displacement is estimated to exceed 200 m (Zilberman, 1983). Bartov (1974) suggested a sinistral displacement along the fault based on evidence from eastern Sinai, and Eyal (1984) and Bar (2003) suggested dextral displacement along the eastern segment of the lineament.

2.2.3. Ramon Fault system

The Ramon Fault system extends along ~200 km from Gabel Gidi in Sinai through the Ramon erosive cirque (i.e., a bowl-shaped landform arising from fluvial erosion) to the western margins of the Arava Valley (Fig. 2). It was mainly studied by Bentor and Vroman (1954), Garfunkel (1964), Zak (1968), and Avni (1993). Faulting and folding are closely associated along this lineament (Garfunkel, 1964, 1993). The structure is dominated by a continuous south dipping steep flexure. The associated fault is sub-vertical with slightly reverse motion, downthrowing to the south. It is noteworthy that while faults are very prominent along the Ramon lineament, a single through-going fault is not obvious at the exposed level (Garfunkel, 1993). In the erosive cirque area, the Ramon fault, located along the southern flank of the Ramon anticline, is a deep-seated fault underlying a narrow zone of deformation of 1–3 km wide and 40 km long, which is associated with thrust faults, steep flexures, overturned folds and complex strata undulations (Garfunkel, 1964; Avni, 1993). A lateral displacement has not been directly discerned along the fault. An apparent offset between the inferred location of the center of a Cretaceous radial dike system and the center of a large magnetic anomaly south of the Ramon lineament suggests a 3 km dextral offset of the fault (Baer and Reches, 1991). This estimate is in good agreement with the 2.5 km of dextral offset of a Miocene dike in the Gebel Minsheh area, along the western extension of the Ramon fault, about 150 km west of the Ramon area (Bartov, 1974; Fig. 1). The fault in this area is vertical to steeply dipping with frequent changes in dip direction from north-northwest to south-southeast (Moustafa and Yousif, 1990; Moustafa and Khalil, 1994). Seismic reflection profiles show a flower structure underneath Gebel Minsherah, confirming the presence of a strike-slip zone (Abdel Aal et al., 1992). The easternmost part of the Ramon fault system is built of two left-stepping segments with a stepover of 1000 m (Bar et al., 2007). The deformation along the Ramon lineament began at the Upper Cretaceous and continued in the Cenozoic (Garfunkel, 1993).

2.2.4. Arif-Batur fault system

The Arif-Batur fault system extends ~85 km from the Sinai to the west and the Arava Valley to the east (Fig. 1). The fault system disappears in the easternmost part of the lineament, where it is manifested by an array of small structures. The tectonic activity along the lineament began in the early Santonian and continued until the early Eocene (Baer, 1981; Zilberman, 1983). The entire fault system was reactivated after the deposition of the Hazeva Formation in the Miocene. Zilberman et al.
ration of a dextral strike-slip fault system, but the exact amount of offset is not well constrained. The throw is often reversed, and each change in fault orientation is associated with the formation of fault-related half-domes and parallel synclines (Baer, 1981).

Table 2
Stratigraphy of exposed rock units in the study area.

<table>
<thead>
<tr>
<th>Era</th>
<th>System</th>
<th>Series/Stage</th>
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<th>Group</th>
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<th>Lithology</th>
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and fault-controlled depressions, which form a conspicuous morpho-tectonic belt (Sakal, 1967; Zilberman, 1985). We focused on the Karkom graben, which is an elongated rhomb-shaped graben 18 km long and 7 km wide bounded by two segments of the Paran lineament (Fig. 2). The margins of the graben are commonly built of well-bedded limestone of the Avedat Group, which are tilted and faulted, typically forming the marginal faults of the graben (Fig. 1c, Fig. 3e). A local clastic unit which accumulated in the Karkom graben during subsidence (i.e., Karkom Member of the Hazeva Formation; Calvo et al., 1998), contains great amounts of reworked sediments from older members of the Hazeva Formation and is intensively faulted and folded. The overlying sequence, which consists of local gravels (the Arava

Fig. 3. Photos showing selected outcrops of the SNSZ. Red rectangle marks sampling areas. For locations of sites see Fig. 2 and Table 1. (a) Zin Fault at site ZF. Santonian-Lower Campanian chalk (Menuha Formation) in the hanging wall is faulted against Turonian limestone (Shihta-Nezer formations) in the footwall. (b) Sa’ad-Nafha Fault at site SaF. Neogene sandstones and conglomerates (Hazeva Formation) in the hanging wall is faulted against Eocene limestone (Matred Formation) in the footwall. (c) Ramon Fault at site RF. Turonian marl and limestone (Ora shales and Gerofit formations) in the hanging wall are faulted against Campanian limestone and dolostone (Tamar Formation) in the footwall. (d) Arif-Batur Fault at site ABF (west). Turonian limestone (Gerofit Formation) is faulted against Santonian chalk (Menuha Formation) and Campanian chert (Mishash Formation). (e) Paran Fault at site PaFN. Neogene sandstone and conglomerate (Hazeva Formation) in the hanging wall is faulted against Eocene limestone (Matred Formation) in the footwall. Plio-Pleistocene conglomerate (Arava Formation) at the top is undisturbed. (f) Thamad Fault at site TF (west). Limestone and chalk (Zihor and Menuha formations) in the hanging wall are faulted against Cambrian sandstone (Shehoret Formation) in the footwall. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
conglomerate), forms an almost undisturbed sequence, filling the tectonic depression. Faulting commenced in the Santonian and continued to the middle Eocene, while a second phase lasted during the Neogene and a third one in the Pleistocene (Zilberman, 1985).

2.2.6. Thamad fault system

The Thamad fault system is the longest in the SNSZ, extending along 200 km from the Suez rift (Gabel Somar) to the west and the Arava Valley to the east (Fig. 1). In the Negev, the northern blocks are commonly downfaulted with vertical throw of up to 1000 m (Garfunkel, 1970). Bartov (1974) estimated 300–500 m of dextral strike-slip offsets of the fault system in Sinai, based on displaced dikes and margins of fault-related folds. Moustafa and Khalil (1994) estimated 300–750 m of dextral strike-slip offsets based on displacement of some second-order folds along this lineament. Garfunkel (1970) presumed that the dextral strike-slip offset of the fault is 2.5 km, but evidence for this amount of offset has not been directly observed. Next to the Arava Valley, the direction of the fault changes from W-E to NE-SW, and may be attributed to the proximity of the Thamad fault to the DSF (Bartov, 1974). Moustafa and Khalil (1994) reported that the age of the slip along the Thamad fault is post-Middle Eocene to pre-Early Miocene.

3. Methods

3.1. Fieldwork

Syn-faulting calcite were sampled from 13 key sites located along the SNSZ in the Negev (Fig. 2). The locations of each site are given in Table 1. All the studied sites were previously mapped in details, their structural settings are well-defined, and the fault planes are well-exposed. Structural measurements include fault, vein, and striae (if observed) orientations. In each site, the stratigraphy of the faulted blocks was documented. Oriented samples for dating and strain analysis were taken from fault-wall breccia, cements and coatings, and calcite-filled veins within the fault zones at maximum distance of several tens of meters from each fault. We collected 77 samples in total, of those 45 samples were adequate for strain analysis. Oriented samples for dating and strain analysis were taken from fault-wall breccia, cements and coatings, and calcite-filled veins within the fault zones at maximum distance of several tens of meters from each fault. We collected 77 samples in total, of those 45 samples were adequate for strain analysis.

3.2. U-Pb Geochronology of calcite precipitates

We dated syn-faulting calcite that exhibit temporal association of precipitation and deformation, including twin calcite, sheared calcite coating or veins, and calcite breccia cement. It has been demonstrated that such calcite precipitates along the DST have very similar composition (e.g., stable isotopes, \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios, and REE pattern) to the hosting carbonate. These observations indicate that the fluid responsible for syn-faulting calcite precipitation is controlled by dissolution enhanced by pressurized solutions of the hosting carbonate rather than local or climatic hydrological conditions (Nuriel et al., 2012a). The calcite precipitates were dated by U-Pb laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the University of California Santa Barbara Geochronology laboratory following the methods described in Nuriel et al. (2017, 2019a). For mass-bias correction of the measured \(^{238}\text{U}/^{206}\text{Pb}\) ratio we used the 3.001 \pm 0.012 (2o) Ma calcite speleothem ASH-15D previously dated by TIMS (Mason et al., 2013); the data were first corrected for the \(^{207}\text{Pb}^{206}\text{Pb}\) ratio using NIST-614, followed by a linear correction on the \(^{238}\text{U}/^{206}\text{Pb}\) ratio such that the primary calcite reference material yields the correct intercept age (i.e., 3.001 Ma). Variation in the U/Pb ratios among individual spot analyses of single samples allows determination of a Tera-Wasserburg (T-W) intercept age with analytical 2o errors better than 5% for most samples. We used secondary reference materials to ensure accuracy, including WC-1 calcite standard (254 Ma; Roberts et al., 2017) and Duff Brown Tank (65 Ma; Hill et al., 2016). For these materials we obtained ages of 259.1 \pm 3.8 Ma, and 68.4 \pm 2.0 Ma, respectively, and equivalent to the accepted values. Given the long-term uncertainty of our standards, we expect the unknowns to be accurate to 5% or better; age uncertainty in figures is first shown in as the analytical uncertainty, followed by the propagated uncertainty in brackets (if necessary).

3.3. Calcite twin analysis

Calcite twins mechanically at low differential stress 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, 2016), calcite twin analyses traditionally are used to infer the finite strain and stress fields (Burkhard, 1993). For calcite strain analyses, we used a four-axis universal stage to measure twin orientations and the crystallographic orientation of the host crystals to calculate the maximum compression (and shortening) using a least-squares technique (Groshong Jr et al., 1984). Calcite strain axes are plotted in lower hemisphere projections with the great circle of the fault (or vein) together with contours of Turner’s (1953) compression axes. For more details about the methodology see Craddock and von der Pluijm (1999).

4. Results

4.1. Meso- and micro-structural observations

Fig. 3 shows several of the studied outcrops with their general setting. All these sites are well-mapped in at least 1:50,000 scale and considered in previous works as key sites for revealing the geological history of the SNSZ (e.g., Zilberman, 1981, 1983, 1985). Table 1 and Fig. 4 summarize the structural data collected along individual faults of the SNSZ. Supplementary data (item #1) includes micro-structural observations of all dated samples, including hand-sample photos, and microscope cross-polarized (XPL), plane-polarized (PPL), and
cathodoluminescence (CL) images of thin-sections. In what follows, we elaborate on our structural finding from each fault system.

4.1. Zin Fault system

We focused on two sites, ZF and ZFW (Table 1; Fig. 2), denoted in Avni and Zilberman (2000) as East Sede Zin fault and Havarim fault, respectively. These sites consist of ~W to WNW trending fault segments, which are two out of many short (~3 km) left-stepping, en echelon segments that form the Zin fault system in the Sede Boker area. In both sites, the Santonian-Lower Campanian chalk (Menuha Formation; see Reiss et al., 1985 for age) in the hanging wall is faulted against the Turonian limestone (Shivta-Nezar formations) in the footwall, with a throw of 20–30 m (Fig. 3a). The faults show mainly dip-slip motion with minor components of dextral or sinistral motion (Table 1; Fig. 4) and well-developed wall breccia and striae. Calcite-filled veins in the Zin fault zone are oriented in various directions (Shamir, 1983), and we sample one vertical WNW-trending vein, sub-parallel to the Zin lineament. Micro-structural observations of the ZF samples show mostly dextral shearing with extensive dilation and breccia cementation (ZF1, ZF4, and ZF5). In sample ZFW2a, the fault-wall is marked by cataclastic breccia with a distinct cementation phase (observed under CL).

4.1.2. Sa’ad-Nafha Fault system

The studied site SaF is a key site along the Sa’ad-Nafha lineament, located in the Wadi Hawwa graben (Figs. 2, 3a), where Zilberman (1981) shows several phases of activity during the Hazeva Formation time based on thickness and dip variations of the Hazeva members. In this site, The Hazeva Formation in the hanging wall is faulted against the Middle-Upper Eocene limestone (Matered and Har Agarab formations) in the footwall. The studied WNW-trending fault forms the northern border fault of the graben. The fault-wall breccia is well-developed but the fault plane lacks kinematic indicators. Micro-structural observations include breccia cement with twinned calcite and no clear shearing direction (SaF5).

4.1.3. The Ramon Fault system

We focused on two representative sites from the eastern (RF site) and central (RFW site) sectors of the Ramon fault system. The RF studied site is located in Wadi Kamai (Fig. 2; Fig. 3c), where systematic calcite-filled veins and fault coating, partly striated, are commonly observed adjacent to the trace of the fault. At this site, the fault trace is well defined by the stratigraphic separation (i.e., Cenomanian Tamar Formation against the Turonian Ora shales and Gerofit formations), but the wall breccia and striae are absent. The RFW site is located within the Ramon erosive cirque, about 10 km to the west of RF site. In this site we sampled striated calcite-filled veins and wall-breccia along subsidiary segments within the fault zone (Table 1). Micro-structural observations show both dextral (RF1, RF3, RF5; RFW1-2; RFWV2) and sinistral (RFW5, RFWV1) shearing with twinned calcite morphology. Syn-faulting indicators include slickenfibers (RF1, RF3), breccia cement (RF5, RFW5), and sheared vein-fill (RFW1-2). Post-tectonic calcite precipitates include vein-fill material that are not clearly sheared (RF4 and RFWV1-2), or do not show twinned calcite morphology (RF2).

4.1.4. Arif-Batur fault system

We studied the eastern part of the Arif-Batur lineament, where a complex of en echelon faults are exposed. The throw is often reversed, and each change in fault orientation is associated with the formation of fault-related half-domes and parallel synclines (Baer, 1981). A few samples were taken next to the trace of the fault in Ma’ale Hamishar, where the Gerofit Formation is faulted against the Menuha Formation (Figs. 2, 3d). Other samples were taken from Wadi Evus (Fig. 2), where a striated set of calcite-filled veins are exposed along a fault-parallel syncline next to the main trace of the fault (Table 1). Micro-structural observations show a clear dextral shearing (AB4-8), and only one sample preserves sinistral shearing (AB3). All samples show twinned morphology. Sample AB1 and AB10 do not show shearing deformation but AB10 is characterized by sutured grain boundaries.

4.1.5. The Poran fault system

We focused on the Karkom graben with its two right-stepping ~W-E trending border faults (Fig. 2). Four main localities were sampled next to the southern border fault (PaFS site) and one along the northern border fault of the graben (PaFN site; Fig. 3e; Table 1). At site PaFN, the fault plane is wavy, trending ~W to WNW and consists of prominent wall breccia and striae, which show oblique (dextral)-normal sense of motion. The Neogene Hazeva Formation in the hanging wall is faulted against Eocene limestone (Matred Formation) in the footwall, and are topped by undisturbed conglomerate of the Plio-Pleistocene Arava Formation (Fig. 3e; Calvo et al., 1998). Localities next to the southern border fault consist of the Neogene Hazeva Formation or the Eocene Avedat Group in the hanging wall, which are faulted against the Cenomanian-Lower Campanian Menuha Formation and the Eocene Avedat Group in the footwall. The fault segments commonly trend between WNW and W, with a mainly oblique-normal sense of motion. Non-systematic sets of calcite-filled injectites are widely exposed, forming intense deformation zones adjacent to the southern border fault in Wadi Sira. Micro-structural observations show a clear shearing of calcite precipitates with syn-faulting features such as breccia cement (PaF1-2, 9, PAFN-2, 4, 10c), hydrothermal veins, partially sheared (PaF10a-c), and small-scale sheared veins within fault wall (PaFN2-5). Sample PaF3 include some randomly-oriented veins that could be related to initial stages of brecciation.

4.1.6. The Thamad fault system

We studied two sites, at Wadi Raham in the east (TF10 site; Fig. 2), and at Wadi Shani in the west, where good exposures of fault planes and fault-related vein systems are exposed (TF1-9 site). In the west, the Zihor and Menuha formations in the hanging wall are faulted against the Precambrian basement rocks and the Cambrian Shehoret Formation in the footwall. In this sector of the Thamad lineament, the faulted units are topped by undisturbed Pleistocene sediments, indicating that this lineament ceased its activity prior to that time (Beyth et al., 2012). In Wadi Raham (TF10), the fault trace is well-defined by the stratigraphic separation (i.e., Cenomanian Hazeva Formation against the Turonian-Coniacian Geroft and Zihor formations), but the wall breccia and striae are absent. Fault-parallel calcite veins occasionally follow the trace of the fault. Micro-structural observations preserve sinistral (TF1-2, TF7, TF10) and dextral (TF8) shearing within small-scale structures.

4.2. LA-MC-ICPMS geochronology and U-Pb ages of syn-faulting calcite

The U-Pb ages of samples from the SNSZ are summarized in Table 3 and a few representative T-W plots are shown in Figs. 5-7. All T-W plots and raw data are available in the supplementary data (item #2). The samples analyzed commonly indicate a single population, but in few samples double and triple populations are also detected from different phases of calcite precipitates (Fig. 7). In such samples, more than one age is reported (Table 3). T-W dates have MSWD (mean square weighted deviation) values that are generally below 5, suggesting that most of the observed scatter can be explained by the analytical uncertainties (Figs. 5-7; Table 3); we interpret excess scatter to minor amounts of remobilization of Pb or U, inheritance, and/or multiple/ lengthy generations of growth. In site RF1, we dated the host rock and obtained dates of 98.9 ± 3.9 Ma (uncertainties are 2σ in-run precision). This age is in excellent agreement with the Cenomanian stratigraphic ages of the host rock in this site. All other ages are of secondary calcite that are younger than the stratigraphic age of the faulted rocks. Fig. 8 shows histograms and plots of age relative probability from SNSZ faults, excluding the Sa’ad-Nafha lineament, in which only a single age was obtained (Table 3). Along the Zin lineament, there is a distinct phase of activity between ca. 26.5 and 22 Ma, and a single
indication for a secondary fault activity at ~10.5 Ma. Along the Ramon lineament, ages range between ca. 23 and 9 Ma, with concentrated dates at ca. 19 and 12 Ma. Overlapping dates are detected along the eastern and western segments of the fault (sites RF and RFW; Table 3).

Along the Arif-Batur lineament, oldest dates are obtained from sheared veins and coatings, forming a distinct phase of activity as early as 73–71 Ma. Another sporadic phase of activity is detected at ~54–47 Ma. The activity along this lineament resumed at ~29 Ma, with probable events at ~19, 14 and 10 Ma. Along the Paran lineament (Karkom graben), the activity began as early as 25.5 Ma, and both southern and northern bounding faults were active at ~20 Ma (Table 3). Since then, fault activity continued until 10 Ma, with significant events between 14 and 11 Ma. Along the Thamad lineament, there is a distinct phase of activity between 17 and 15 Ma. Based on micro-structural observations, calcite with older dates (> 25 Ma) are associated with small-scale oblique normal-dextral shearing, while calcite with younger dates between 19 and 9 Ma are associated with either oblique normal-sinistral or normal-dextral shearing (see supplementary data; item #1).

4.3. Calcite twin analysis

Results of calcite twinning strain analysis of 57 samples from the SNSZ are summarized in Table 4. In cases where the data appears to be inhomogeneous, incompatible twins (“NEV”-negative expected values) were separated from compatible twins (“PEV”-positive expected
values). In most sites, 20–30 grains were analyzed, with low NEV (denoted as %NEV, Table 4) percentages indicated no twinning strain overprint is recorded. Three samples (ZFW, PaF-10 and PaFn-1) had high enough %NEVs such that a secondary twinning strain could be calculated (Table 4). Differential stress magnitudes are commonly between −40 to −30 MPa for twinning events along the SNSZ. Spatial and temporal variations of the principal strain axes are presented in Fig. 9, indicating that these directions generally vary within individual sites and between sites. The strain/stress directions obtained from the calcite in conjunction with the fault orientation suggest the sense of motion along individual lineaments and at certain times. In the early phase of activity (27–22 Ma) along the Zin lineament, both lateral and vertical senses of motion are detected, whereas at the late phase (~11 Ma) oblique-normal faulting is deduced. Along the Ramon and Arif-Batur lineaments, lateral motions are much more dominated than vertical motions. Along the Paran lineament (Karkom graben), lateral and vertical variations are detected, with notable variations of the direction of maximum shortening direction over time. An oblique-normal faulting is recorded along the Thamad lineament. We have plotted the shortening and extension axes for all dated samples in different groupings by U-Pb age and find a complex pattern of shortening and extension between 32 and 10 Ma along the various faults in the study (Fig. 10).

5. Discussion

5.1. Time of activity along the SNSZ

The present results provide the first direct ages of activity along the SNSZ based on in-situ U-Pb dating of syn-faulting calcites (Fig. 8). This activity began in the late Campanian-Maastrichtian or earlier, as the earliest ages were obtained along the Arif-Batur lineament at 73–71 Ma. These oldest ages were recorded by calcite-filled veins within the Arif-Batur deformation zone, but were not detected directly from fault planes. Quite sporadic activity along the Arif-Batur and Thamad lineaments was recorded at ~50 Ma (early Eocene). The main phase of activity began in the late Oligocene – early Miocene (27–22 Ma) as documented primarily along the Zin fault, as well as along the other lineaments of the system. Around 20–19 Ma (early Miocene), the Ramon, Arif-Batur and Paran lineaments were all intensively active, with the Thamad lineament resuming its activity about 2 Myr later. Subsequently, the activity along the Zin and Thamad lineaments significantly decreased post 20 and 14 Ma, respectively. Along the other fault lineaments, activity had continued until ~10 Ma. The results suggest that the Arif-Batur and Thamad lineaments were reactivated several times in the past 73 Ma, with long (~10–20 Ma) intervals of ‘dormancy’ in between its more active phases. The most significant reactivation or initiation of individual faults occurred at the late Oligocene - early Miocene. Since that time, all the SNSZ faults have been (re)active for about ~10 m.y. No direct ages have been detected in our data post late Miocene (< 10 Ma).

Several studies demonstrated the activity of the SNSZ post ~10 Ma. Zilberman et al. (1996) used morphological markers to detect Plio-Pleistocene tectonic activity along the Arif-Batur lineament. Paleoseismic studies along the Zin lineament suggested minor Holocene activity (Avni and Zilberman, 2006). Sharon et al. (2020) assessed the seismic sources and capable faults in Israel and environs and concluded that there are geologic indications for activity along the SNSZ until the early Pleistocene. Several seismically-oriented studies indicated that the SNSZ is presently active (e.g., Salamon et al., 1996; Abdel-Rahman et al., 2009). These studies are based mainly on analyses of two earthquake events located in central Sinai, the Mb 4.8, September 24, 1927 event (Ben-Menahem and Aboodi, 1981) and the Mb 4.5, April 6, 1984 event (Salamon et al., 1996), as well as some other minor (M < 3) earthquakes. Sawires et al. (2016) noted that the seismogenic sources in central Sinai include low seismic activity related to the

![Fig. 5. Example of fault-related calcite from Zin fault zone (site ZF, Fig. 2; sample ZF4). (a) subvertical striae along the fault plane (see Fig. 4). (b) photomicrograph of coarse-grained calcite cement under cross-polarized light (XPL). (c) plane-polarized light (PPL) images of laser ablation spot analyses (red pluses) within the calcite cement. Number of spots are given for the sample (d) photo of cathodoluminescence (CL) showing low-luminescence of the well-crystalized calcite in the dilation site in comparison to the high-luminescence of the surrounding micritic carbonate. (e) U-Pb Tera-Wasserburg concordia plots with 2σ error ellipses; MSWD - mean square of weighted deviates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](https://example.com/fig5.png)
Thamad and Paran lineaments and the Paran-DSF (B巴拉) fault junction in the Arava Valley (Figs. 1, 2). This fault junction was also highlighted as a potential seismic source of activity in the study of Hofstetter et al. (2007). Following these studies and our own results, we suggest that while the SNSZ is still active today. The lack of surface-rupture exposures of the SNSZ from the past ~10 m.y. are related to low-magnitude (< 5.5 M) seismicity during this period. Accordingly, syn-faulting calcite precipitates at near-surface conditions (< 500 m) are less likely to form under low-magnitude seismicity and limited surface rupturing (Nuriel et al., 2012a; Nuriel et al., 2019b). Syn-faulting calcite precipitates might form at shallow crustal depth (< 1000 m) along fault zones of the SNSZ, however, these fault zones have not been exhumed yet, as the estimated truncation (erosion) rate for the Israeli Negev during the Plio-Pleistocene is 20–60 m/Myr (Begin and Zilberman, 1997).

5.2. Temporal relations between the SNSZ and DSF systems

Nuriel et al. (2017) evaluated the onset and evolution of the DSF based on in-situ U-Pb dating of syn-faulting calcites. They applied
similar methodology and techniques used in the present SNSZ’s study. They obtained 30 ages from inactive DSF strands, 27 of which are from the Arava sector of the southern DSF, where the SNSZ and the DSF come across (Fig. 1). To facilitate a comparison between the SNSZ and DSF temporal activity over the last 30 m.y., histograms and relative probabilities of ages from the SNSZ ($n = 43$) and the southern DSF ($n = 22$) are presented together (Fig. 11). The dominant phase of activity along the SNSZ from ca. 27–22 Ma preceded the initiation of sinistral activity at ~20–18 Ma along the DSF by 2–7 Myr. Contemporaneous activity is detected along the two systems between ~20 and 12 Ma, while post-12 Ma activity is only observed along the SNSZ (until ca. 9 Ma). The apparent lack of activity along the seismically-active DSF post-12 Ma is a consequence of localization processes within the DSF that shifted the activity towards the main central axis at the Arava Valley (Fig. 1; Nuriel et al., 2017). The localized segments within the Arava Valley are covered by a thick pile of sediments and thus could not be sampled. Only exhumed and abundant strands off the central axis of the DSF were dated and no age younger than 12 Ma was detected (Nuriel et al., 2017). However, a late Pleistocene activity was dated by U-Th method in tectonically uplifted domains such as the Metulla saddle in northern part of the DSF (Nuriel et al., 2012b, 2012a; Weinberger, 2014).

Considering the vast number and the spatial distribution of the dated samples from the SNSZ, a relatively high number of obtained ages may serve as proxy for dominant period of fault activity. Fig. 11c shows a relative probability plot for both the SNSZ and DSF. For the overlapping period of activity between 20 and 12 Ma, episodes of fault activity along the SNSZ at ~19 Ma, ~17 Ma and 15–14 Ma were followed by episodes of fault activity along the DSF at 18, 16 and 13 Ma, respectively. Moreover, intense episodes of activity along one fault system were associated with a decrease in activity along the other system (Fig. 11c). An interconnected behavior of activity is also known from other pair of strike-slip fault systems. Records of faulting in

Fig. 8. Relative probability of ages along the individual faults within the SNSZ during the last 80 m.y. (a) Zin fault, including one age of 28.9 Ma from Sa‘ad-Nafha Fault; (b) Ramon fault; (c) Arif-Batur fault; (d) Paran fault; and (e) Thamad fault.
Anatolian Fault Zone (NAFZ) and East Anatolian Fault Zone (EAFZ) (Dolan et al., 1993) and the San Andreas Fault (SAF) and East California Shear Zone (ECSZ) (Dolan et al., 1993). The temporal relations between the SNSZ and DSF highlight the possibility that these fault systems are mechanically interrelated. The exact mechanism for this fault interaction needs further study, but its timescale is certainly much longer than the earthquake cycle.

As the lineaments of the SNSZ actually expressed the reactivation of structures that are much earlier than 10 Ma, which contradicts the initiation time of 20–18 Ma based on in-situ U-Pb ages (Nuriel et al., 2017) and other geological evidence summarized in Garfunkel (2014). Hence, the Miocene movement along the SNSZ actually expressed the reactivation of structures that are not consistent with the inferred age constraints.
and spatial relations between the two systems raise the possibility that the (re)activation of the SNSZ might be related to the 25–18 Ma phase of extensional tectonics during rifting and Africa-Arabia breakup. We therefore review other temporal and spatial evidence for late Oligocene-early Miocene activity in the Sinai and Western Arabia plates postulated to be related to Africa-Arabia breakup.

According to Stockli and Bosworth (2019), during the latest Oligocene – early Miocene (~25–21 Ma) the Red Sea rift system exhibited diffuse stretching, affecting a wide area of ~1200 km around the northern Red Sea. The areas affected include the Western Desert in Egypt, Nile Valley, and Saudi Arabian and Jordanian interior. Fission track evidence suggests a pre-DSF exhumation of SW Jordan, which occurred at the time of rifting initiation at the Red Sea, despite being ~200 km from the rift margin (Feinstein et al., 2013). Farther away, ~500 km from the Red Sea rift margin, the NW-trending Azraq-Shihran graben and the Iribid rift zone in NW Jordan were reactivated during the Oligocene (Segev et al., 2014). At that time, a graben-forming event in the region was reported by Avni et al. (2012), who recognized several small-scale grabens preserving late Eocene-early Oligocene successions, several of which are trending NW-SE (Red Sea parallel) and E-W (SNSZ parallel). The rifting and Africa-Arabia breakup might also reactivate the Levant passive margin during the late Oligocene, forming a margin-parallel fault zone (Gvirtzman et al., 2008; Gvirtzman and Steinberg, 2012). In Harrat Ash Shaam, volcanic activity started at ~27 Ma along NW-trending fissure eruptions located ~350 km from the Red Sea rift margin (Ilani et al., 2001). Most voluminous, early Miocene magmatism occurred outside the main Red Sea-Gulf of Suez rift in the greater Cairo area (e.g., Stockli and Bosworth, 2019). Closer to the Red Sea – Suez rift margin, in a ~50–150 km wide zone and 1700 km long, a swarm of rift-parallel NW-trending dikes were emplaced mainly between 25 and 20 Ma (e.g., Camp and Roebel, 1989; Bosworth and Stockli, 2016), coeval with the main phase of significant exhumation and extensional tectonics. Bar et al. (1974) determined absolute ages of faulting by measuring fission track ages of epidote, which crystallized along fault planes that cutting Neoproterozoic rocks in Sinai. Two reported dates were obtained from epidote coating E-W trending faults in SE Sinai, and yield ages of 27.2 ± 0.8 and 14.9 ± 1.9 Ma. These ages attest for the possibility that activity along E-W trending faults in Sinai are coeval with that of the E-W trending SNSZ. Moreover, most of the epidote-based samples from Sinai yield Oligocene-Miocene ages of 32–11 Ma. The temporal and spatial relations between the wide (~1200 km) area of extensional faulting in the northern Red Sea – Gulf of Suez and the strike-slip faulting in the Sinai-Negev region strongly suggest that the SNSZ was (re)activated by the ~25–20 Ma main phase of rifting. We therefore include the Sinai-Negev region within the location of synchronous faulting during rifting around the northern Red Sea – Gulf of Suez (Fig. 12).

By incorporating the low temperature Apatite (U-Th)/He age constraints and thermal modeling, Morag et al. (2019) demonstrated that the phase of enhanced exhumation waned by ~18 Ma. Gvirtzman and Steinberg (2012) reported that the Levant continental margin fault zone ceased its activity at about that time. This waning correlates with an intense episode of activity along the DSF at 18–16 Ma, which started to accommodate the sinistral motion along the Sinai-Arabia boundary a bit earlier at ~20 Ma (Nuriel et al., 2017). Stratigraphic constraints from Midyan basin in NW Saudi Arabia suggest that strike-slip faulting commenced at that region after ~14 Ma (Bosworth et al., 2005), attesting to the complex evolution of the DSF as a through-going plate boundary during the early-middle Miocene. In summary, the Africa-Arabia breakup led to reactivation of several fault systems, including the SNSZ, and the initiation of intraplate volcanism in the region that highlight the significance of NE-SW extensional tectonics in the region during the late Oligocene – early Miocene. In the early Miocene, rifting along the Gulf of Suez diminished, emplacement of the Red Sea dikes ceased, strain was localized along the Red Sea rift, and the sinistral motion along the DSF commenced concurrent with activity along the SNSZ.

5.3. Temporal relations between the SNSZ, the Red Sea - Suez rift and neighboring structures

The onset of Red Sea rifting is marked by basaltic dike emplacement, syn-rift subsidence and sedimentation, and rapid rift-related fault block exhumation at ~25–23 Ma along the entire Red Sea-Gulf of Suez rift system (see Stockli and Bosworth, 2019 for review). An extensive fission track dating of samples from the western margin of the Gulf of Suez indicate that rift flank exhumation started at ~23–21 Ma, approximately coeval with the basin subsidence (Omar et al., 1989). Omar and Steckler (1995) suggested an early pulse of exhumation and an onset of rifting at ~34 Ma, but geological and thermochronometric evidence make this cooling event enigmatic (Garfunkel and Beyth, 2006; Stockli and Bosworth, 2019). Apatite (U-Th)/He and fission track data from the Sinai constrains a prominent pulse of extensional-related exhumation along the Suez rift at 25–18 Ma (Morag et al., 2019). This pulse of exhumation coincides with the main phase of activity (27–22 Ma) detected along the SNSZ in this study. As the SNSZ is located 200–300 km away from the Red Sea - Suez rift, these temporal

considerably older than the DSF, and that the younger phases of their activity occurred after the initiation of the DSF.
5.4. Paleo-strains (stresses) at the SNSZ over the last ~70 Ma

During the Cenozoic, Gondwana fragmented into several plates (Africa, Arabia) and sub-plates (e.g., Sinai, Somali) and variable intraplate paleo-stresses might have imposed within the central Sinai-Negev by the growing Red Sea and Dead Sea plate boundaries. The paleo-stresses are the prime factor that control the evolution and style of fault systems such as the SNSZ. We therefore assess them at the central Sinai-Negev region over the last ~70 Ma. For this analysis, we distinguish between first, second and third-order of stresses (e.g., Zoback et al., 1989), and assume that the paleo-stresses are coaxial with the paleo-strains. First are the regional stresses of the eastern Mediterranean subduction and collision areas (Letouzey and Tremolieres, 1980; Bahat et al., 2005), which prevailed since the Upper Cretaceous. These stresses later interfered with stresses exerted by the opening of the Red Sea - Suez rift, and the transcurrent motion along the DSF. Second are the stresses that originate within the SNSZ and cause structural and style changes in the system. Third are local stresses that are confined to particular outcrops and structures along the SNSZ. For the sake of simplicity, we present four snapshots of the inferred strains (stresses) at 70 Ma, 25 Ma, 12 Ma, and Recent (Fig. 13), and discuss these phases below.

The Syrian Arc fold belt (Krenkel, 1924) forms a sigmoid fold system that stretches from Syria in the north, through Israel and Egypt in the south. The presence in the strata of several hiatuses and angular unconformities demonstrates that several folding episodes occurred along this belt from early Coniacian to the Maastrichtian/Paleocene transition, and then in Cenozoic times (Bartov et al., 1980; Eyal, 1996; Zur et al., 1996; Guiraud and Bosworth, 1997). However, only faint activity of folding occurred after the deposition of the Hazeva Formation (Zilberman et al., 2011). Offshore at the Levant basin, the folding has peaked in the entire basin during the early Miocene, and has gradually

Fig. 10. (a)-(h) Lower hemisphere projections of calcite strain data (Table 4) colour-coded to U-Pb ages (Table 3). Filled circles are shortening axes; open circles are extension axes. In (f) and (g) all dated calcite (n = 39) are projected, and in (h) is all data (n = 60).
decreased since the late Miocene up to the Pliocene (Sagy et al., 2018). The close proximity of the Syria Arc fold belt and the SNSZ (Fig. 1) suggests that these systems were affected by the same paleo-stresses, termed the Syrian Arc stress field (SAS; Eyal and Reches, 1983). The SAS is the first-order regional stresses at the eastern Mediterranean, prevailing during the formation and growth of the fold belt (and up to Recent; Eyal, 1996) with dominating maximum horizontal shortening trending WNW-ESE (denoted SH\text{max}). The SAS is concomitant with a second-order coaxial stress within the SNSZ that promoted emergence of NNE-trending folds along fault irregularities (Fig. 13a; Bartov, 1974), and possibly dextral motion along the E-W and ENE-WSW lineaments.

The displacement of the ~22–20 Ma Red Sea dikes gives an age constraint on the SNSZ dextral motion, nonetheless there is no indication that the older, pre-Miocene contacts are displaced by the same amount as the dikes. Hence, the possibility that part of the dextral motion occurred pre-20 Ma could not be excluded. Indeed, U-Pb ages highlight the activity along oblique normal-dextral faults prior to 20 Ma, at 73–71 Ma, 50–49 Ma, and in particular between 27 and 22 Ma (Tables 1, 3). A snapshot of the paleo-strains at ~70 Ma is presented in Fig. 13a.

Deformation during the Eocene was relatively mild (e.g., Flexer, 2001). Based on studies of joint orientations, it appears that NW-SE maximum horizontal shortening operated since the early Eocene and continued into the middle Eocene (for summary see Bahat et al., 2005 and Levi et al., 2019). Deformation during the Oligocene - early Miocene, when the break up of Arabia from Africa commenced, was significantly intensified (e.g., Chorowicz, 2005; Bosworth et al., 2005). It is widely accepted that a major phase of extensional tectonics at the Red Sea - Suez rift took place between 25 and 18 Ma (e.g., Omar and Steckler, 1995; Bosworth et al., 2005; Garfunkel and Beyth, 2006; Morag et al., 2019), suggesting that stresses imposed by this extension were superimposed upon the SAS. The extensional-related features, mainly the NW-trending normal faults and dikes (Fig. 1), indicate that the maximum extension Sh\text{min}, (i.e., minimum horizontal shortening) at the boundaries of these features trended NE-SW. Several Red Sea dikes, tens of kilometers long, were emplaced in the SNSZ region (Fig.1, Bartov, 1974), indicating that local (second-order) extension prevailed in the central Sinai the very early Miocene. The NE-SW trending Sh\text{min} extension promotes dextral motion along pre-existing E-W to ENE-WSW lineaments of the SNSZ. These dikes have later been dextrally offset by the SNSZ, indicating that post-emplacement paleo-strains- were also compatible with the dextral motion. A snapshot of the paleo-strains at ~25 Ma is presented in Fig. 13b.

In the early Miocene (~20–18 Ma), the transcurrent DSF was initiated (Nuriel et al., 2017), transferring laterally the opening of the Red Sea to the Bitlis convergent zone in Turkey. Accordingly, the extension direction along the Red Sea was changed from rift-normal to oblique extension. The paleo-stresses attributed to the DSF are known as the Dead Sea stress field (DSS; Eyal and Reches, 1983), which was superimposed on the SAS during the Miocene-Holocene. The maximum horizontal shortening trends NNW-SSE (Sh\text{max}, Eyal, 1996). The proximity of the two systems (DSF and SNSZ) suggests that the DSS should originate second-order stresses within the SNSZ and possibly cause structural and style changes in the system. Because of the high angle (> 70°) between the traces of the SNSZ and the direction of the NNW-SSE trending SH\text{max}, the dextral motion along the SNSZ was certainly suppressed since the early Miocene. However, pre-existing E-W to ENE-WSW lineaments of weakness might still accommodate oblique-normal faulting. Locally, even an oblique normal-sinistral faulting could occur as indicated by third-order stresses inferred from a few thin sections. A snapshot of the paleo-strains at 12 Ma after ~40–50 km of sinistral motion along the DSF are presented at Fig. 13c.
The dominant DSS potentially effect the central Sinai-Negev region in the Holocene. Close (< kms) to the southern DSF, trajectories of the DSS aligned themselves parallel to the trace of the transform as predicted theoretically by Garfunkel (1981) and was detected by joint orientations (Levi et al., 2019) and magnetic fabric-based studies (Issachar et al., 2019). Borehole breakout studies in exploration well indicate that the minimum horizontal stress (i.e., coaxial with Shmin) in the Holocene. Close (< kms) to the southern DSF, trajectories of the transform as predicted theoretically by Garfunkel (1981) and was detected by joint orientations (Levi et al., 2019) and magnetic fabric-based studies (Issachar et al., 2019). Borehole breakout studies in exploration wells indicate that the minimum horizontal stress (i.e., coaxial with Shmin) in the southern Gulf of Suez is presently aligned ~NNE-SSW, parallel to the relative slip trajectory of Sinai versus Arabia along the DSF in the Gulf of Aqaba (Bosworth et al., 2019). GPS-based analysis across the Red Sea (e.g., ArRajehi et al., 2010) demonstrate that the extension direction along the northern Red Sea is oblique to the plate boundary. A snapshot of the modern strains are presented at Fig. 13d.

The stress directions obtained from SNSZ syn-faulting calcite twins show pronounced spatial and temporal variations between faults and along individual faults (Fig. 9; supplementary data; item #3). Traditionally, calcite twins are considered reliable indicators for long-term, regional paleo-stresses (e.g., Burkhard, 1993). This could certainly be the case for a long-lasting, first-order regional stress field, in which the associated maximum compression (shortening) is uniformly recorded by twinning of the tectonically deformed calcite-bearing host rock. For the SNSZ, we demonstrate that the imposed paleo-stresses within the central Sinai-Negev were not uniform over time, but have changed with the formation of new plate boundaries in the region. This implies that the twins in the present case study might have resulted from third-order stresses at an outcrop scale, which evolved during the faulting processes at breccia cements and fault gouges. This view is strengthened by several rock-mechanics experiments and field-based studies. For example, Delle Piane et al. (2018) explore the micro-mechanical processes that occur during fault nucleation and slip at sub-seismic rates (~3 × 10^{-6} m s^{-1}) in carbonate rocks. Their experiments demonstrate that the alignment of twins in syn-faulting gouge could be locally varied in their directions, and, hence, the causative inferred stress directions are slip-dependent. Smith et al. (2013) and Smith et al. (2013) report on gouge layers that deformed mainly by twinning and fracturing during shear experiments performed at low- to high-velocity designed to impose realistic co-seismic slip pulses on calcite fault gouges. Their results indicate that the mechanical twinning could form at high strain rates and shear velocities that are comparable to those in co-seismic events. Bullock et al. (2015) studied the micro-structure of the Gubbio fault, which is an active (1984, Ms. = 5.2) normal fault in Italy. They characterize fault-core domains derived from limestone and show that syn-faulting calcite twins are common within the breccia cement of the fault. They demonstrate that twins at different domains of the fault core can deform at different stages of the seismic cycle, and, at certain domains may record directions of stress relaxation rather than the direction of imposed shear during slip. We therefore suggest that the spatial and temporal variations in the third-order stress (strain) distribution documented by the calcite twins and micro-structures (Supplementary data #1) reflect fault-zone processes under the action of an inhomogeneous stress field extracted by the growing new plate boundaries at the region.

The 60-90° dihedral angle between the SNSZ and the DSF, the opposite sense of lateral shearing and the contemporaneous activity along the two systems since the early Miocene apparently attest for the systems being a conjugate set. However, this possibility can be rejected based on the obtained U-Pb ages, as they unequivocally indicate that the activity along the SNSZ significantly pre-dated that of the DSF. In that sense, the two systems originated under different stress field, and therefore could not be considered a conjugate set. For the DSF, the DSS is optimally oriented leading to the accrual of 105 km of sinistral displacement. For the SNSZ, the DSS is unfavorably oriented and,
consequently, the total accumulated dextral displacement is only a few kilometers.

We envision the SNSZ fault activity being a reactivation of pre-existing discontinuities in the underlying Precambrian crystalline rocks (Dvory, 2002). Reactivation in the Cenozoic was associated with faulting and folding of the sedimentary cover above. The faults commonly breach the surface, although the western sector of the Sa'ad-Nafha lineament is not exposed. Our analysis indicates that since the Oligocene, the pre-existing SNSZ was not optimally oriented relative to the intraplate paleo-stresses. However, some overall dextral motions have continued on the SNSZ concurrent with the sinistral motion along the DSF during the early and middle Miocene. These contemporaneous motions have not obscured each other, similar to the present situation in southern California, where the active transverse East California Shear Zone (ECSZ) meets the San Andreas Fault (SAF) (e.g., Jennings, 1973; Garfunkel, 2014). The total observed dextral motion along the SNSZ is two orders of magnitude smaller than that of the sinistral motion along the DSF, and, hence, might be absorbed without significantly distorting the trace of the DSF at the junctions between the two systems.

Fault architecture and kinematics at these junctions are not yet clear. There is very limited subsurface data (Frieslander, 2000; Dvory, 2002; Medvedev, 2004) and most of the interpretation is based on fault traces at the surface. At a distance between 20 and 10 km from the DSF, the Thamad lineament trends 265°-85°, whereas at a distance less than 10 km it trends ~240°-60°. This ~25° counterclockwise rotation in the strike of the fault may be the result of proximity to the DSF (Bartov, 1967); the sense of the strike rotation compatible with the expected sense of dragging during sinistral motion along the DSF. Moustafa and Khalil (1994) suggested that such dragging would lead to block rotation and re-activation of the bounding faults of the SNSZ by dextral strike slip. However, direct indications (e.g., rotation of paleomagnetic vectors) for block rotation are absence. Further north, the

Fig. 13. Synthesis of main events along the Sinai-Negev shear zone (SNSZ) and environs. The strain directions (assumed to be coaxial with the stress directions) dominated at each event is indicated in the vicinity of the SNSZ and marked with red arrows. $SH_{\text{max}}$ - maximum horizontal shortening; $Sh_{\text{min}}$ - maximum horizontal shortening (i.e., maximum extension). Traces of faults, anticlines and dikes are schematic. Black and gray traces refer to active and inactive lineaments, respectively. Present-day coastlines are marked with blue lines and are shown for orientation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Paran lineament approaches the DSF at nearly a right angle, although ~10° counterclockwise rotation of the fault strike is observed at a distance less than 20 km from the DSF. At the subsurface, an intensely fractured zone is observed without a clear continuation of the Paran lineament further to the east (Frieslander, 2000). While the fault traces of the Thamad and Paran lineaments at the junction with the DSF are quite clear, those of the other SNSZ faults are indistinct. For the Ramon lineament, it has been suggested that close to the DSF it splits into two NE-SW (termed Massor) and SE-NW (termed Marzeva) trending strike-slip faults (Bentor and Vroman, 1954). This may imply that the Ramon lineament propagated into this zone after the formation of the DSF. On the other hand, subsurface data suggests that the Ramon lineament protrudes straight into the DSF (Frieslander, 2000), exemplifying the complex relations and the lack of coherent view of the fault architecture at depth.

6. Conclusions

We review the geologic setting of the Sinai-Negev Shear Zone (SNSZ), a major fault system that is composed of several ~E-W to ENE–WSW trending faults, tens to hundreds of kilometers long forming a ~120 km wide shear zone in the Sinai sub-plate. In order to better constrain the spatial and temporal activity along the SNSZ, recent advances in U-Pb geochronology of syn-faulting calcite are implemented to date directly the activity along this system. In this contribution, we also assess the complex relations between the SNSZ and the Dead Sea Fault (DSF). The results indicate that deformation along the SNSZ initiated in the late Campanian-Maastrichtian or earlier, as the earliest dates were obtained at 73–71 Ma. The main phase of fault activity began in the late Oligocene – early Miocene (27–22 Ma) as documented along several lineaments of the SNSZ. This main phase of activity was mainly dextral and precedes the activity along the DSF, but coincides with a prominent pulse of exhumation along the Suez rift at 25–18 Ma. As the SNSZ is located 200–300 km away from the Red Sea - Suez rift, these temporal and spatial relations between the two systems suggest that the (re)activation of the SNSZ might be related to the phase of extensional tectonics during rifting and Africa-Arabia breakup.

The in-situ U-Pb ages are compatible with previous stratigraphic evidence for the age of SNSZ activity (e.g., Bartov, 1974; Zilberman, 1985), but in details provide a much better age constraint on phases of activity and ‘dormancy’. The dominant phase of activity along the SNSZ at 27–22 Ma preceded the timing of initiation of lateral faulting along the DSF at ~20–18 Ma by a few Myr. For the overlapping period of activity between 20 and 10 Ma, dominant episodes of fault activity along the SNSZ were followed by dominant episodes of fault activity along the DSF ~1 Myr later. Moreover, episodes of activity along the DSF were associated with a decrease in activity along the SNSZ. The temporal relations between the SNSZ and DSF highlight the possibility that these fault systems are mechanically interrelated. The exact mechanism for this fault interaction needs further study, but its timescale is certainly much longer than the earthquake cycle.

We show that the formation of new plate boundaries in the region (Red Sea - Suez rift; DSF) affects the stress field within the SNSZ. The proximity of the two systems indicates that the DSF-related stress originated within the SNSZ and possibly caused structural and style changes in the latter system. We demonstrate that the imposed stress within the central Sinai-Negev was not uniform over time as the stress directions obtained from syn-faulting calcite twins and micro-structures within the SNSZ show pronounced spatial and temporal variations between and along individual faults. We suggest that small-scale movements along some deep-seated pre-existing discontinuities reactivated various parts of the SNSZ. It seems that the deformation has never been localized along one single fault in the past ~70 Ma. Because of the high angle (~70°) between the traces of the SNSZ and the direction of the DSF-related maximum compression (shortening), the dextral movement along the SNSZ was suppressed post-20 Ma. However, some oblique normal-dextral and normal-sinistral motions have continued on the SNSZ concurrent with the sinistral motions along the DSF during the early and middle Miocene. These contemporaneous motions have not obscured each other, similar to the present situation in southern California. Notably, geological evidence, and U-Pb dates shows that the SNSZ has been active during the Miocene, and current seismicity indicate that it may still be active today alongside with the dominantly seismically-active DSF.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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