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# Nature of slip transfer between strike-slip faults: The Eastern Sinai (Egypt) shear zone, Dead Sea Transform

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A B S T R A C T

The western margin of the Gulf of Elat (Aqaba), a sector of the Dead Sea Transform, is characterized by an N–S striking shear zone with cumulative sinistral (left-lateral) offset of 24 km. The crystalline basement in the study area is unique in its excellent rock and fault exposures forming a >50 km long, shear zone with abundant offset of linear features as well as the contact of the basement with the Infracambrian sub-horizontal peneplain. These features enable accurate measurement of the horizontal and vertical displacements along the major and secondary faults to ±50 m. The small vertical offset of the peneplain surface and a measurement of about 8° net-slip plunge along one of the major faults suggest that along all strike-slip faults, movement was almost pure horizontal slip. Part of this horizontal slip was transferred to neighboring major strike-slip faults by secondary strike-slip faults with negligible loss of displacement. The amount of horizontal slip transferred by normal faults, even in releasing bends, is small due to the high dip angle of these faults. Wide breccia zones and distributed deformation of a small fraction of the horizontal slip is observed when the angle between the strike-slip faults exceeds 30°.


## 1. Introduction

Faults are among the most common structures in the earth's crust and usually appear as sub-parallel sets of normal, reverse, thrust and strike-slip faults (e.g. Freund et al., 1970; Ziegler, 2002; Garfunkel, 1974; respectively). Transform faults are plate boundaries and therefore of global tectonic importance. Continental transforms, such as the San-Andreas, Alpine and Dead Sea faults tend to be long with large (>100 km) horizontal displacements. Transform faults, as well as other large strike-slip faults, may be associated with significant wide or narrow shear-zones. Shear zones of more than 100 km wide characterize the Alpine and southern part of the San Andreas faults (Norris and Toy, 2014; Crowell, 1979; respectively), whereas narrow shear zones occur along faults such as the eastern part of the north Anatolian fault (Betkas et al., 2007). For both of these geometries most slip occurs along the main fault with the remainder distributed among secondary faults of the shear zone. Localization of slip may change along the same fault, as for example, the North Anatolian fault, where slip is localized along the western part but distributed between several faults in the eastern part (Betkas et al., 2007). Hence, shear zones along transforms and other large strike-slip faults play an important role in their kinematic behavior. The geometry and kinematics of secondary structures in these zones are important contributors to accommodating displacement transfer through or into the systems. Stepping of strike-slip faults often forms rhomb-shaped grabens (pull-aparts) or push-ups, depending on the sense of motion relative to sense of stepping (e.g. Aydin and Nur, 1982; Garfunkel and Ben-Avraham, 1996). Diminishing of horizontal displacement along strike-slip faults of different scales may occur within short distances when the main fault branches into a horsetail splay (Christie-Blick and Biddle, 1985), with partitioning of slip between the branches (e.g. Freund, 1971; Spicakova et al., 2000). Strike-slip shear zones are often characterized by anastomosing splitting and merging of secondary faults (Christie-Blick and Biddle, 1985). Slip transfer between major strike-slip faults via secondary normal faults occurs Eyal et al. (1986), Reheis et al. (1996), Mouslopoulou et al. (2007). The Dead Sea Transform (DST) is one of the important continental transforms, and therefore, the behavior of faults and transfer of displacement between faults forming its shear zone can shed light on other transforms in the world. This study investigates and demonstrates transfer of horizontal slip between three major strike-slip faults in the crystalline

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basement in the eastern Sinai shear zone (Fig. 1) via secondary strike-slip faults. The change of displacement and absorption of slip along the faults is analyzed by measurements based on precise mapping of displaced markers.

## 2. Geological setting

### 2.1. The Bir Zereir shear zone

The Gulf of Elat (Aqaba) is the southernmost segment of the 1000 km-long sinistral DST (Fig. 1, inset a). This transform is associated with the breakup of the African and Arabian plates and opening of the Red Sea (Freund, 1965; Girdler and Styles, 1974). It initiates at the southern end of the Gulf of Elat and terminates in the Bitlis collision zone southern Turkey. Along this fault system, 105 km of sinistral displacement has been identified in the sector between Elat and the Dead Sea (e.g. Quennell, 1959; Freund et al., 1970; Bartov, 1974). Left-stepping of the DST segments in the Gulf of Elat resulted in the formation of five pull-apart basins partly filled with young gulf sediments (Ben-Avraham, 1985). Shear zones occur on either side of the Gulf of Elat in Sinai and Arabia.

In Sinai the width of the shear zone is about 30 km with NNE-SSW to N–S trending faults sub-parallel to the gulf axis (Bartov et al., 1980). A cumulative displacement of 24 km was measured, independently, at several localities across the belt (Eyal et al., 1981). These zones are associated in places with rhomb-shaped grabens, thick fault breccia zones, fault gouge zones and sandstone dikes. The shear zone along the western margin of the Gulf of Elat has been divided into five segments (Eyal et al., 1981) of which the eastern part of the central segment (Figs. 1 and 2), the Bir Zereir segment, constitutes the focus of the present study. This area, >50 km long and 10–15 km wide, is located between the Gulf of Elat and the Nuweiba-Dahab road (Fig. 1) in the northern part of the Arabian-Nubian shield exposure. Nine late Proterozoic magmatic plutons were identified in the study area with compositions ranging from gabbro to granite (Fig. 1). The contacts between the plutons are sub-vertical, their general trend is E–W, and they cross the major faults at high angles. The plutons are often cut by sub-vertical NE-to NNE-trending dikes that sometimes form swarms comprising more than 70% of the area, indicating a significant late Precambrian extension phase. The Miocene NW Mutarish olivine basalt dike, a few tens of meters thick, transects the northern part of the study area (Fig. 1) and is associated with the opening of the Red Sea (Eyal et al., 1981).

### 2.2. The infracambrian peneplain

An Infracambrian sub-horizontal peneplain widely exposed on the Arabian-Nubian shield margin (Weissbrod, 1969) can be viewed in this area. This peneplain is overlain by a basal siliciclastic sedimentary succession dominated by the Nubian sandstone ranging in age from Cambrian to early Cretaceous (Weissbrod, 1969), overlain by platform carbonates with chert and sandstone interbeds of Cenomanian to Eocene age (Bartov and Steinitz, 1977). In the Bir Zereir region a nearly complete sedimentary section is found only within grabens, whereas outside grabens only the lowermost units of the Nubian sandstone may be found in patche. Most of the sedimentary cover was removed during the Neogene, exposing the late Precambrian crystalline basement during uplift of about 3 km (Kohn and Eyal, 1981; Garfunkel, 1988).

In the study area, as in the northern part of the crystalline basement of Sinai, the peneplain is a flat erosional plane almost without relief. The upper erosional surface of the peneplain is also characterized by a black patina rich in iron oxides sometimes a few meters thick. This surface can serve to identify the peneplain where the overlying sediments are totally removed. The peneplain surface dips 2°–3° northward, so that the sedimentary cover to the south has been totally removed, whereas the crystalline basement dips beneath sedimentary cover to the north.

### 2.3. Structures and offsets

Five major N–S- trending sinistral strike-slip faults, named, from west to east, the Gharib, Uqda, Amid, Risasa and Abu Galum, transect the Bir Zereir shear zone segment (Fig. 1), and either start or terminate at the Gulf of Elat. Secondary faults that connect the major faults, and transfer horizontal slip between them, mostly trend NNE with a few striking NW. Grabens, tilted blocks and rhomb-shaped grabens formed along the major faults according to the geometry governed by their change of trace geometry with respect to the overall kinematics of the zone. Thin breccia zones occur at the major faults as well as most NE-trending faults when the angle between them and major faults is less than 20°. However, thick breccia zones up to 100 m wide are observed when the angle between two segments of a fault or between a major and a secondary fault is 30–40°. The horizontal offset along the faults ranges from tens of meters to ten kilometers, and the cumulative horizontal displacement across the entire width of the Bir Zereir shear zone, along E–W cross sections, is about 24 km (Eyal et al., 1981). The vertical separation along faults ranges from a few tens of meters to about 900 m. Equal horizontal offset of both Precambrian contacts and early Miocene olivine basalt dikes along the same fault indicate commencement of slip after emplacement of the Miocene dikes (Bartov et al., 1980; Eyal et al., 1981). Therefore, a detailed kinematic analysis of displacements along faults is possible based on the precise dataset of horizontal and vertical displacement.

## 3. Method

The high quality of exposure in the Sinai desert enables precise measurements of both horizontal and vertical offset components (Table 1). The horizontal component is based mainly on displaced subvertical intrusive contacts between magmatic plutons. Abundant NNE-to NE-trending Infracambrian dikes can be ideal for measuring horizontal displacements, but not all dikes may be used because the correlation of specific dikes on both sides of a fault is difficult due to their high density and the small angles of their strike with the faults. Only dikes that are sub-perpendicular to the faults, and with unique diagnostic features, such as uncommon petrography, color or thickness can be used. The Miocene Mutarish dike is a particularly useful marker due to its unique alteration and NW trend, which is sub-perpendicular to the strike of the major faults.

The contacts between the plutons were followed in the field, mapped on high quality color 1:40,000 air photos, and then transferred to 1:50,000 topographic maps. The accuracy of measured offset was about ±100 m. Using Google Earth images and the Ruler tool application enabled enhancement of accuracy to ±50 m. The amount of horizontal slip transferred between the major faults via secondary faults was calculated by measuring the offsets along the faults south and north of every major/secondary fault junction. Vertical fault separation was calculated based on elevation differences of the sub-horizontal Infracambrian peneplain on either side of the fault, and its accuracy is in the order of 50 m. Estimation of the net slip angles for several fault segments was calculated based on the horizontal and vertical offsets (Table 1). Where an intersection between the planes of the horizontal peneplain and the subvertical magmatic contacts and fault occur, a piercing point that enables measurement of the net-slip displacement is established.