Sinai hinge belt: a major crustal boundary in NE Africa

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Abstract: The Sinai hinge belt is a major crustal boundary in northern Sinai separating different tectonic terranes. This boundary started as a number of ENE–WSW-oriented faults of Precambrian or Palaeozoic age and played a major role in the Mesozoic and Cenozoic tectonic evolution of NE Africa. The Sinai hinge belt was reactivated by normal faulting during Early Mesozoic opening of Neotethys and was later reactivated by dextral transtension during Late Cretaceous–Early Tertiary closure of Neotethys and dextral transtension in the Miocene. This study highlights the structural characteristics of the hinge belt and the nature of deformation of its fault segments. It also highlights the role of this basement structure as a crustal boundary between terranes of different tectonic settings as well as its relationship to the structural development of the nearby areas in NE Africa.

Supplementary material: A Google Earth image and structural form-line map of Rishat Saada Fault, Google Earth image and Landsat TM image of Rishat Lehman Fault and G. Ras Ebeid, geological map of El Risha El Hamra Fault, Landsat TM image and structural form-line map of the Burqa–Riash Fault, and Google Earth image and geological map of El Bruk Fault are available at www.geolsoc.org.uk/SUP18697.

The Sinai hinge belt is a narrow structural belt in northern Sinai that includes several ENE–WSW-oriented faults associated with other structures. It extends from western Sinai to the Dead Sea transform, affecting an area 250 km long and 20–25 km wide in northern Sinai and the Naqib Desert (Fig. 1). This belt forms a major crustal boundary separating a platformal area with a relatively thin Mesozoic section and shallow Precambrian basement depth to the south (in central and southern Sinai) from an area with thicker Mesozoic sedimentary section and deeper basement depth to the north. The northern area includes the large Syrian Arc (Krenkel 1925) inversion folds of northern Sinai (namely G. (Gebel = mountain) Maghara, G. Yelleg and G. Halaf folds, Fig. 1). The Syrian Arc folds in northern Sinai are Late Cretaceous–Early Tertiary, NE–SW-oriented, doubly plunging anticlines.

The term Sinai hinge belt was introduced by Shata (1959) to describe a 20 km wide fractured area forming the boundary between the northern Sinai strongly folded area (where inverted Mesozoic basins are located; Moustafa 2010) and the north–central Sinai gently folded area. The Sinai hinge belt was also referred to as the Central Sinai–Negev Shear Zone in several publications (e.g. Bartov et al. 1980).

The main objective of this paper is to throw light on the nature of deformation and tectonic evolution of the Sinai hinge belt as well as demonstrating its significant role in affecting the regional structural architecture of NE Africa. The Sinai hinge belt offers a unique opportunity for showing the role of basement structures in controlling the tectonic deformation of large areas. In NE Africa, these basement structures have controlled the limits of extensional basins formed in different geological times and have separated areas of different structural styles. Although east–west- to ENE–WSW-oriented basement faults were reported in northern Egypt and were described at various scales in both surface and subsurface (e.g. Bartov et al. 1980; Orwig 1982; Moustafa et al. 1998; Bosworth et al. 1999), the nature and geometrical characteristics of these faults and their associated structures are not completely understood. We present here in detail the structural characteristics of one such crustal-scale zone of basement faults (the Sinai hinge belt) and discuss its tectonic evolution as well as its significant role in affecting the structural architecture of NE Africa.

This study was carried out through detailed surface geological field mapping at scales of 1:20000 and 1:50000. Photogeological study and analysis of satellite images (Landsat and Google Earth) was carried out in the extreme western part of the area (Giddi and Mitla Passes area) where the threat of land mines from previous wars is significant.

Stratigraphy

The stratigraphic units exposed in the area of the Sinai hinge belt are of Triassic to Miocene age and are covered by Quaternary alluvium and sand dunes (Fig. 2). The oldest unit (Triassic) is exposed in the core of the G. Araif El Naqa Anticline (Fig. 3) whereas the Jurassic rocks are exposed in the cores of the Araif El Naqa, Giddi, and El Minsherah Anticlines. Lower Cretaceous exposures are present in the cores of the El Kherim, Araif El Naqa, El Minsherah, and Giddi Anticlines. Upper Cretaceous outcrops are widespread in the area of the Sinai hinge belt and are surrounded on the north, east, and south by Paleocene and Eocene outcrops. Lower Miocene igneous dykes dissect the Mesozoic and Tertiary outcrops of the area and are oriented NNE–SSW, NNW–SSE, and NW–ESE (Fig. 3). They were dated as 20.5 ± 0.7 Ma (K–Ar age) by Steinitz et al. (1978).

The Triassic rocks of the area are ≥185 m thick and include two units (Fig. 2); a lower sandstone unit and an upper limestone unit (Awad 1946; Jenkins 1990). The exposed Jurassic rocks are 141 m thick in G. Araif El Naqa and 80 m in G. El Minsherah with the base unexposed. The Araif El Naqa section is Early Jurassic (Jenkins 1990) and the G. El Minsherah section is Middle Jurassic (Farag & Shata 1954). The Triassic and Jurassic sections in the Sinai hinge belt are incomplete and thin compared with the inverted
basins area north of the Sinai hinge belt (914 m of Triassic rocks and 3234 m of Jurassic rocks in the Halal-1 well in G. Halal area; Jenkins 1990; and about 2000 m of Jurassic rocks in G. Maghara area; Al-Far 1966 (Fig. 1)).

The Lower Cretaceous rocks in the area of the Sinai hinge belt are 190–250 m thick (Farag & Shata 1954; Bartov et al. 1980) and are made up of sandstone (Fig. 2). The Cenomanian and Turonian rocks (Halal and Wata Formations respectively) are made up mainly of massive limestones, which form the flanks of all the folds in the area. The Halal Formation is 300–553 m thick whereas the Wata Formation is 132–200 m thick. It is not known if the changes in thickness of the Cenomanian and Turonian rocks are related to tectonic activity at these times or not.

The Coniacian–Santonian rocks of the area (Themed Formation; Ziko et al. 1993) are 85–105 m thick and are made up of chalky limestone and marl. The Campanian–Maastrichtian rocks are made up of snow-white chalk (Sudr Chalk; Ghorab 1961) that is 160–200 m thick. At G. Araif El Naqa (Fig. 3), a clastic unit is located in the middle of the Sudr Chalk and is made up of brecciated sandstone, conglomerate, sandy limestone, and chert (Bartov et al. 1980; Luning et al. 1998; Kuss et al. 2000). According to Luning et al. (1998) this sandstone unit is ?mid-Campanian to Early or Late Maastrichtian. It reflects multiple reworking and recycling of older sandstones exposed in the G. Araif El Naqa fold (Bartov et al. 1980).

The Paleocene (Esna Shale) and the overlying Lower and Middle Eocene limestones (Egma and Mokattam Formations respectively) are located in the structurally low areas to the north, east, and south of the Sinai hinge belt with horizontal attitudes (Fig. 3). The horizontal attitude and the existence of these rocks in the topographically low areas between the folded Upper Cretaceous rocks does not necessarily imply that they were deposited after waning of the Syrian Arc folding. Comparison with the inverted basins area north of the Sinai hinge belt where the Paleocene and Eocene rocks are folded (e.g. northern part of G. El Fallig, Fig. 3) implies that these rocks were involved in the Syrian Arc deformation.

Sinai hinge belt

The ENE–WSW-oriented faults of the Sinai hinge belt exist in two subparallel sub-belts where the faults have a right-stepped en echelon arrangement (Fig. 3). The northern sub-belt includes seven segments termed Giddi Pass, Rishat El Baha, Rishat Saada, Minsherah, El Risha El Hamra, Burqa–Riash, and Wadi Lussan. The southern sub-belt includes five other segments termed Mitla Pass, El Bruk, Kherim, SW Um Hosaira, and Araif El Naqa. The distance between the northern and southern structural sub-belts decreases from west to east (Fig. 3).

Most of the segments of the two structural sub-belts of the Sinai hinge belt are controlled by ENE–WSW-oriented faults and a few are represented by right-stepped en echelon folds (e.g. Rishat El Baha and Mitla Pass segments (Figs 3 and 4)). The structures affecting the area lying between the two structural sub-belts are larger in size compared with those in the two sub-belts. They are represented by NE–SW-oriented anticlines such as the El Giddi Anticline and the G. Um Hosaira Anticline. Also, a large WNW–ESE-oriented graben exists to the north of the El Risha El Hamra and the Burqa–Riash Fault segments (Fig. 3).

The exposed folds of the Sinai hinge belt underwent different degrees of shortening and erosion. For these reasons, some of these folds expose in their cores old rocks of Triassic, Jurassic, or Early Cretaceous age. Except for these few cases, most of the folds of the hinge belt expose Upper Cretaceous (mostly Cenomanian and Turonian) rocks in their cores. A detailed description of each of the segments of the Sinai hinge belt is given below.

Giddi Pass, Rishat El Baha, and Mitla Pass segments

The Giddi Pass, Rishat El Baha, and Mitla Pass segments of the Sinai hinge belt lie at the extreme western end of the belt (Figs 3 and 4). In this area, the hinge belt structures are represented by faulting and folding. ENE–WSW-oriented faults affect the Giddi Pass area whereas small en echelon folds affect the exposed Eocene rocks to the east of the pass at Rishat El Baha area as well as the exposed Cretaceous rocks in the Mitla Pass area (Fig. 4).

The Giddi Pass is a narrow passage bounded by the Um Khiseib Plateau to the north and the G. El Giddi to the south. A 22 km long ENE–WSW-oriented fault (Giddi Pass Fault) marks the southern boundary of the Um Khiseib Plateau (Fig. 4). Folded Cretaceous rocks lying on the southern side of the fault are juxtaposed against
the flat-lying Tertiary rocks of the Um Khisheib Plateau with about 1100 m throw toward the north. The Cretaceous and Jurassic rocks south of the fault are folded by a 25 km long doubly plunging anticline lying parallel to the Giddi Pass Fault. Close to the fault, the Upper Cretaceous rocks are further folded by two very narrow and tight folds that also run parallel to the fault (Fig. 4).

To the east of the Giddi Pass Fault is the Rishat El Baha Fault segment, which has an ENE–WSW orientation and affects the exposed Paleocene and Eocene rocks, which have low topographic relief (Fig. 4). These rocks are folded by five en echelon folds on the northern side of the fault, forming an ENE–WSW-oriented belt where the folds are aligned at acute angles to the fault. This narrow fold belt shows the effect of right-lateral strike-slip movement on the Rishat El Baha Fault segment.

The Mitla Pass segment of the Sinai hinge belt is represented by folds affecting mainly the exposed Upper Cretaceous rocks, which are bounded on the south by flat-lying Tertiary rocks of Sudr El Heitan Plateau and on the NW by another flat-lying Eocene outcrop (Fig. 4). The Mitla Pass structures are represented by five right-stepping en echelon doubly plunging anticlines, which are 3–8 km long and are aligned along an ENE–WSW-oriented belt. These folds are dissected by a number of faults that are generally aligned transverse to the fold axes. Folding affects the exposed Cenomanian, Turonian, and Coniacian–Santonian rocks, which have dip angles up to 45°, whereas the flat-lying rocks of Sudr El Heitan Plateau include the Campanian–Maastrichtian, Paleocene, and Eocene rocks. As one follows some of these anticlines southward toward the plateau, the change in dip from the folded rocks to the flat attitude is obvious at the middle part of the northern footslopes of the plateau. Tilted Paleocene and Eocene rocks lying to the west of the en echelon fold belt are related to later tilting associated with the Gulf of Suez rifting (Moustafa 2004).

The en echelon pattern of the Mitla Pass folds indicates Late Cretaceous right-lateral strike-slip movement, time equivalent to the unconformity between the folded Upper Cretaceous rocks and the non-folded Campanian–Maastrichtian and Tertiary rocks of the Sudr El Heitan Plateau (see also Moustafa & Khalil 1990; Noweir...
Fig. 3. Simplified geological map of the Sinai hinge belt. Main fault segments: N1, Giddi Pass; N2, Rishat El Baha; N3, Rishat Saada; N4, Minsherah; N5, El Risha El Hamra; N6, Burqa–Riash; N7, Wadi Lussan; S1, Mitla Pass; S2, El Bruk; S3, Kherim; S4, SW Um Hosaira; S5, Araif El Naqa.
et al. 2006). Continued deformation took place in Early Tertiary time (up to Middle Eocene) as indicated by folding of the Paleocene and Eocene rocks at the Rishat El Baha Fault segment.

**Rishat Saada Fault**

The Rishat Saada Fault lies on the southwestern side of the G. Yelleq inversion fold (Fig. 3). This ENE–WSW-oriented fault is 16 km long and dips 57–66° NW (Fig. 5). The eastern portion of the fault has apparent reverse slip of about 220 m whereas the western portion has apparent normal slip of about 100 m based on the juxtaposition of rock units of different ages (Fig. 5). Slickenside lineations on the fault surface are horizontal and together with the associated chatter marks indicate right-lateral slip on the fault.

The Upper Cretaceous rocks exposed on both sides of the Rishat Saada Fault are highly deformed by folding and faulting. The trace of the fault lies very close to the axial trace of a tight anticline where the rocks on the north side of the fault represent the northwestern flank of the anticline and those on the south side represent the southeastern flank. At both ends of the fault, the fold nose is exposed where the fault cuts the anticlinal axis at a small angle. Therefore, at the eastern end of the fault, the fold nose is exposed on the north side of the fault, making an acute angle of about 25° with the fault, whereas at the western end of the fault, the fold nose is exposed on the south side and makes a small acute angle with the fault (Fig. 5). These structural relations probably indicate that the area was affected by a tight and narrow ENE–WSW-oriented doubly plunging anticline that, shortly after its development, was dextrally displaced by the Rishat Saada Fault for about 0.75 km. The Rishat Saada Fault cuts the anticline at a small angle ranging from zero to 25°. Alternatively, the folding of Cretaceous rocks on both sides of the fault is related to drag by the dextral Rishat Saada Fault and the folds at the two ends of the fault were formed to accommodate the termination of the horizontal slip at the fault tips. We favour this alternative interpretation, which indicates strike-slip related folding.

The rocks lying on both sides of the Rishat Saada Fault are dissected by NW–SE-oriented normal faults of relatively small throw (a few tens of metres) and these end against the Rishat Saada Fault. Also, the direction of throw of the NW–SE-oriented faults lying on the north side of the Rishat Saada Fault is toward the SW whereas the direction of throw of those on the south side of the fault is mostly toward the NE. These faults are aligned normal to the lengthening direction associated with the dextral slip on the Rishat Saada Fault.

**Minsherah Fault**

The Minsherah Fault segment extends for about 30 km in an ENE–WSW direction in the north–central part of the Sinai hinge belt (Fig. 3). This segment is marked by three pervasive ENE–WSW-oriented faults associated with folding on one or both sides of the fault. These three faults are the Rishat Lehman Fault, the main Minsherah Fault, and the Abu Sweira Fault (Fig. 6). The Rishat Lehman Fault and main Minsherah Fault have a right-stepped en echelon arrangement whereas the Abu Sweira Fault represents the eastern continuation of
the main Minsherah Fault. At G. El Minsherah, folded Mesozoic rocks lie on both sides of the fault whereas at G. Abu Sweira, only the Turonian and Coniacian–Santonian rocks lying on the south side of the fault are folded into what appears to be a half anticline with dip angles up to 12°. Further to the ENE (across Wadi El Arish), a short ENE–WSW-oriented fault might represent the continuation of the Minsherah Fault segment at the G. Ras Ebeid area (Fig. 3) where the Upper Cretaceous rocks are folded by a SW-plunging anticline that lies on the southern side of the fault and makes an acute angle with it. The flanks of the G. Ras Ebeid Anticline dip at angles as high as 30° and the fault dips 74–75° NW.

The main Minsherah Fault has an ENE–WSW orientation. G. El Minsherah is characterized by faulted folds where two structurally high ridges lie to the south and NE of the main Minsherah Fault and are separated by a central graben (Fig. 6). These highs are the Minsherah Ridge and Wadi El Hasana fold respectively. The main Minsherah Fault was active at two times, in the Late Cretaceous and post-Middle Miocene. The early phase of slip was transpressional, when the Minsherah NE–SW-oriented doubly plunging anticline was formed above the fault, whereas the second phase of slip was transtensional, leading to collapse of the crest of the Minsherah Anticline. The structure looks now like a negative flower structure (cross-section X–X’ in Fig. 6).

The Minsherah Ridge is dissected by three NW–SE-oriented normal faults (Fig. 6), two of which are abutted by the main Minsherah Fault whereas the third fault (Galb El Minsherah Fault) dissects the main Minsherah Fault and laterally displaces it for about 500 m, indicating a second phase of deformation in the area. The structurally highest part of the G. El Minsherah area lies where the main Minsherah Fault and Galb El Minsherah Fault join.

The main Minsherah Fault extends further to the ENE toward G. Abu Sweira, where it dips 70° NW. At G. El Minsherah, the main Minsherah Fault dips in two opposite directions (Fig. 6). The easternmost one-third of the fault dips 65° NW whereas the central and western parts dip 65–82° SE showing apparent reverse slip on the fault with a hanging-wall anticline. At the extreme western part of the main Minsherah Fault, the fault bifurcates into two branches, and the northern branch dips to the NW. The main Minsherah Fault has a diagonal slip indicated by oblique slickenlines that plunge 46°/S84°E indicating a right-lateral strike-slip component and a reverse dip-slip component (i.e. the first movement on the Minsherah Fault was transpressional).

The Wadi El Hasana fold is a NE-plunging anticline in the north–central part of the G. El Minsherah area (Fig. 6) and is bounded on the south by an ENE–WSW-oriented normal fault dipping 66° SSE. Several NW–SE-oriented normal faults with a few tens of metres throw dissect the southeastern flank of the fold (Fig. 6).
Fig. 6. Field geological map and cross-sections of the G. Minsherah area showing the Rishat Lehman Fault (RLF), main Minsherah Fault (MMF), and Abu Sweira Fault (ASF) modified after Moustafa & Yousif (1990). GMF, Galb El Minshera Fault; WHF, Wadi El Hasana Fault. (See Fig. 3 for location.)
The central graben extends ENE–WSW in the centre of the G. El Minsherah area. It is bounded on the south by the main Minsherah Fault and on the NE by the Wadi El Hasana fold (Fig. 6). There are two other ENE–WSW-oriented faults in the central part of the graben and they enclose highly folded Upper Cretaceous rocks. The folds are oriented ENE–WSW, parallel to the enclosing faults, and are tight with flanks dipping steeply at angles up to 65°. The enclosing faults dip very steeply at 62–87°. The northern one of these two faults (the Wadi El Hasana Fault; Fig. 6) changes dip direction from NW to SE and has slightly oblique slickenlines plunging at 5° and 12°, indicating right-lateral slip. Moustafa & Yousif (1990) mentioned that the lowermost part of the Campanian–Maastrichtian section is missing at the northern flank of these anticlines, marking an important unconformity corresponding to the time of folding and the first phase of deformation in the G. Minsherah area. In the easternmost part of the central graben, the Paleocene and Lower Eocene rocks are faulted down, indicating that the age of the graben is post-Early Eocene (second phase of deformation of the Minsherah Fault).

The structural setting of the G. El Minsherah area indicates two phases of deformation. The older phase is Late Cretaceous and is marked by the base Campanian–Maastrichtian unconformity mentioned above whereas the younger phase is post-Early Eocene (most probably post-Early Miocene as indicated from the area between the main Minsherah and Rishat Lehman Faults, as will be discussed below). The Late Cretaceous phase of deformation proceeded by dextral transpression (indicated by slickenside data on the main Minsherah Fault as mentioned above). This phase led to the development of the Minsherah Anticline with the main Minsherah Fault dissecting it longitudinally. The crestal part of the Minsherah Anticline was in the middle part of the area now represented by the central graben. Deposition of the Campanian–Maastrichtian chalk started in the downdip areas of the Minsherah Anticline and by the time the crest of the anticline was covered by these sediments a younger part of the chalk was deposited, defining the base Campanian–Maastrichtian unconformity at this part of the fold. The main Minsherah Fault was probably associated with other ENE–WSW-oriented faults like those mapped in the central graben. The Minsherah Anticline and the ENE–WSW-oriented right-lateral strike-slip faults formed a positive flower structure during the first phase of deformation. This flower structure collapsed during the second phase of deformation (post-Early Eocene or post-Early Miocene), which proceeded by dextral transtension leading to reactivation of some of the ENE–WSW-oriented faults by right-lateral
slip and the development of NW–SE-oriented normal faults, one of which is the Galb El Minsherah Fault (Fig. 6). The crestal part of the Minsherah positive flower structure collapsed as a result of this transtensional phase of deformation and the structure acquired the shape of a negative flower structure (see cross-section X–X’ in Fig. 6). This phase of transtensional deformation separated the central graben from the structurally high blocks lying to the south and NE.

The ENE–WSW-oriented Rishat Lehman Fault is about 6 km long and shows right stepping with the main Minsherah Fault (Fig. 6). A Lower Eocene section is preserved within a small pull-apart graben between the overlapping ends of the Rishat Lehman Fault and the main Minsherah Fault (Fig. 6). At that locality, the Rishat Lehman Fault dextrally offsets a basic igneous dyke of Early Miocene age (Steinitz et al. 1978) for about 120 m. For this reason, we date the second phase of deformation of the Minsherah Fault as post-Early Miocene.

Good exposure of the Rishat Lehman fault surface shows that it strikes N77°E and dips 74° SE. The fault surface also shows oblique slickenlines that plunge 14°/N253° indicating a predominant right-lateral strike-slip component and a minor reverse dip-slip component.

**El Risha El Hamra Fault**

The El Risha El Hamra Fault is to the east of the Minsherah Fault segment and extends for about 16 km in an ENE–WSW direction (Fig. 3). The western and eastern ends of the fault are covered by Quaternary alluvial deposits. The fault dissects the exposed Upper Cretaceous rocks and has northward dip of 59–83°. The juxtaposed rocks indicate about 150 m of apparent reverse slip at the eastern part of the fault and 130 m of apparent normal slip at the western part of the fault. Slickenside lineations on the fault surface plunge 75° NE indicating oblique slip with a right-lateral strike-slip component and normal dip-slip component. Several NW–SE-oriented normal faults dissect the rocks lying on both sides of the El Risha El Hamra Fault and all of them are abutted by the fault. Similarly, a large WNW–ESE-oriented graben lies to the NE and is abutted southward by both of El Risha El Hamra Fault and the Burqa–Riash Fault (Fig. 3). These normal faults and the graben indicate NE–SW lengthening consistent with the right-lateral slip on the El Risha El Hamra Fault.

**Burqa–Riash Fault**

The Burqa–Riash Fault is to the east of the El Risha El Hamra Fault and extends in an ENE–WSW direction for 10 km (Fig. 3). The fault dissects the exposed Upper Cretaceous to Lower Eocene rocks (Fig. 7) and dips 58–66° northward. The eastern part of the fault shows apparent reverse slip of about 240 m. Oblique slickenlines on the fault surface plunge at 61° NNE. Folded Campanian–Maastrichtian rocks on the southeastern side of the fault are steeply dipping and are overlain by gently dipping Paleocene and Lower Eocene rocks indicating displacement on the fault during the Late Campanian–Maastrichtian.
Cretaceous with reactivation in the Early Tertiary. A characteristic feature of the fault (like the Rishat Saada Fault) is the existence of anticlinal noses at its two ends making acute angles of 10° and 15° with the fault. These anticlinal noses are located at the northeastern and southwestern ends of the fault, and their existence is consistent with dextral slip on the fault. Another plunging anticline at an acute angle to the fault is located north of the middle part of the fault and deforms the Upper Cretaceous rocks (Fig. 7).

The rocks on both sides of the Burqa–Riash Fault dip at steep angles away from the fault defining an antiformal structure parallel to the fault (Fig. 7, cross-section G–G'). This structural setting indicates that the rocks were folded on both sides of the fault owing to the strike-slip movement.

The Upper Cretaceous rocks on the south side of the Burqa–Riash Fault are highly dissected by NW–SE-oriented normal faults (Fig. 7). These faults propagated toward and terminated at the Burqa–Riash Fault. These faults also lie normal to the direction of lengthening associated with the dextral slip on the Burqa–Riash Fault.

Wadi Lussan Fault
The Wadi Lussan Fault lies to the east of the Burqa–Riash Fault and is about 15 km long. It is represented by three east–west-oriented right-stepping normal faults (Fig. 3); the westernmost fault dips 47° N, the middle fault dips 42° N, and the easternmost fault dips 78° S. The three faults dissect Campanian–Maastrichtian, Paleocene and Lower Eocene rocks, indicating post-Early Eocene movement.

El Bruk Fault
The El Bruk Fault lies in the south–central part of the Sinai hinge belt and extends in an ENE–WSW direction for 9.5 km (Fig. 3). The fault dissects Upper Cretaceous, Paleocene, and Eocene rocks, which are folded on both sides of the fault by an ENE–WSW-oriented anticline longitudinally dissected by the fault. The fault laterally offsets the two parts of the fold in a right-lateral sense and shows about 180 m of apparent dip-slip movement. A WNW–ESE-oriented basic igneous dyke of Early Miocene age is dextrally offset by the fault for about 120 m.

The structure of the areas on both sides of El Bruk Fault is similar to that of the other structures in the Sinai hinge belt, such as Rishat Saada, El Minsherah, El Risha El Hamra, El Burqa–Riash as well as the Kherim and Araif El Naqa structures, where the deformed rocks were folded into ENE–WSW-oriented anticlines as the strike-slip faults started to move.

Kherim Fault
The Kherim Fault is to the east of El Bruk Fault and extends for about 15 km in an ENE–WSW direction through G. El Kherim (Fig. 3). The Cretaceous outcrops of this area are folded by an anticline that is cut longitudinally by the Kherim Fault (Fig. 8). The area lying to the
NW of the fault roughly corresponds to the northwestern flank of the anticline and that to the SE of the fault corresponds to the other flank, with a remarkable horizontal shift of the outcrops across the fault. Juxtaposed rocks show 100–120 m of apparent reverse slip on the Kherim Fault. The fault dip changes from 57–83° NW at the northeastern part of the fault to 51–84° SE at the southwestern part. Oblique slickenlines (plunging 15–22°) indicate oblique slip with a predominant right-lateral strike-slip component.

The southeastern part of the Kherim Anticline is further dissected by two east–west-oriented faults that added further complication to the structure (Fig. 8). These two faults have dextral slip indicated by oblique slickenlines on the northern fault and horizontal shift of a fold axis on the southern fault. These two faults probably represent Riedel shears and are abutted by the Kherim Fault. The two triangular areas lying between these two east–west faults and the Kherim Fault are push-up areas leading to local increase in the dip of the rocks. Several NW–SE-oriented normal faults with few tens of metres throw dissect the northwestern flank of the Kherim Anticline and lie normal to the lengthening direction as a result of the dextral slip on the Kherim Fault.

A gentle syncline affects the Paleocene and Lower Eocene rocks to the SW of the Kherim Fault (Fig. 8). The syncline lies parallel to the fault along its southwestern extension. The folded rocks record a later phase of deformation on the Kherim Fault in post-Early Eocene time.

**SW Um Hosaira Fault**

The SW Um Hosaira Fault lies to the east of the Kherim Fault and to the SW of the G. Um Hosaira Anticline, extending in an ENE–WSW direction for 11 km (Figs 3 and 7). One outcrop of the fault surface on the south side of G. Um Hosaira shows a 69° SE dip. It is not clear if the SW Um Hosaira Fault extends further to the SW underneath the Quaternary alluvial deposits. The G. Um Hosaira Anticline lies between the SW Um Hosaira Fault and the Burqa–Riash Fault and is interpreted herein to be a push-up area occupying the stepover lying between these two faults.

The rocks affected by the G. Um Hosaira Anticline are Upper Cretaceous to Lower Eocene. The anticline is highly dissected by a large number of transverse faults dipping steeply at 58–88°. These faults indicate a genetic relationship to both of the anticline and the two bounding faults (the Burqa–Riash Fault and SW Um Hosaira Fault). Most of these faults are normal whereas some are right-lateral oblique-slip. A few NNE–SSW- to north–south-oriented faults also dissect the Um Hosaira Anticline and two of them have left-lateral oblique-slip.

**Araif El Naqa Fault**

The Araif El Naqa Fault lies to the east of the SW Um Hosaira Fault and extends for about 16 km with a wavy outline made up of three segments, two of which are oriented east–west to ENE–WSW and the third (middle) segment is oriented NE–SW (Figs 3 and 9). The fault dips 60° NNW and is bounded on the north by the G. Araif El Naqa Anticline, which is structurally and topographically the highest area in northern Sinai.

The G. Araif El Naqa Anticline is an asymmetric doubly plunging anticline lying on the hanging wall of the NE–SW-oriented segment of Araif El Naqa Fault (Fig. 9). The southeastern flank of the anticline lies close to the fault and has narrow width and very steep
The Triassic to Upper Cretaceous rocks of this flank are overturned or very steeply dipping. The northwestern flank of the anticline also dips steeply at an average of 45° NW. The middle segment of the Araif El Naqa Fault thus has apparent reverse slip of about 850 m where the Triassic and Jurassic rocks are juxtaposed against the Campanian–Maastrichtian chalk. As the reverse (middle) segment of the Araif El Naqa Fault joins the two east–west- to ENE–WSW-oriented segments, it is interpreted here that the whole fault was affected by right-lateral slip and the Araif El Naqa Anticline is a push-up structure formed in the hanging wall of the middle segment of the fault. No slickensides were observed on the fault because of poor exposure of the fault surface.

Two phases of deformation affected the Araif El Naqa Fault. Brecciated and slumped siliciclastic beds within the Campanian–Maastrichtian chalk of the Araif El Naqa Anticline are thought to have been eroded from Lower Cretaceous sandstones exhumed in the core of the anticline (Luning et al. 1998). This indicates that the formation of the Araif El Naqa Anticline, and hence the movement on the Araif El Naqa Fault, took place just before deposition of these siliciclastic rocks (Middle Campanian to Early or Late Maastrichtian; Luning et al. 1998). As the lowermost Tertiary rocks (Paleocene and Lower Eocene) are also folded by the Araif El Naqa Anticline, folding continued in post-Early Eocene time. Angular unconformity between the Middle Eocene rocks and the underlying Lower Eocene rocks is obvious in the northern flank of the anticline, indicating that the deformation preceded the deposition of the Middle Eocene rocks. The gentle dip of the Middle Eocene rocks on the northern flank of the anticline (Fig. 9) also indicates continued folding and probably another phase of movement on the Araif El Naqa Fault in post-Middle Eocene time.

**Structural characteristics of the Sinai hinge belt**

Detailed structural field mapping of the various fault segments of the Sinai hinge belt indicates common characteristics, which are outlined below.

1. The fault segments of the Sinai hinge belt are pervasive through-going segments with right-stepped en echelon arrangement in two sub-belts.
Each fault segment shows clear evidence for right-lateral strike-slip deformation, indicated by horizontal or oblique slickenlines on the fault surfaces (Fig. 10), dextral offset of igneous dykes (Figs 3 and 6), and/or right-stepped en echelon fold belts (e.g. Mitla Pass and Rishat El Baha areas; Fig. 4).

Some lozenge-shaped compressional structures are formed between the ends and stepover areas of some of the fault segments (e.g. the Um Hosaira fold, Fig. 7) or at restraining bends in the fault segments (e.g. the Araif El Naqa Anticline, Fig. 9). These structures provide further evidence for the right-lateral strike-slip movement in the Sinai hinge belt.

The sense of apparent dip-slip movement on the fault segments changes along the fault from reverse to normal, which adds evidence for the strike-slip movement on the fault segments.

Strike-slip faulting of the Sinai hinge belt appears to have affected the rocks by folding before they were dissected by the fault segments of the hinge belt. Therefore, the structures formed are ENE–WSW-oriented lozenge-shaped anticlines dissected longitudinally by the fault segments of the hinge belt.

The magnitude of strike-slip movement on each fault segment of the hinge belt is small. The dextral slip is accommodated at the two ends of each fault segment by folding of the rocks at the fault ends to form one anticline north of the eastern end of the fault and another south of the western end of the fault (e.g. Figs 5 and 6).

NW–SE-oriented normal faults dissect the rocks lying on both sides of the right-lateral strike-slip fault segments of the Sinai hinge belt. These normal faults are abutted by the strike-slip fault segments and represent extensional deformation in response to the strike-slip movement.

Strike-slip movements took place in two phases, during the Late Cretaceous (corresponding to the unconformity in

Fig. 12. Conceptual model for the evolution of the structures in northern Sinai and nearby areas. (a) Pre-Mesozoic. Pervasive ENE–WSW to east–west-trending fabric of faults. (b) Jurassic–Early Cretaceous. Extensional reactivation of Precambrian(?)-Palaeozoic fabric along the Sinai hinge belt and development of half graben basins in north Sinai. (c) Late Cretaceous–Early Tertiary. Dextral transpression along the Sinai hinge belt and basin inversion in north Sinai. (d) Early Miocene–present. Rifting in the Gulf of Suez and dextral transtension along the Sinai hinge belt. M, Maghara; Y, Yelleq; H, Halaf; R, Ramon; K, Kurnub; Q, Qatan.
the lower part of the Campanian–Maastrichtian chalk of the G. El Minsherah area and the sandstone in the middle of the Campanian–Maastrichtian chalk of the Araif El Naqa Anticline) and in the post-Early Miocene (leading to dextral offset of the Lower Miocene igneous dykes). Some areas show that the Late Cretaceous phase of deformation continued until Eocene time (e.g. G. Araif El Naqa).

Structural analysis

The Sinai hinge belt represents the boundary between a platformal area with crystalline Precambrian basement at shallow depth and a thin Mesozoic section to the south and a basinal area with deeper basement and a thicker Mesozoic section to the north (a cross-section has been given in fig. 2 of Moustafa 2010). In the platformal area to the south of the hinge belt, the Abu Hamth-1 well (Fig. 1) records Precambrian basement subsea depth at 1730.5 m. In the same well and in the nearby Nakhl-1 well, the thickness of the Mesozoic rocks is 1433 m and 1639 m, respectively (Moustafa 2010). Similarly, the Araif El Naqa well (Fig. 1) was drilled through the core of one of the folds in the Sinai hinge belt (Araif El Naqa Anticline) and reached Precambrian basement at a shallow depth of 80 m below ground surface; Issawi et al. 2009). The total thickness of Mesozoic rocks at Araif El Naqa Anticline is about 1400 m. In contrast, thick Mesozoic sections occur in the basin area located to the north of the hinge belt; for example, ≥5011 m in the G. Halal inverted basin (Moustafa 2010).

In addition to the difference in basement depth and in the thickness of the Mesozoic section between the basinal area and the platformal area, the Sinai hinge belt also shows contrasting structural styles between the belt itself and the northern basinal area. The present-day structure of the basinal area is dominated by large (several tens of kilometres long) inversion folds (e.g. the Maghara, Halal, and Yelleq folds) whereas the hinge belt is dominated by strike-slip faults and segmented en echelon folds. The same structural style of the hinge belt is also seen further south along the Themed Fault (Fig. 1; Moustafa & Khalil 1994).

The two sub-belts of the Sinai hinge belt represent strike-slip reactivation of two ENE–WSW-oriented faults underlying the two sub-belts. As most of the fault segments of the hinge belt show northward dip, the two deep-seated faults probably had northward dip as well (toward the basinal area). This is also evidenced by the increase in thickness of the Mesozoic section northward across the hinge belt (i.e. in the hanging wall of the faults of the hinge belt). These two deep-seated normal faults were active in the Jurassic, forming a major crustal boundary between the basinal and platformal areas of northern Sinai.

Moustafa (2010) indicated that extensional faulting in the northern basinal area took place in the Jurassic based on evidence from seismic reflection data and changes in the thickness of the Jurassic rocks. He did not have enough data about the thickness of the Triassic rocks to indicate if extensional faulting dates earlier than the Jurassic. Moustafa & Khalil (1989, 1990) proposed that ENE–WSW-oriented faults in northern Egypt were formed as a result of Late Triassic–Early Jurassic rifting of Afro-Arabia to form the Eastern Mediterranean passive continental margin (Biju-Duval et al. 1979; Argyriadis et al. 1980; Robertson & Dixon 1984; Ducourt et al. 1986). These faults formed the boundary between the stable platformal area to the south and the basinal area to the north, where some extensional basins such as Maghara, Halal, and Yelleq were formed. During that phase of extensional deformation the faults were normal, accommodating the extension and opening of Neotethys in the Eastern Mediterranean area.

Later deformation proceeded by Late Cretaceous–Early Tertiary closure of Neotethys and convergence between Afro-Arabia and Eurasia. Smith (1971) concluded that Africa moved WNW relative to Eurasia in the Late Cretaceous to Late Eocene. This convergent movement led to inversion of the extensional basins in the basinal area of northern Sinai and dextral transpression along the Sinai hinge belt. According to Savostin et al. (1986), relative motion between Africa and Eurasia changed dramatically in the Late Santonian from sinistral divergence to dextral convergence leading to basin inversion and wrench faulting. Analysis of fault-slip data of the fault segments of the Sinai hinge belt (Fig. 10) indicates that $\sigma_1$ was oriented N113° and $\sigma_2$ was oriented N22° with a subvertical $\sigma_3$ axis. Analysis of mesostructures in the inversion folds of northern Sinai (Eyal & Reches 1983) indicated that $\sigma_1$ was oriented N287°±3°, showing a good match with $\sigma_2$ determined in the Sinai hinge belt area in the present study (Fig. 10).

The second phase of dextral slip of the Sinai hinge belt identified in the present study is somehow puzzling. The Early Miocene dykes indicate regional NE–SW extension and they were followed by a second phase of dextral slip in the Sinai hinge belt. The reason for this post-Early Miocene phase of reactivation is probably related to the extensional deformation of the region associated with the NE drift of Arabia away from Africa and Miocene opening of the Gulf of Suez and ancestral Red Sea rift (Patton et al. 1994). Detailed structural studies of the Gulf of Suez rift (Nelson 1987; Colletta et al. 1988; Patton et al. 1994; Moustafa 2004) indicated abrupt termination of the rift at the latitude of Suez city (Figs 1 and 11). It is proposed herein that the Sinai hinge belt inhibited the Gulf of Suez rift from northward propagation and led to its termination. This would cause the reactivation of the Sinai hinge belt by dextral slip at that time, accounting for the second phase of slip in the hinge belt.

Discussion and conclusions

The Sinai hinge belt shows the reactivation of ENE–WSW-oriented deep-seated (basement) faults in Late Cretaceous and Miocene times. These basement faults were reactivated by normal faulting (perhaps with a small sinistral strike-slip component) in the Early Mesozoic and formed a crustal boundary between a platformal area to the south and a Mesozoic basin area to the north. The basin area includes early Mesozoic extensional basins at G. Maghara, G. Yelleq, and G. Halal with half-graben geometry bounded on their southeastern sides by NE–SW-oriented basin-bounding normal faults (Moustafa 2010). Figure 11 shows the structural architecture of northern Sinai and nearby areas, and Figure 12 presents a conceptual model for the evolution of these structures. The stress history in the Early Mesozoic was dominated by NW–SE extension and opening of the half-graben basins. It is not logical to consider the age of the deep-seated faults of the Sinai hinge belt as Early Mesozoic as they are not parallel to the NE–SW-oriented faults bounding the half-grabs in the basin area (Fig. 11). In other words, the deep-seated faults of the Sinai hinge belt are most probably older than the Early Mesozoic extensional deformation of northern Sinai (Fig. 12a and b).

The ENE–WSW-oriented deep-seated faults of the Sinai hinge belt are parallel to other faults in northern Egypt (Orwig 1982; Moustafa et al. 1998). The age of these faults is not known but it is definitely pre-Mesozoic. The Precambrian basement outcrops of the northern Eastern Desert of Egypt (the region lying between the Nile River and the Gulf of Suez–Red Sea) are pervasively dissected by ENE–WSW-oriented faults whereas the Mesozoic sedimentary rocks lying to the west of these Precambrian outcrops are not dissected by these faults (Egyptian Geological Survey 1981). This
provides further evidence for the pre-Mesozoic age of the ENE–WSW-oriented faults, which could be Palaeozoic or Precambrian.

The Late Cretaceous convergence between Afro-Arabia and Eurasia led to inversion of the northern Sinai extensional basins (Moustafa 2010) and similar basins in offshore northern Sinai (Ayyad & Darwish 1996; Yousef et al. 2010). Based on integration of geological and geophysical data from the Levant margin and the Eastern Mediterranean region, Segev & Rybakov (2010) suggested that the most intensive convergence occurred between the Campanian and Late Maastrichtian, as a result of collision of the Mesotethys plate and the NW Arabian plate. The maximum compressive stress axis in the Late Mesozoic was oriented NW–SE (Lettouzey 1986; Moustafa & Khalil 1995) or WNW–ESE (Eyal & Reches 1983) and led to reactivation of the deep-seated faults of the Sinai hinge belt by dextral transpression (Fig. 12c). As a result, the deep-seated faults propagated upward through the overlying Mesozoic rocks in the form of right-stepped en echelon faults and folds. Therefore, two sets of right-stepped en echelon faults associated with folding were formed and correspond to the two sub-belts identified in the present study (see Fig. 3). The regional tectonic setting of northern Sinai owing to the Late Cretaceous convergent movement between Afro-Arabia and Eurasia was dominated by an inverted basins province bounded on the south by dextral strike-slip deformation along the Sinai hinge belt and the Thamed Fault (Moustafa & Khalil 1994).

Miocene divergence between Africa and Arabia and the opening of the Gulf of Suez and ancestral Red Sea rifts was mainly in the platformal area lying south of the Sinai hinge belt (Fig. 12d). The rift-parallel faults of the Gulf of Suez rift are oriented NNW–SSE and NW–SE and are related to a regional extension direction oriented N65°E–S65°W (Lyberis 1988; Moustafa 1993; Khalil 1998; Khalil & McClay 2001). As these faults approached the Sinai hinge belt they were abutted by the deep-seated faults of the hinge belt. During this time, the deep-seated faults of the Sinai hinge belt were reactivated by a second phase of dextral wrenching (Fig. 12d), which was transtensional (see the G. El Minshera fault segment, Fig. 6). Nelson (1987) and Moustafa & Abd-Allah (1992) described the northward termination of the Gulf of Suez rift and mentioned that the termination led to westward transfer of the extension toward the area west of the Gulf of Suez (Cairo–Suez District, Said 1962), which was accommodated by NW–SE normal faulting (Fig. 12d). The NW–SE-oriented normal faults of the Cairo–Suez District are abutted by several belts of east–west-oriented faults, which perhaps represent the western continuation of the Sinai hinge belt (Figs 11 and 12).

On a regional scale, the termination of the northward propagation of the Gulf of Suez rift by the Sinai hinge belt appears to have played another role during the Neogene rifting and tectonic evolution of the Gulf of Suez–Red Sea rift system. Several researchers (including Quennell 1958; Freund 1970; Steckler et al. 1988; Abdel Khalek et al. 1993; Bosworth et al. 2005) argued that extension decreased in the Gulf of Suez in the late Mid-Miocene and the Red Sea opening was linked to sinistral strike-slip displacement along the Gulf of Aqaba–Dead Sea transform fault system by c. 62 km in Mid-Miocene to Pliocene time and a further 45 km in Pliocene to Quaternary time (Freund 1970; Quennell 1984; Hempton 1987; Joffe & Garfunkel 1987; Eyal 1996). In this study, we assume that the role of the Sinai hinge belt in controlling the northward propagation of the Suez rift was probably linked to and synchronous with the first motion on the Aqaba–Dead Sea transform. Palinspastic restoration of the Red Sea–Gulf of Aden rift system by Bosworth et al. (2005) constrained the onset of the Aqaba–Dead Sea transform boundary and by-passing of the Gulf of Suez basin at c. 14Ma (Mid-Miocene), with the sinistral motion along this boundary corresponding to the collision between Arabia and Eurasia at that time.

This study shows that a crustal boundary with basement faults of Palaeozoic or Precambrian age played a major role in controlling the structural architecture and tectonic evolution of NE Africa. It separated crustal blocks with different tectonic regimes (a platformal area from an area with Mesozoic extensional basins). The same crustal boundary also played a fundamental role in delimiting the propagation of a Cenozoic rift basin, leading to the existence of the rift on one side of this crustal boundary. The reactivation of the basement faults of this crustal boundary also led to the development of a unique structural style along a narrow elongated area, different from the styles affecting the areas north and south of it. Our analysis of the deformation characteristics of the crustal boundary indicates that the pre-existing basement faults were reactivated by convergent wrenching in the Late Cretaceous–Early Tertiary and by divergent wrenching during the Miocene.

Such wrench deformations resulted from far-field stresses transmitted from the plate boundaries (first, during the Late Cretaceous–Early Tertiary closure of Neotethys and convergence between the Afro-Arabian and Eurasian plates; second, during the Miocene opening of the Gulf of Suez–ancestral Red Sea rift). This study also clarifies the structural styles that typically form in association with wrench-reactivated basement weak zones in general. Here these zones are dominated by pervasive en echelon fault segments associated with elongated to lozenge-shaped push-up and fold structures parallel to the main fault segments during transtensional deformation as well as negative flower structures during transtensional deformation. Extensional faults, Riedel shears and flower structures are also common structures associated with these zones. In comparison with structural deformations formed by positive inversion of pre-existing faults, where the deformation mainly dominates a relatively wide area of the hanging wall, this study shows that structural deformations formed by wrench reactivation of pre-existing (basement) faults affect narrow elongated areas and dominate both the hanging-wall and footwall blocks of the reactivated basement faults.

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