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A review of the Pan-African evolution of the Arabian Shield

Pierre Nehlig, Antonin Genna and Fawzia Asfirane, BRGM, France
with the collaboration of N. Dubreuil, C. Guerrot, J.M. Eberlé, H.M. Kluyver,
J.L. Lasserre, E. Le Goff, N. Nicol and N. Salpeteur, BRGM, France,
M. Shanti, BRGM, Jiddah, D. Thiéblemont and C. Truffert, BRGM, France

ABSTRACT

Recent fieldwork and the synthesis and reappraisal of aeromagnetic, geologic, structural, geochemical, and geochronologic data have provided a new perspective on the structural evolution and geologic history of the Arabian Shield. Although Paleoproterozoic rocks are present in the eastern part of the Shield, its geologic evolution was mainly concentrated in the period from 900 to 550 Ma during which the formation, amalgamation, and final Pan-African cratonization of several tectonostratigraphic terranes took place. The terranes are separated by major NW-trending faults and by N-, NW- and NE-oriented suture zones lined by serpentinized ultramafic rocks (ophiolites). Terrane analysis using the lithostratigraphy and geochronology of suture zones, fault zones, overlapping basins, and stitching plutons, has helped to constrain the geologic history of the Arabian Shield. Ophiolites and volcanic-arcs have been dated at between 900 and 680 Ma, with the southern terrane of Asir being older than the Midyan terrane in the north and the Ar Rayn terrane in the east.

Final cratonization of the terranes between 680 and 610 Ma induced a network of anastomosing, strike-slip faults consisting of the N-trending Nabitah belt, the major NW-striking left-lateral transpressive faults (early Najd faults), lined by gneiss domes and associated with sedimentary basins, and N- to NE-trending right-lateral transpressive faults. Following the Pan-African cratonization, widespread alkaline granitization was contemporaneous with the deposition of the Jibalah volcanic and sedimentary rocks in transtensional pull-apart basins. Crustal thinning was governed by the Najd fault system of left-lateral transform faults that controlled the formation of the Jibalah basins and was synchronous with the emplacement of major E- to NW-trending dike swarms throughout the Arabian Shield. The extensional episode ended with a marine transgression in which carbonates were deposited in the Jibalah basins. Continuation of the thinning process may explain the subsequent deposition of the marine formations of the lower Paleozoic cover.

Our interpretation of the distribution and chronology of orogenic zones does not correspond entirely to those proposed in earlier studies. In particular, the N-trending Nabitah and NW-trending Najd fault zones are shown to be part of the same history of oblique transpressional accretion rather than being two distinct events related to accretion and dispersion of the terranes.

INTRODUCTION

The general theory of plate tectonics provides a link between the geological processes of sea-floor spreading, subduction, and mountain building. However, details of how this theory relates to ancient continental tectonic processes are unclear in many parts of the world. Although early enthusiasm led many geologists to propose paleogeodynamic reconstructions for ancient orogenic belts, many of these models need revision in the light of increased understanding of accretion-related orogenic tectonic deformation and postaccretion dispersion (Howell, 1989).

As in many other ancient continental areas, the tectonostratigraphic units that comprise the Arabian Shield are mostly fault-bounded, and the geologic histories of neighboring units commonly have contrasting elements. These fault-bounded 'tectonostratigraphic terranes' are allochthonous and were brought together by processes of accretion. Because of the low regional metamorphic grade and the

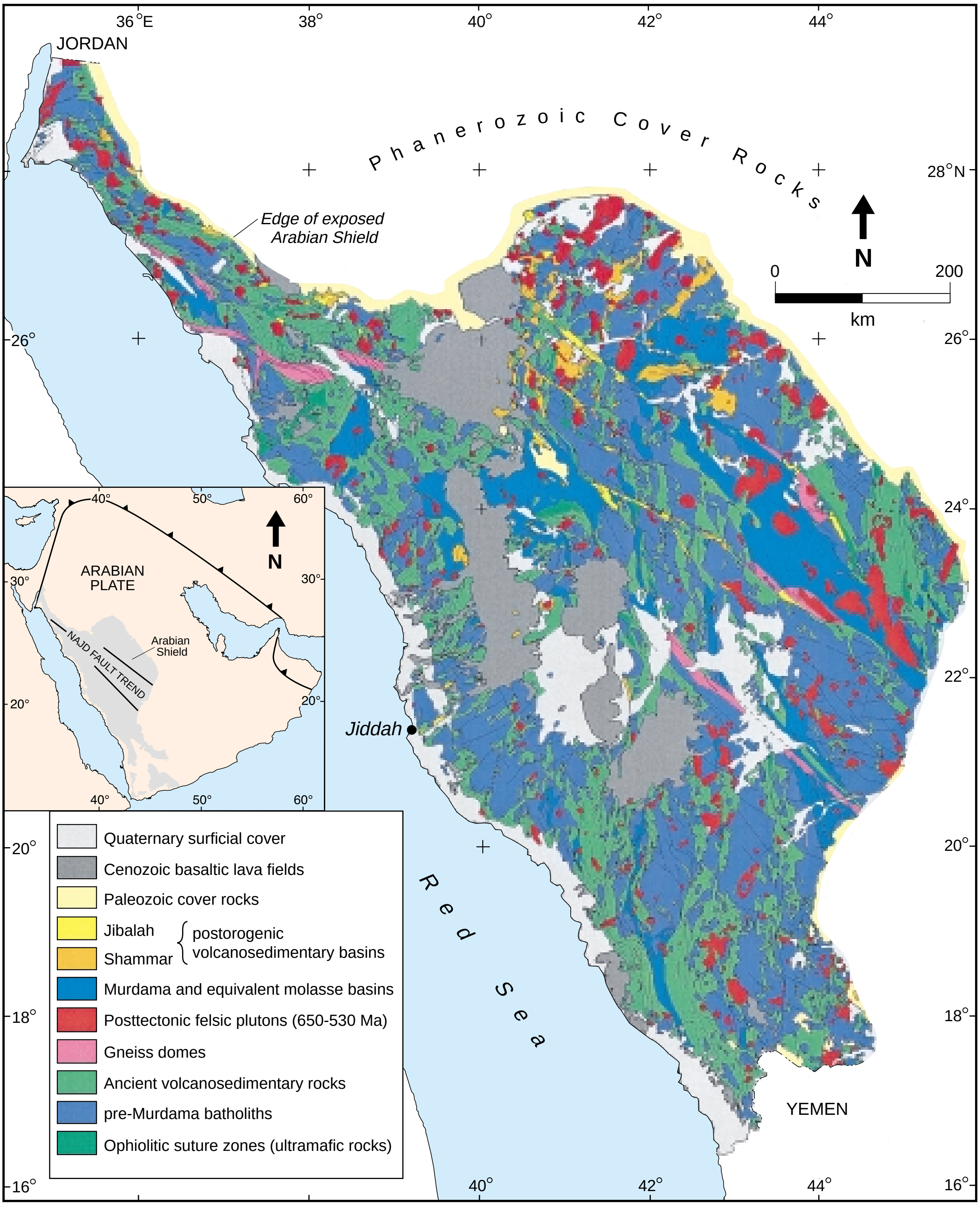

Figure 1: Simplified geologic map of the Arabian Shield showing the distribution of the major ophiolitic suture zones (ultramafic rocks), arc formations (pre-Murdama batholiths and ancient volcanosedimentary rocks), gneiss domes, molasse basins (Murdama), syn- to postorogenic intrusions, postorogenic volcanosedimentary basins (Shammar and Jibalah groups), and major fault zones attributed to the collisional phase of Shield evolution. Inset map shows Najd fault trend.

excellent exposures that result from a general absence of surficial cover, the Arabian Shield in Saudi Arabia is a unique laboratory in which to study the mechanisms of continental accretion.

The Arabian Shield (Figure 1) has been mapped by the Saudi Arabian Deputy Ministry for Mineral Resources (now the Saudi Geological Survey) and its associates—the French Bureau de Recherches Géologiques et Minières (BRGM) and the US Geological Survey (USGS). Since the early 1980s, the

Shield has been regarded as the product of accretion in Neoproterozoic times of volcanic arcs (Fleck et al., 1980; Gass, 1981; Kröner, 1985; Stoeser and Camp, 1985). The evidence for such a history is the association of voluminous calc-alkaline volcanic and plutonic rocks separated by ophiolite-lined sutures that divide the Shield into distinct tectonostratigraphic terranes (Johnson and Vranas, 1984; Stoeser and Camp, 1985).

A BRGM research project, involving the synthesis and re-evaluation of all available geologic and metallogenic data on the Arabian Shield, led to a reappraisal of the structure and geologic history of the Arabian Shield. The project involved the following: (1) new field and geochemical and geochronological work in several areas of the Shield; (2) the compilation of 1:250,000-scale geologic maps; (3) the production of a new aeromagnetic map of the Shield; and (4) an exhaustive synthesis and re-evaluation of geochemical, geochronologic, metallogenic, and mineral-exploration data.

Some of the main geologic results of this work are presented here. The synthesis and re-evaluation of the metallogenic data will be published in a separate paper elsewhere. All data will be available as a digital report and attached databases (ArcView GIS) available from BRGM, France and the Saudi Geological Survey.

REGIONAL GEOLOGIC SETTING

Although Paleoproterozoic rocks may occur in the eastern part of the Shield, the formation of the Shield essentially took place in the Neoproterozoic over a relatively short time span from about 900 to 550 Ma (Figure 2). This led to the formation of a continental crust more than 40 km thick. The morphology and present shape of the Shield are mainly the result of relatively recent geologic events linked to the opening of the Red Sea.

Before the Red Sea began to open at about 25 to 30 Ma (Camp and Roobol, 1992), the Arabian Shield of 650,000 sq km formed part of a larger geologic unit known as the Arabian-Nubian Shield. Today, the

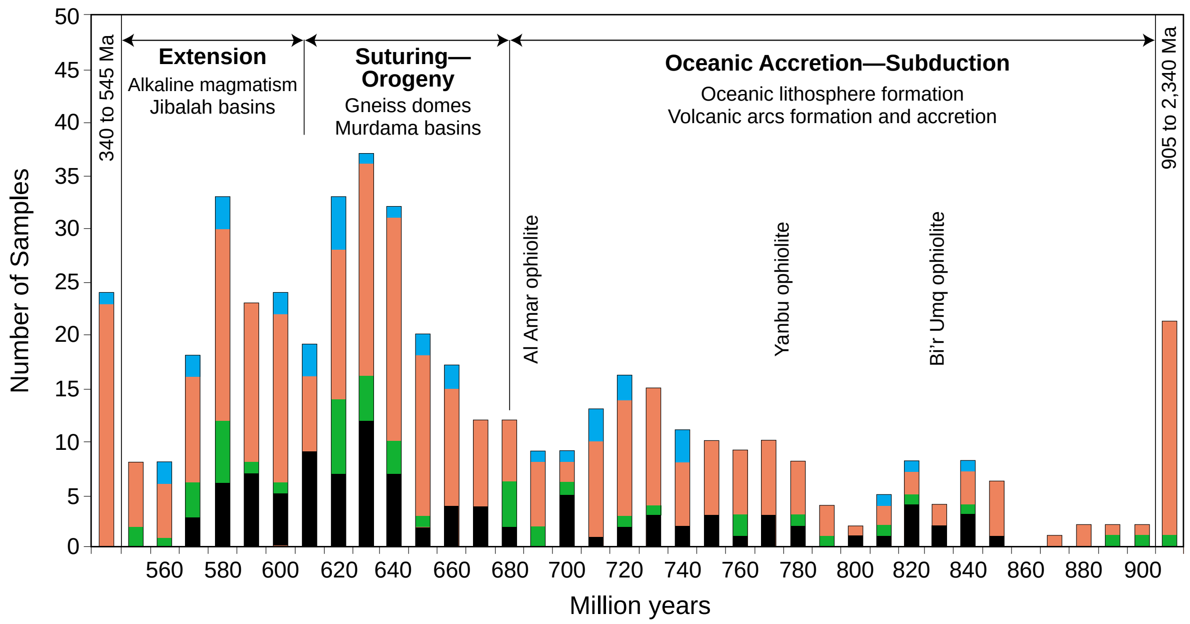

Figure 2: Chronology of geologic events in the Arabian Shield and the distribution of age determinations and their analytical confidence. Of the 507 available ages, 97 are considered to be of very good quality and an additional 52 are acceptable with restrictions. Note the change in the time scale. MSWD = Mean Squares of Weighted Deviation.

CONFIDENCE LEVELS:

- ■ Acceptable
- 🟩 Acceptable with restrictions (little available data; high MSWD)
- 🟧 Not acceptable (MSWD too high; not enough data; distant samples)
- 🟦 Not enough published data for re-evaluation

rocks of the Nubian Shield are exposed in eastern Egypt, Eritrea, western Ethiopia, northern Somalia, and in the Sudan, whereas the Arabian Shield occupies much of western Saudi Arabia and has smaller exposures in southern Levant, southern Jordan, and in Yemen. The exposed area of the Arabian Shield is 2,200 km long from north to south and has a maximum width of about 700 km.

The Arabian-Nubian Shield consisted mostly of juvenile crust interpreted as an area of transpressive suturing between East and West Gondwana (Johnson and Kattan, 2001). It formed through the accretion of mainly interoceanic island arcs along sutures marked by ophiolites (Bakor et al., 1976; Gass, 1981; Bentor, 1985; Kröner, 1985; Stoeser and Camp, 1985; Vail, 1985; Pallister et al., 1987; Quick, 1991; Al-Saleh et al., 1998; Johnson, 1998). This occurred between about 900 and 550 Ma as the Mozambique Ocean closed (Stern, 1994). It may also have included an oceanic plateau formed by the head of an upwelling mantle plume (Stein and Goldstein, 1996).

The accretion resulted in the formation of tectonostratigraphic terranes that are separated either by major suture zones—trending mainly north and northeast and lined by serpentinized ultramafic rocks (ophiolites and tectonic slices)—or by major NW-trending faults. Stoeser and Camp (1985), Cole (1988), and Johnson (1998) compiled tentative maps of the tectonostratigraphic terrane boundaries and their associated orogenic zones for the Arabian Shield (Figure 3).

The Arabian Shield of Saudi Arabia is only slightly metamorphosed (except for some areas of gneissic rocks) and it constitutes one of the best-preserved and well-exposed Neoproterozoic assemblages resulting from the accretion of volcanic arcs. It is overlain to the east, north, and south by a thick succession of Phanerozoic sedimentary rocks, and is bounded to the west by the Red Sea that now separates the individual Arabian and Nubian shields.

Geochronologic Constraints

Over 500 U-Pb, Rb-Sr, Sm-Nd, K-Ar, and Ar-Ar age determinations of Arabian Shield rocks are available either as published data (see synthesis by Johnson et al., 1997) or obtained as part of this project. The age determinations were re-evaluated analytically using the Isoplot software (Ludwig, 1991) and subdivided into four confidence levels (Figure 2). They span a time interval from about 2,340 to 340 Ma with three main maxima at about 730 to 720 Ma, 640 to 630 Ma, and 590 to 580 Ma. Acceptable ages fall in the range of 850 to 560 Ma with a maximum at around 630 to 620 Ma, and ages acceptable with minor restrictions are within the range of 900 to 550 Ma. Two geologically suspect Rb-Sr ages are from Wadi al Faqqh [1165 ± 110 Ma; Fleck et al. (1980)] and from the Khamis Mushayt batholith [495 ± 3 Ma; Qari (1985)].

AEROMAGNETIC DATA AND CONSTRAINTS

Several aeromagnetic surveys were carried out from 1962 to 1983 by commercial companies under the auspices of the Ministry of Petroleum and Mineral Resources of the Kingdom of Saudi Arabia, and supervised by BRGM and USGS. The surveys were conducted over individual blocks. They had ground clearances of 150, 300, or 500 m and a line spacing of about 800 m. The 1962 and 1965 to 1967 surveys supervised by BRGM covered the entire Shield, and were flown using fluxgate Gulf Mark III magnetometers with analog recording. In addition, five general and several less-extensive surveys, were carried out over targets of economic interest using a CSF cesium-vapor magnetometer in 1976 and 1981, and a Geometrics G813 proton-precession magnetometer in 1983, both with digital recording.

The 1962 and 1965 to 1967 data were originally presented as total-intensity contour maps compiled at 20-gamma intervals to a scale of 1:50,000. These data were later recompiled into a set of colored 1:500,000-scale, 100-gamma-interval total-intensity maps and photographically compiled and reduced to 1:1,000,000 scale by Blank and Andreasen (1991). Subsequently, Georgel et al. (1985) digitized the analytical data from the original records. Although more arduous than gridding the contour maps, this method allowed integration of all the original data without the filtering effect of the contouring. To produce the aeromagnetic map presented as Figure 4, we used analytical data that were digitized from the original records rather than from the contoured maps.

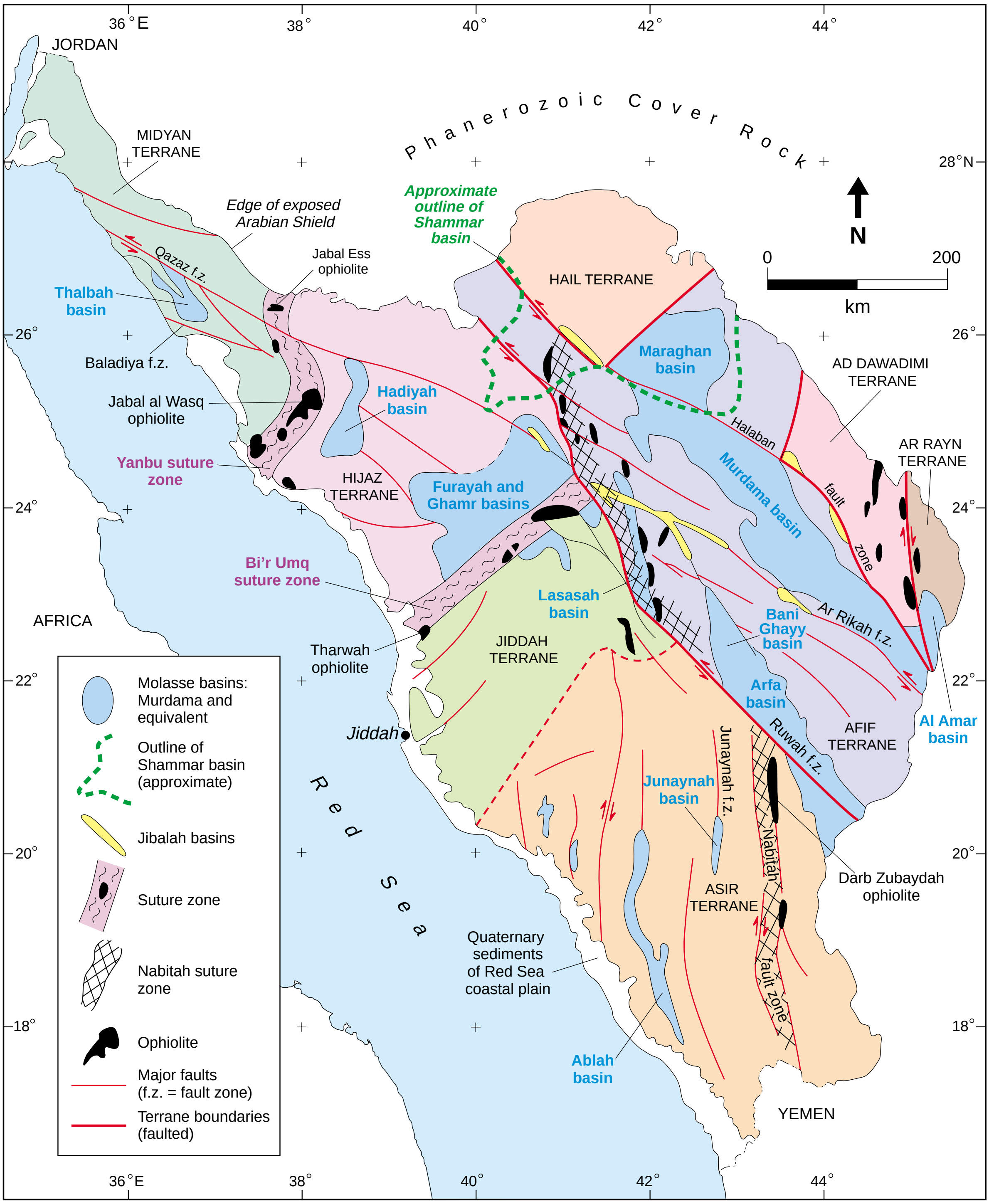

Figure 3: Simplified geologic sketch map of the Arabian Shield showing the terranes and their boundaries, and the main Pan-African structural features and sedimentary basins. Major fault zones, such as Ruwah, Ar Rikah, Halaban, and Qazaz, belong to the Najd fault system.

Because the original data obtained by digitizing the profiles do not correspond to the total magnetic field, a regional field was calculated for each profile and subtracted from the original data. The resultant data were compiled to produce a map with an altitude of 300 m and a grid spacing of 500 m in a UTM-38 projection. No artifact appears between the different blocks, implying that the regional field was correctly calculated. Full information about the original data can be provided upon request.

Analysis of the Aeromagnetic Data

The aeromagnetic anomalies (Figure 4) generally correlate well with known lithostratigraphic units at large scales. Mafic and ultramafic rocks typically show much stronger anomalies than metasedimentary rocks, whereas metavolcanics cause strongly disturbed patterns. Most of the aeromagnetic anomalies are 'normal', whereas 'reversed' anomalies are mainly associated with Red Sea dikes and ultramafic-decorated fault zones.

In order to clarify the interpretation of the aeromagnetic map, we subdivided it into several sectors bounded by some of the dominant aeromagnetic trends and lineaments. These boundaries, either sharp or gradual, generally corresponded to the province boundaries of Delfour (1979), and to the terrane boundaries defined by Johnson and Vranas (1984), Stoeser and Camp (1985), and Johnson (1998), for which we used the generally accepted nomenclature (Figure 3).

Major long-wavelength magnetic anomalies are observable on the 10-km upward continuation aeromagnetic map (not shown here but available at http://gisarabia.brgm.fr/geophysi.htm). In order of spatial importance, the anomalies are associated with (1) Murdama-age basins in the northeast and northwest, (2) NW-trending Najd faults, and (3) E-trending anomalies in the south. The N-trending Nabitah orogenic belt and most of the terrane boundaries mapped by Johnson and Vranas (1984) and Stoeser and Camp (1985) do not show up clearly on this map. This suggests that, unlike the Najd fault system, they are not major vertical fault zones but rather a series of thrust faults that do not extend very deeply into the crust, as had been shown earlier by Gettings et al. (1986).

The southern terranes

In the south of the Shield, the NW-trending Ruwah fault zone forms the northern boundary of the Asir terrane. The fault zone is the southernmost element of the Najd fault system. Although geologic mapping and aerial and satellite imagery show that the Asir terrane is marked by mainly N-trending lithostructural features, the predominant magnetic features in this region have a W- to NW-trend.

A very weak N-trending, long-wavelength discontinuity on the vertical-gradient map correlates well with the major northerly trending tectonic belts of Wadi Bidah and Wadi Shwas. The Nabitah suture zone in the easternmost part of the terrane is marked by a weak discontinuity in the dense E-W trend that disappears eastward beneath the Phanerozoic sedimentary cover. This weak discontinuity is surprising, because the Nabitah fault zone is generally interpreted as a major fault zone lined by ultramafic tectonic slices (Stoeser and Camp, 1985). Similarly, the transition to the Jiddah terrane defined by Johnson and Vranas (1984) and by Johnson (1998) is not marked by a clear-cut lineament but rather by a long-wavelength transition. The northern part of the Asir terrane and all of the Jiddah terrane show a large arcuate magnetic pattern open to the southwest.

The northern terranes

The Ad Dawadimi, Afif, Hijaz, and Midyan terranes are characterized by major long-wavelength, low-relief anomalies associated with the main Murdama, Thalbah, Hadiyah, and Furayh molasse basins (Figure 3) in the northeast and northwest, and with the Abt formation west of the Al Amar fault. The largest of them, the Murdama basin, appears as a 200-km-long elliptical, long-wavelength magnetic anomaly that contains several local anomalies associated with posttectonic intrusions.

The Ad Dawadimi terrane (Delfour, 1979; Johnson and Vranas, 1984) is in sharp contrast to the eastern Ar Rayn terrane. It has very low magnetic relief and shows no clear trend. The few sharp magnetic anomalies are associated with N-trending ultramafic tectonic lenses within the terrane and to subcircular posttectonic intrusions. The western border of the terrane is marked by a sharp, short-wavelength magnetic anomaly linked to the Halaban ophiolites. The intrusive complexes of the Nabitah fault zone, such as the Furayhah and Al Bara batholiths, have a typical sigmoidal fabric. Major positive magnetic anomalies correlate with large gneiss domes associated with the Najd faults, such as the Wajiyah and Hamadat domes in the north, and the Halaban and Jabal Kirsh domes in the central Shield.

The Tharwah-Bi'r Umq suture zone at the limit between the Jiddah and Hijaz terranes is only weakly marked and is parallel to the arcuate fabric noted in the northern part of the Asir and Jiddah terranes.

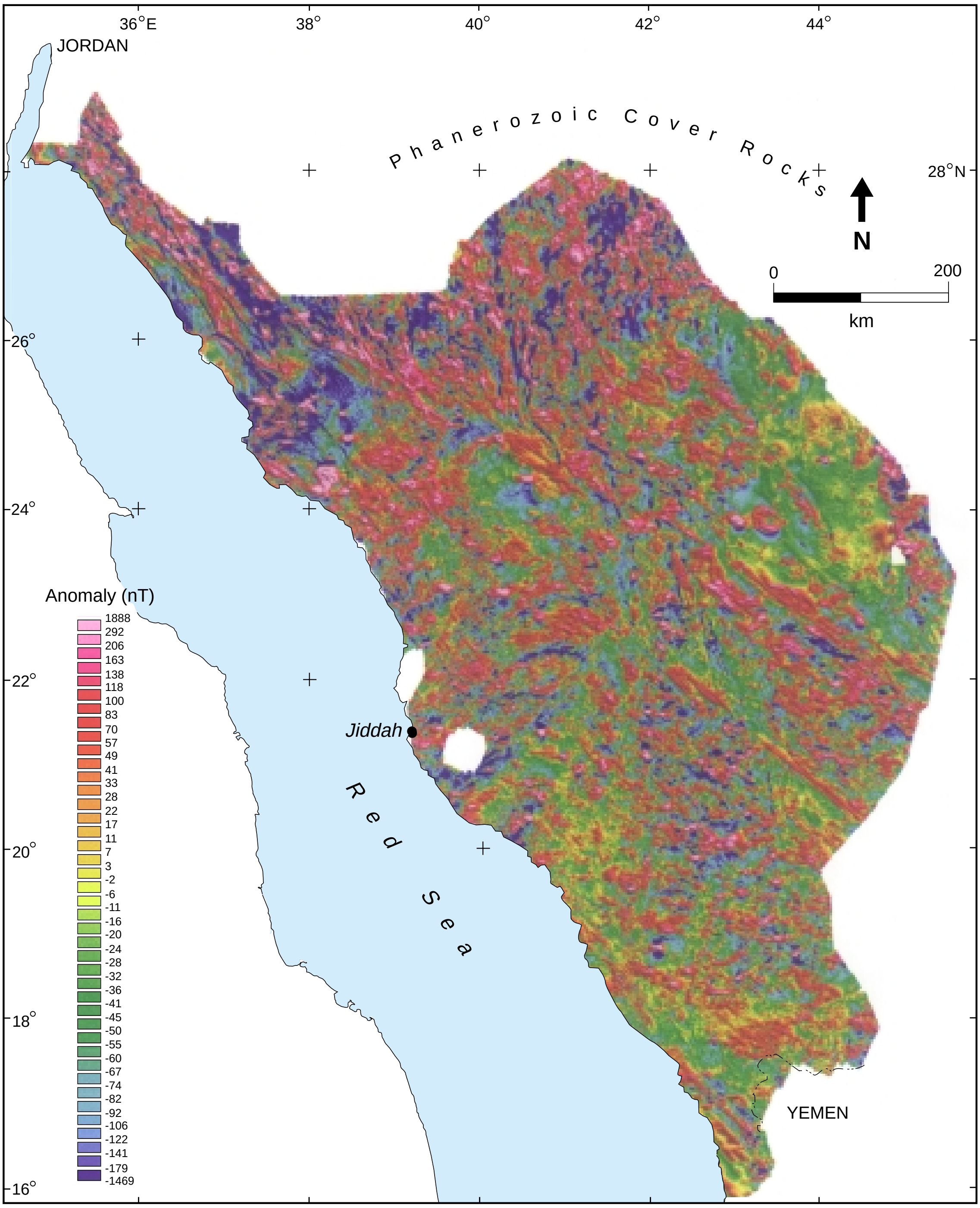

Figure 4: Aeromagnetic map of the Arabian Shield as a raster image of the magnetic field reduced to the pole.

Similarly, the northern Yanbu suture zone between the Midyan and Hijaz terranes is only marked by short-wavelength anomalies associated with ultramafics, and is offset by the Najd faults. Close to the Red Sea, the main NW-striking Najd pattern is spatially associated with negative magnetic lineaments that are subparallel to the coast and mark major Cenozoic dikes.

The Ar Rayn terrane (Delfour, 1979; Stoeser and Camp, 1985) shows a mosaic of anomalies with no clear trend. Ultramafic rocks of ophiolitic affinity line the Al Amar fault on the western boundary of the terrane. Johnson and Stewart (1995) showed that the magnetic anomaly of the Ar Rayn terrane extends at least as far north as latitude 29°N and probably to the Zagros suture, and that the Al Amar fault—although largely obscured by Paleozoic deposits—is a major regional structure.

A mosaic of short-wavelength anomalies characterizes the northern Ha'il terrane. Their marked N to NW orientations reflect the Nabitah trend and Najd trend, respectively. The southeastern limit shows a progressive transition to the Murdama basin. An anastomosing sigmoidal network of dominantly Najd faults and Nabitah structures poorly defines the southwestern limit of the Ha'il terrane.

Well-defined subcircular and annular anomalies scattered throughout the Shield are the signatures of major posttectonic intrusions and ring complexes that range in composition from gabbro to alkaline, peralkaline, or peraluminous granites and syenites.

Major Lineaments

The aeromagnetic lineaments can be grouped into the following four main trends (Figures 4 and 5):

1. A dominant Najd trend of N135ºE to N150°E, clearly related to the Najd faults and present throughout most of the Arabian Shield;
2. A Red Sea trend of N150ºE to N160°E, parallel to the coast and found only in the hinterland;
3. A minor N-S trend associated with the Nabitah fault zone, which appears faintly on the aeromagnetic map, but is largely obscured by the Najd lineaments;
4. An E-W trend that is widespread in the southern Asir terrane.

ARABIAN PLATE ACCRETION AND CRATONIZATION

Precratonic Formations and Events (before 680 Ma)

Old continental crust—Where is the eastern margin of the Arabian Shield?

The Arabian-Nubian Shield formed through the accretion of several volcanic arcs along sutures marked by ophiolites (Bakor et al., 1976; Gass, 1981; Bentor, 1985; Kröner, 1985; Stoeser and Camp, 1985; Vail, 1985; Pallister et al., 1987; Quick, 1991; Johnson, 1998; Al-Saleh et al., 1998), between about 900 and 550Ma. Accretion took place as East and West Gondwana collided and the Mozambique Ocean closed (Stern, 1994).

As a result, the Arabian-Nubian Shield is not generally underlain by old continental crust. However, terranes with pre-Pan-African continental affinities have been identified on the basis of zircon Pb-Pb and U-Pb geochronology and radiogenic-tracer studies. They are found along the eastern margin of the Shield in Saudi Arabia and Yemen, and west of the River Nile (Stacey and Hedge, 1984; Stacey and Agar, 1985; Stoeser and Camp, 1985; Stoeser and Stacey, 1988; Schandelmeier et al., 1990; Agar et al., 1992; Windley et al., 1996, and references therein).

In Saudi Arabia, 12 age determinations of between 2,340 and 1,000 Ma (see Figure 2) were published by Aldrich et al. (1978), Fleck et al. (1980), Calvez et al. (1983, 1984), Calvez and Delfour (1985), Stacey and Hedge (1984), Stacey and Agar (1985), Stoeser and Stacey (1988), and Agar et al. (1992). The samples are all from the Al Amar fault zone and the area to the south within the Asir terrane. Most data sets have a Mean Squares of Weighted Deviation too high to be acceptable on analytical grounds; others are clearly mixed-zircon grains. The only analytically acceptable old date is a Rb/Sr date of 1,165 ± 110 Ma (Fleck et al., 1980) from Wadi al Faqh in the Asir terrane. However, it is anomalously old in comparison with nearby zircon data that provided an age of 842 ± 17 Ma (Kröner et al., 1992).

The old zircon ages are probably from zircon grains that were either eroded from ancient continental crust or incorporated into plutonic rocks as xenocrysts. However, evidence for old continental crust is also provided by lead-isotope data from galena and feldspars (Stacey et al., 1980; Stacey and Stoeser, 1984; Bokhari and Kramers, 1982; Stacey and Agar, 1985). They show that the western and southern parts of the Shield have oceanic affinities, whereas the eastern part of the Shield has a more continental signature. On this basis, the southern portion of the Afif terrane was considered by Stoeser and Camp (1985) to be underlain, at least in part, by continental basement of Paleoproterozoic to Archean age.

Similarly, old ages around 1,200 Ma have been reported by Pallister et al. (1987) for xenocrystic zircons within gabbro of the Thurwah ophiolite. The xenocrysts were interpreted as inclusions of detrital zircon from metasedimentary rocks in the structural basement.

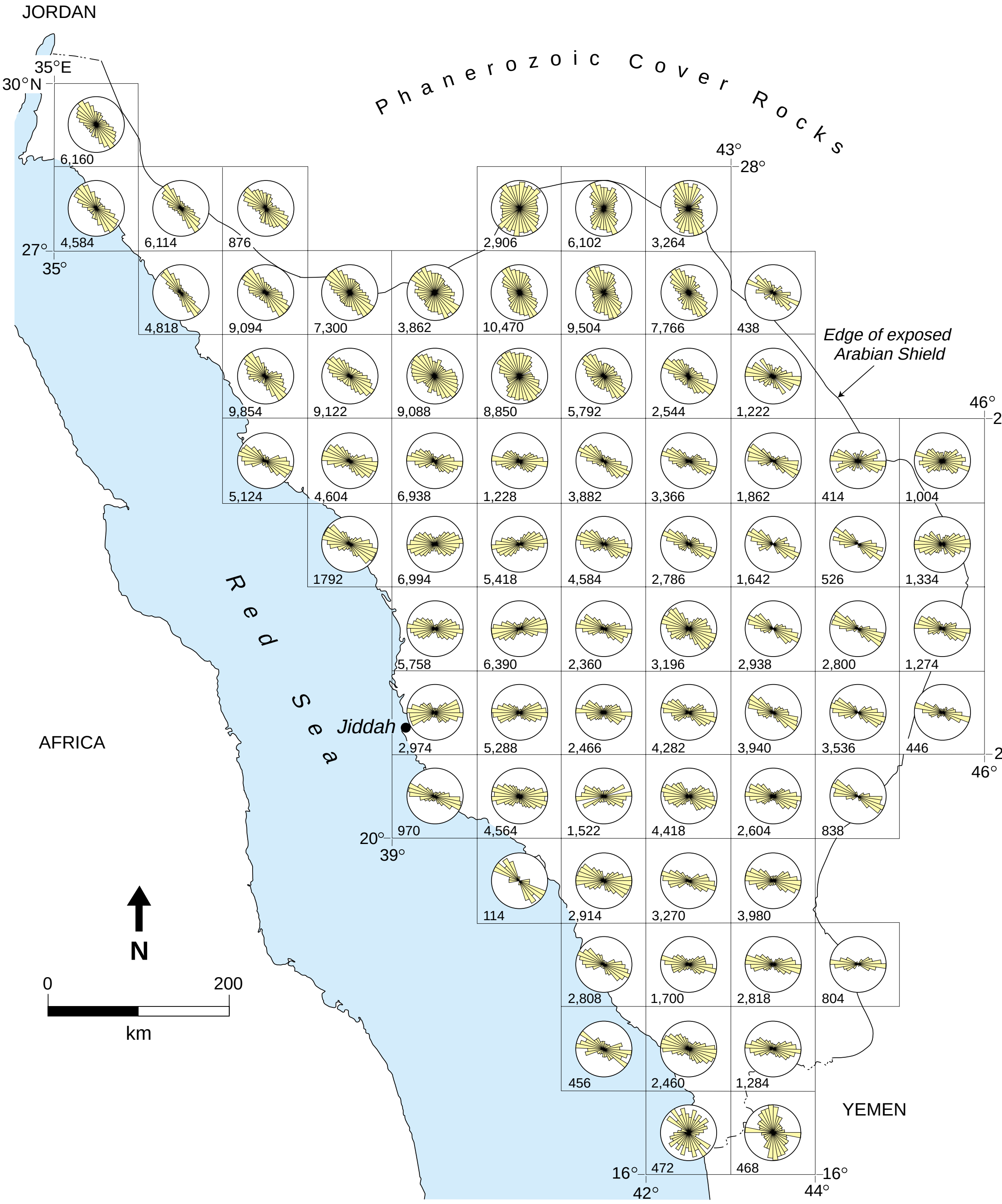

Figure 5: Rose diagrams for each degree square of the principal aeromagnetic lineaments computed from the reduced to the pole aeromagnetic map (Figure 4). The number in each degree square is twice the total number of lineaments used to compute the rose diagram.

Previous models for the formation of the Arabian Shield favored repeated rifting of an Archean to Mesoproterozoic craton, involving the formation and closure of small ocean basins (Delfour, 1979; Kemp et al., 1980; Delfour, 1979). Field and geochronological data indicating the absence of old continental crust in the western part of the Shield, imply that these models are no longer tenable. This is further supported by the ultramafic and associated rocks within the suture zones being slightly older (or of the same age) as the dated rocks on either side.

Within the Precambrian of Yemen, Windley et al. (1996) identified four gneissic and two island-arc terranes based on mapping, and on geochronologic and isotopic data. The two western gneiss terranes are correlated with the Afif and Asir terranes in Saudi Arabia. To the east of these, the Abas and Al Mahfid gneiss terranes yielded Nd model ages of about 2,700 to 1,300 Ma. They could not be correlated with any documented terranes in Saudi Arabia.

In conclusion, there is clear isotopic and geochronological evidence for Paleoproterozoic and Archean crust in the eastern part of the Arabian Shield (Whitehouse et al., 2001). However, the absence of clear geologic indicators and of a marked aeromagnetic anomaly, leads us to consider that the eastern continental margin of the Arabian Shield has to be looked for beneath the thick Phanerozoic sedimentary succession of the Arabian Platform.

Ophiolitic suture zones: remnants of precratonic oceanic lithosphere?

The presence of ophiolites and their association with calc-alkaline volcanic rocks of island-arc affinity, suggests that the continental crust of the Arabian Shield developed by a process of horizontal crustal accretion of oceanic terranes between about 900 to 680 Ma (Bakor et al., 1976; Greenwood et al., 1980; Gass, 1981; Kröner, 1985; Vail, 1985; Stoeser and Camp, 1985; Quick, 1991; Johnson, 1998). This implies that several hundreds to even thousands of kilometers of oceanic lithosphere must have been subducted to produce the accreted crustal material that is incorporated into the approximately 40-km-thick crust of the Arabian Shield (Mooney et al., 1985; Stern, 1994).

Fragments of Neoproterozoic oceanic crust and mantle, for example, the Jabal Ess ophiolite (Shanti and Roobol, 1979; Pallister et al., 1987, and references therein), occur within several major fault zones and are well-defined on the aeromagnetic map (Figure 4). Most available ages on the ophiolites were obtained by U-Pb zircon dating of hornblende gabbro, quartz diorite, plagiogranite, and quartz keratophyre from all the main ophiolitic suites of the Arabian Shield (Pallister et al., 1987). Pallister et al. (1987) applied a Pb-loss model to the data based on the assumption that lead-loss due to dilatancy in the zircons was caused by uplift during Tertiary Red Sea rifting (Cooper et al., 1979; Stoeser et al., 1984). Additional data on the ophiolites are provided by Sm-Nd isochron ages (Claeson et al., 1984; Dunlop et al., 1986) and Ar/Ar dating by Al Saleh et al. (1998). Pallister et al. (1987) showed that, with the exception of the Jabal Ess ophiolite in the northeast of the Shield that predates the oldest rocks by as much as 40 Ma, all ophiolites are coeval with or slightly predate the early magmatic phases of adjacent arcs. They interpreted this to mean that most ophiolites formed within the arc complexes, chiefly by back-arc spreading.

The consensus is that most, if not all, of the ophiolites are crustal remnants from small, short-lived ocean basins that formed offshore in close proximity to the locus of tectonic accretion, rather than being fragments of standard oceanic crust. Several geochemical studies have been published on the main ophiolite complexes; for example, the Turwah ophiolite in the Bi’r Umq suture zone (Nassief et al., 1984); the Darb Zubaydah ophiolite in the Nabitah suture zone (Quick, 1990); and the Jabal al Wask (Bakor et al., 1976) and Jabal Ess (Shanti and Roobol, 1979) ophiolites in the Yanbu suture zone. Geochemical analyses indicate that the basalts of these ophiolites are not typical Mid Ocean Ridge Basalts in character. New Inductively Coupled Plasma Mass Spectrometry (ICP-MS) geochemical data (this project) from the pillow basalts of the Turwah ophiolite showed that they all have trace-element characteristics of lavas associated with present-day back-arc settings. Furthermore, the stratigraphic relations of several ophiolites indicated that they are commonly only a little older than the surrounding arcs (Shanti and Roobol, 1979). This, in turn, implied that the ophiolites must have formed near to their accretion location, such as a marginal basin, rather than in a remote mid-ocean spreading-ridge setting. The common association of ophiolites with felsic lava, graywacke, turbidites, and the like, further supports this assumption.

The main ophiolite bodies were dated by several teams at around 838 to 828 Ma (Bi’r Umq), 782 to 706 Ma (Yanbu), 698 Ma (Al Amar), and 680 Ma (Halaban) (Al-Saleh et al., 1998; Pallister et al., 1987; Quick, 1990). However, due to analytical uncertainties the formation age of the Nabitah suture-zone ophiolites is poorly constrained; according to Pallister et al (1987) it is about 751 to 709 Ma in the Ad Dafinah region but much older (847–823 Ma) farther north in the Bi’r Tuluhah region.

Present-day lithospheric plates move at velocities averaging 5 cm/year. With ophiolitic rocks within the Arabian Shield spanning a period of about 150 Ma, crustal displacements of several thousands of kilometers can be part of this history, involving rifting, amalgamation, accretion, rotation, and dispersion. This must be kept in mind when trying to reconstruct the paleotectonic settings of the various suspect terranes.

Volcanic arcs

Our objective in this section is not to review the individual lithostratigraphic characteristics of the different terranes. These have been discussed in detail in the Explanatory Notes to the various 1:250,000-scale geologic maps of the Arabian Shield and reviewed by several authors; for example, Johnson and Vranas (1984); Stoeser and Camp (1985); Cole (1993); Johnson (1998). Instead, we outline the common nature and specific characteristics of the terranes.

The number of suspected terranes (10 for Johnson and Vranas, 1984; 5 for Stoeser and Camp, 1985; 17 for Cole, 1993; 8 for Johnson, 1998) remains a matter of geologic debate. Magnetic-data autocorrelation studies (Galdeano, personal communication, this project) and magnetic-trend orientations show that the terranes cannot be distinguished on the basis of magnetic anisotropy (Figure 5). Similarly, an orientation study of Shield-wide dikes cannot be used to discriminate between different terranes (Figure 6). No marked differences exist between them and only the southern part of the Shield (the Asir and Jiddah terranes) has a slightly different orientation from the well-marked modal orientation of N100ºE.

The tectonostratigraphic terranes in the Arabian Shield are compositionally very similar, although their ages differ significantly. They generally consist of alternating belts of greenschist-grade volcanic and sedimentary rocks, and high-grade gneisses. Several geochemical studies of the volcanic belts in the Arabian Shield have led to the recognition of their island-arc affinities (Greenwood et al., 1976; Roobol et al., 1983; Reischmann et al., 1983). The ICP-MS data obtained as part of this project confirm these results. Similarly, the older-than-700 Ma tonalite-trondhjemite plutonic rocks have a trace-element signature typical of arc-related intrusive rocks. They include Al-depleted granitoid rocks, characteristic of present-day oceanic arcs, and adakitic-type plutons typical of present-day young, hot lithosphere-subducting plates.

Volcanic-arcs are generally sub-parallel to the structures that generate them and, when amalgamated and accreted to a continental margin, remain sub-parallel to the suture zones unless disrupted by dispersive tectonics. The major volcanic belts that correspond to old volcanic arcs in the Arabian Shield trend northward in the southern Asir terrane, northeast in the Jiddah and Hijaz terranes, and north in the eastern Afif and Ar Rayn terranes (Johnson and Vranas, 1984; Stoeser and Camp, 1985; Cole, 1993).

The arc-related aeromagnetic signatures are now largely obscured by a dominant and penetrative NW-oriented Najd trend in the north that reflects the importance of transposition of pre-existing rocks along the Najd fault system (Figure 4), and by an E-W trend in the south that signals major late orogenic intrusions.

Arc magmatism began in the southwestern Asir terrane. There the oldest dated rock is the Bidah tonalite (Rb-Sr, 901 ± 37 Ma; Marzouki et al., 1982), and the oldest dated volcanic rock is a basalt from the Kulada suite (Rb-Sr, 847 ± 34 Ma; Kröner et al., 1983). Toward the east and north, the terranes become progressively younger. The youngest terrane is Ar Rayn that is separated from the Ad Dawadimi terrane by the Al Amar fault zone along its eastern boundary.

The Ad Dawadimi terrane is composed of mafic to ultramafic ophiolitic complexes and clastic rocks. The ophiolite complexes consist of gabbro, dolerite, and plagiogranite (with chilled margins in places), and volcanic rocks, in a serpentinite matrix (Shanti and Gass, 1983). Clastic rocks of the Abt formation form a monotonous, 40-km-wide, tightly folded succession of sericite and chlorite schist (Delfour, 1979). Detrital zircons from the Abt schist were derived from source rocks with a mean age of 710 Ma, and ophiolitic gabbro near Halaban yielded ages of about 690 to 680 Ma (Stacey et al., 1984; Al Saleh et al., 1998). These dates imply that the Abt schist was formed during this time period and that it predates the final closure of the oceanic basin that lay west of the Ar Rayn terrane. The 641 ± 25 Ma age of syntectonic leucogranite intrusive into the Abt schist gave a lower age limit for the schist (Stacey et al., 1984).

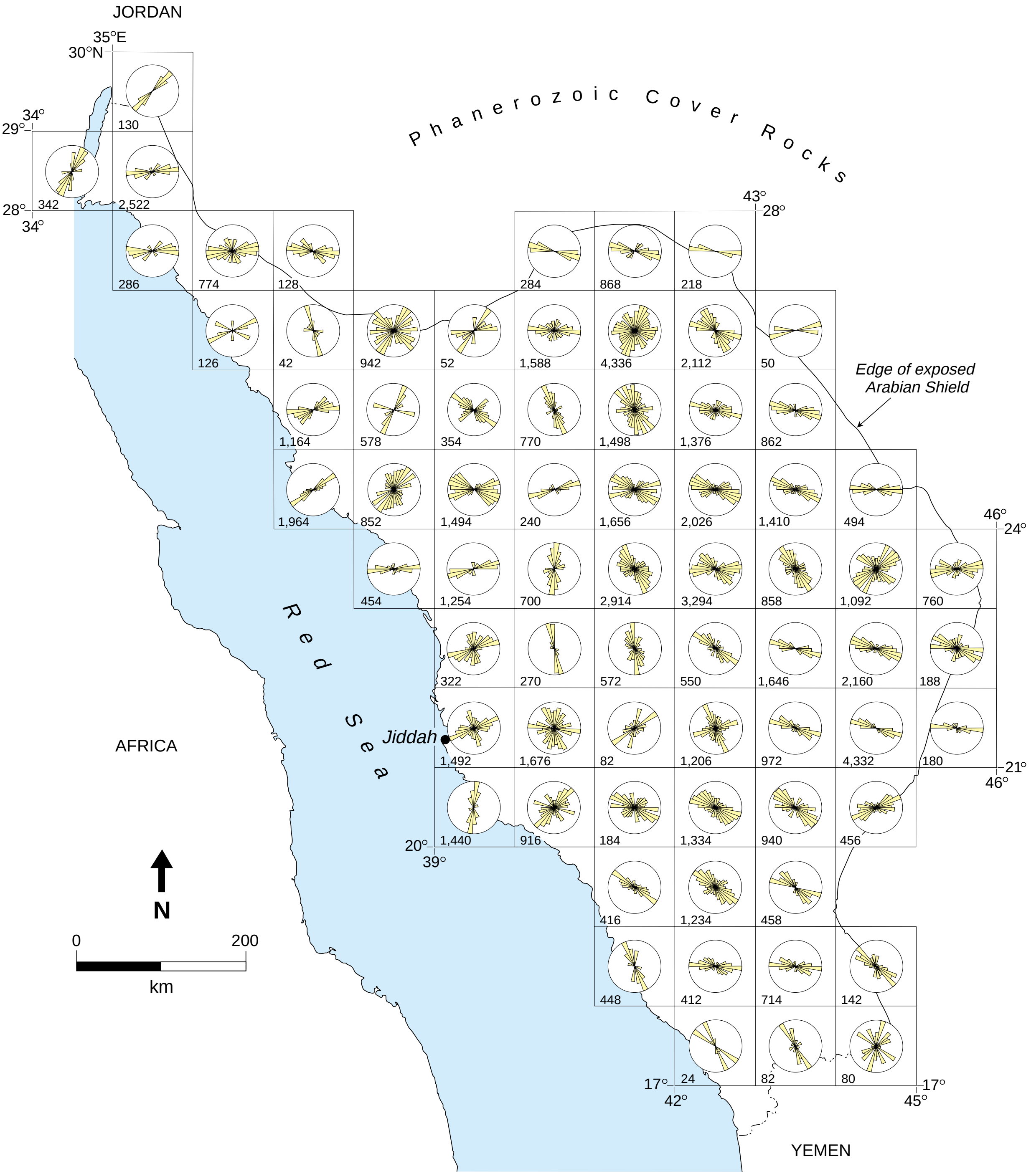

Figure 6: Rose diagrams of all dikes (N = 33,115) recorded on the 1:250,000-scale geologic maps of the Arabian Shield and plotted by 1° quadrangles. The Shield is crosscut by a dense network of dikes that are well exposed and appear clearly on aerial and satellite imagery. They provide excellent markers of paleostress fields. The computed dikes have lengths of up to 30 km with a modal length slightly over 1 km. The rose diagrams take into account all measured dikes including a minor set of dikes, abundant along the Red Sea coast, that is associated with the opening of the Red Sea. The number in each degree square is twice the total number of lineaments.

In contrast to the Ad Dawadimi terrane, the Ar Rayn terrane consists mainly of syntectonic tonalitic to granodioritic gneisses dated at less than 670 Ma (667 ± 17 Ma, Calvez et al., 1983; 645 ± 35 Ma, Baubron et al., 1976) that intrude typical arc-type calk-alkaline volcanic rocks. In turn they are intruded by younger-than-645 Ma posttectonic monzogranite and granodiorite (Calvez et al., 1983; Stacey et al., 1984).

Pan-African Cratonization (about 800 to 680 Ma)

The final stage of suturing of the various terranes is generally well constrained. It postdates the ophiolites in the suture zones and the adjacent island-arc rocks, and predates the posttectonic stitching intrusions and overlapping volcanic and sedimentary basins. The oldest suturing is that of Bi'r Umq, which can be dated at about 810 to 780 Ma, and the youngest is that of Al Amar of around 690 to 670 Ma. This last suturing event caused a major orogeny and is interpreted as representing the final closure of the Mozambique Ocean basin that separated East Gondwana from West Gondwana.

Major fault zones marked by ultramafic rocks, such as serpentinite and listwaenite—as well as mylonite, phyllonite, or gneiss domes—now separate the tectonostratigraphic terranes. The fault zones form an anastomosing network of primarily left-lateral strike-slip faults. They include the inner part of the Nabitah belt, several peripheral NW-trending Najd faults, and N-trending structures (Figure 3). The inner 200-km-wide zone of the Nabitah belt is composed of large intrusions and sedimentary formations that underwent compressional deformation. Sigmoidal, fish-shaped shear zones are clearly visible on satellite images, with the most striking features being the Furayhah batholith (Kemp et al., 1982) and the Al Bara batholith (Letalenet, 1979). The outer zone, in contrast, is characterized by lateral slip, reflected by the presence of gneiss domes.

Most fault zones are characterized by subhorizontal lineations. However, a few N-trending faults show steeply dipping lineations concentrated in corridors as much as several kilometers wide. They are the Ad Dafinah fault (folds with vertical axes), the Al Amar fault (boudinaged tension gashes), and the Nabitah fault (boudinaged quartz). Most subhorizontal lineations have generally left-lateral kinematic indications on NW-trending faults and show right-lateral movement along those faults that trend northeast (Figure 3). Such indications are consistent with an ENE–WSW to E–W principal stress orientation (present-day configuration) during the final suturing of the Arabian Shield.

Early age of Najd faults

The chronology of displacements along the Najd faults can be constrained by dating either the pre-existing rocks present as melange (such as ophiolite) within the faults, or the syntectonic gneiss domes, overlapping volcanic and sedimentary basins, and stitching plutons.

The syntectonic NW-trending Tin granodiorite gneiss in the Ruwah strand of the Najd fault zone (Figure 3) in the central part of the Shield provides the oldest indication of movement on the Najd fault system. The U/Pb zircon age of 683 ± 9 Ma (Stacey and Agar, 1985) for the Tin complex is very close to the 680 Ma Ar/Ar age obtained for the Halaban ophiolite by Al Saleh et al. (1998). It implies very early transpressive deformation synchronous with or immediately following the accretion of the last terranes to the east. Younger ages on Najd faults are provided by deformed plutons that have intruded the Asir terrane; for example, the Damar complex granodiorite has a U/Pb zircon age of 635 ± 5 Ma (Stoeser and Stacey, 1988).

Similarly, several NW-trending gneiss belts occur in the northeastern part of the Shield (Qazaz, Wajiyah, and Hamadat gneiss domes) that are in geographic continuity with the Ar Rikah left-lateral transpressional Najd fault. Satellite imagery, field data, and aeromagnetic imagery have revealed a unique structural arrangement consisting of an anastomosing network of planar structures that demarcate large 'fish-shaped' units. Fieldwork has shown the existence of a network of ductile left-lateral transcurrent faults with a few right-lateral faults. The age of deformation is constrained by several isotopic ages. Some of the orthogneiss is derived from the Ar Ra'al granodiorite that was dated at 636 ± 23 Ma (Rb/Sr; Calvez et al., 1982). Syntectonic tonalites emplaced in the Baladiyah and Qazaz faults have been dated at 676 ± 4 and 672 ± 30 Ma (U/Pb on zircon and whole-rock Rb/Sr; Hedge, 1984). These three dates constrain the formation of the gneiss belts to between 680 to 630 Ma, that is similar to the age of the Ruwah fault zone of the Najd fault system.

The synchronous formation of the Najd faults and the Nabitah fault zone is also indicated by several trends on the aeromagnetic map that show very large curvatures and delineate major sigmoidal blocks between the Nabitah and Najd faults. This implies that the Nabitah belt cannot be used as a marker for displacement on the Najd faults, as was done in earlier studies by, for example, Brown (1972) Davies (1982, 1984), Cole and Hedge (1986), and Johnson and Kattan (1999).

Molasse basins in relation to the Najd faults

Obvious relationships exist between gneiss domes and the adjacent sedimentary formations of Murdama age. Sedimentologic and structural field studies of the basins during this project showed that they were formed during intense crustal deformation, with the basins occupying synclinal depressions and the domes representing the anticlines of the same crustal fold train. The kinematic processes were accompanied by deposition of sedimentary molasse successions in the basins, with large wedges and internal unconformities that sealed the successive movements of the basement.

The molasse basins (Figure 3) collected Murdama group and equivalent-age sediments derived from the progressive erosion of the Nabitah belt. They are the Murdama and related Maraghan, Bani Ghayy, and Arfan basins in the east of the Shield, the Ablah and Junaynah basins in the south, the Hadiyah and Thalbah basins in the northwest, and the Furayah and Ghamr basins in the central Shield. The total sedimentary thickness is at least 10 km in places (this project). The minimum ages of the Maraghan and Murdama basins are provided by early-stage cross-cutting intrusions, such as the An Najadi dacitic plug at 631 ± 12 Ma (Walker et al. 1994), the As Asfar granodiorite at 620 ± 7 Ma (Cole and Hedge, 1986), the Darat al Jibu granodiorite at 614 ± 5 Ma (Cole and Hedge, 1986), and the Uwaiyah granodiorite at 611 ± 3 Ma (Agar et al., 1992).

The large Murdama basin to the east of the Nabitah belt, displays increasing degrees of deformation and metamorphism from east to west. It is bounded to the west by gneiss domes with foliation folds that have curved axes and merge progressively southwestward into the Nabitah structures and northeastward into folds of the sedimentary basin. Deposition of the Murdama group occurred after 677 Ma (age of the As Sawda tonalite; Stacey et al., 1984). This constrains its formation to a period between 677 and 631 Ma that is synchronous with the development of the gneiss domes.

Other basins that formed at about the same time as the Murdama basin are the Bani Ghayy, Arfan, Furayah, Thalbah, Hadiyah, and Ablah. The Bani Ghayy basins form overlapping sedimentary and volcanic assemblages in the central part of the Shield and are disrupted by the Najd faults. They are dated by an interlayered rhyolite that gave a zircon U-Pb age of 620 ± 5 Ma (Stacey and Agar, 1985). The central Furayah basin provided an analytically suspect Rb / Sr age of 633 ± 15 Ma on dacite from the Qidirah formation (Brown et al. 1978). In the southern part of the Shield, the Ablah basin has been dated at 642 ± 1 Ma (Genna et al., 1999) making it contemporaneous with the Murdama basins in the north of the Shield.

Early enthusiasm led geologists to propose paleogeodynamic reconstructions in which these molasse basins represented pre-accretion and synsubduction fore-arc and / or back-arc basins. For example, Quick (1991) suggested that the clastic sedimentary rocks of the Murdama group are relicts of a fore-arc basin synchronous with the Nabitah volcanic arc and Abt accretion wedge, all belonging to the same subduction system. However, the chronologic constraints and geologic relationships presented here imply that they can no longer be viewed as such, but that they represent orogenic-foreland molasse basins related to the cratonization of the Arabian Shield.

Gneiss domes and molasse basins

An important result from this study is an understanding of the genesis of the gneiss domes and their close relationship to associated intracontinental sedimentary basins. The gneiss domes fit into a left-lateral kinematic deformation pattern. They are contained within the Pan-African belt of the Arabian Shield, whose axial zone is represented by the Nabitah belt, described above. Uplift of the high-grade gneisses occurred by transpression before the deposition of the Bani Ghayy group, that is, before 620 Ma, and before or during the formation of the Murdama basins (670 to 630 Ma) prior to the emplacement of undeformed granites in the Shammar basin (630 Ma). The extent of vertical uplift can be estimated to be about 10 to 15 km on the basis of the metamorphic assemblages of the Kirsh dome.

Late- and post-Pan-African Plutonic Activity

Abundant late and posttectonic plutons were intruded into the Arabian Shield between 680 and 550 Ma (Figure 2). They have a great variety of compositions and shapes. The felsic intrusions are circular, elongate, or raindrop-shaped, whereas the mafic intrusions generally form sills. Dike swarms and ring dikes give an indication of the existence and general shape of concealed batholiths.

Two main groups can be distinguished in this association; they are (1) a potassic calc-alkaline group including mainly monzogranite, granodiorite, and alkali-feldspar granite (intruded between 680 and 580 Ma); and (2) an alkaline group of alkali-granite, monzonite, and syenite (ranging in age from 635 to 550 Ma).

This ‘postorogenic’ calk-alkaline magmatism distinguishes itself from subduction magmatism by its generally felsic and highly potassic nature that suggests a crustal origin. Geochemical modeling studies (D. Thiéblemont, unpublished BRGM technical report, 1999) confirmed that partial melting of the arc-related tonalite-trondhjemite suite could produce melts with trace-element signatures similar to the ‘postorogenic’ granitoids. This is in support of their origin by partial melting as a result of underplating of the accreted magmatic arc terranes and general thickening of the Arabian Shield. However, the alkaline granites cannot be derived from a crustal tonalite-trondhjemite source and require the participation of intraplate mantle.

Late Pan-African Extension

The late-stage Neoproterozoic formations in Saudi Arabia indicate that crustal thickening brought about during the Pan-African orogeny was followed by an episode of crustal thinning associated with important volcanic activity, and a return to marine sedimentation.

Normal faults and late Najd faulting and associated basins

The northern part of the Arabian Shield is cut by a system of late NW-striking faults (Figures 1 and 3) known as the Najd faults (Moore, 1979). They are left-lateral strike-slip faults that either follow or cut across the margins of earlier Pan-African structures. They also control the formation of the Jibalah basins that formed on relay-zones or bifurcations of the Najd faults and can be identified as pull-apart basins.

Despite the fact that various authors mention extensional phases in the structural evolution of the basement (for example, Camp, 1986; Bokhari and Forster, 1988), few normal faults have been described in the Arabian Shield. However, our field observations led to the discovery of two major faults that have principally normal slip—they are the Jabal Farasan and Wadi Fatima faults. The Jabal Farasan fault extends northeastward for about 200 km (Figure 7) as a corridor several hundred meters wide in which the pre-existing foliation has been refolded. The axial planes of these structures are horizontal. Shear planes that developed in a brittle environment dip about 30ºSE and display striations with an azimuth of 160º. The Wadi Fatima fault also has a northeasterly strike, and dips about 50ºNW. Drag folds and tension gashes at right angles to the striations indicate normal slip.

The largest detachment fault attributable to identified gravitational sliding is located at the base of the Murdama basin in the northeastern Shield. Above this fault, various low-angle normal and reverse faults cut the Murdama molasse with a general north-northeasterly shear direction. These are primarily faults lined with quartz veins that were identified during mineral exploration in the Silsilah district of the Murdama basin (Récoché, Al-Jehani and Shanti, 1998; Récoché, Al-Jahdali, Khalil and Lopes, 1998).

Other signs of late extension

Widespread extension could have facilitated or induced the partial melting of the mantle that produced the abundant postorogenic alkaline granite batholiths and volcanic rocks between 635 and 550 Ma. Major NW-trending short-wavelength anomalies are ubiquitous on the aeromagnetic map of the Shield and crosscut the structural lineaments. They are oblique to the N-S Nabitah structures, sub-parallel to major dike swarms (Figure 6), and show up particularly well in the southern part of the Shield (Figure 4). The NW-trending magnetic anomalies are mainly related to a major Shield-wide postorogenic intrusion event, expressed at the surface by major W- to NW-oriented dike swarms. The geometry of the dike swarms indicates N–S to NE–SW extension (Figure 6), which is surprising as the main orogenic Nabitah belt has a northerly orientation. It implies that extension was not simply gravitational but was accommodated by the NW-trending left lateral faults.

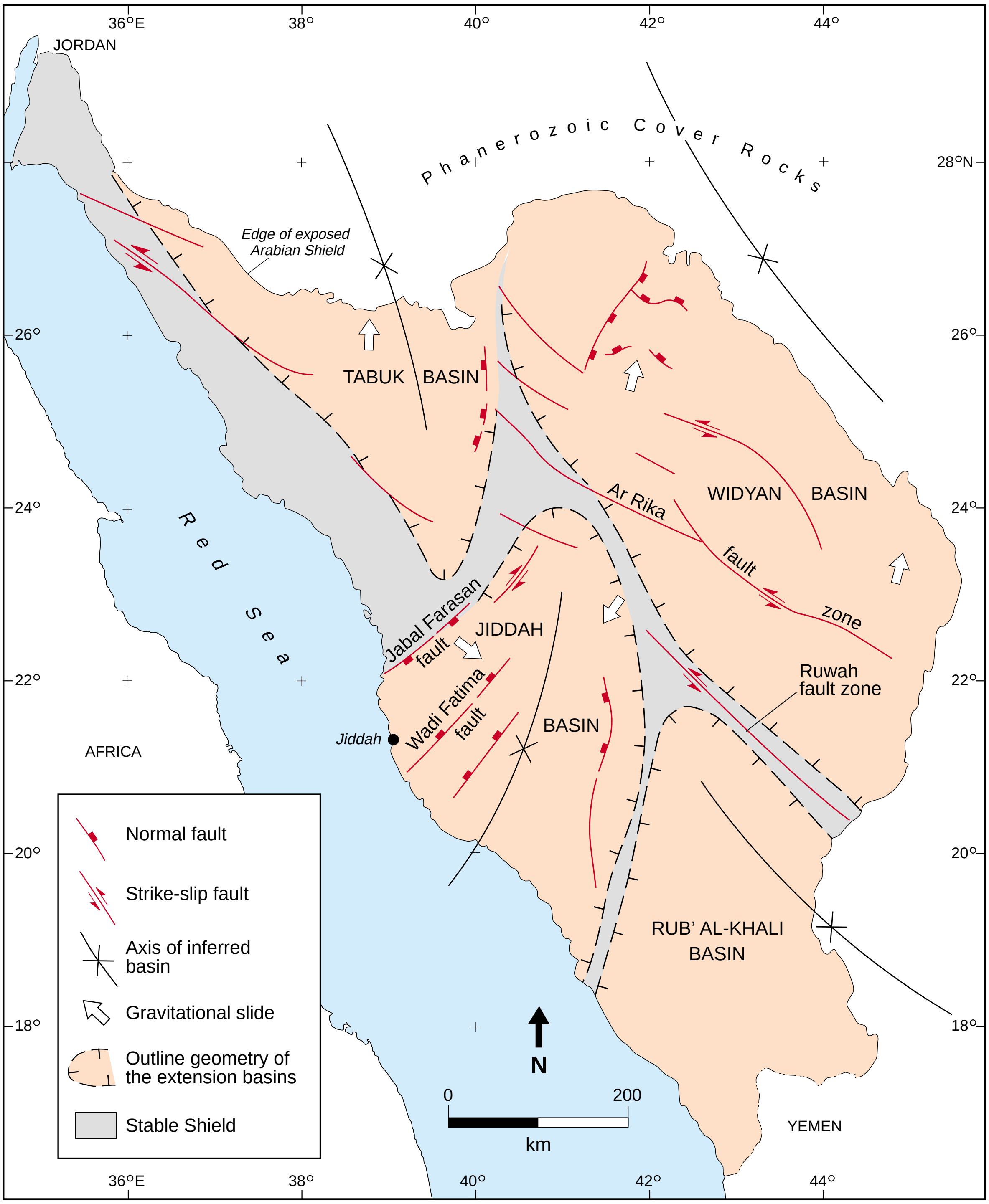

Figure 7: Simplified structural framework of Neoproterozoic extension in the Arabian Shield.

Continued extension and erosion led to total peneplanation of the Shield and the deposition of the continental Siq and Yatib formations (late Early Cambrian) and the Saq Formation (Late Cambrian to Early Ordovician).

Proposed model for the post-Nabitah extension

Three large structures (Figure 7) were preserved through the Paleozoic and may represent the continuation of the Jibalah basins (Delfour, 1970; Basahel et al., 1984) extensional event. They are the Tabuk and Widyan basins in the north (having the Saq Sandstone at their base), and the Rub' Al-Khali basin to the south (containing the Paleozoic Wajid Sandstone and the Eocambrian salt formations)

(Faqira and Al-Hauwaj, 1998). The 'Jiddah basin' may have been another unit to this assemblage, marked by the late Proterozoic to Early Cambrian carbonate-bearing Fatima formation (group) (Basahel et al., 1984).

Similar postorogenic extension has been documented in the Sinai Peninsula, where NW–SE extension is marked by NE-trending dikes (Brooijmans, 1999; Blasband et al., 2000). Extension was associated with the intrusion of granite plutons and dikes (590–530 Ma), and high-temperature / low-pressure metamorphism (Brooijmans, 1999) dated at 600 to 530 Ma. Al-Husseini (2000) suggested that the Najd fault system extends beneath the Paleozoic cover east of the Arabian Shield and accompanied NE-oriented intracontinental rifts in Oman, Pakistan, the Zagros Mountains, and the Arabian Gulf. The relationship between this mainly E–W extensional phase and the extension that we document in the Arabian Shield is still poorly understood and requires more studies.

CONCLUSIONS

Arc accretion and cratonization of the Arabian Shield produced gneiss domes and molasse basins over a system of intracontinental shear zones. The resultant belt was then subjected to tangential late-orogenic extension and crustal thinning controlled by the Najd transcurrent faults. Widespread erosion brought about gradual peneplanation of the Shield, and crustal thinning instigated a late-marine transgression.

These conclusions have major implications concerning the respective meaning of the Nabitah and Najd fault zones. The NW-striking 'Najd faults' are generally viewed as late-stage, left-lateral strike-slip faults (Moore, 1979; Stoeser and Camp, 1985). Our work, however, shows that they are the result of a two-phase evolution. Early left-lateral transpressional movements along the faults developed major gneiss domes and large volcanosedimentary Murdama-type basins. Later movements controlled the deposition of clastic sediments in pull-apart basins.

The synchronous formation of the early Najd faults and the Nabitah fault zone implies that the Nabitah belt cannot be used as a passive marker of the amount of cumulative displacement along the Najd faults, as was done in earlier studies (Brown, 1972; Davies, 1982, 1984; Cole and Hedge, 1986; Johnson and Kattan, 1999). However, late-stage, left-lateral brittle displacement led to the formation of the Jibalah basins. Such displacement presumably also contributed to the opening of Najd-orthogonal, salt-filled rift basins in Oman, Pakistan, the Zagros Mountains, and the Arabian Gulf that form the foundations of most of the hydrocarbon traps in the Arabian Platform, as demonstrated by Husseini (1988, 1989) and Al-Husseini (2000).

The Arabian-Nubian Shield was formed over a relatively short period, which led Reymer and Schubert (1986) to suggest an arc-addition rate of 310 cu km / km-arc-length / million years. This calculation assumes an area of 6 million sq km, a volume of 300 million cu km, a 300-my-interval, and an arc length of 2,500 km. This is one order of magnitude higher than the present-day arc addition rates of 30 cu km / km-arc-length / my, and has led several authors to suggest that much higher spreading rates existed in the past than today (see Howell, 1989, for discussion). Although questioned by some authors, Stein and Goldstein (1996) used this high growth rate as evidence for a major oceanic-plateau component to the Arabian-Nubian Shield. Not only has such an oceanic-plateau component not been demonstrated geochemically in the Arabian Shield (this study), but the important dispersion / accumulation tectonics exposed here imply that simple orthogonal convergent-type accretion models cannot be used to estimate the continental growth rate of the Arabian-Nubian Shield.

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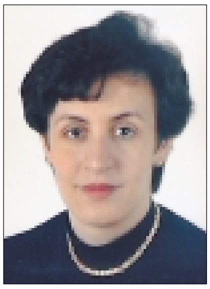
ABOUT THE AUTHORS

Pierre Nehlig *is Manager of the National Digital Map Database project at the French Bureau de Recherches Géologiques et Minières (BRGM). He joined BRGM in 1990 after a postdoctoral fellowship at the University of Washington. For five years he managed a research project on the Arabian-Nubian Shield. Pierre is a quantitative earth scientist with extensive research, commercial, and teaching experience in geology and geochemical and geophysical analysis as applied to continental formations, ore deposits, and the sea floor. His scientific interests cover the fields of hydrothermal systems and related mineralization, the evolution of oceanic lithosphere from accretion to subduction, and continental growth and evolution. His broad experience covers the USA, Saudi Arabia, Oman, India, Indonesia, Kenya, New Zealand, Europe, and the Pacific. Pierre is a guest lecturer at the universities of Paris, Orleans, and Tours. He is the author of more than 50 peer-reviewed papers in international journals, and of over 100 presentations at international and national meetings.*

Corresponding author. E-mail: nehlig@brgm.fr

Antonin Genna *is a Structural Geologist with the French Bureau de Recherches Géologiques et Minières (BRGM). He joined BRGM in 1989, working first on reconnaissance studies to investigate potential radioactive-waste storage sites. Soon after, he began to concentrate on mineral exploration and mapping in France and in Indonesia, Canada, Saudi Arabia, Morocco, Romania, Gabon, Bolivia, India, Russia, and elsewhere, mainly for gold, base metals, and industrial minerals. He has extensive field experience in basin analysis, mapping, and mineral exploration. Antonin has been involved in many mapping, mineral exploration, and research projects in the Arabian Shield since 1990 and has extensive knowledge of its structural evolution. His primary scientific interest is in the early deformation that accompanied the formation of sedimentary basins.*

E-mail: a.genna@brgm.fr



Fawzia Asfirane *is a Research Scientist with the French Bureau de Recherches Géologiques et Minières (BRGM). She obtained a PhD in Geophysics at the École Normale Supérieure de Paris in 1994 on the processing and interpretation of aeromagnetic data from northern Algeria. Fawzia then joined Total where she worked on seismic exploration data using wavelet transforms for controlling zero phasing. At BRGM she has been focusing on aeromagnetic data of French Brittany and of the Arabian Shield, using various processing techniques to interpret anomalies in terms of their geological significance.*

E-mail: f.asfirane@brgm.fr

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