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The Wadi Mubarak belt, Eastern Desert of Egypt: a Neoproterozoic conjugate shear system in the Arabian–Nubian Shield

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Abstract

The Wadi Mubarak belt in Egypt strikes west–east (and even northeast–southwest) and crosscuts the principal northwest–southeast trend of the Najd Fault System in the Central Eastern Desert of Egypt. The belt therefore appears to be a structural feature that formed postdate to the Najd Fault System. In contrast, it is shown here that the deformation in the Wadi Mubarak belt can be correlated with the accepted scheme of deformation events in the Eastern Desert of Egypt and that its geometry and apparently cross-cutting orientation is controlled by a large granite complex that intruded prior to the structural evolution. Structural correlation is facilitated by a series of intrusions that intrude the Wadi Mubarak belt and resemble other intrusions in the Eastern Desert. These intrusions include: (1) an older gabbro generation, (2) an older granite, (3) a younger gabbro and (4) a younger granite. The structural evolution is interpreted to be characterized by early northwest directed transport that formed several major thrusts in the belt. This event is correlated with the main deformation event in the Eastern Desert, elsewhere known as D2. During this event the regional fabric of the Wadi Mubarak belt was wrapped around the El Umra granite complex in a west–east orientation. The Wadi Mubarak belt was subsequently affected during D3 by west–east and northwest–southeast trending sinistral conjugate strike–slip shear zones. This event is related to the formation of the Najd Fault System. Detailed resolution of superimposed shear sense indicators suggest that D3 consisted of an older and a younger phase that reflect the change of transpression direction from east-southeast–west-northwest to eastnortheast–westouthwest. The El Umra granite complex is dated here with single zircon ages to consist of intrusion pulses at 654 and 690 my. These ages conform with the interpretation that it intruded prior to D2 and that the structural pattern of the Wadi Mubarak belt was initiated early during D2.

Keywords: Central Eastern Desert; Egypt; Najd Fault System; Wadi Mubarak belt; Conjugate strike–slip shear zones; Neoproterozoic

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1. Introduction

The Central Eastern Desert of Egypt is characterized by a series of high-grade core complexes surrounded by low-grade volcano-sedimentary nappes of Neoproterozoic age (Fig. 1; Fritz et al., 1996, 2002). The core complexes and the major tectonic trend on both sides of the Red Sea strike northwest–southeast and are related to a crustal-scale sinistral shear zone called the Najd Fault System (Stern, 1985). However, in some regions the principal fabric strikes east–west, discordant to the Najd Fault System. The Wadi Mubarak belt is one of these belts and its structural and tectonic setting within the Central Eastern Desert remains unclear. Nevertheless, as elsewhere in the Central Eastern Desert, the Wadi Mubarak belt comprises a thick

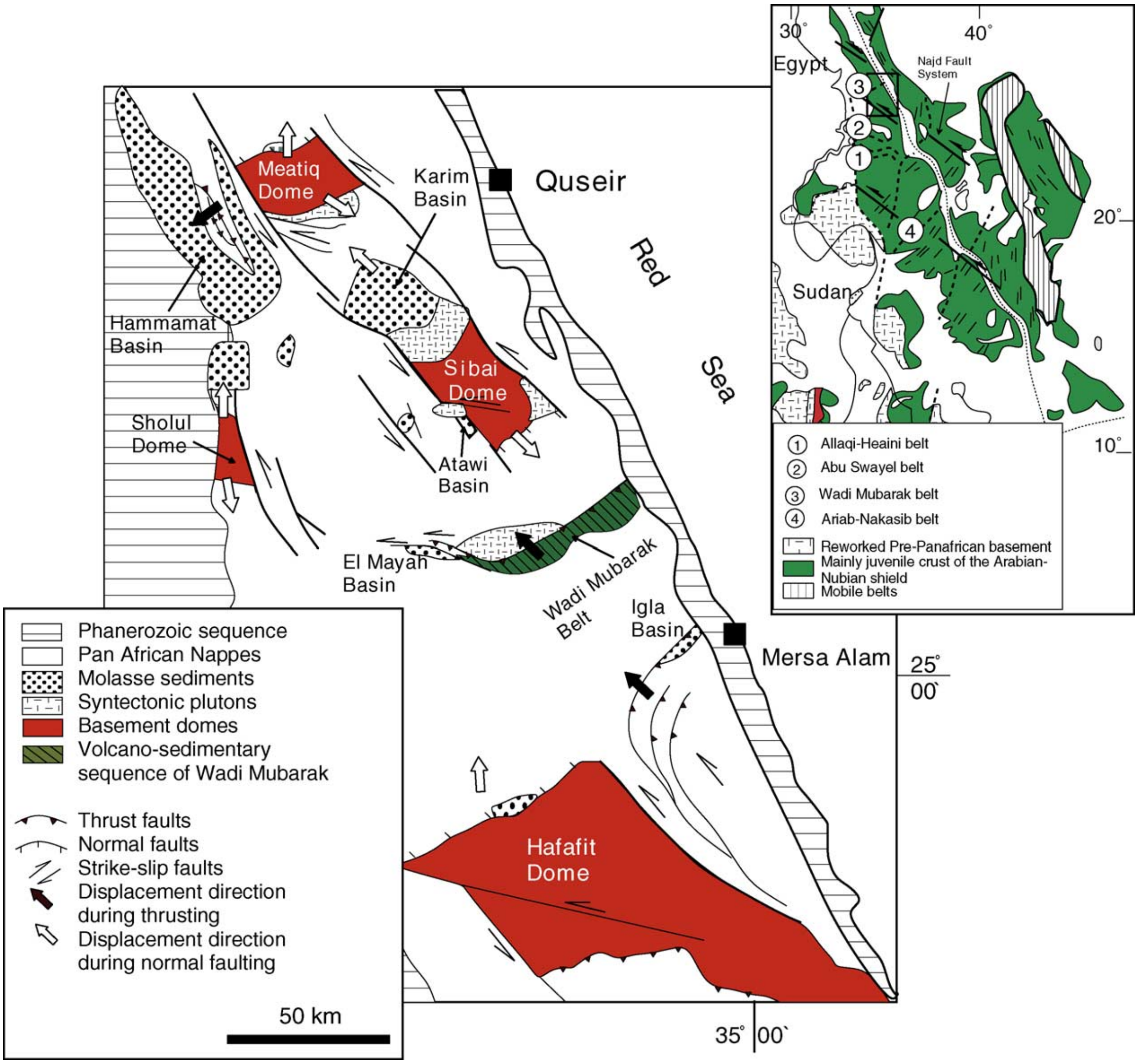


Fig. 1. Tectonic map of the Central Eastern Desert showing the core complexes, the northwest–southeast striking Najd fault system and the location of the Wadi Mubarak belt (modified after Fritz et al., 1996). The inset shows the Najd Fault System and other deformation belts in the Arabian–Nubian Shield.

succession of low-grade volcano-sedimentary rocks of arc and back-arc affinity (Akaad et al., 1995). It also contains large granitoids of unknown tectonic origin. In order to clarify the tectonic position of these east–west striking belts, we present here the first detailed discussion of the field geology and structure of the Wadi Mubarak region. The manuscript presents a field based descriptions of the macroscopic structure of the belt, complemented by absolute age dating for one of the granites. We will demonstrate that the major shear zones in the belt can be interpreted as a conjugate set to the Najd Fault System. Our data also allow to resolve details of the regional stress field during what is known as D3 elsewhere in the Central Eastern Desert.

2. Regional geological setting

The Egyptian Eastern Desert, Sudan, western Saudi Arabia, Ethiopia, Eritrea, Jordan and Yemen have collectively been termed as the Arabian Nubian Shield, which is characterized by four main rock sequences: (i) an island arc assemblage; (ii) an ophiolite assemblage; (iii) a gneiss assemblage that comprises the core complexes; and (iv) granitoid intrusions (Abdel Naby et al., 2000; Abdel Naby and Frisch, 2002). All four rock sequences occur in the Egyptian Eastern Desert which formed initially by accretion of island arcs during the Neoproterozoic (Gass, 1982; Kröner, 1984; Kröner et al., 1994). The Eastern Desert is made up of low grade metamorphosed ophiolitic and island arc-related rocks tectonically emplaced over poly-metamorphosed and poly-deformed basement (El Gaby et al., 1990; Greiling et al., 1994; Fritz et al., 1996; Neumayr et al., 1996, 1998). This upper crustal sequence, generally referred to as the “Pan-African nappes” developed in thin-skinned tectonic style during the accretion phases and suffered greenschist metamorphism. Subsequent extensional tectonics exposed the basement beneath the Pan-African nappes in a series of high-grade core complexes (Fig. 1; Fritz et al., 1996, 2002; Fritz and Puhl, 1996; Neumayr et al., 1995). The most widely recognized basement domes are the Meatiq, the Sibai and the Hafafit domes. These domes are bound at their northwestern and southeastern margins by low angle normal faults (e.g. Sibai dome, Bregar et al., 2002). Typically these low angle normal faults are associated with the formation of molasse basins (Fritz and Messner, 1999). The best example of a molasse basin related to the core complex formation is given by parts of the Hammamat Basin related to the Meatiq core complex (Fritz and Messner, 1999). Other examples are the Karim and the Atawi basins, which are related to the Sibai dome (Bregar et al., 1996, 2002). These molasse basins are filled with Hammamat type sediments which constitute a sequence of coarse conglomerates and other fluvial sediments (Grothaus et al., 1979). The core complexes are bound to the northeast and southwest by northwest–southeast striking sinistral shear zones (Wallbrecher et al., 1993; Fritz et al., 1996) that splay off the Najd Fault System and which extend for some 1000 km across the Red Sea into the Arabian Shield (Stern, 1985).

Several belts in the Eastern Desert are discordant to the general northwest–southeast trend of the Najd Fault System. These belts include the Allaqi-Heaini and Abu Swayel belts in the southern Eastern Desert (Abdel Naby et al., 2000; Abdel Naby and Frisch, 2002) and several others further south within the East African Orogen (Fig. 1; Tadesse, 1996; Wipfler, 1996). These belts are mostly northwestward propagating thrusts (Berhe, 1990). They have been linked to possible subduction and collision phases during the suturing events during the Neoproterozoic Pan-African orogeny (Abdelsalam and Stern, 1993; Stoeser and Camp, 1985; Blasband et al., 2000). The tectonic setting of most of these belts is explained as a part of the Pan-African nappe sequence (Berhe, 1990; Abdel Rahman, 1995; Abdel Naby et al., 2000; Blasband et al., 2000). Understanding the evolution of these belts is important for the interpretation of the Eastern Desert within the tectonic framework of the Neoproterozoic Pan-African orogeny.

The Wadi Mubarak belt is one of these belts, but it is located much further north; in the center of the Najd Fault System between the Sibai dome and the Hafafit dome (Fig. 1). As such it is of particular interest to study the nature of the east–west striking belts. The Wadi Mubarak belt is also associated with a small molasse basin containing Hammamat type sediments, referred to as the El Mayah basin. The El Mayah basin is apparently unrelated to core complex formation and formed in a pull-apart setting (Shalabi et al., 2004). However, as all other basins in this part of the Eastern Desert, it is filled with a sequence of fluvial sediments including conglomerates, sandstones and fine grained mudstones.

3. General geological outline of the Wadi Mubarak region

The Wadi Mubarak belt is defined as a wedge shaped discrete region of east–west and northeast–southwest striking, highly deformed rocks of lower greenschist metamorphic grade surrounded by less deformed metavolcanics, generally referred to as "undifferentiated metavolcanics" (Akaad et al., 1996). It is one of the longest low-grade volcano-sedimentary belts in the Eastern Desert and extends for over 65 km in length with an average width of about 20 km (Figs. 1 and 2). This highly deformed region extends from the Red Sea in the east to Gabel El Hadid in the west (Fig. 2), which is well known for its iron deposits (Akaad et al., 1996). To the north the belt is juxtaposed against the Gabel El Umra granite complex. To the south, the belt is bound by the Mubarak–Dabr Metagabbro–Diorite Complex (Akaad et al., 1996). This complex is here referred to as the "diorite complex" (Figs. 2–4 and 5b).

The volcano-sedimentary sequence of the belt can be divided into two major parts. (1) In the western half the fine grained metavolcanic and metasedimentary schists are intercalated with banded iron formation. This part extends from the Gabel El Hadid in the west to Gabel El Mayet in the center of the belt (Fig. 2). (2) The eastern half of the belt is characterized by the absence of banded iron formation and is almost entirely made up of fine grained extremely low grade volcano-sedimentary rocks including fine grained tuffs, shales and schists. However, in the eastern half of the belt there are some gabbros, serpentinites and other mafic and ultramafic rocks collectively referred to here as ophiolitic rocks. This eastern part of the belt is deformed by a series of imbricate thrust sheets forming a typical tectonic mélange (Abu El Ela, 1985; El Bayoumi and Hassanein, 1987; Akaad et al., 1995, 1996). Two of the thrust-bound ophiolitic slabs within the eastern half exceed several kilometers in length (Fig. 2). The southern slab is a massive serpentinite body that forms the summit of Gabel El Mayet. The second slab is a gabbro that is located 10 km to the northeast.

The belt is also intruded by igneous rocks that are used here as time markers to establish a relative chronology. Four different types of intrusives may be discerned (Fig. 2). These include an older and a younger gabbro and an older and a younger granite. The temporal sequence of intrusion of these bodies is: (1) older gabbro, (2) older granite, (3) younger gabbro and (4) younger granite. The gabbroic bodies intrude the western half of the belt and are both related to different stages of formation of the Um Nar Shear zone, which represents a major structure in the Wadi Mubarak belt. The older granite correlates with what is known as the "calk-alkaline older granitoid" elsewhere in the Eastern Desert (Akaad et al., 1996). In Wadi Mubarak, these older granites are represented by the Gabel El Umra granite in the north and the Gabel Abu Karahish granite to the south (Fig. 2). The younger granites are scattered throughout the belt, particularly at its southwestern part (Fig. 2). They correlate with the alkaline granites known as "younger granite" elsewhere in the Eastern Desert (Akaad et al., 1996). These younger granites are easily distinguished by their pink color and lack of deformation.

4. Structural observations

The Wadi Mubarak belt contains two types of major structures: thrusts with intermediate dip and steep shear zones with a dominant strike slip component of motion (Fig. 3). Major thrusts bound the belt in the south and north, but local thrusts are also common within the belt and are related to the development of the regional fabric. The thrusts are usually truncated by the west–east and northwest–southeast trending strike–slip faults. Narrow zones of phyllonites and sheared metavolcanics define both structural elements. On map scale the thrusts and strike–slip shear zones are curvilinear suggesting deflection around the intrusive bodies.

4.1. Thrusts and thrust sheets

Two major thrusts delineate the belt. The *southern* thrust is exposed in the eastern part of the mapped area and is truncated by the Gabel Abu Karahish granite (Figs. 2 and 3). It strikes northeast–southwest and moderatly dips towards the southeast. The *northern* thrust extends for over 30 km along the entire length of the belt

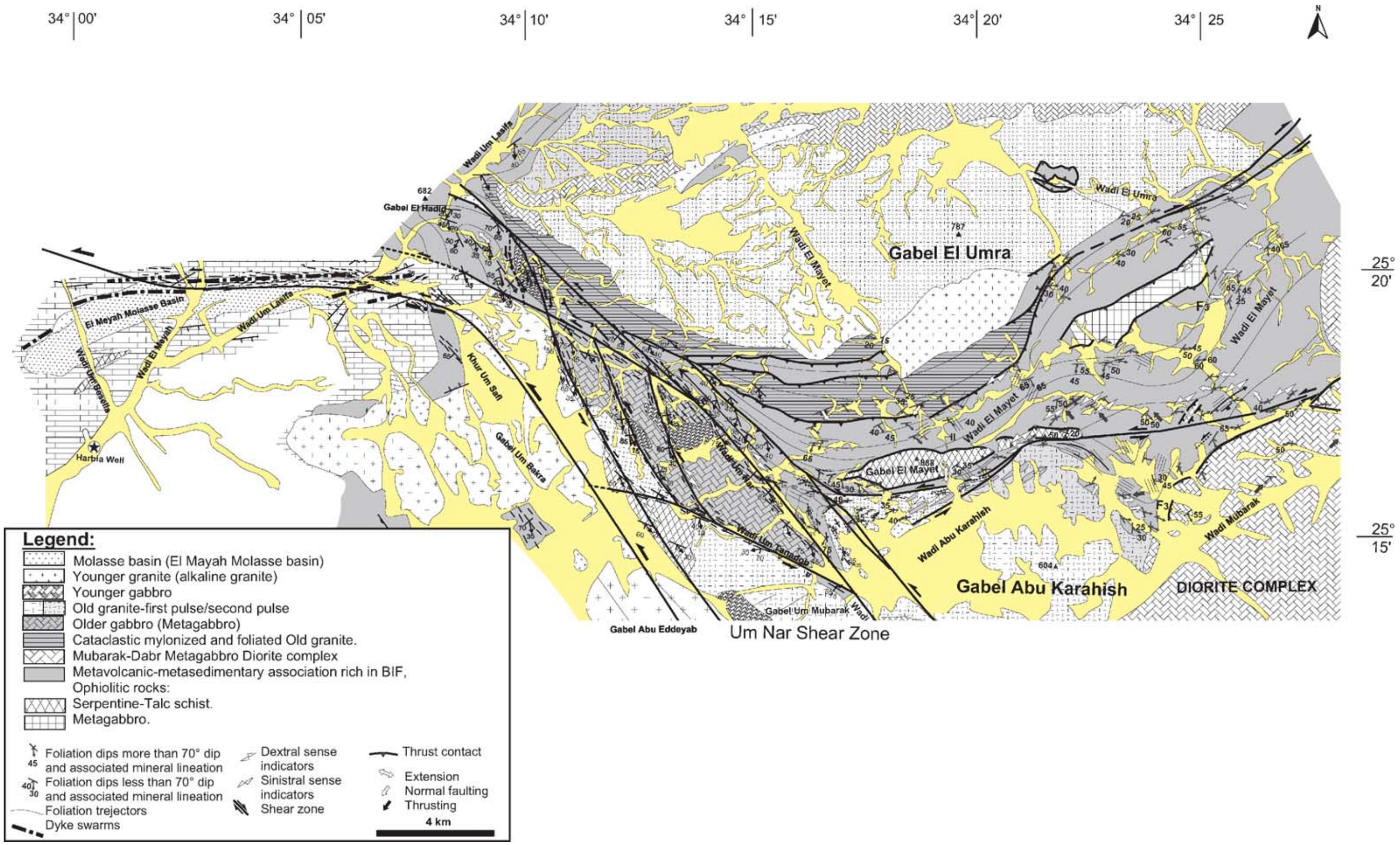


Fig. 2. Geological map of the Wadi Mubarak belt mapped during this study.

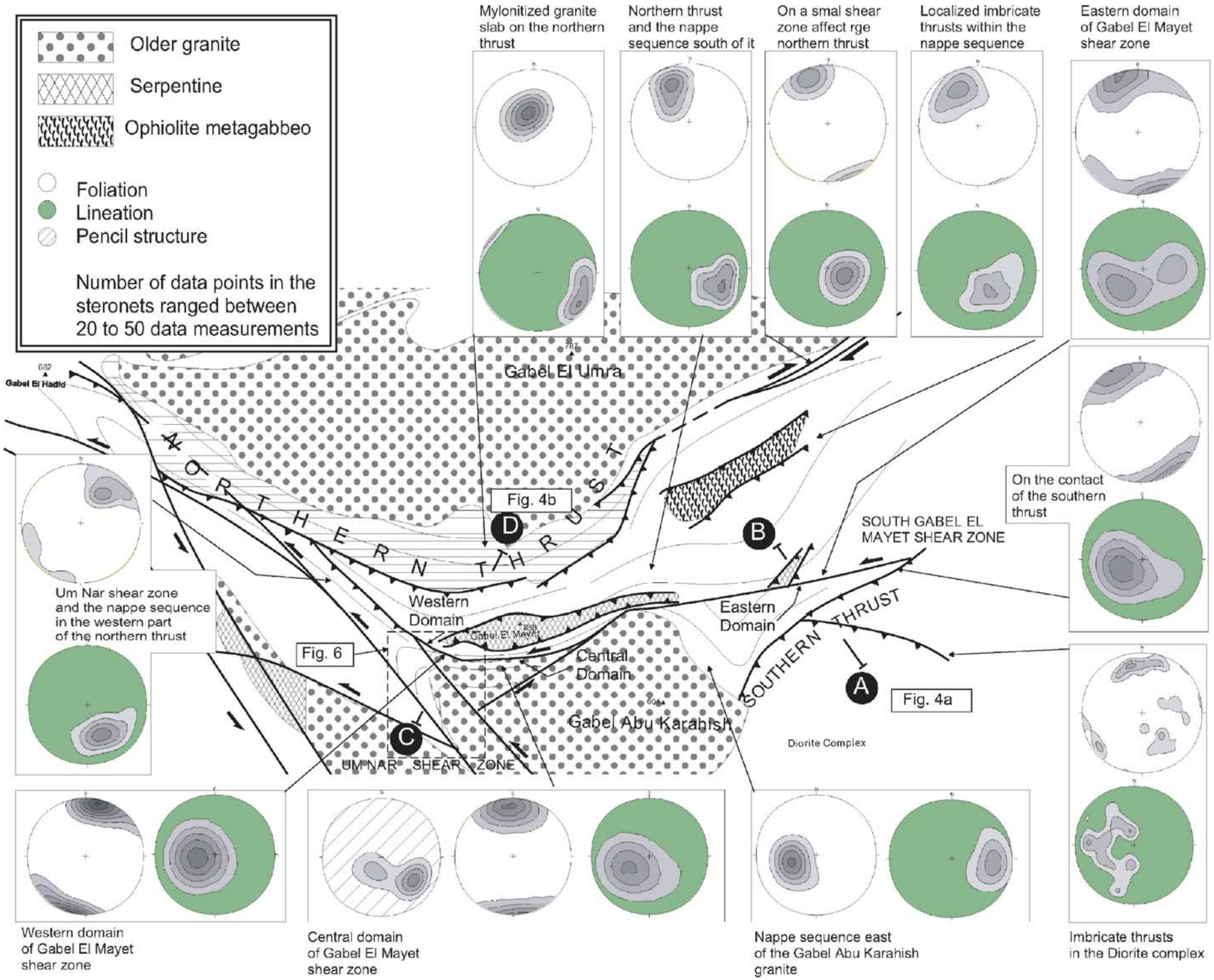


Fig. 3. Geological map of the Wadi Mubarak belt simplified from Fig. 1 showing major structures discussed in the text only. Foliation and lineation data measured in the field are shown as insets.

and separates the Wadi Mubarak belt from the Gabel El Umra granite.

4.1.1. The southern thrust and the area south of it

The southern thrust is about 10 km long and strikes northeast–southwest. It separates the belt from the southern diorite complex (Figs. 2–4 and 5b). Within the thrust zone rocks are tightly folded about horizontal fold axes (Fig. 5a) associated with duplexes indicating top-to-the north directed tectonic transport (Fig. 4a). The thrust surface is marked by vertical foliation (Fig. 3) that extends for some 10s of meters into the diorite complex where it is recognized as a weak foliation defined by mica flakes, amphiboles and quartz aggregates. A stretching mineral lineation plunges moderately to the west-southwest indicating oblique high-angle thrust motion. In the southwestern part of this thrust a series of synthetic normal faults occur (Fig. 7g and h). In many places, these synthetic splays are later intruded by sheet-like granitic bodies (Fig. 7a).

South of the thrust the diorite complex is deformed by an imbricate thrust fan that indicates northeast tectonic transport direction similar to the southern

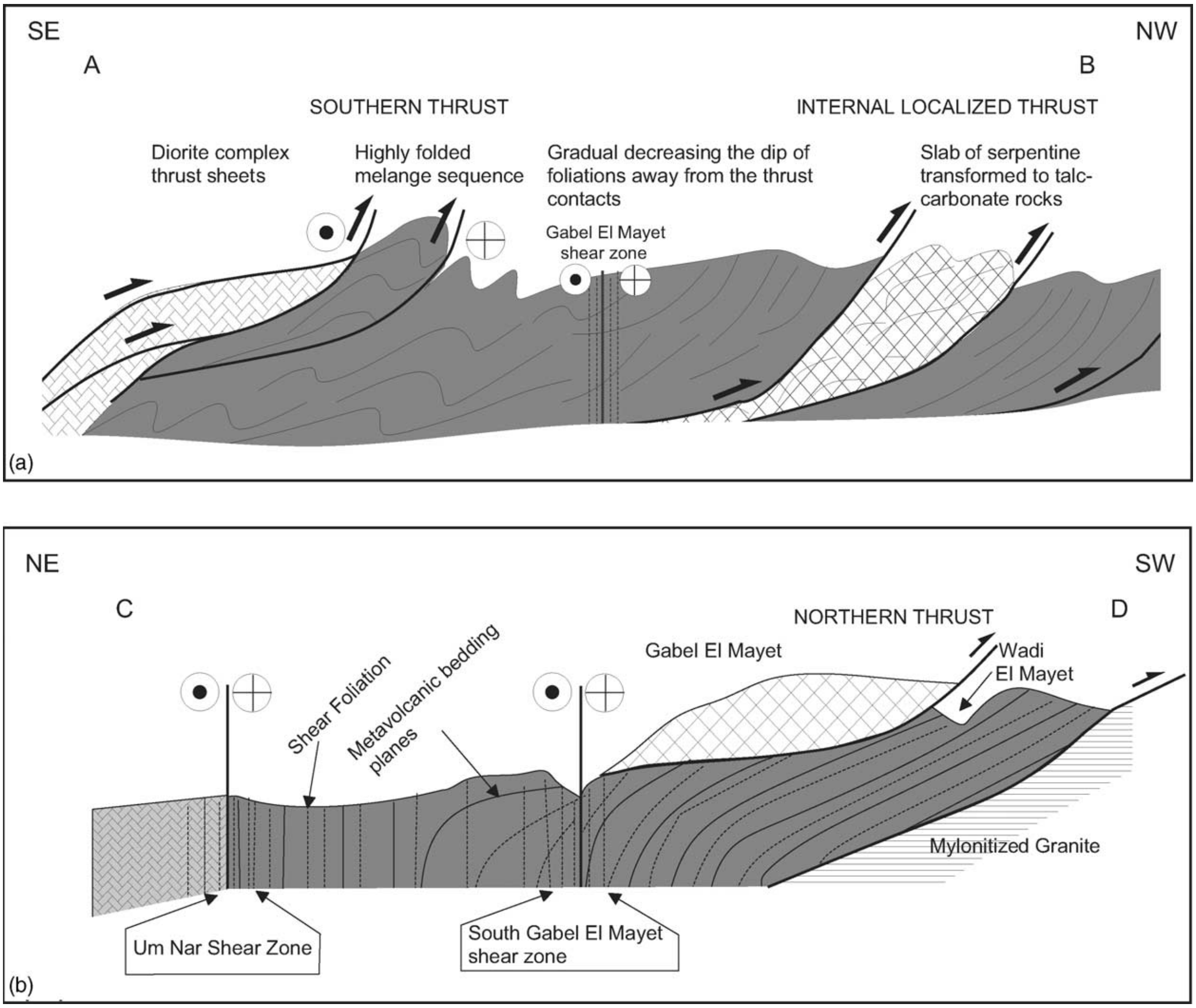
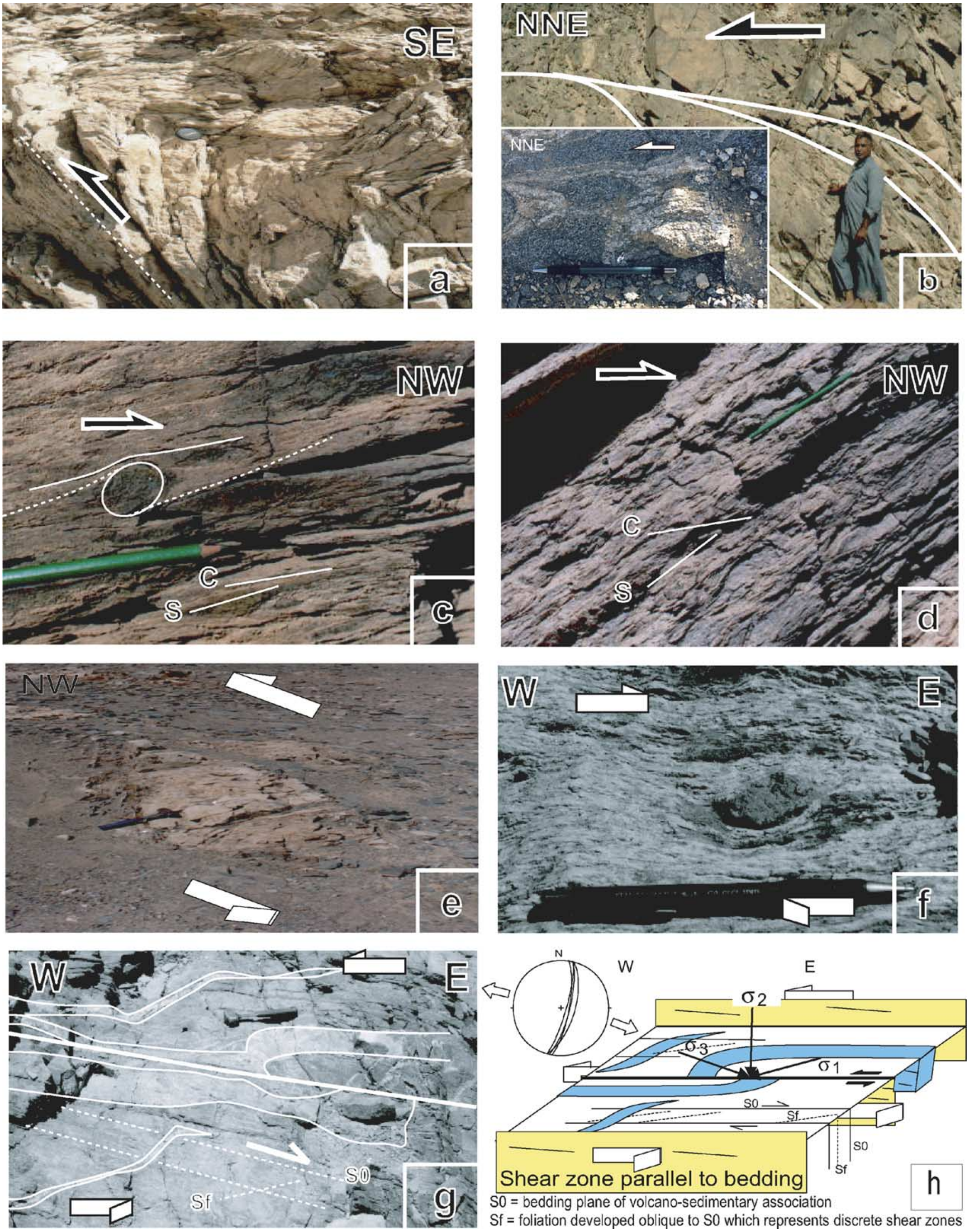


Fig. 4. Geological sections across the Wadi Mubarak belt: (a) across the southern thrust; (b) showing the relationships between the northern thrusts and the two major shear zones. Location of profiles is shown in Fig. 3.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Sf
g
N
W
E
σ2
σ3
σ1
S0
Sf
S0
Sf
Shear zone parallel to bedding
h
S0 = bedding plane of volcano-sedimentary association
Sf = foliation developed oblique to S0 which represents discrete shear zones

thrust (Fig. 4a). However, in contrast to the Wadi Mubarak belt, the metagabbro and/or diorite bodies between these thrusts are undeformed. Similar to the southern thrust, the thrusts deforming the diorite complex are frontal ramps with steep fronts that flatten out at depth. This is reflected by the wide range of orientation of foliations and mineral lineations (Fig. 2).

4.1.2. The northern thrust and the Wadi Mubarak belt

The curvilinear trace of the northern thrust extends for about 30 km generally in an east–west direction (Fig. 3). This thrust separates the Wadi Mubarak belt from a highly mylonitised granite, which forms a 4 km wide and 10 km long tapering body along the southern boundary of the Gabel El Umra granite (Figs. 2 and 3). The northern thrust is terminated in the east by the Gabel El Umra granite which includes numerous enclaves of amphibolites, metavolcanics and metagabbro. The western end of the thrust is displaced by the Um Nar shear zone which will be discussed below. Around Gabel El Hadid region (Figs. 2 and 3) the northern thrust is close to an overturned limb of a kilometer-scale southwest plunging antiform (Akaad and Noweir, 1980; El Aref et al., 1993; Akaad et al., 1996). The mylonite fabric along the thrust contact dips moderately to the south. This fabric contains a mineral lineation that plunges shallow to the southeast.

The foliation in the volcano-sedimentary sequence south of the northern thrust dips steeply to the southeast and southwest in the eastern and western part of the belt, respectively (Fig. 2). However, the mineral lineation constantly plunges moderately to the southeast throughout the entire belt (Figs. 2 and 3). Well developed rotated volcanic clasts in the melange (Fig. 5c) and S-C structures (Fig. 5d) indicate northwestward tectonic transport direction. The S-surfaces are defined by intensively deformed and flattened volcanic clasts. The C-surfaces are represented by discrete highly deformed zones of fine aggregates of metavolcanic fragments of phyllonitic texture. Folds associated with this thrusting are northwest-verging with northeast–southwest trending sub-horizontal fold axes. The foliation trajectories indicate a regional open antiformal structure along the northern thrust. Shallowing of the foliation dip from the thrust front southward, suggests that all thrusts sole into a common décollement (Fig. 4a).

4.2. Strike–slip shear zones

The thrusts described above are cut by east–west and northwest–southeast trending strike–slip shear zones with vertical foliation. Two major strike–slip shear zones are found in the study area: (i) the Um Nar shear zone and (ii) the south Gabel El Mayet shear zone (Figs. 2 and 8).

4.2.1. The Um Nar shear zone

The Um Nar shear zone generally strikes northwest–southeast and deforms the rock units of the western part of the Mubarak belt. It forms a 25 km long and up to 4 km wide zone of anastomosing discrete strike–slip shear zones (Figs. 2 and 3). The intensively deformed volcanic clasts and aggregates of metasediments form vertical foliations of the Um Nar shear zone that strike northwest–southeast, whereas the stretching lineations plunge moderately to the southwest (Fig. 3). Boudinaged aplitic dykes occur within the melange sequence (Fig. 5e). These boudinaged dykes are folded about vertical fold axes indicating sinistral sense of shearing. In the northwest the shear zone forms a tectonic contact

Fig. 5. Field photographs of critical features of the major thrusts and shear zones. (a) The contact between the southern diorite complex and the southern thrust. (b) Imbricated ramps within the southern diorite complex south of the southern thrust. The photo inset shows deformed gabbro on the thrust contact showing the direction of transportation. (c) Delta clast within mylonites of the northern thrust indicating top to the northwest tectonic emplacement. (d) S-C structure on the northern thrust showing top to the northwest tectonic emplacement. (e) Boudinaged aplitic dyke showing sinistral sense of shearing in Um Nar shear zone. (f) Dextral shear kinematic indicator in the central domain of the Gabel El Mayet shear zones. (g) Superposition of sinistral shearing on dextral shearing within the central domain of the Gabel El Mayet shear zone. (h) Sketch illustrating the relationships between mesoscopic structure at outcrop (g) showing principle stress directions inferred from orientation of tensional gashes (northeast–southwest compression and northwest–southeast extension). The stereonet shows the orientation of tensional gashes.

to the El Mayah basin (Shalabi et al., 2004) and its southern end continues into the Gabel Abu Karahish granite (Fig. 2). However, from the unpublished Landsat Thematic Mapper (TM) images of the Central Eastern Desert, the shear zone appears to extend substantially further northwest and southeast (Fig. 2). Structural style of the Um Nar shear zone and the nature of sedimentary facies of the El Mayah basin suggest that deformation and sedimentation were synchronous (Shalabi et al., 2004).

The shear zone is intruded by several of the intrusion types mentioned above. A lozenge shaped older gabbro body covers about 10 km^2 in the center of the shear zone (Fig. 2). Later activity of the shear zone separated this body into three parts. While the bodies are internally practically undeformed, they do show alignment of a magmatic foliation parallel to the intrusive contacts with the surrounding metavolcanics. The shear zone is also intruded by a younger generation of gabbro which is exposed as four bodies that are 1–2 km^2 in size. These bodies are elongated northwest–southeast parallel to the main direction of the trend of Um Nar shear zone. The boundary of the host rocks which involved these bodies show evidence of semi-ductile strike–slip shear zones and normal faults. Finally, the shear zone also cuts several generations of granitic intrusions.

4.2.2. *The Gabel El Mayet shear zone*

The Gabel El Mayet Shear Zone extends for about 20 km from east to west across the Wadi Mubarak belt. It varies in width from few meters in the east to approximately tens of meters to the west. On the basis of foliation trend and sense of shear, the shear zone can be divided into three different domains (Fig. 8).

The eastern domain extends for about 8 km in the eastern part of the Wadi Mubarak belt just north of the southern thrust. This part of the shear zone is characterized by east-northeast–west-southwest trending vertical foliation defined by highly deformed and well oriented clasts of metavolcanics and sedimentary fragments of the melange rocks (Fig. 3). The stretching lineation plunges shallowly to the southwest or southeast (Figs. 3 and 8). Shear sense indicatores such as well-rotated volcanogenic fragments within the melange sequence and S-C fabrics indicate that the eastern domain of Gabel El Mayet shear zone is characterized by only sinistral shear.

The western domain is about 2 km long and is located west of the Gabel Abu Karahish. The foliation is vertical and strikes in a west-northwest–east-southeast direction with a moderately west-plunging lineation defined by needle-shaped crystals of actinolite and chlorite (Fig. 3). This domain is also characterized by drag folds and S-C fabrics that indicate sinistral shear sense. The transition zone between the northwestern end of the shear zone and the northern thrust is chaotically deformed (Fig. 8).

The central domain connects the eastern and western domains and is about 8 km long (Fig. 8). It was formed on the steep sloping part of the ramp structure which cuts off the serpentine block that forms the summit of the Gabel El Mayet (Fig. 4b). The intersection between the thrust-related shallow foliation of the ramp and shear-related vertical foliation produces an intersection lineation in the form of pencil structure that shallowly plunges to the southeast. The width of the central domain changes gradually from few meters in the east to about twenty meters in the west. The foliation strikes east–west and the mineral lineation plunges to the southwest (Fig. 3). The rotated fragments in the mélange rocks and the development of shear bands indicate that the shear was deformed by dextral sense of shearing (Fig. 5f). However, these dextral kinematic indicatores are crossed by quartz filled extension gashes indicating sinistral sense of shear (Fig. 5g and h). We interpret that this domain originated with a dextral shear sense and was later overprinted by sinistral shearing (Fig. 5h and Fig. 8).

4.2.3. *The region between the Um Nar shear zone and the Gabel El Mayet shear zone*

The area between the two major shear zones is marked by the formation of a spectacular major scale fold (Figs. 6 and 8). The fold is composed of a sequence of metavolcanics and metasedimentary rocks intercalated with banded iron formation. The bedding planes are vertical and strike east–west and northwest–southeast in the northern and southern limbs of the fold, respectively (Fig. 6a, inset). The foliation consistently strikes northwest–southeast and dips vertically (Fig. 6b). The stretching lineation plunges steeply to the southwest (Fig. 6b) and is composed of stretched pebbles and boudins of quartz veins, while the foliation is defined by well-oriented amphibole and mica crystals. The bedding planes on the western limb of

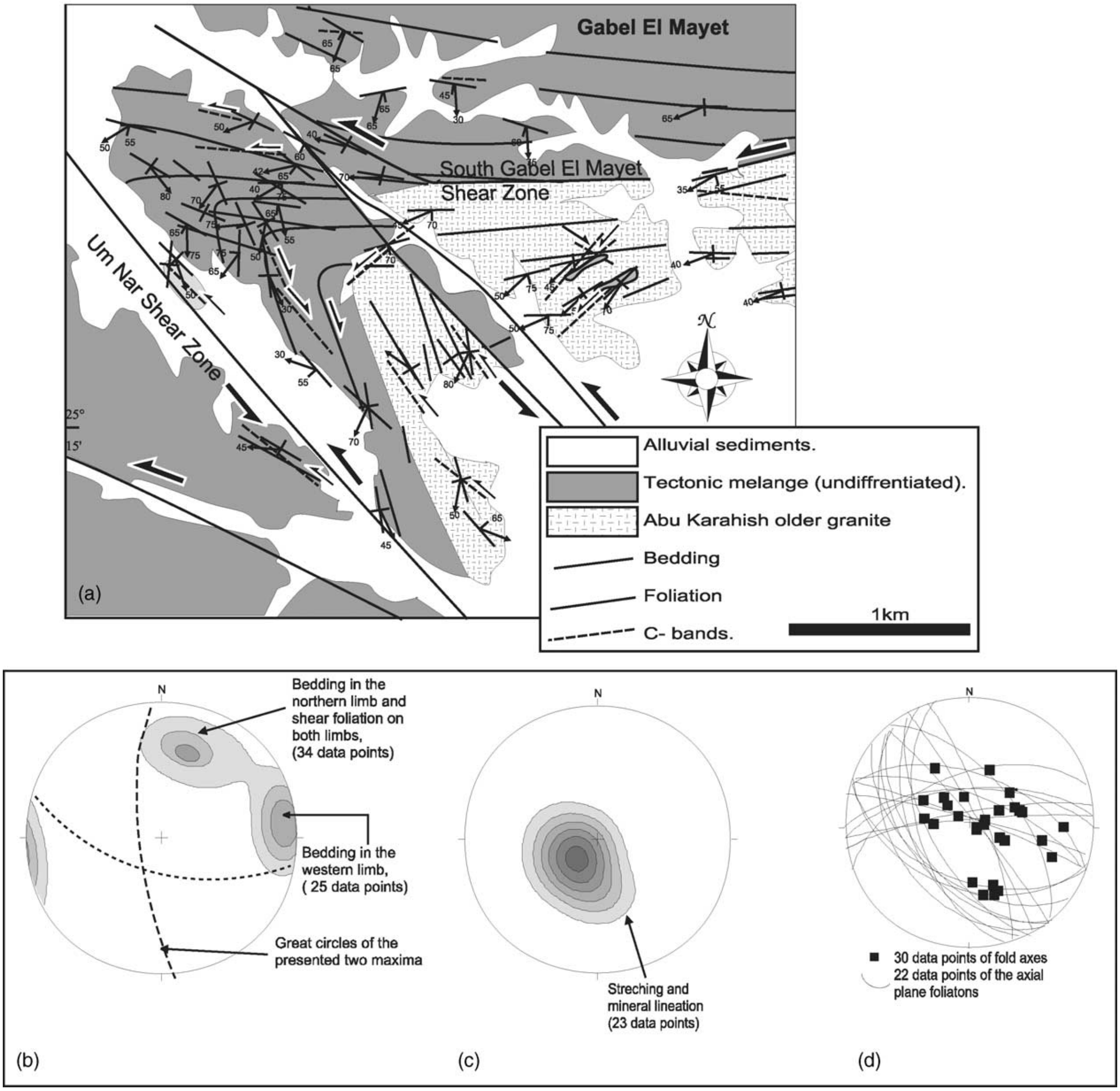


Fig. 6. (a) Structural map of the area between the Um Nar and Gabel El Mayet shear zones. Note that the foliation on the northern limb of the fold continues into the Gabel Abu Karahish granite indicating that deformation occurred after its intrusion. (b) Plot of poles to bedding and foliation from area in (a) indicating folding about vertical axis. (c) Plot of stretching and mineral lineation from area in (a). Note that these lineations are sub-parallel to the fold axis in (b). (d) Plot of fold axis (solid squares) and fold axial planar of mesoscopic shear folds associated with the map scale fold in (a). All plots are in lower hemisphere equal area stereonet.

the fold show internal deformation with dextral shear sense indicators (Fig. 6a, inset). On the northern limb kinematic indicators indicate sinistral shearing with the development of S-C structures (Fig. 6a, inset). North of the fold hinge, an east–west trending flower structure is formed (Fig. 8). Rootless folds between bedding planes are common and minor parasitic fold axes are vertical (Fig. 6b and c).

Table 1
Zircon U–Pb ages of two samples from the El Umra Granite complex. Ratios are corrected for fractionations; spike, blank, and common Pb. Lead and U fractionations for the analyses are 0.13% amu and 0.001% amu, respectively. Total procedural blank (including chemical separation) is less than 10 pg. Common Pb correction was done following Stacey and Kramers (1975) at apparent $^{207}Pb/^{206}Pb$ age. Data reduction, evaluation, and error propagation were conducted using offline program and in-house Excel spreadsheet. Concordia–discordia plots and age calculations using Isoplot/Ex version 2.2 (Ludwig, 2000). Reported errors for the ages are at 2S.D. (Shalabi et al., 2004; Table 1)

Samples	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{235}U$	2S.D.	$^{206}Pb/^{238}U$	2S.D.	$^{207}Pb/^{206}Pb$	2S.D.	Age (Ma)		
								$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$
Umra West (Sample 24)										
Grain 1	112	0.962772	0.056912	0.111903	0.001467	0.062399	0.003701	688 ± 41	685 ± 40	684 ± 9
Grain 2	123	0.718578	0.041493	0.083546	0.002081	0.062380	0.003615	687+40	550 ± 32	517 ± 13
Grain 3	278	0.933717	0.110491	0.108544	0.003923	0.062389	0.007393	687 ± 81	670 ± 79	664+24
Grain 4	103	0.978971	0.044274	0.113480	0.001419	0.062568	0.002843	694+32	693 ± 31	693 ± 9
Grain 5	231	0.973369	0.025220	0.112987	0.001244	0.062481	0.001629	691+18	690 ± 18	690 ± 8
Grain 6	180	0.945971	0.024865	0.109849	0.001102	0.062457	0.001657	690 ± 18	676+18	672 ± 7
Umra Center (Sample 80a)										
Grain 1	2158	0.886142	0.018762	0.104632	0.000958	0.061424	0.001313	654 ± 4	644 ± 4	641 + 6
Grain 2	423	0.930731	0.008964	0.109971	0.000472	0.061383	0.000618	653 + 7	668 ± 6	673 ± 3
Gram 3	822	0.872537	0.006222	0.102961	0.000442	0.061463	0.000468	655 + 5	637 + 5	632 ± 3
Grain 4	671	0.897496	0.007697	0.105961	0.000454	0.061431	0.000555	654 + 6	650 ± 6	649 ± 3
Grain 5	1765	0.901585	0.008840	0.106525	0.000458	0.061384	0.000627	653 ± 78	653 + 69	653 ± 33
Grain 6	38	0.851040	0.129253	0.105628	0.006262	0.058435	0.008900	546 + 3	625 + 5	647 + 8

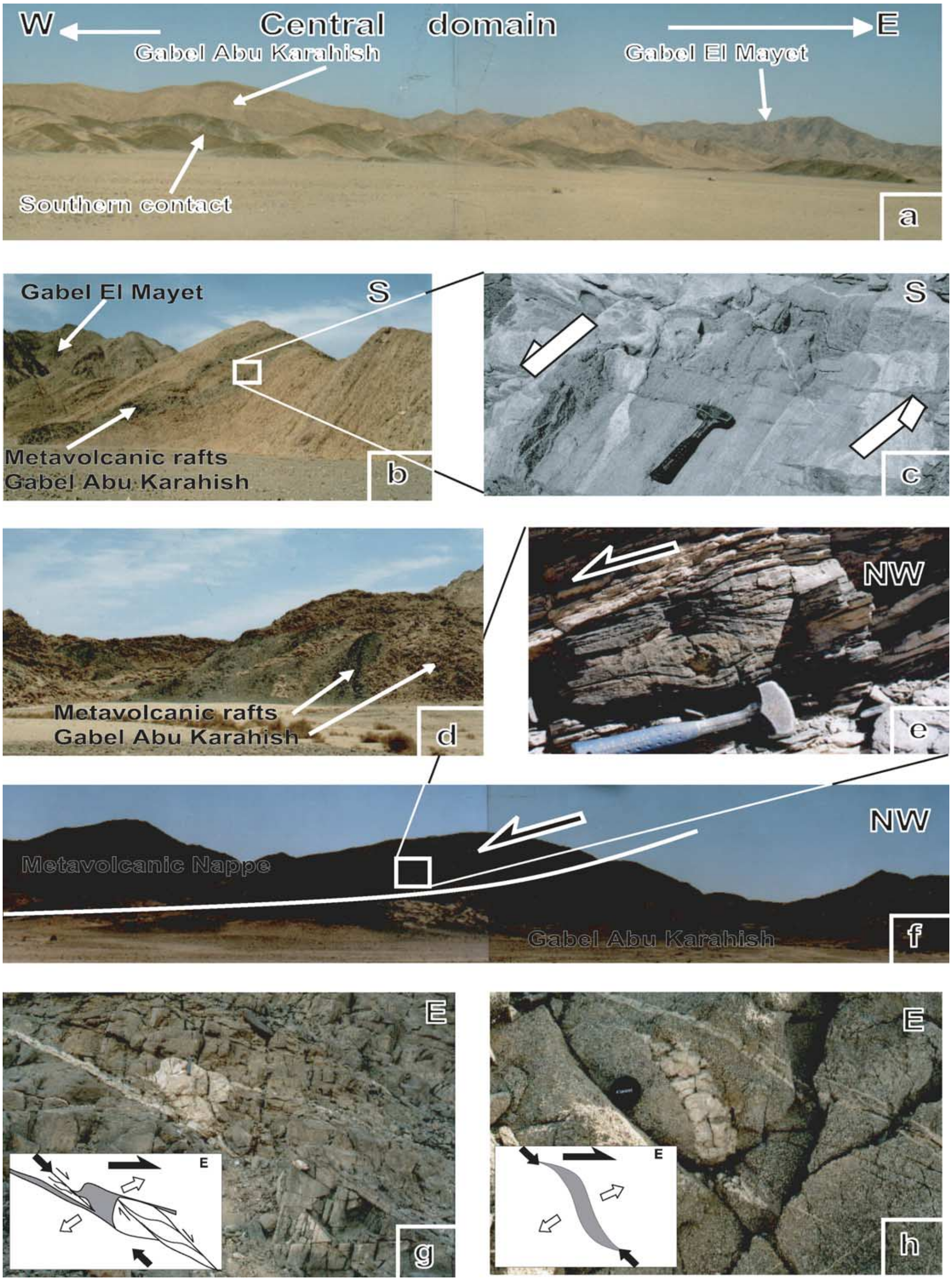
4.3. Granitoids

The Wadi Mubarak region is intruded by a series of granitoid bodies that intrude or are crossed by the shear zones and thrusts. The granites occur in two locations both of which contain several types of granite: (i) the northern group is known as the Gabel El Umra complex; and (ii) the southern group is referred to as the Gabel Abu Karahish complex. In both regions, the granitoids have a field appearance that allows them to be correlated with what are known as the “younger” and the “older” granite suites in the Central Eastern Desert (Abu El Ela, 1985; Akaad et al., 1996). The “older granites” are coarse grained, yellow to white in color, occasionally display a magmatic foliation and are of alkaline affinity. The “younger” granites are pink in color, undeformed, cross cutting the older generation.

4.3.1. The Gabel El Umra granite complex

This complex bounds the Wadi Mubarak belt north of the northern thrust. It has an oval shape extending in east–west direction for about 20 km (Akaad et al., 1996). The complex is of variable composition ranging from granodiorite to tonalite with abundant deformed amphibolite and metavolcanic enclaves. We recognized up to three separate intrusion stages within the complex. Intrusions of younger granite are found at the contact between the older granite and the nappe pile and within the older granite further north. Two

Fig. 7. Tectonic elements of the Gabel Abu Karahish granite complex. (a) Southern contact of the complex with the southern diorite complex. (b) Deformed granite near the northern contact with the Gabel El Mayet shear zone. The granite contains deformed rafts of metavolcanics shown in (c). (d) Undeformed eastern contact of the complex containing deformed enclaves of country rock. (e) and (f) show southeastward normal faulting along the eastern contact of the complex. (g and h) Formation of extension gashes near the contact between granite and metadiorite complex.



W
Central domain
E
Gabel Abu Karahish
Gabel El Mayet
Southern contact
a
Gabel El Mayet
S
Metavolcanic rafts
Gabel Abu Karahish
b
S
c
Metavolcanic rafts
Gabel Abu Karahish
d
NW
e
NW
Metavolcanic Nappe
Gabel Abu Karahish
f
E
E
g
E
E
h

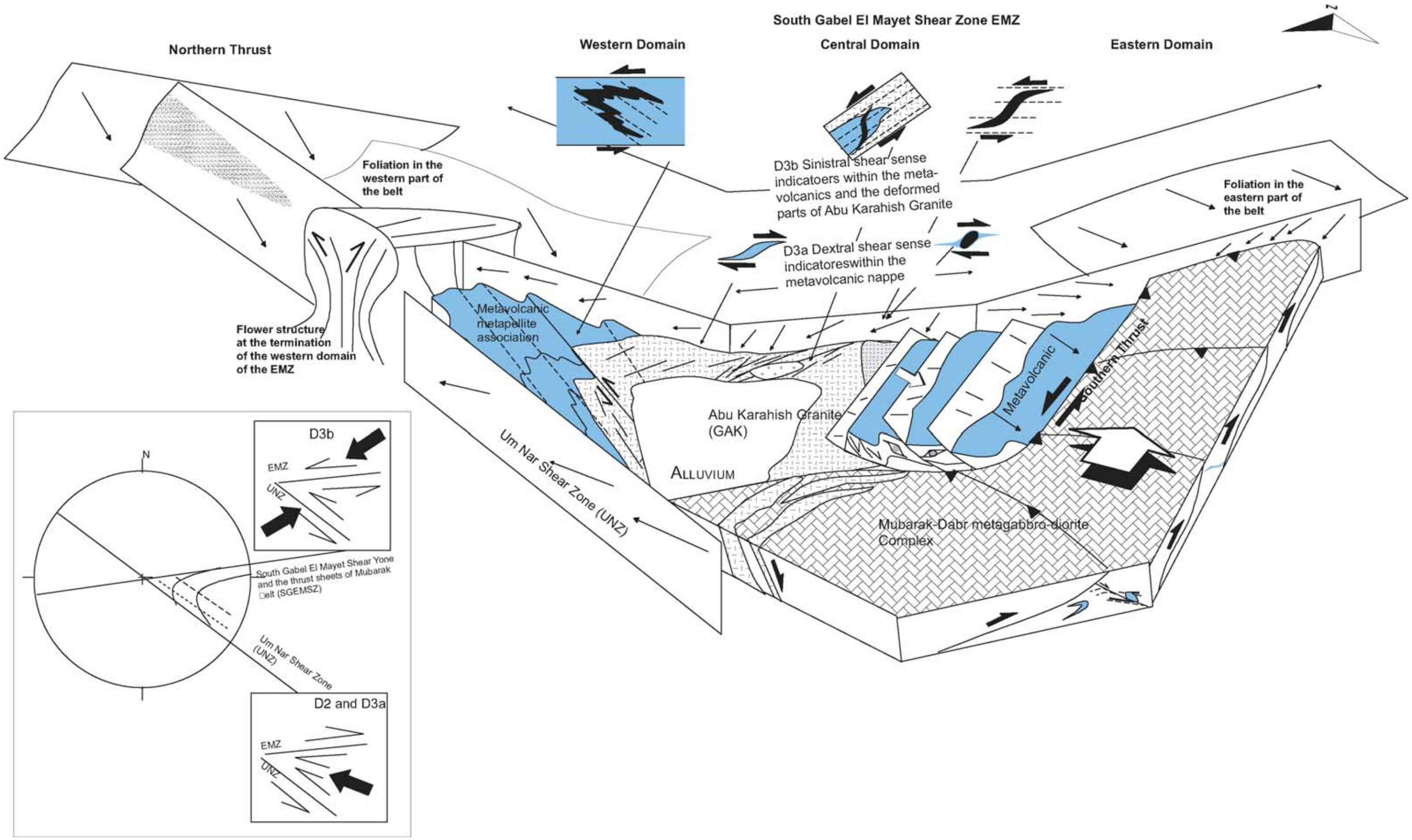


Fig. 8. Three dimensional illustration showing the relationships between the Gabel El Mayet and Um Nar shear zones as well as the Gabel Abu Karahish complex. Note the change in lineation along the three domains of the Gabel El Mayet shear zone. The inset illustrates the change in stress direction between D3a and D3b.

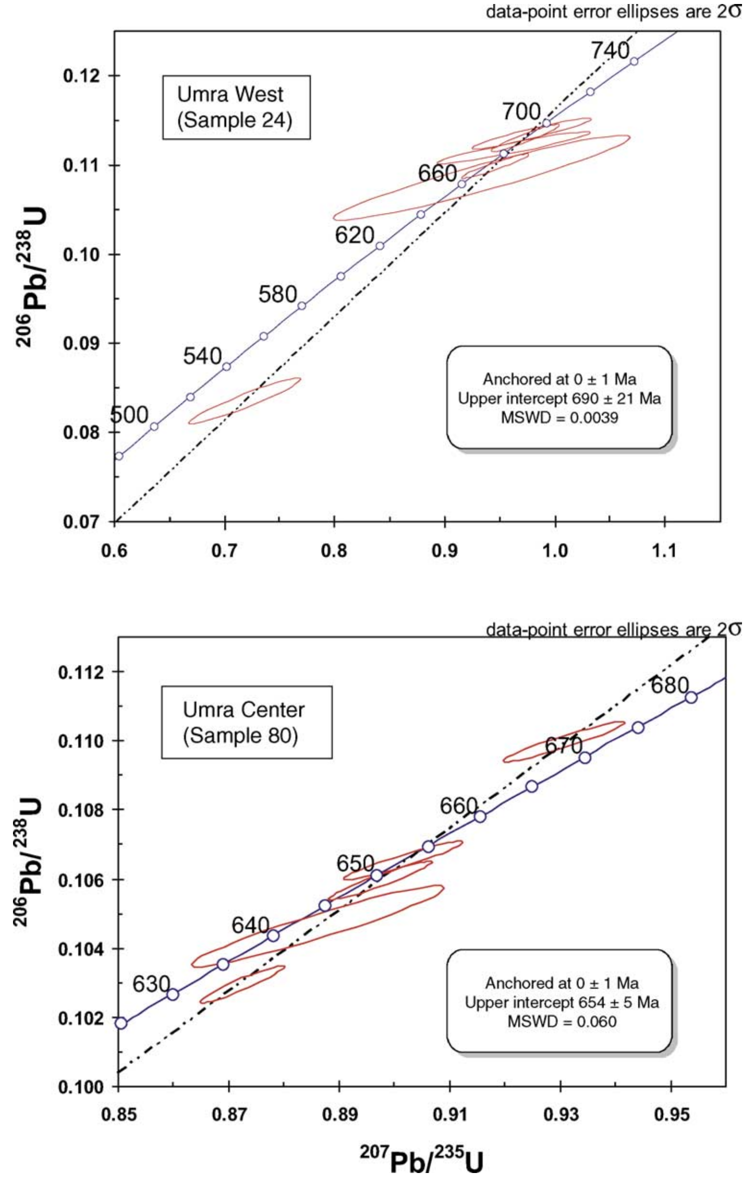


Fig. 9. Isochrons from two samples from the El Umra Granite. Sample 24 ("Umra West") was taken at 25°22′00″N, 34°11′00″E. Sample 80 ("Umra Center") was taken at 25°18′30″N, 34°14′10″E.

samples from this granite complex were dated for this study using U–Pb dating of zircons (Fig. 9; Table 1). These samples gave ages of 690 ± 90 my and 654 ± 5 my for the upper intercepts of several grains, respectively. The analytical method for zircon geochronology is summarized in the appendix in this paper.

4.3.2. The Gabel Abu Karahish granite complex

The Gabel Abu Karahish granite complex is somewhat smaller than the Gabel El Umra granite and is exposed in the southern part of the belt. It is also of variable composition with several intrusive events characterizing its evolution. It is bound by different structures that are now discussed individually: *The* *eastern* and the *southern contacts* of the granite with the volcano-sedimentary nappe are largely undeformed (Fig. 7d). The development of tensional gashes and rotated fabrics within the melange on the eastern margin normal faults (Fig. 7e and f) indicates bulk eastward extension. Similarly, there are some minor synthetic normal faults along the southern contact indicating bulk extension towards the east (Fig. 8). The tonalite on the southern contact intrudes this extensional fabric whereas the metagabbro exists as dyke-like enclaves within the granite (Fig. 7a). *The northern contact* is defined by the central domain of the Gabel El Mayet shear zone (Fig. 8). This part of the shear zone was originally a dextral strike–slip shear zone but was subsequently overprinted by sinistral shearing (see above). However, there is no evidence of dextral shear indicators affecting the granite at this contact. Only rafts of metavolcanics (few tens to more than one hundred meters in length) show dextral shear indicators. Asymmetric tension gashes and S-C fabrics indicating sinistral shearing overprint both the granite and the rafts (Fig. 7c). *The western contact* of the granite against the metavolcanic nappe is defined by the Um Nar shear zone and is intensively deformed. The foliation within the granite strikes east–west, parallel to the northern limb of the map-scale fold developed in the vicinity of the Gabel El Mayet shear zone. The granite occupies the fold from the central part along subsidiary shear parallel to the axial plane of the mega fold (Fig. 6a). Along this shear zone, a sinistral offset of 200 m occurs. This harmonic deformation of the granite and the fold suggests that folding and shear zone activity are largely contemporaneous with intrusion (Fig. 8, inset). Enclaves of highly deformed high-grade metapelite rocks were observed only within the northwestern part of the deformed granite.

5. Interpreted structural evolution

The descriptions above can be interpreted within the most recent subdivision of deformation events in the Central Eastern Desert as proposed by Loizenbauer et al. (2001) and Fritz et al. (2002) (Fig. 11). In this scheme, the oldest observed deformation phase (D1) is related to the pre-Pan-African deformation. Loizenbauer et al. (2001) suggested that D1 is only recognized in amphibolite enclaves within the core complexes. D2 deformation is related to the Pan-African deformation associated with oblique convergence of the arc and back arc assemblage onto the Nile craton around 620–640 Ma (Fritz et al., 1996). D3 deformation is linked to the formation of crustal-scale northwest–southeast sinistral shear zones of the Najd Fault System (Stern, 1985) followed by exhumation of core complexes within orogen parallel extension around 620–580 Ma (Fig. 11). D4 deformation occurred much later and may be related to brittle deformation associated with the Red Sea rifting.

5.1. D2 thrusting and earlier structures

The formation of the two major thrusts is the first major deformation event recognized in the Wadi Mubarak region. Thrusting has the same tectonic transport direction – top to northwest – described as D2 elsewhere in the Central Eastern Desert (e.g. Morgan, 1990; Stern, 1994). It is therefore interpreted to correlate with the pervasive Pan-African D2 thrusting. Generally, D2 deformation in the Central Eastern Desert took place at greenschist facies conditions (Neumayr et al., 1996, 1998). This is consistent with the minerals forming stretching lineations and foliations in Wadi Mubarak. During D2, the low-grade volcano-sedimentary sequence was thrusted from southeast to northwest over the El Umra granite in the north and wrapped in a roughly west–east orientation around it. The ages dated for the El Umra granite here are consistent with its intrusion prior to D2 thrusting (Fig. 9). D2 thrusting is also interpreted to have formed the thrust duplexes and the ramp which formed the summit of Gabel El Mayet (Fig. 4b).

The mylonitised granite located between the northern thrust and the Gabel El Umra granite complex is correlated with the mylonitised granites exposed in the center of the Meatiq core complex (Loizenbauer et al., 2001) and at the southern boundary of the Sibai dome (Bregar et al., 2002). It intruded the early Neoproterozoic Pan-African volcano-sedimentary sequence during rifting around 880 Ma (El Manharawy, 1977). As for the mylonitised granite inthe center of the Meatiq dome, the Gable El Umra mylonitised granitoid is deformed with a shallow foliation and was gneissified during the D2 accretion of the Pan-African nappe pile. However, unlike the Meatiq or other core complexes (Akaad et al., 1996), no core complex formation is associated with the exhumation of the Gabel El Umra granite and no amphibolite enclaves are found in it. Interestingly, garnet-bearing metapelites are preserved in Wadi Mubarak only within the deformed zone of the Gabel Abu Karahish granite. We interpret these metapelites as relics of a metasedimentary slab thrust within the nappe pile during Neoproterozoic Pan-African accretion. Metamorphism that produced medium- to high-grade minerals such as garnet has only been reported from core complexes (Neumayr et al., 1996, 1998). Thus, we suggest that the syn-metamorphic foliation recognized in these enclaves may be some evidence for D1 deformation in the Wadi Mubarak region. Rootless folds within the banded iron formation layers throughout the Wadi Mubarak region have also been correlated with D1 (El Aref et al., 1993).

5.2. D3 deformation

D3 deformation in the Central Eastern Desert is characterized by an overall northwest trending, sinistral transpression regime (Loizenbauer et al., 2001). This event is known to have formed the Najd Fault System and is related to the formation and exhumation of the core complexes (Fritz et al., 1996). In the Wadi Mubarak region the formation of the two major shear zones may be correlated with this event because: (1) The Um Nar shear zone strikes parallel to the Najd Fault System and is also characterized by sinistral displacement. It is also associated with the syn-tectonic intrusion of gabbros (see above) and with the formation of a Hammamat-type molasse basin—the El Mayah basin (Fig. 2; Shalabi et al., 2004). Finally, the shear zone is also known to be deep-rooted as indicated by magnetic and radiometric studies (Ghazala, 2001). (2) The early Gabel El Mayet shear zone has the orientation and shear sense of a conjugate set to the Um Nar shear zone. (3) Both shear zones have the size and deformation style that is also characteristic of other shear zones developed elsewhere in the Central Eastern Desert during D3. We therefore interpret D3 in the Wadi Mubarak belt to be also a transpressional event. However, in the Wadi Mubarak belt, the D3 event can be resolved into several stages.

5.2.1. D3a transpression

During D3a deformation, The Um Nar shear zone was deformed in a sinistral sense. As a conjugate shear zone, the Gabel El Mayet shear zone experienced dextral displacement along its early-formed central segment (Fig. 10). The Um Nar shear zone is also intruded by a lozenge-shaped block of older gabbro that may be controlled by the formation of a pull-apart structure (Shalabi, 2003). This gabbro is subsequently intruded by a granodiorite at Gabel Um Mubarak (Fig. 2). This suggests that the Um Nar shear started its deformation history earlier than the Gabel El Mayet shear zone. However, we also will show that the Um Nar shear zone had a long-lived history of subsequent reactivation. From these observations, a stress field is inferred during D3a where the principle compressive stresses are oriented in east-southeast–west-northwest direction (Fig. 10). The Gabel Abu Karahish granite complex intruded late during D3a. This is indicated by the oval morphology of this granite and the fact that it remains practically undeformed by dextral shearing along its northern contact, while enclaves of the country rock do contain dextral shear sense indicators (Fig. 8).

5.2.2. D3b transpression

During D3b the Gabel El Mayet shear zone lengthened towards the east and west while deforming in a sinistral sense of shear. Dextral shear sense indicators are overprinted by extensional asymmetrical gashes and shear folds suggestive of sinistral displacement (Figs. 5h, 8, 10). The eastern and western domains of the shear zone bear only sinistral shear kinematic indicators and are therefore interpreted to have only formed in this later D3 stage (Fig. 10). However, a younger phase of the Gabel Abu Karahish granite intruded in a regional southeast-northwest extension, and in response to northeast–southwest D3b compression, but remained internally undeformed and the contact between the nappe sequence and the eastern boundary of the pluton is a low angle normal fault (Figs. 7g, h and 10).

In contrast to the Gabel El Mayet shear zone, the Um Nar shear zone shows only sinistral shear sense indicators even during its later stages of deformation. However, there is evidence that it has been active during both D3a and D3b. This evidence includes the intrusions around the Um Nar shear zone: (1) The shear zone is intruded by a granite, which has a field appearance similar to the Gabel Abu Karahish granite which is interpreted in the Gabel El Mayet shear zone to have been intruded at the end of D3a (Fig. 11).

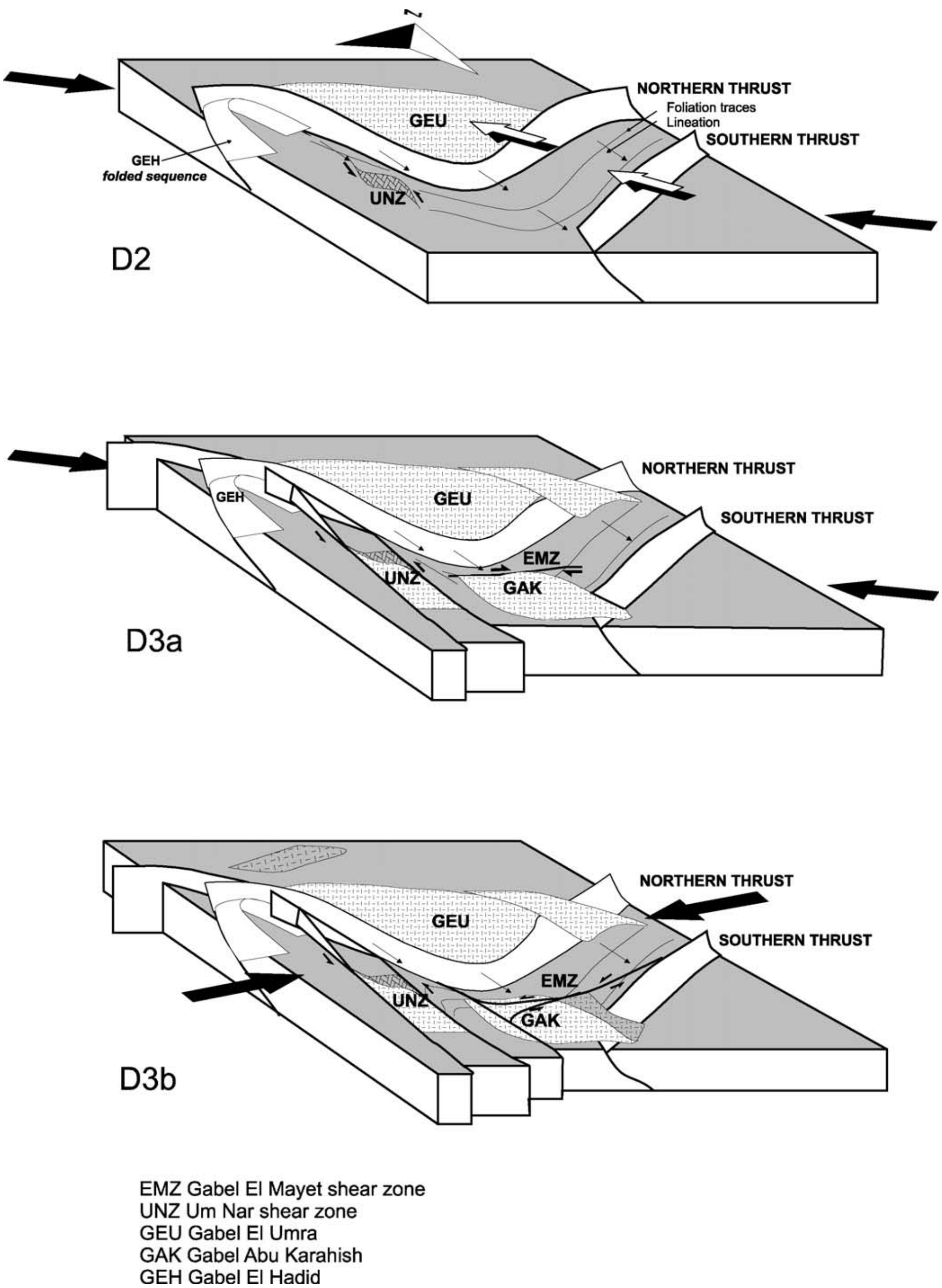


Fig. 10. Three-dimensional illustration showing tectonic evolution of the Wadi Mubarak belt. Symbols for different units are those used in Fig. 2.

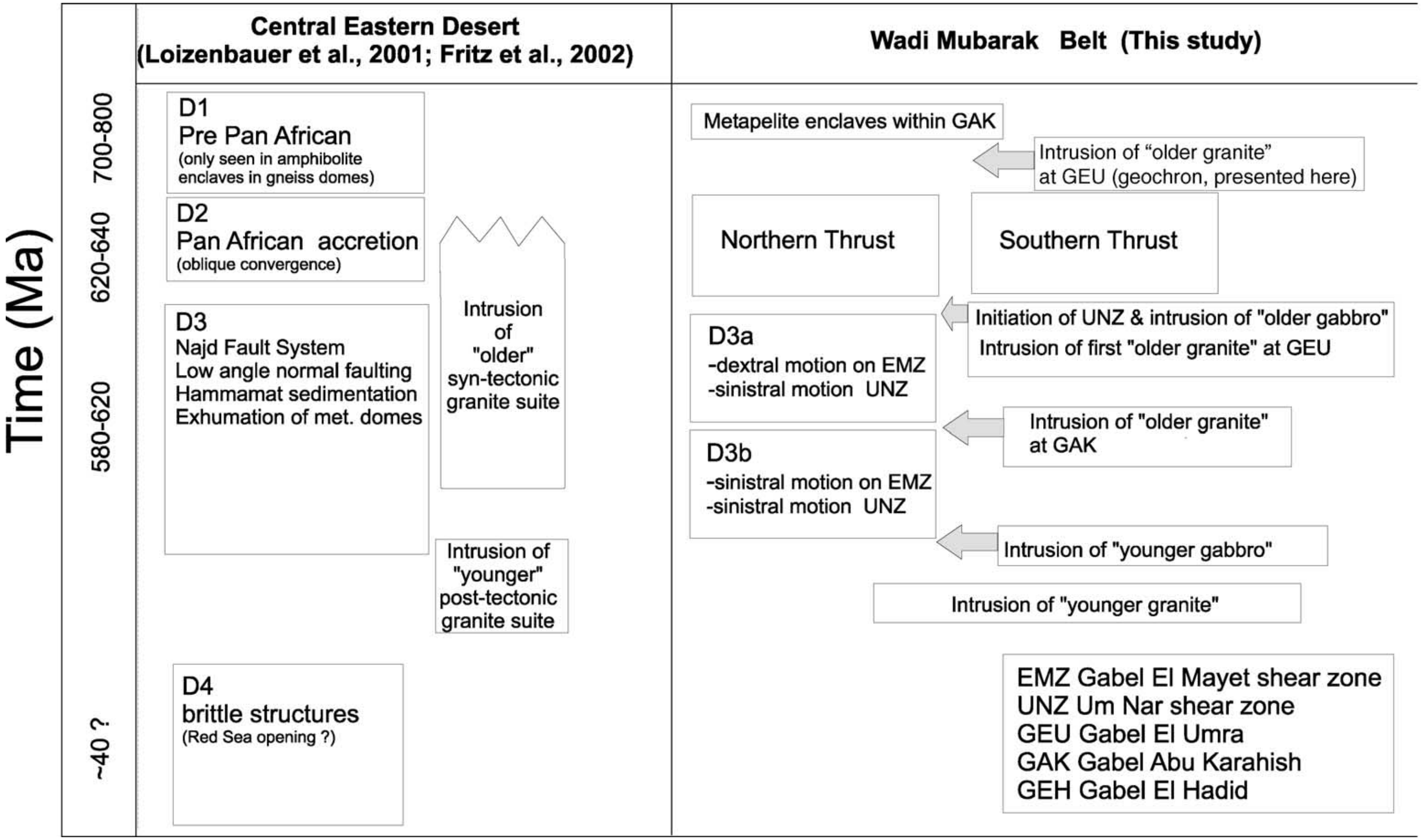


Fig. 11. Relative timing of tectonic events in the Wadi Mubarak belt and their correlation with similar events the Central Eastern Desert.

This granite intruded the metagabbro which in turn intruded the Um Nar shear zone during D3a (Fig. 11). The Gabel Abu Karahish granite is sinistrally sheared at its margins during D3b indicating that it intruded between D3a and D3b. (2) Similar to the intrusions of the later generation of older granite along the eastern margin of the Gabel Abu Karahish granite, undeformed small intrusive bodies of a later generation of older granite that are formed near the Um Nar shear zone. From these interpretations it is inferred that the stress field rotated during D3b counter-clockwise by about 30–45° to an eastnortheast–westsouthwest direction (Figs. 8 and 10).

5.3. Later events

The Gabel El Mayet shear zone was intruded by a post-D3b undeformed pink granite body. This indicates that its deformation history terminated before intrusion of the younger granite suite. The Um Nar shear zone was also intruded later by younger gabbro and granites. The younger gabbro has intruded the shear zone as small patches along secondary shear zones developed within the intrusive bodies. The younger gabbro does not display syn-magmatic or liquid stage of deformations. This indicates that it was passively intruded into small-scale pull-apart structures developed in response to D3b sinistral re-activation. Evidence for solid stage deformation is represented by the formation of granodioritic dykes which show north–south extension (Shalabi, 2003). The deformed younger granite within the Um Nar shear zone extends as a northwest–southeast oriented chain. Between the Um Nar shear zone and the northern thrust, at Gabel El Hadid, a small body of younger granite is also found. This indicates that the Um Nar shear zone has deformed the gneissified granite after D3b (Fig. 2). Brittle normal faults overprinting the older granite support north–south extension. The northwest–southeast extending Um Nar shear zone and north–south extension indicate that the younger gabbro and granite were intruded during transtension.

6. Regional implication

On a map scale, the Wadi Mubarak belt strikes northeast–southwest direction across the general northwest–southeast fabric of the Eastern Desert (Fig. 1). This invites to interpret the belt as a structure that is younger than the Najd fault system. This is implicit in interpretative cross sections drawn across the Central Eastern Desert (Fritz and Messner, 1999). The present study has shown that tectonic events in the Wadi Mubarak belt can be correlated with the tectonic events elsewhere in the Central Eastern Desert (Fig. 11).

The apparently cross cutting nature of the Wadi Mubarak belt is caused by the east–west orientation of the northern and the southern thrust formed during Pan-African oblique convergence (Wallbrecher et al., 1993; Fritz et al., 1996). In many parts of the Central Eastern Desert – including the Wadi Mubarak belt – tectonic transport direction during this event is manifested by the development of stretching lineations and other kinematic indicators (Fig. 5c and d). In contrast, thrusting in the Wadi Mubarak belt involved ramp formation in the gneissic granite south of the Gabel El Umra granite where the ramp is defined by an east–west striking fabric curving around the gneisses (Fig. 3). We suggest that the thrusting over the El Umra granite caused the east–west orientation of the entire belt. Due to the strong rheology contrast with the volcano-sedimentary sequence this orientation was retained throughout the main deformation events in the region.

Later deformation during D3 formed the northwest–southeast striking Najd Fault System in other parts of the Eastern Desert. We suggest that this orientation was not initiated in the Wadi Mubarak belt because of the regional lateral rheology contrasts between the Gabel El Umra granite and the volcano-sedimentary sequence. Instead, D3 stress field was compensated in Wadi Mubarak by an early conjugate shear zone system constituting the Um Nar and Gabel El Mayet shear zones. The Um Nar shear zone was already active during the end of D2 thrusting. Hence, D3 was affecting the pre-existing structure. The change in orientation of the Gabel El Mayet shear zone as well as the deflection of the Um Nar shear zone at its western end support this interpretation.

The orientation of the Um Nar shear zone can also be explained within the framework of the Hafafit dome (Figs. 1 and 12). The structure within the Wadi Nugrus east of the Hafafit dome was interpreted as thrust duplexes (Greiling et al., 1988; El Ramly et al., 1993). However, Fritz et al., (1996) and Makroum (2003) proposed that the structure of Wadi Nugrus is a sinistral

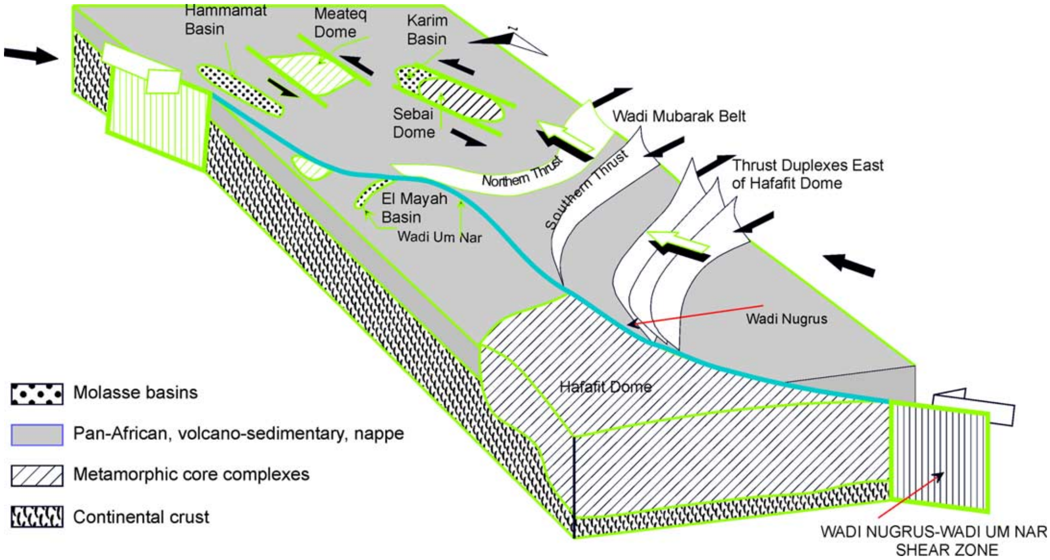


Fig. 12. Three dimensional illustration showing the position of the Wadi Mubarak belt as a conjugate set to the Najd Fault System.

shear zone which is part of the Najd Fault System (Stern, 1985) in Central Eastern Desert. The Wadi Nugrus shear zone is dominated by strike–slip duplexes (Makroum, 2003) similar to the Um Nar shear zone in which the strike–slip duplexes are linked with imbricate ramps and thrusts east of the shear zone. The Um Nar shear zone crosses the northern thrust of the belt of Wadi Mubarak in the west indicating reactivation of the shear zone. The area between the Um Nar and Wadi Nugrus shear zones is intruded by the Homret Wagat granite which is a "younger" or late to post kinematic granite (Akaad et al., 1996; Fig. 12). We propose that the younger granite was intruded in a transtensional structure and the Um Nar shear zone can be traced into the Wadi Nugrus shear zone (Fig. 1). Hence, we can conclude that the Um Nar and Wadi Nugrus shear zones represents a continuous regional structure which separates the Eastern Desert of Egypt into two subregions, the southern one includes the Hafafit dome while the northern one includes the Sibai and Meatiq domes (Fig. 12).

7. Conclusion

The Wadi Mubarak belt strikes east–west and is therefore discordant to the general northwest–southeast fabric in the Central Eastern Desert associated with the Najd Fault System. We can conclude that:

1. The first deformation event in the belt is a northwestward thrusting which resulted in the development of two major thrusts that bound the belt in the north and south. These thrusts ramp over an older gneissified granite and can be correlated with D2 in the remainder of the Central Eastern Desert. An older granite containing intrusive pulse of a minimum age of 654 and 690 my age to the north governed the regional fabric during this deformation event. The wrapping of this D2 deformation event around the northenr El Umra granite complex initiated the general west–east strike of the belt that was retained during subsequent deformation phases.
2. The second pervasive deformation event is characterized by the formation of the Um Nar and Gabel El Mayet conjugate shear system during what is known as D3 elsewhere in the eastern desert. The development of the Hammamat type molasse basin (the El Mayah basin) is associated with this event (Shalabi et al., 2004).
3. D3 in the Central Eastern Desert is caused by bulk east–west compression and is related to the exhumation of the core complexes. In Wadi Mubarak belt, this event is divided into D3a and D3b. D3a is characterized by east-southeast–west-northwest compression and caused sinistral strike–slip shearing

along the Um Nar shear zone and dextral strike–slip along the central segment of the Gabel El Mayet shear zone. D3b is characterized by a counter-clockwise rotation of the stress by 30–45° causing sinistral strike–slip shearing on both the Um Nar and the Gabel El Mayet shear zones.

4. We interpret Wadi Mubarak belt as an extension Wadi Nugrus belt. The Um Nar and the Wadi Nugrus shear zones subdivide the Central Eastern Desert into a northern region dominated by the Sibai and Meatiq domes and a southern region dominated by the Hafafit dome.

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Appendix A. Analytical method for zircon geochronology

Zircons were extracted using standard techniques involving crushing, sieving, Wilfley shaking table, Franz magnetic separator, heavy liquid (methylene iodide), and hand picking. The least magnetic zircons were collected and further classified into different fractions based on their morphology, colour, optical homogeneity (presence or absence of inclusions or inherited cores), shape (angularity or roundness for the metasediments), and elongation. The surface features of these zircons were studied by means of transmitted light microscopy attached to a digital camera in order to exclude crystals with micro-cracks and corroded surfaces.

The high quality zircons (inclusion free, without visible core, non-metamictic, generally idiomorphic, and magmatic grains) were air abraded following the procedures by Krogh (1982) to remove the outer surfaces affected by leaching, overgrowth, alteration, or cracks to produce more concordant ages. These zircons were then cleaned in diluted HNO_3 and acetone in ultrasonic bath, followed by cleaning in supra pure ethanol (for several hours) and warm 3N HNO_3 (for 20 min.). The clean zircons were then loaded into Teflon dissolution bombs, spiked with a mixed ^{205}Pb–^{233}U spike solution and heated in an oven at 210 °C for 3–5 days to dissolve in a 48% HF + HNO_3 acid solution. The completely dissociated zircons were dried on the hot plate at 140 °C and then re-dissolved in 2.5N HCl to convert fluorides to chlorides by heating at 210 °C for 12 h. Chemical separation of Pb and U was carried out using mixture of TRU-spec and Sr-spec resins (3:1; Paquette and Pin, 2001). Isotopic ratios of Pb and U were measured using ion counter equipped with secondary electron multiplier on a MAT 262 Mass Spectrometer. Standard analyses (NBS 982) at the beginning and the end of eight samples batch to monitor fractionations. Accordingly the Pb and U fractionations for the whole period of analyses are 0.13% per amu and 0.1% per amu, respectively. Data reduction, evaluation, error propagation, and individual age calculations were done using offline program and in-house Excel spreadsheet. Concordia–discordia plots and ages were calculated using Isoplot/Ex version 2.2 (Ludwig, 2000). Common Pb correction was applied following Stacey and Kramers (1975) at $^{207}Pb/^{206}Pb$ age. Reported errors are at 2σ standard deviation.

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