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The Kirsh gneiss dome: An extensional metamorphic core complex from the SE Arabian Shield.

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Abstract

A number of gneiss-cored domes and antiforms are exposed along the regional strike-slip Najd fault system in the Arabian Shield and the eastern desert of Egypt. The mode of origin is still controversial although plausible comparisons with modern metamorphic-core complexes were made in some well-studied areas. The Kirsh dome is located within the major Ar Rika shear zone and consists of a core of orthogneiss /migmatite and an envelope of paragneisses with locally-abundant kyanite-bearing quartzites. The dome is surrounded by the low-grade metasediments of the Murdama Group, and is bound from the south by a low-angle dip-slip fault. Beyond the southern strand of the Ar Rika fault is the Kibdi Basin which hosts unmetamorphosed sediments belonging to the Jibalah Group; this group occupies scattered pull-apart basins closely associated with releasing bends along the Najd fault system. Little dating was done on the gneiss domes of the Arabian Shield; however, recent dates from similar structures in the eastern desert and Sinai range from 580 to 620 Ma. A similar, albeit younger $^{40}Ar/^{39}Ar$ age of 557 ± 15 Ma was obtained form a biotite paragneiss south of Jabal Kirsh; this age difference probably represent the time interval it took the Kirsh rocks to cool below the biotite closures temperature and would place a lower age limit for the dome. The Kirsh dome occupies an extensional zone between left-stepping faults; movement within this zone might have caused enough decompression to trigger fluid-absent melting in the middle crust especially as the rocks cross the biotite dehydration solidus. Diapiric ascent aided by strike slip

dilatancy pumping led to the emplacement of the Kirsh rocks in their present position within the Murdama Group metasediments.

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Gneiss domes were identified from most of the terranes of the Arabian-Nubian Shield and especially from the intervening sutures where they had conventionally been ascribed to the compressional stresses that accompanied terrane amalgamation (Schmidt *et al*, 1979). More recently, many of these structures were re-interpreted as metamorphic core complexes similar to those of the North American Cordillera and as such were taken to represent a stage of crustal extension concomitant with orogenic collapse (e.g. Brooijmans *et al*, 2003), although other viable models such as fold interference patterns and folded nappes were proposed (Fowler *et al*, 2007; Fowler and El-Kalioubi, 2002). The difference between gneiss domes and core complexes has been blurred in recent years owing to the fact that many author tend to take the two terms as being synonymous. Some metamorphic core complexes are indeed domes or contain gneiss domes within them (Whitney *et al*, 2004), but not all gneiss domes posses the essential elements of a true metamorphic core complex. A core complex consists of a metamorphic interior and an unmetamorphosed (or slightly metamorphosed) cover separated by a mylonitic decollement along a low-angle normal fault (detachment fault).

The structures are often dome-like with the major fold axis parallel to the regional extension (Yin, 1991).

The Arabian-Nubian Shield marks the northern collision zone between East and West Gondwana, a process that began at *c*. 870 Ma with the breakup of Rodinia and the formation of island arcs within the Mozambique Ocean, which were later amalgamated during collision to form the terranes of the Arabian-Nubian Shield; orogenic activity ceased and a passive margin formed at *c.* 550 Ma **(**Johnson and Woldehaimanot, 2003). Al-Saleh *et al* (1998) suggested that oblique convergence induced a major transpressional orogeny that affected the eastern half of the Arabian Shield culminating at c. 600 Ma, and was probably followed by major movement along the Najd sinistral strike-slip System. Transpression is an efficient mechanism in crustal thickening and if accompanied by transcurrent movement then it would be a favorable milieu for the generation of migmatites and anatectic granites (D'Lemos *et al*, 1992). It is generally accepted that tectonism in the Arabian shield has changed form convergence to extension after 600 Ma (Genna *et al*, 2002); a manifestation of which is an inferred widespread unroofing induced by low-angle detachment faults resulting eventually in the exhumation of mid-crustal segments in metamorphic core complexes akin to those of the Basin and Range province of the North American Cordillera (e.g. Blasband *et al*, 2000). Although the deeper erosion level of the Arabian Shield precludes direct comparison with assumed modern analogues, it is still nevertheless possible to notice some similarities in deformational style especially in the vicinity of major crustal-scale structures.

Among the most interesting domal-structures in the Southeastern Arabian Shield is the Jabal Kirsh gneissic antiform and its enveloping mantle of kyanite-bearing metavolcanics (Delfour, 1979), which are exposed along a segment of the Ar Rika sinistral strike-slip fault, one of the major lineaments of the regional Najd Fault System (Johnson and Kattan, 1998).

Regional Geology:

The study area is located close to the southeastern periphery of the Arabian shield (Fig-1), and is underlain by Late Proterozoic layered rocks and intrusives belonging to the Afif Composite Terrane (Stoeser and Stacey, 1988; Johnson, 1998). The main structural feature is the Ar Rika Fault which extends for more than 1000 km from the southeastern boundary of the shield to the northern Red Sea coast and possibly into the Sinai Peninsula. For much of its length, the Ar Rika Fault displays a brittle-ductile nature with numerous exposures of gneissic belts most conspicuous among them are the Kirsh granitic gneisses, as well as the Qazaz, Wajiyah and Hamadat domes further north (Nehlig *et al*, 2001). These complexes display contrasting structural/metamorphic features

(Genna *et al*, 2002) that may reflect different modes of origin. The Kirsh dome is unique in having extensive outcrops of kyanite-bearing quartzites, signifying uplift of high-pressure mid-crustal material. On the decompensative isostatic residual gravity map of Mogren *et al* (2008) the Ar Rika fault zone is characterized by broad positive gravity anomalies (20–30 mGal), which they consider as the signature of a deep-lying high density gneissic mass.

In the study area, the Ar Rika Fault is bound to the northeast by the molassic sediments of the Murdama Group, while a heterogeneous assemblage of metavolcanics and intrusives is exposed on the opposite side; beyond which is the extensive Dahul gneissic terrain (Ramsay *et al*, 1984), an extensive structural/lithologic province made up of migmatites, granitic gneisses as well as syn- and post-tectonic granites. Further south the fault cuts through the Murdama rocks and its associated granites for a distance of about 120 km to the SE edge of the Shield where it is covered by Paleozoic sediments. To the north it cuts through various units and sutures and hosts a number of pull-apart basins infilled with the unmetamorphosed sediments and volcanics of the Jibalah Group.

According to geologic map of the Wadi ar Rika Quadrangle (Delfour, 1980), the Kirsh Dome is an anticlinorium cored by the Hawriyah orthogneiss which he interprets as an elliptical syntectonic intrusion of biotite granite emplaced within amphibolite-grade leptites and amphibolites; this metamorphic envelope is referred to by Delfour (1980) as the Mahadib Belt, which he considers to be derived from volcanic rocks and sediments attributed to the Hulayfah Group of the Nuqrah area in the northern shield on the basis of lithological and assumed age similarity. Along the contacts, the granitic gneisses are strongly foliated and posses the same shallow-plunging lineations of the host metamorphites; the contact between these two units is gradational with thick concordant sheets of granite injected into the metamorphic rocks; towards the central part of the intrusion, foliation is less pronounced, yet enclaves of country rocks are still common.

The granitic core and its surrounding metamorphic assemblage were designated by Johnson (2003) as orthogneiss and paragneiss respectively and the whole suite was referred to as the Kirsh gneiss belt. Both segments appear on the compiled 1:1,500,000 map of the Arabian Shield as one unit of “unassigned schist and gneiss” not included within any of the stratigraphic groups of the shield (Johnson, 2006a); this description applies to other metamorphic suites associated with Najd faults. The igneous core was described by Johnson and Woldehaimanot (2003) as a strongly foliated biotite monzogranite orthogneiss (Al Hawriyah Anticlinorium) intruded into steeply dipping kyanite-quartz schist at the southeastern end of the Ar Rika-Qazaz Shear System. On the presumption that the Al Khushaymiyah complex to the NE, which is composed of massive monzogranite, is an undeformed equivalent of the Hawriyah orthogneiss, they assumed that activity on this section of the Ar Rika Shear Zone is dated at c. 610Ma.

The detailed geologic setting of the Kirsh Dome is clearly a matter of debate; however, there is a general agreement on the igneous intrusive nature of its core and the presence of volcanosedimentary protoliths in the metamorphic mantle; the latter is believed to have been originally made up of felsic and siliceous tuffs grading to chert with andesitic pyroclastics and graywackes on the basis of correlation with the Hulayfah Group (Collenette and Grainger, 1994). Nevertheless, it seems improbable that the rocks of the Kirsh area are an extension of the Hulayfah Group because of the great distance from, lack of mapped continuity with, and inferred different tectonic settings between the Wadi ar Rika and Nuqrah areas (Johnson, 2006b); it is more likely that they are the high-grade equivalents of the adjacent Siham Group (Agar, 1985), or the Rika Formation (Johnson, 2005) which is located only 15 km from the southern extension of the Ar Rika Fault and has a volcanosedimentary assemblage metamorphosed in the greenschist facies.

Further east from the Kirsh Dome is a similar structure known as the Artawi Structural Window (ASW) which is basically a migmatite dome emplaced within the easternmost major strand of the Najd System (Fig-1), and which is believed to be coeval with movement along the

Rika Fault (Al-Saleh *et al*, 1998). The ASW is dominated by basic migmatites and high-grade biotite and garnet–biotite paraschists admixed with granites from the heterogeneous Abu Isnun pluton which range in composition from pyroxene diorites and tonalites to porphyritic alkali-feldspar granites

Local Geology:

The northern tip of the Kirsh Dome was the main focus of field work in this study (Fig-2) due mainly to its excellent outcrops of the different lithologies that make up the dome and also because it has extensive outcrops of kyanite-bearing quartzites that are unique in the Arabian Shield, and may have important implications for the evolution of this domal structure. The physiography of the region is dominated by the Jabal Kirsh inselberg, a 1300 m-high massif of biotite paragneiss that marks the northern end of the Kirsh Dome. The main strand of the Ar Rika Fault runs about 20 km southwest of Jabal Kirsh, and has many exposures of well-developed ultramylonite.

Scattered outcrops of kyanite-bearing quartzite are located about 7 km west of Jabal Kirsh in a 15 km long belt that contains layers of quartzite with up to 20% of white kyanite. On the basis of relict textures, the protolith of these quartzites is believed to be an alumina-rich rhyolite rather than a metapelite (Delfour, 1980). East of the dome are the extensive molassic sediments of the Murdama Group which are mainly greywackes and conglomerates belonging to the Zaydi Formation and showing the effect of contact metamorphism up to amphibolite facies conditions. Mineral and grain lineations are well-developed in the Murdama rocks all along the contact and are mainly concordant with those of the adjacent dome rocks. Beyond the main Rika Fault are the unmetamorphosed clastic sediments of the Jibalah Group, occupying a wedge-shaped half graben known as the Kibdi Basin. These sediments are associated with Najd faulting throughout the central and northern shield, and the Kibdi Basin is the southernmost exposure of the group; they are believed to occupy pull-apart basins formed at the releasing bends of the Najd system (Matsah, 2000). A thin sliver of Murdama rocks separates the Jibalah sediments from the dome; the contact of this segment of the Murdama with the Kirsh gneisses is marked by a 50 km long thrust fault according to the map of Delfour (1980).

Inside the dome most of the rocks are metamorphosed to the amphibolite facies with the intensity of metamorphism increasing towards the center. The rock types are mainly gneissic with minor metabasites and quartzofeldspathic lithologies; abundant streaks of mylonite delineating minor shear zones run roughly parallel to the main segment of the Ar Rika Fault. Most rocks are foliated and some exhibit well-developed mineral lineations defined by hornblende, kyanite and mafic lenses. Delfour (1980) identifies two phases of folding, the first of which (F_1)

was coeval with amphibolite grade metamorphism and induced an axial-plane cleavage and NW plunging lineations. The second phase (F_2) is a post-metamorphic event and is less conspicuous; it affected mainly the Murdama sediments through flexuring perpendicular to F_1 and produced a noticeable crenulation cleavage in pelitic beds.

Structural Geology and Geochronology:

Observations during the field work of this study are in general agreement with the findings of Delfour (1979, 1980) and Genna *et al* (2002) as regards rock types and structures. Foliation with a strike generally parallel to the long axis of the dome and moderate to steep dips (45-90°) is generally well-developed especially in the paragneisses. Mineral and grain lineations have a general NW trend and shallow to moderate plunge (Fig-3). It was suggested by Johnson and Woldehaimanot **(**2003) that the gentle plunge of the northwesterly trending mineral and elongate-pebble lineations indicates a large component of constriction, or unidirectional stretching. Similar structural relations are to be found in metamorphic core complexes in the eastern desert of Egypt lying roughly on the same Rika lineament (e.g. Fritz *et al*, 1996; Loizenbauer *et al*, 2001). According to the structural model of Genna *et al* (2002) the Kirsh kyanite-bearing quartzites represent the exhumation of a deep metamorphic facies within a domain of transpressive ductile deformation; the extent of vertical uplift induced by transpression was estimated to be about 10 to 15 km on the basis of the metamorphic assemblage of the Kirsh dome (Nehlig *et al*, 2002).

The fact that gneiss domes in the Arabian-Nubian are in many cases associated with crustal-scale transcurrent fault systems is highly suggestive of a genetic role as relates to emplacement and possibly magma genesis. Much work has been carried out in the past two decades on the gneiss domes of Sinai and the eastern desert of Egypt, and their relationships with presumed extensions of the Najd faults (Fritz *et al*, 2002; Abd El-Wahed, 2008), and there is a general agreement on the causative role of sinistral strike-slip movement in the exhumation of core complexes with varying tectonic scenarios and timing. Most models envisage some form of extension (Brooijmans *et al*, 2003; Fritz et al, 2002; Fowler and Hassan, 2008) accompanied by the formation of peripheral pull-apart basins infilled with the sediments of the Hammamat Group (Abd El-Wahed, in press; Shalaby *et al*, 2006). A zone of intense high-temperature mylonite that separates a brittle attenuated upper crust from a deep exhumed crust in the Sibai domal structure was recognized by Abd El-Wahed (2008); he concludes that the existence of sub-horizontal lineation, sub-vertical foliation, strike-slip shear zones and the pull-apart Atawi basin supports the idea of wrench-dominated transpression and regional extension during formation and exhumation of the Sibai core complex.

Age determinations from gneissic antiforms and belts in the eastern desert of Egypt lie mainly within the late stages of cratonization of the Arabian-Nubian Shield, with a clear clustering of ages in the period 620-580 Ma (Fritz *et al*, 1996; Fritz *et al*, 2002; Andresen *et al*, 2009; Loizenbauer, 2001; Eliwa, 2008). Recent evidence utilizing SHRIMP U-Pb on zircons revealed that the time interval 579-594 Ma was the main period for the generation of extension-related monzogranites, syenogranites and alkali granites in Sinai (Ali *et al*, 2009). However, there is a noticeable dearth of chronological data from Arabian Shield gneissic terrains, especially as relates to their metamorphic/exhumation ages. The only well-constrained emplacement ages for a granite-migmatite dome in the eastern Arabian Shield are two $^{40}Ar/^{39}Ar$ dates from the migmatitic metabasites and garnet-biotite schists of the Artawi Structural Window which are concentrated around 600 Ma (Al-Saleh *et al*, 1998).

In order to obtain an age estimate of the uplift of the Kirsh gneisses, a sample of biotite paragneiss was collected from the southern exposure of Jabal Kirsh and a biotite concentrate was prepared and irradiated for age determination using the step-heating $^{40}Ar/^{39}Ar$ technique. Analysis was carried out at the Department of Earth Sciences, Liverpool University. The mica separate, purified using an isodynamic separator, was sealed in a quartz vial which was packed in a 150 mm canister and irradiated with a neutron flux of 2 x 10^{20} mm^{-2} in the Petten reactor, Holland. Cadmium shielding was used to reduce the thermal neutron flux, and flux gradients were monitored with the MMhb-1 standard using an age of 520.4 Ma. The irradiated sample was placed in degassed molybdenum crucible, heated for 30 minutes for each step, and the released gases were purified using getters and liquid N_2 cold fingers. Argon isotope composition was measured with a modified AEI MS10 mass spectrometer with a 0.45-T magnet and automatic scanning. The errors are quoted at the 95% confidence level.

The gas was released in 13 heating steps giving a total gas age of 458 ± 1.1 Ma; steps 2-10 were chosen for age calculations and they contained 62% of the ^{39}Ar. Since such deep seated rocks commonly display non-atmospheric initial $^{40}Ar/^{36}Ar$ ratios, isochron ages are preferred to plateau ages because they need no prior assumption regarding initial Ar composition. On the $^{40}Ar/^{36}Ar$ vs. $^{39}Ar/^{36}Ar$ isochron diagram (Figure-4), the points yield a robust linear array with a mean squared weighted deviate (MSWD) value of 1.73, and an age of 557 ± 15 Ma. This age estimate is coeval with the nearby Dahul gneisses form which ages of 535-599 Ma were determined (Kroner *et al*, 1979 and references therein), but slightly younger than the above quoted dates from Egyptian complexes, due probably to the low closure temperature of biotite (c.300 °C) for argon (Hodges, 1991); this date should therefore be considered as a cooling rather than an emplacement age, and would serve as a minimum age for the development of the Kirsh structure.

The age of the Jibalah basins and the equivalent Hammamat Group of Egypt has a direct bearing on the age of the Najd faults and associated gneisses, yet direct determinations are hampered by the lack of rock types suitable for isotopic measurements and hence most age estimates of these sediments are based on cross-cutting relationships with igneous lithologies. A 576 ± 5 Ma U–Pb zircon crystallization date from a felsite dyke the cuts the Al Jifn basin (Matsah and Kusky, 2001) constrains the lower age limit of the Jibalah in the north-central shield. Miller *et al* (2008) obtained concordant SHRIMP ages as young as 599 ± 4.8 (core) and 570 ± 4.6 (rim) from detrital zircons extracted from a diamictite interval in the Dhaiqa Basin which lies within a putative extension of the Rika Fault. Granitic basement in the Jabal Jibalah type area yields a Rb–Sr whole-rock age of 574 ± 28 Ma (Calvez *et al*., 1983), and K–Ar ages of 567 ± 6 and 581 ± 7 Ma were reported by Brown *et al* (1989) from volcanic horizons in basins from the central shield. Available age estimates as well as field relations and overall geologic setting led Johnson (2003) to conclude that the deposition of the Jibalah Group took place mainly in the time interval 580–570 Ma. In Egypt, SHRIMP dates from detrital zircons collected from the basal part of the Hammamat Group are as young as 585 ± 13 Ma (Wilde and Youssef, 2002); previous estimates include a zircon 'model' age of 583 Ma for a cross-cutting granite (Stern & Hedge 1985), and a 585 ± 15 Ma Rb-Sr whole-rock age from the sediments of Gebel Dokhan (Willis *et al*, 1988).

Exhumation of the Kirsh Dome:

It is evident from field relations and the various age estimates that many gneiss domes in the Arabian-Nubian Shield have developed in a close association with Najd faulting following terrane amalgamation and cratonization, and most of those in the eastern Egyptian desert and Sinai have been interpreted as metamorphic core complexes. The classic model of core complex exhumation requires the presence of a low angle normal fault (detachment fault) to induce unroofing and initiate crustal flow and isostatic uplift, with no melting or plutonism required. However, in the case of the Kirsh Dome it is necessary to explain the origin of the Hawriyah granite and provide a viable mechanism for its emplacement. Melting of crustal rocks is viewed as an essential part of gneiss dome development (Teyssier and Whitney, 2002); therefore most domes are in fact anatectic migmatite domes, and this is borne out by the fact that many Precambrian domes in particular are dominated by granitic plutons (Whitney *et al*, 2004).

Johnson and Woldehaimanot **(**2003) describe the Hawriyah monzogranite as being located in a zone of extension between left-stepping faults along the sinistral Ar Rika Fault Zone. The presence of the

Kibdi pull-apart basin indicates a releasing bend along the Rika Fault in the Kirsh area, it is suggested here that extension concomitant with such movement could have caused enough decompression to trigger substantial partial melting in the middle or even lower crust which generated a buoyant granitic diapir. Such a process would have been greatly assisted by the development of a detachment fault leading to rapid exhumation and near-isothermal decompression. The Najd fault system in the eastern desert of Egypt is associated with low-angle normal faults marking the northern and southern boundaries of metamorphic complexes and forming extensional bridges between them (Fritz *et al*, 1996); it is believed that the combined effect of strike-slip and normal faulting led to the rapid late stage exhumation of the Meatiq and Hafafit domes and continued to c. 580 Ma (Fritz *et al*, 2002).

It was noted by Johnson (2000) that southwest-directed extension and normal dip slip characterized later movement on the Ar Rika shear zone. The lineament defining the western boundary of the Kirsh dome and identified by Delfour (1980) as a thrust is an excellent candidate for the role of a detachment fault since it has the necessary strike direction and a low dip angle; more importantly, it is inconceivable how a slice of the Murdama molasses could have been transported westward from the main Murdama basin along a an easterly moving thrust; this thrust is clearly going the wrong way, and despite the lack of proper kinematic indicators to establish the sense of slip, a more plausible explanation for the existence of the Murdama sliver west of the dome is that a low-angle normal fault had sliced part of the Murdama sediments that once covered the Kirsh area and moved it westward. This model would establish a situation where the ductile interior of the Kirsh dome is surrounded by a brittle domain made up of the unmetamorphosed Jibalah sediments and the slightly (lower greenschist facies) metamorphosed Murdama molasses, with a detachment fault separating the two domains in a manner identical to that of typical Phanerozoic core complexes.

Deep burial of the Kirsh paragneisses during continental collision and the ensuing crustal thickening is evident from their high-P mineralogy; similar deep crustal rocks were reported from gneiss domes associated with major strike-slip systems with pressures reaching up to 12 kbars (e.g. Jolivet *et al*, 1999). Pressure estimates form Sinai complexes are much lower being mainly in the range of 3–5.5 kbar with temperatures of 500-650 °C (Brooijmans *et al*, 2003; Eliwa *et al*, 2008), and thus define a relatively high geothermal gradient (30–50 °C/km) for a collisional orogeny. Such a steep gradient and the LP/HT mineral assemblages suggest that they were formed in an extensional setting with heat flow transferred from nearby granitic intrusions (Eliwa *et al*, 2008). This type of scenario is untenable for the Kirsh dome which appears to have developed through a process not controlled by thermal relaxation;

similarly, models where continuous magma generation weakened the crust leading to facilitation of lateral extrusion tectonics do not apply (Fritz *et al*, 2002). However, recent evidence from the Feiran–Solaf migmatite/gneiss complex in Sinai which is located within a northerly segment of the Najd system indicates peak metamorphic conditions at 700–750 °C and 7–8 kbar with subsequent isothermal decompression to 4–5 kbar, followed by near isobaric cooling to 450 °C (Abu-Alam, and Stuwe, 2009). The prograde path of migmatites from this particular complex corresponds roughly to a geothermal gradient of 25-30 °C/km and reaches down to a depth of 25-29 Km.

The Artawi Structural Window (ASW) which is roughly coeval with the Kirsh dome and occupy a similar structural setting (a dilational segment of a Najd fault) has a clockwise P-T t path indicating thickening prior to extensive heating, and with a relatively low geothermal gradient for the prograde path averaging about 20 °C/km (Al-Saleh *et al*, 1998), thus intersecting the wet granite solidus at a depth of approximately 30 Km (Thompson, 1999). The high variance assemblage of the Kirsh rocks precludes the use of conventional thermobarometric techniques; however, if the same conditions from the ASW apply to the Kirsh dome then the entire prograde path would be within the kyanite stability field and intersection with the granite solidus and the muscovite dehydration-melting line (Thompson, 2001) would be attainable in the lower crust. A more plausible scenario would be that dilation within the Rika Fault induced substantial decompression that led to the intersection with dehydration solidi at mid-crustal levels. This situation is commonly recorded by migmatites in gneiss domes, and the typical magnitude of decompression is at least 4–6 kbar (Teyssier and Whitney, 2002). As the rocks decompress further and with a slight increase in temperature due to the onset of thermal relaxation they would cross the biotite dehydration-melting curve (Fig-5) beyond which a greater degree of melt is produced (Vielzeuf and Holloway, 1988).

Extensional segments of regional strike-slip shear zones are favorable sites for the production and ascent of granitic magma, which may form by a combination of decompression-dehydration melting, and then infiltrate the shear zone at extensional jogs to be later squeezed upwards in zones of compression through the mechanism of strike slip dilatancy pumping (Brown, 1994). The Kirsh dome is situated within a major extensional offset of the Rika Fault that could have produced the necessary decompression and the ensuing dehydration melting through the reactivation of the thrust on its western boundary as a low-angle normal fault.

According to Clemens (1984) most granitic magmas were initially water-undersaturated, indicating that melting reactions were fluid-absent; and even if water-saturated melting was to occur a smaller fraction of melt (>10%) is produced, and would be exceedingly difficult to segregate into a mobile mass. A higher degree of melting (c. 40%) is attained by the breakdown of hydrous phases, especially micas (Vielzeuf and Holloway, 1988); the positive slopes of these dehydration-melting solidi allow intersection with even a near-isothermal decompression path (Fig-5), and the resulting melt would then begin to flow into dilatant zones or move upward diapirically due to density contrast, a process that would lead to more isothermal decompression and which would halt solidification until the migmatite-granite mass is emplaced within the upper crust where it becomes subjected to rapid cooling. According to Teyssier and Whitney (2002) the signature of the rapid ascent of partially molten crust is a gneiss dome cored by migmatite ± granite which is similar to the situation in the Kirsh dome. In their reviews of core complexes in the eastern desert of Egypt Fritz *et al* (1996) and Fritz *et al* (2002) conclude that although a regime of overall convergence and transpression prevailed, displacement partitioning allowed overall orogen-parallel extension during a bulk compressive regime. It is proposed here that the Kirsh dome with its granitic core represents a metamorphic core complex generated and exhumed by localized extension along a major releasing bend of the Rika Fault following a major transpressional orogeny in the eastern Arabian Shield.

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Figures

Fig-1: Terrane map of the Arabian Shield showing the main segments of the Najd Fault System and their associated gneissic domains (from Johnson, 2006b).

Fig-2: Simplified geologic map of the northernmost part of the Kirsh Dome (after Delfour, 1979 & 1980; Johnson, 2003). Due to the left-stepping nature of the Rika Fault in this region the main fault line marks the western border of the dome while the northern contact with the Murdama sediments is more or less intrusive. The grey area marked (ky) is the main belt of kyanite-bearing quartzites.

Fig-3: Lower hemisphere stereoplot of mineral lineations in the metamorphic mantle of the Kirsh Dome.

Fig-4: $^{39}Ar/^{36}Ar$-$^{40}Ar/^{36}Ar$ normal isochron diagram of a biotite separate from a paragneiss showing the errors at the 2σ level and a best-fit regression line.

Fig-5: Postulated P-T-t path for the Kirsh migmatites (dashed bold line) showing the location of the wet granite solidus (WGS) and the dehydration solidi for muscovite (MDS) and biotite (BDS). A combination of dehydration melting and unroofing could have led to isothermal decompression. P-T-t path from the ASW (Al-Saleh *et al*, 1998), Meatiq Dome = Md (Neumayr *et al*., 1998) and the Feiran-Solaf core complex = FS (Abu-Alam, and Stuwe, 2009) were added for comparison, and they define a metamorphic field gradient of about 30°C/ km. A distinct decrease in the depth of burial/exhumation for the last two regions might indicate a diminishing depth for the Najd system in the northern Nubian Shield.

Figure
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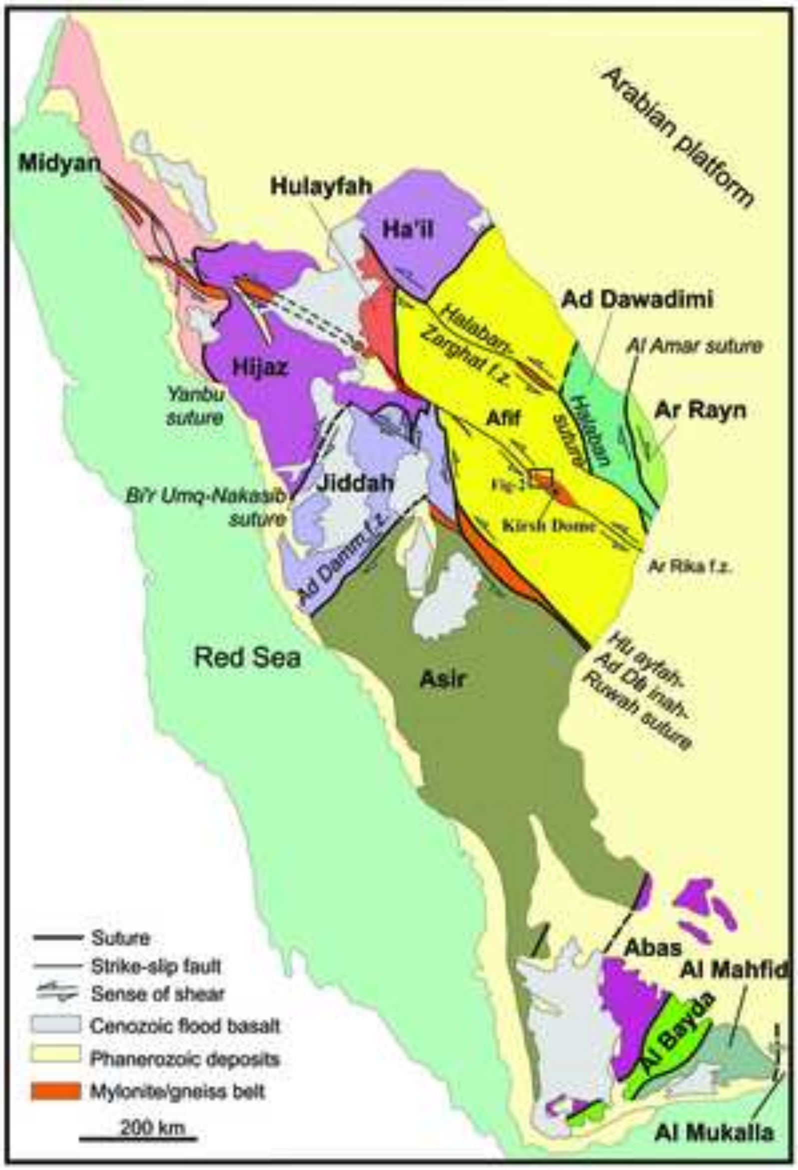

Fig -1

Figure

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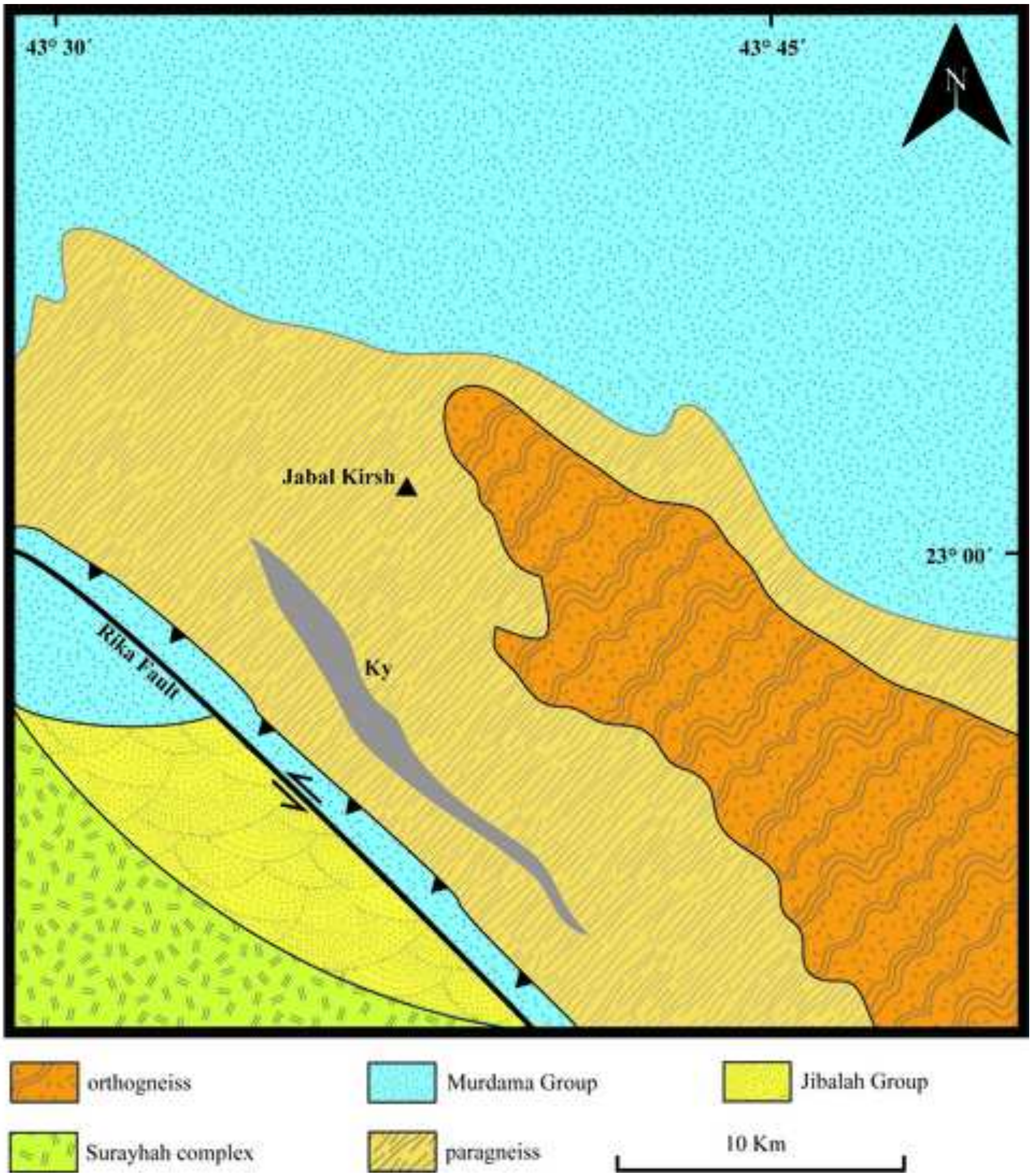

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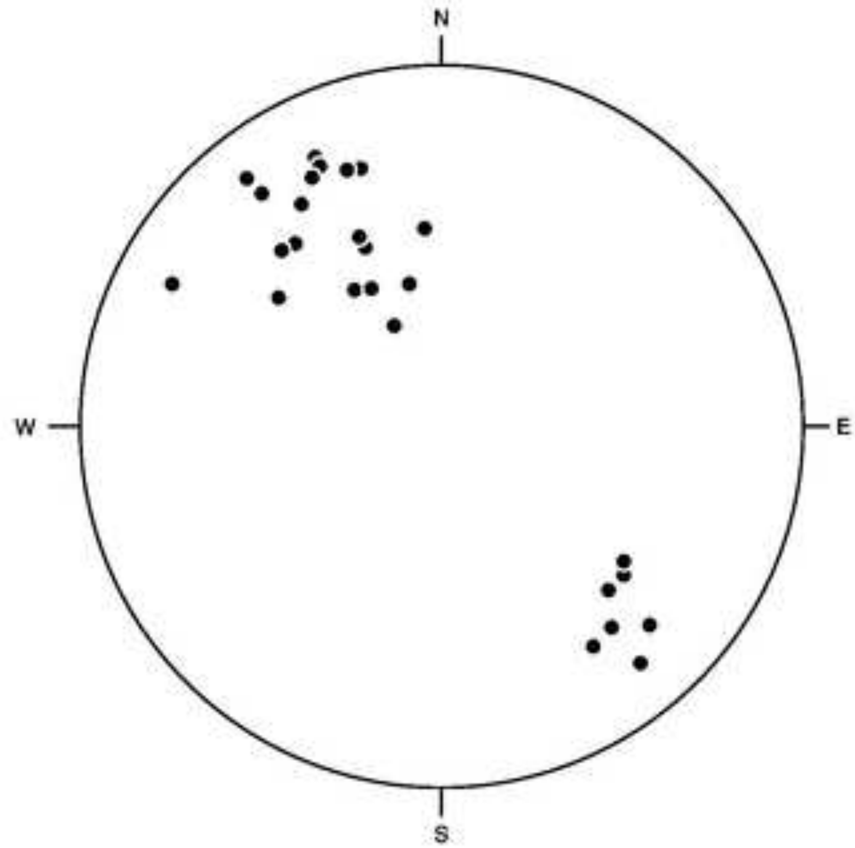

Fig-3

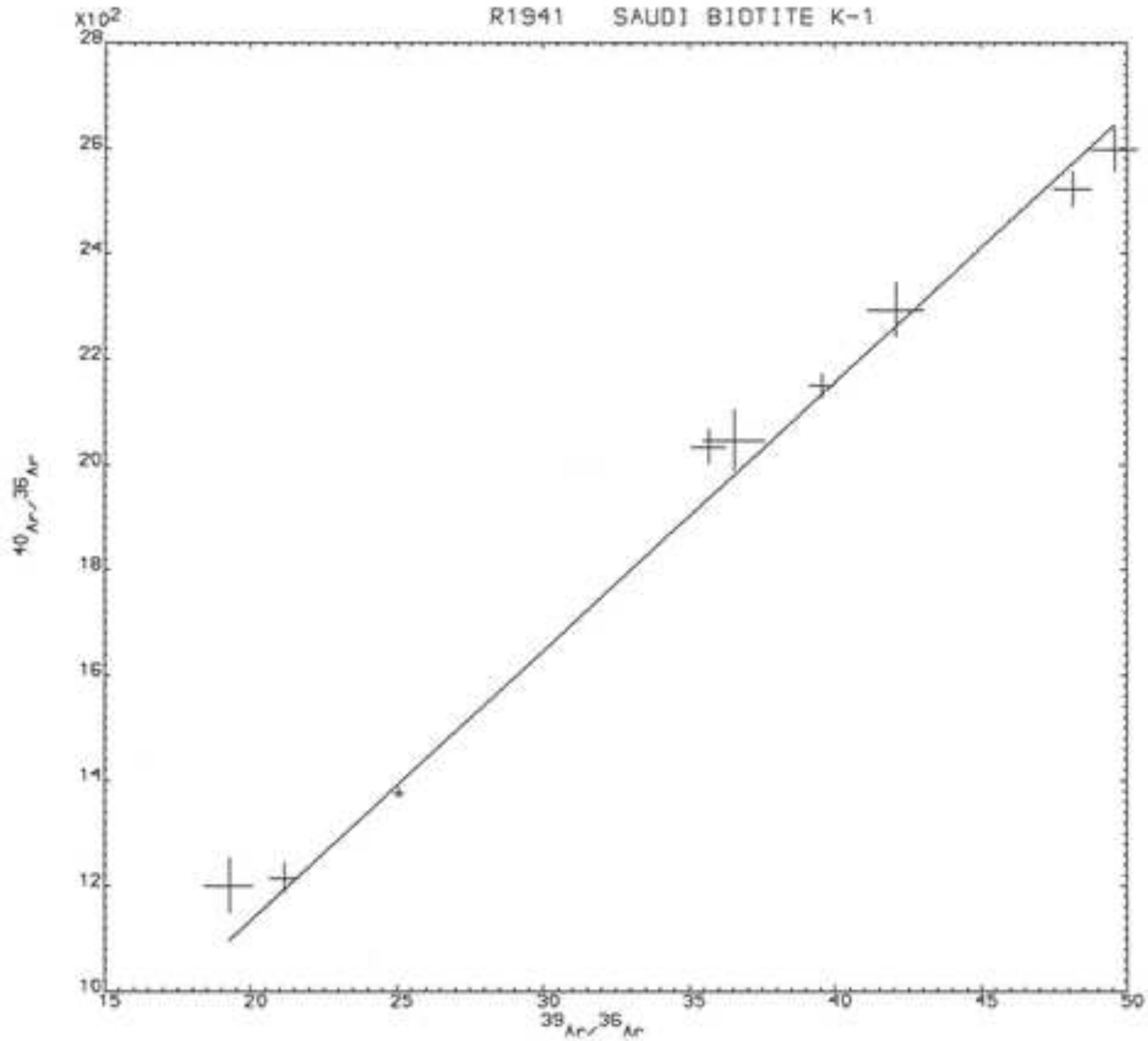
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Fig-4

Figure
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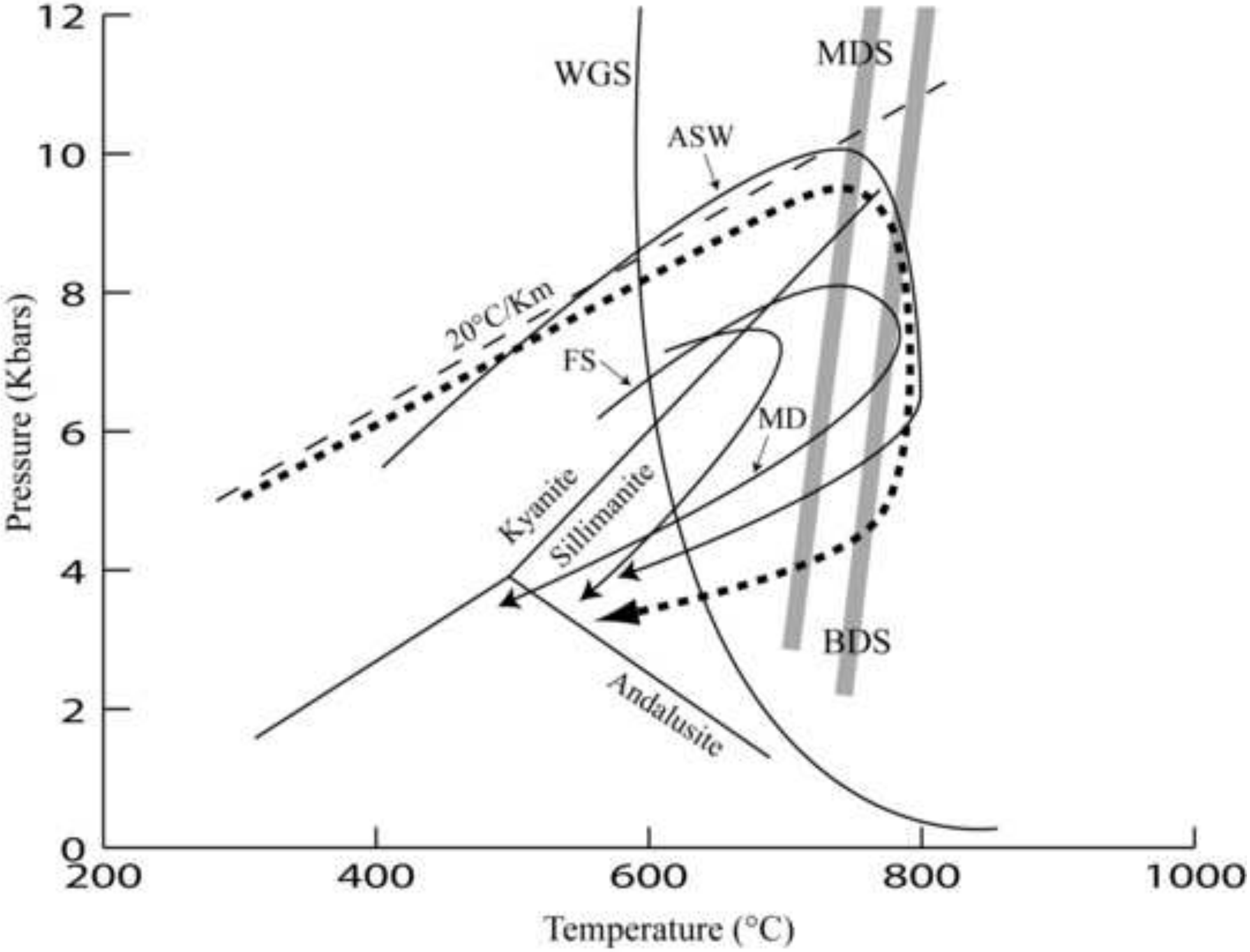

Fig-5