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Morphotectonics inferred from the analysis of topographic lineaments auto-detected from DEMs: Application and validation for the Sinai Peninsula, Egypt

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ABSTRACT

Morphotectonic lineaments observed on the Sinai Peninsula in Egypt were auto-detected from Shuttle Radar Topography Mission 90-m digital elevation model (DEM) and gravity grid data and then analyzed to characterize the tectonic trends that dominated the geologic evolution of this area. The approach employed consists of DEM shading, segment tracing, grouping, statistical analysis of the distribution and orientation of the lineaments, fault plane characterization, and smooth representation techniques. Statistical quantification of counts, mean lengths, densities, and orientations was used to infer the relative severity of the tectonic regimes, to unravel the prominent structural trends, and to demarcate the contribution of various faulting styles that prevailed through time. Restored to the present-day geographic position, prominent N50°–60°W, N20°–40°W, N50°–60°E, and N20°–30°E and less prominent N–S, E–W, and ENE trends were common. The prominence of these trends varied through time. The NW and NE trends showed relatively equal abundances in the Precambrian and the Cambrian whereas the prominence of the NW trends prevailed from the Carboniferous to the Holocene. Lineaments in all formations were near vertical and on average, about 65% showed as strike-slip, 22% as reverse, and 13% as normal faulting styles. Statistics from the detected linear features and the reference geological data reveal the relative severity of five dominant tectonic regimes: Precambrian compression followed by extension at its end, Cretaceous compression, Eocene compression, Miocene extension, and finally Holocene compression. Auto-detected lineaments and the severity of the characterized tectonic periods correspond well with reference data on the geologic structure, geodynamic framework, and the gravity anomaly. Furthermore, the recent significance of the broad structural zones was confirmed by the foci of the earthquake epicenters along and at the intra-plate intersections of the broad lineament zones and at the plate boundaries. The spatial distribution of trends with varying styles of faulting distinguished four main tectonic provinces of marked geodynamics variances.

1. Introduction

Crustal tectonic deformation and topography share a common origin in the large-scale dynamics of the underlying mantle and upper mantle thermal perturbations (Cloetingh et al., 2003, and references therein). These dynamics affect various mechanisms of observed large-scale crustal uplift (Gurnis et al., 2000; Lithgow-Bertelloni and Silver, 1998) and subsidence (Mitrovica et al., 1989; Stern and Holt, 1994). Stress fields driving lithospheric tectonic deformation are largely confined to plate boundaries, but can transmit to the plate interior where they interplay over the long term with climatic/geomorphic processes and give rise to continental domains (e.g., Burbank and Anderson, 2001; Roessner and Strecker, 1997; Summerfield, 2000). The structures and orientations of these domains are largely controlled by pre-existing crustal discontinuities and stress fields (Cloetingh et al., 2006, 2009, and references therein). Therefore, the orientation of landforms, drainage patterns, linear elements of rivers and valleys, ravines, escarpments, and lower edges of terrace slopes all have a bearing on mass transfer at the Earth's surface (Cloetingh et al., 2006) and can be used to constrain future earthquake ruptures (Gorshkov et al., 2000).

Tectonic characterization of topographic features has recently become a major concern, motivated by the global availability of large-scale digital topographic datasets. The morphometrics of fluvial channel networks and location of the modern knick points are important in the estimation of variations in rock uplift and hence faulting (e.g., Peakall et al., 2000; Snyder et al., 2003; Whipple, 1999, 2009). Numerical dating of geomorphic surfaces can provide rates for the tectonic processes (e.g., Barbero et al., 2010; Hetzel et al., 2002). The geomorphic process of preferential weathering commonly acts on topographic discontinuity zones and enhances their linear features to develop geomorphologic lineaments in the form of linear valleys and slope breaks or ridges (Jordan et al., 2005). Geomorphologic

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lineaments have been found to have common geologic origins due to compositional contrasts at geologic contacts or heterogeneity of rock strength as characterized by fault scarps, joints, and fold axes (Ramsay and Huber, 1987), which commonly extend to the subsurface (Sabins, 2000).

Tectonics played a key role in establishing the present-day surface configuration of the Sinai sub- or micro-plate (Badawy et al., 2008; Ben-Menahem et al., 1976). The micro-plate exhibits complicated interactions at its active boundaries with Africa, Arabia, and Eurasia. Inter-plate movements and intra-plate adjustments between crust and mantle processes have dominated Sinai's geodynamic evolution. These processes are commonly associated with the rifting, uplift, and sometimes rotation that have controlled Sinai's morphotectonic structures and overprinted its geomorphology in the form of topographic lineaments. An approach that detects and relates such lineaments to dominant tectonics is therefore extremely desirable to better understand the regional tectonic evolution. Furthermore, such tectonically-controlled features are commonly identified as conduit zones for fluid migration; as such their accurate characterization is of paramount importance in the exploration for water, oil, gas, geothermal energy, and ore deposits (Krishnamurthy et al., 2000; Lattman and Parizek, 1964; Magowe and Carr, 1999).

Despite the importance of Sinai tectonics, research efforts devoted to lineament detection and mapping on the peninsula are scarce and commonly rely on the visual inspection of either a set of filtered images of local geophysical data such as the total magnetic intensity (Rabeh and Miranda, 2008; Rabie and Ammar, 1990) or linear features traced from satellite image data (Kusky and El-Baz, 1998). These techniques are tedious, time-consuming, and likely to be biased by subjective interpretations. Moreover, the accuracy of lineament detection from satellite images is strongly conditioned by the sensor characteristics, illumination conditions, and spatio-spectral resolution (Smith and Wiseb, 2007). Digital-elevation-model (DEM) derived shaded relief images and terrain spatial parameters (e.g., gradient, aspect, and curvatures) have proven to be promising alternative data sources for lineament and fault extraction that avoid the limiting factors mentioned above (Ganas et al., 2005; Hooper et al., 2003; Jordan, 2003a, 2003b).

Based on the above background, a set of integrated data-processing techniques has been employed to extract lineaments from the DEM and global gravity grid data of Sinai, which aims to unravel its crustal structures. Furthermore, spatial and statistical analyses of these features, with the incorporation of surface geology, are performed to characterize the tectonic regimes that were dominant through time to lead to better understanding of the geodynamic evolution of the Sinai Peninsula.

2. Geologic and tectonic setting of the Sinai Peninsula

Widespread extensional processes alternating with short compressional processes (e.g., Be'eri-Shlevin et al., 2009; Guiraud and Bosworth, 1999) have interplayed to control Sinai's active boundaries, its present-day local geomorphology, and the patterns of rock distributions spanning from the Precambrian to Recent. Plate movements and adjustments between crust and mantle processes formed the basement complex (Be'eri-Shlevin et al., 2009; Blasband et al., 2000; Cochran and Karner, 2007; Mahmoud et al., 2005; Meert, 2003). Expansion and contraction of the ancient Tethys Ocean, mostly related to mantle thermal perturbations, controlled the northward dominance of the extensive veneer of Phanerozoic cover (Bumby and Guiraud, 2005; Guiraud and Bosworth, 1999).

Details of the geology of Sinai, covering an area of ~61,000 km^2 are addressed by Said (1962, 1990) and references therein. Precambrian igneous and metamorphic basement rocks belonging to the Arabian–Nubian Shield reach an altitude of 2629 m (G. Saint Catherine) in the south and are overlain by a Phanerozoic sedimentary wedge in the north that gently dips and generally becomes more recent towards the Mediterranean coast (Fig. 1). The Phanerozoic sediments are composed mainly of: (1) Paleozoic (Cambrian and Carboniferous) sediments, (2) Mesozoic limestone, marl, and chert, and (3) Tertiary (except Oligocene) and Quaternary sediments; these are interspersed with Phanerozoic volcanics. According to the Atlas of Israel (1985), the scattered occurrences of Oligocene sedimentary rocks, associated with Miocene sedimentary rocks, are limited to the Gulf of Suez side. Recent surfaces in the northern Sinai are dominated by dunes and sand plains made up of unconsolidated and aeolian sands, wadi alluvium, clays, conglomerates and gravel terraces, and uplifted beaches and coral reefs. Sandy dune ridges dominate in the northwest between Bardawil Lake and the Great Bitter Lake. In the southern part of the dune sheets, a few outliers of massive limestone, such as G. Yelleq, Maghara, and Halal, rise above the undulating surface. In the central Sinai the Tih and Egma Plateaux continue the dominant southward rise, culminating at the Tih escarpment with elevations as high as 1600 m. South of the escarpment, elevations drop where the drainage systems of Feiran (west) and Watir (east) flow between the plateau and the Precambrian complex and finally to the gulfs of Suez and Aqaba. Quaternary sediments largely made up of a series of Mesozoic and Tertiary rocks cover the Qaa Plain at the western coastal belt in the south.

The Sinai microplate (Fig. 2) consists of a triangular continental crustal block locked between the major Arabia and Africa plates and the Anatolian–Aegean microplate (Joffe and Garfunkel, 1987; Le Pichon and Francheteau, 1987; McKenzie, 1970; McKenzie et al., 1970). The microplate is bounded eastward by the Dead Sea left-lateral transform and its submerged extension in the Gulf of Aqaba. The Dead Sea connects to the north with the left-lateral East Anatolian transform fault zone that is in continuity with the Cyprus active margin (Ben Avraham et al., 1995, and references therein) that demarcates the microplate's northern boundary. The Cyprean Arc is dominated by subduction and transcurrent processes along its western and eastern extents, respectively (Wdowinski et al., 2006). The Gulf of Suez is a confirmed segment of the microplate's western boundary. Recent evidence from shallow seismic activities (Badawy et al., 2008; Kebeasy, 1990) and marine geophysical data (Mascle et al., 2000) confirm the northward offshore extension of the Gulf of Suez as a boundary of the microplate.

Plate motion along this boundary is still a matter of debate (Badawy et al., 2008). Minor transcurrent components have been recognized in the Gulf of Suez (Abdel-Gawad, 1969; Joffe and Garfunkel, 1987): their sense of motion favors a relative left-lateral strike-slip movement, which agrees with focal mechanisms of fault-plane solutions from the region (Abdel-Gawad, 1969; Badawy et al., 2008; Garfunkel and Bartov, 1977; Joffe and Garfunkel, 1987; McKenzie, 1977). Seismological and GPS constraints reveal the dominance of slab-pull rather than ridge-push forces for the motion of Sinai relative to Africa (Badawy et al., 2008). Badawy et al. (2008) show that the southern Gulf of Suez is characterized by extensional deformation with left-lateral strike slip that is consistent with the kinematic model of Badawy (2005), Badawy and Horváth (1999b), and Mahmoud et al. (2005). However, the northern segment is characterized by unexpected compressional deformation, inconsistent with earthquake focal mechanisms and regional tectonics. Earthquake focal mechanisms are dominated by normal faulting accompanied by a left-lateral strike slip component. The strike-slip component gradually increases northward (Badawy et al., 2008).

The separation of the Sinai microplate from Africa in the Miocene, in the framework of the Red Sea opening, continued onwards (Ben-Menahem et al., 1976, Cochran, 2005, and references therein; McClay and Khalil, 1998; Steckler et al., 1988). The Suez Rift was faulted in the Miocene, jointly with the northern Red Sea (Bartov et al., 1980c; Garfunkel and Bartov, 1977). The rate of tectonic activity there has reduced considerably since the latest Miocene (Garfunkel and Bartov, 1977 and Steckler, 1985), concurrently with the opening of the Aqaba Rift. The Aqaba and the more regional Dead Sea transform fault (offset