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Analysis of structural architecture in western Saudi Neom City area, northwestern Arabian Plate: Field investigation

Abstract

Saudi Neom City is an urban mega-project being built in the northwestern Arabian plate at the southeastern part of the NNE-oriented sinistral Dead Sea continental transform fault, which links the NNW-oriented Red Sea Rift to the Zagros collision through the NE-oriented sinistral East Anatolian Fault. This study seeks to analyze the structural features of western Neom City. It also attempts to provide valuable data to help decision-makers for better achievement of such vital projects. Field investigation shows that the subject area is mostly Neogene sedimentary sequence with complex structural architecture characterized by extensional- and wrench-style deformations. Different fault orientations (NNW–SSE striking extensional faults, WNW–ESE and ENE–WSW striking oblique-slip faults, and NNE–SSW and NNW–SSE striking strike-slip faults) dissect the western Neom area. Individual NNW-oriented Red Sea Rift-related extensional faults and fault blocks are antithetically tilted to the northeast.[1] The left-lateral movement along the Dead Sea Transform Fault occurred after the formation of the Burqan Formation in the Lower Miocene period. In the western Neom area, a sinistral strike-slip regime is characterized by several structures. These structures include normal faults, folds, and reverse faults, which cause contraction, and structures that indicate horizontal shear on near-vertical planes. NNW-oriented negative flower structures and forced folding occur along a synthetic NNW-oriented sinistral strike-slip fault set. NE-oriented left-handed en echelon-arranged folds have been observed in the Middle Miocene deposits. A proposed strain ellipse reveals these structures are associated with the NNE-oriented sinistral Dead Sea

Transform Fault. The geology of western Neom, influenced by Red Sea extensional rifting and Dead Sea transform faulting, makes its structural architecture complex.

Keywords: Dead Sea Transform; Neom; transtension; negative flower structure; sinistral fault; Arabian plate

1. Introduction

Saudi Arabia wants to build Neom City on the northern shore of the Red Sea. It will cover an area of 26,500 km^2. This unique urban project includes a world trade hub, a modern floating industrial complex, attractive tourist resorts, and an environment-conservative linear city powered by renewable energy sources (wind and solar power). [1]Neom City is located on the northwestern edge of the Arabian plate. [0]The Red Sea rift defines the southern boundary of Neom, while its western border is formed by the Dead Sea Transform Fault (DSTF) (Fig. 1).

The DSTF is a continental sinistral transform boundary, linking the divergent Red Sea to the Zagros continental collision area via the NE-oriented sinistral East Anatolian Fault System in Turkey (Freund 1965; Freund et al., 1968; Garfunkel 1981; Le Beon et al., 2008; Bosworth et al., 2017). This left-lateral fault system extends ~1000 km. It has accommodated ~105 km of left-lateral transform movement owing to the northward movement of the Arabia Plate relative to the Sinai subplate since the Early Miocene (~20 Ma; Quennell 1958; Freund et al., 1970).

The slip rate along the DSTF is 3-7.5 mm/year (Garfunkel 1981; Klinger et al., 2000; Niemi et al., 2001; Daëron et al., 2004; Marco and Agnon 2005; Reilinger et al., 2006;

Ferry et al., 2007; Le Beon et al., 2008, 2010, 2012; Marco and Klinger 2014).[0] The Dead Sea tectonic region was subjected to NNW–SSE compression and ENE–WSW extension related to the Middle Miocene-Recent sinistral movement along the Dead Sea Transform and the rifting of the Red Sea (Diabat et al., 2004). A paleoseismological trench along the southern section of the DSTF revealed 12 historical surface-rupturing earthquakes during the last 8000 years (Lefevre et al., 2018). The Mw 7.3 earthquake in the Gulf of Aqaba in 1995 indicates recent strong seismotectonic activity along the entire DSTF (Klinger et al., 1999; Hofstetter 2003).[0] The investigated area of the western Neom area is located at the southeastern part of the DSTF system and northern reaches of the Red Sea Rift (Fig. 1). It displays a sequence of Neogene-Recent sedimentary rocks resting nonconformably on Precambrian metamorphic and igneous rocks of the Arabian Shield.

The western Neom area offers a distinct opportunity to examine the intricate tectonic stresses that have influenced the region throughout various historical periods. Few studies have been conducted regarding some structural settings of the area (Kahal 2020; Kahal et al., 2021). The study attempts to detect and interpret the diversity of deformational structures and their field relationships within the exposed Neogene sequence in western Neom City.

2. [0] Tectonic Setting

Neom City is situated at the intersection of the Red Sea Rift and the Dead Sea Transform Fault (DSTF). The Red Sea Rift began during the Late-Oligocene–Early-Miocene period when the Arabian Shield separated from the Nubian Shield (Le Pichon and Francheteau 1978; Joffe and Garfunkel 1987; Cochran and Martinez 1988; Ghebreab 1998;

Bosworth et al., 2005). The Red Sea Rift has an average orientation of N150° from its southern end to Suez, and it experiences an average extension in the ENE–WSW direction. [1]The basaltic dikes in southern Sinai, which are oriented in the NNW direction, along with the thick Miocene marine sediments, provide evidence that the Gulf of Suez rift and the northern Red Sea experienced faulting during the Early Miocene period (Bartov et al., 1980; Garfunkel and Bartov 1977). Strike-slip tectonic activity along the DSTF began in the Early Miocene (~20 Ma) (Freund et al., 1970). This type of tectonic activity yields a complex system of en-echelon arrays of fractures, faults, and folds developed within narrow, elongated zones (Wilcox et al., 1973; Woodcock, 1986; Sylvester, 1988). The DSTF is composed of numerous fault segments and accompanying transtensional and transpressional structures, such as pull-apart basins, pressure ridges, and fault scarps (Garfunkel 1981; Garfunkel and Freund, 1981; Atallah 1992; Meghraoui et al., 2003; Daëron et al., 2004, 2007; Elias et al., 2007; Ferry et al., 2007; Marco 2007; Ben-Avraham et al., 2008; Abou Romieh et al., 2009; Le Beon et al., 2012). The geometrical and structural differences between the pure strike-slip Dead Sea pull-apart basin and transtensional Gulf of Aqaba complex series of pull-apart basins compare well with Wu et al.'s (2009) analog model results.[0]

The Neom Basin area in Saudi Arabia and the southern Sinai in Egypt were affected by the deformation caused by the Dead Sea Transform system (Bayer et al., 1988; Bosworth et al., 2005). Two stages of offset were found. The initial event, spanning a distance of 62 kilometers, took place during the Miocene epoch. The subsequent event, covering a distance of 45 kilometers, happened during the Pliocene to Recent period (Quennell, 1958). The Gulf of Aqaba Rift and the triangular shape of Neom were formed by the connection of a succession of en-echelon faults and fractures, which created a curving boundary between Neom and Sinai (Bayer et al., 1988). Bosworth et al.[0] (2005) proposed transferring the motion along the Gulf of Suez to the new Aqaba transform boundary in the Serravalian (Middle Miocene). The southern Gulf of Suez extends at only ~0.1 cm/year; nonetheless, the area is seismically active, whereas the southern Gulf of Aqaba has not experienced any instrumentally recorded $M \geq 5$ earthquakes (Bosworth et al., 2017). A major structural event, including folding and faulting, attributed to sinistral shearing, occurred in the Neom area during the Middle Miocene at 14–12 Ma (Bayer et al., 1988; Bosworth et al., 2005).

3. Stratigraphic Sequence and Structural Architecture

In the western Neom area, the Neogene sedimentary cover rests nonconformably on the Neoproterozoic metamorphic and crystalline rocks of the Midyan terrane at the northwestern Arabian Shield (Fig. 1). The oldest exposed Neogene sedimentary rocks belong to the Oligo–Miocene and are assigned to the Tayran Group composed of the Al-Wajh, Yanbu, and Musayr Formations. The Al-Wajh Formation (Hughes and Filatoff 1995) comprises laterally extensive, poorly sorted conglomerates with subordinate sandstones, red siltstones, and paleosols. These deposits rest unconformably on the Neoproterozoic basement rocks. In the subsurface, Hughes and Filatoff's (1995) Yanbu Formation consists of anhydrite and halite, overlaying the Al-Wajh siliciclastics and, in places, are interbedded with them. Isolated hypersaline ponds deposited evaporites of the Yanbu Formation.

The siliciclastics of the Al-Wajh Formation reach a thickness of 600 m at certain subsurface localities (Johnson et al., 1995). Still, where exposed in the Neom area, Lower Miocene shallow marine carbonates overlay them (the Musayr Formation of Clark 1986). They are well displayed north of Al-Bad and conformably overlain by Lower Miocene carbonates at Wadi Al Hamd. The Lower Miocene Burqan Formation unconformably rests on the Tayran Group. It comprises a thick succession of deep-marine calcareous mudstones with thick sand interbeds. The Middle Miocene Jabal Kibrit Formation unconformably overlays the Burqan Formation (Hughes and Filatoff 1995). Hughes et al. (1999) proposed that localized basement highs during the deposition of the Burqan Formation and sites of non-deposition continued until late Early Miocene when the carbonates of the Wadi Waqb member (Jabal Kibrit Formation, Maqna Group) were deposited. The carbonates of this formation are rich in corals.

The Middle Miocene Kial Formation of the Maqna Group, consisting of four members (Hughes and Filatoff 1995; Johnson et al., 1995), conformably overlies the Jabal Kibrit Formation. A thick succession of massive gypsum, anhydrite, and halite, known as the Mansiyah Formation, overlays the Kial Formation. The Middle to Upper Miocene Ghawwas Formation of Hughes and Filatoff (1995) conformably overlies this Middle to Upper Miocene Formation (Hughes et al., 1999). The Ghawwas Formation consists of a thick sequence of interbedded coarse- and fine-grained siliciclastics and thin anhydrite beds. The Plio-Quaternary sediments are mainly represented by raised beaches and wadi deposits.

Red Sea Rift Extensional Structures

The NNW-oriented Red Sea continental rifting was initiated in the Late-Oligocene–Early-Miocene with normal faulting, extension, and subsidence accompanied by episodic movements of the Arabian plate away from Africa (Le Pichon and Francheteau 1978; Joffe and Garfunkel 1987; Cochran and Martinez 1988; Ghebreab 1998; Bosworth et al., 2005). The Red Sea Rift is perpendicular to ENE–WSW-oriented extensional stresses generated by the convergence of the northeastern Africa–Arabia and Eurasian plates (Davison et al., 1994; Burke 1996).

The coastal margins of the Gulf of Aqaba display N150° (NNW-oriented) en echelon right-stepping extensional faults that were linked to form a significant zigzag pattern (Ben-Avraham et al., 1979). The NNW-oriented normal faults form significant fault scarps along most of the boundary between the Proterozoic basement rocks and the Neogene sedimentary cover in the Neom area (Fig. 1). During the Oligo-Miocene period, the Red Sea Rift began to form.[0]▸ At that time, the Neom area was located in the northern part of the rift. This was when the left-lateral motion, which moved approximately 105 kilometers, along the Dead Sea Transform was reestablished.[0]▸ The initial stage of rifting was marked by the formation of normal faults, resulting in the creation of many fault blocks oriented in a NNW direction.[3]▸ The thin, linear magnetic anomalies in the Neom area, which extend parallel to the Red Sea Rift for several kilometers, are believed to be dikes that have intruded through faults formed during the syn-rift process (Fnais et al., 2016). South of Magna, NW-striking negative flower structure resulted from a left-lateral strike-slip faulting in the lower Miocene Burqan Formation, south of Maqna area. The dip-slip movement of the faults reflects extension by normal faults. The faults are filled with gypsum. The blue pen in the middle of the photo is for scale (Fig.2). In addition, the NE trending fault originated in the Burgan Formation, south of Magna area (Fig. 3). Near the Maqna area, Lower Miocene deposits are dissected by the N150°-oriented listric normal faults (Fig. 4) dissect the Lower Miocene deposits. Individual fault blocks are antithetically tilted to the northeast. Field investigations revealed N50°–N60°-oriented oblique faults dissecting the NNW-oriented faults. These cross faults were activated during the extension of the Red Sea Rift. Figure (5) shows a NW-striking fault in the Lower Miocene Burqan Formation, located in the northern reaches of the study area while Figure (6) illustrates NW-striking step normal planar faults (F1&F2) in the Lower Miocene Burqan Formation. Note Fault (F3), on the right side of the photo, has a listric surface.

Dead Sea Transform Wrench Structures

Extensive strike-slip faulting developed transtensile structures in western Neom. Transtension (divergent strike-slip) combines strike-slip displacement and extension, where the strike-slip fault might show a change in the strike direction or bend. The extension component causes normal faulting and subsidence. Transtension forms a significant deformation feature called a negative flower structure (Harding and Lowell 1979) or a tulip structure (Naylor et al., 1986). In the western Neom area, several subsidiary structures are associated with strike-slip faults (Fig. 7). These secondary fractures are classified based on their orientation and sense of slip relative to the overall NNE-oriented strike-slip zone trend. One set is a synthetic NNW-oriented sinistral strike-slip fault (R shear), making a low angle (10°–15º) with the overall imposed shear zone and showing the same sense of slip (Harding, 1974; Sylvester, 1988). Another set of NNE-oriented fractures, known as P-shear fractures (P-shears), develops after establishing R-fractures, and their development relates to temporal variations in the local stress field along the shear zone as offset accumulates. The faults of this set are roughly parallel to the rift and diverge by approximately −10° from the Dead Sea Rift. The third set of shear fractures (R′ shears) is antithetic WNW-oriented dextral strike-slip faults, making a high angle (70°–80°) to the zone (Fossen 2010).

Oblique faults with strike-slip and normal displacements occur within a few kilometers of the coast of the Gulf of Aqaba. In western Neom, the fault planes are wavy and branch upwards, characteristic features of a negative flower structure (Fig. 8). As the negative flower structure evolves, connecting faults die out individually, and new faults form. Each fault connects with the master strike-slip fault, assuring a linkage and kinematic organization. Field investigations of the slicklines indicate sinistral movement along the NNW-oriented master strike-slip fault and normal dip-slip movements along the branching faults of the negative flower structure. This master fault represents the synthetic NNW-oriented sinistral strike-slip fault set (R shear) (Fig. 5).

Folds are associated with sinistral strike-slip faults in the western Neom (Fig. 1) and characterized by their en-echelon arrangement. They are formed either in sets or as isolated anticlines and synclines.[0] A set of NE-oriented left-handed en-echelon-arranged folds occurred in the Middle Miocene deposits of the study area (Fig. 1).

4. Discussion and Conclusions

The western Neom area displays NNW-oriented normal faults parallel to the Red Sea Rift.[1] The extensional tectonics of the Red Sea rift influence the investigated area.[1] In the Late Miocene, the kinematics of the Red Sea regime underwent a transition from rifting with an extension in the ENE–WSW direction to a left-lateral shear along the NNE-oriented sinistral transform fault system that runs along the Gulf of Aqaba and the Dead Sea. From GPS datasets, Arabia would move NNE relative to Africa/Nubia at ~0.68 cm/yr (Reilinger et al., 2006). In western Neom, the sinistral motion onset along the DSTF postdates the Lower Miocene Burqan Formation deposition.[1] The sinistral strike-slip regime of the western Neom area consists of extensional structures, including normal faults, contractional structures, such as folds, and deformation reflecting a horizontal shear on nearly vertical planes. The concept of wrench tectonics can explain the occurrence of these structures (Anderson 1942; Moody and Hill 1956; Wilcox et al., 1973).

The variety and complexity of these structural elements display three main characteristics (Naylor et al., 1986): (1) lateral offsets of basement-involved strike-slip faults, creating extensional or contractional structures; (2) en echelon arrangement of faults and folds; and (3) complications owing to reverse or normal dip-slip components on deep-seated faults. A set of NE-oriented left-handed en echelon-arranged folds deformed the Middle Miocene deposits. The synthetic NNW-directed sinistral strike-slip fault complex (R shear) in the southwestern portion of the Neom area experienced the development of negative flower structures and an overturned anticline oriented in the N7^{o}W direction. The overturned anticline developed as a fault-propagation fold. Variable fault orientations

(NW–SE-oriented normal faults, WNW–ESE and ENE–WSW-oriented oblique-slip faults, and NNE–SSW and NW–SE trending strike-slip faults) dissect the rocks in the Neom area. These fault trends might reflect rejuvenated basement faults because they are expected within the Precambrian basement rocks. The suggested strain ellipse shows these structures are associated with the NNE-oriented sinistral Dead Sea Fault. Therefore, the complexity of the structural architecture in western Neom indicates that its evolution has passed through two tectonic scenarios depending on the effect of stress. Extensional stress that led to the Red Sea-Gulf of Suez rifting governed the first scenario, whereas shear stress that resulted in the Dead Sea wrench structures controlled the second one.