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A Geochemical Approach to Allochthonous Terranes: A Pan-African Case Study [and Discussion]

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A geochemical approach to allochthonous terranes: a Pan-African case study

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The recognition of Mesozoic and Cenozoic terranes can best be made from palaeomagnetic, structural and palaeontological studies, but older regions of continental crust require geochemical constraints to evaluate crustal growth through terrane accretion. For Precambrian shields, the pattern of Pb and Nd isotopic provinces may reveal the mechanism of crustal growth.

The Afro-Arabian Shield was generated by calc-alkaline magmatism between 900 and 600 Ma ago. This example of Pan-African crustal growth underlies an area of at least 1.2×10^6 km^2, which may extend to 3.5×10^6 km^2 beneath Phanerozoic sediments and Tertiary volcanic cover. Field evidence and trace element geochemistry suggest that Pan-African tectonics began as a series of intra-oceanic island arcs that were accreted to form continental lithosphere over a period of 300 Ma. The great majority of Nd and Pb isotope ratios obtained for igneous rocks from the shield are indicative of a mantle magma source. Although many of the dismembered ophiolites cannot be identified with inter-terrane sutures in their present location, the eastern margin of the Nabitah orogenic belt is a major tectonic break that coincides with a critical boundary between Nd and Pb isotopic provinces and is marked by a linear array of ophiolite fragments across the length of the shield. Other terrane boundaries have not been identified conclusively, both because coeval island arcs can not be distinguished readily on isotopic grounds and because many ophiolites are allochthonous. However, the calculated rates of crustal growth (measured as volume of magma, extracted from the mantle per unit time) between 900 and 600 Ma are similar to those calculated for Phanerozoic terranes from the Canadian Cordillera. Such high rates in the Afro-Arabian Shield suggest that island arc terranes have accreted along a continental margin now exposed in NE Africa, together with minor continental fragments. If crustal growth rates during this time were no greater than contemporary rates, *ca.* 4000 km of arc length are required, which is considerably less than that responsible for crustal growth in the SW Pacific.

1. Introduction

The recognition that some continental margins result from the accretion of lithospheric fragments, each with a distinctive stratigraphy and separated by tectonic contacts, was initially made in the North American Cordillera during the 1970s. Over 200 terranes have been recognized in the Cordillera which is now believed to be a collage of oceanic plateaus, intra-oceanic volcanic arcs and continental fragments, brought together over large distances (greater than 10^3 km) by oblique convergence (Oldow *et al.* 1989). This discovery had a profound influence on the interpretation of older tectonic margins, and led to a series of criteria being erected to identify allochthonous terranes by the recognition of lithological, structural, palaeomagnetic or faunal contrasts across terrane boundaries. Where faunal or palaeomagnetic data are available to aid reconstruction, or where inter-terrane boundaries have not been disturbed by subsequent tectonic activity, displaced terranes can often be readily recognized as in the North American Cordillera or the Tibetan Plateau. However, for Precambrian plate margins, none of these conditions commonly applies. Consequently, terrane recognition must be necessarily more speculative. This paper reviews the contribution that geochemical studies can make to the identification of terranes in general, and uses the Afro-Arabian Shield as a late Proterozoic example.

2. The geochemistry of terrane accretion

The recognition of terranes rests either on the study of the tectonic boundaries separating the terranes or on the contrasting properties of the terranes themselves. In general, geochemical studies of igneous rocks can indicate the magma source, and by comparison with present-day magma geochemistry can identify the processes responsible for magmagenesis. For example, trace element studies of basic rocks can help to identify the tectonic setting in which they have formed (Pearce 1982). By using discriminant diagrams based on critical trace elements, ophiolite fragments can be identified as components of oceanic lithosphere and the nature of this lithosphere (for example MORB-type or supra-subduction zone) determined. Such ophiolites, if occurring within suture zones, will then provide constraints on the original tectonic setting of inter-terrane oceanic lithosphere which pre-dated docking. Information can also be obtained from granitic complexes that occur within terranes (Pearce *et al.* 1984). For example, their trace elements can indicate the presence of subduction-related magmatism which resulted from the pre-accretion closure of large ocean basins.

Isotopic dating of igneous rocks by using conventional U–Pb zircon or Rb-Sr whole rock techniques will determine periods of magmatic activity within each terrane. Where contrasting periods of magmatism occur within terranes, which then become juxtaposed through docking, simple age dating may constrain inter-terrane boundaries. Unfortunately, this is rarely if ever the case. Terranes commonly have overlapping periods of magmatism and idealized patterns may be subsequently complicated by post-collision magmagenesis. So, in general, the ages of magmatic provinces do not define terrane boundaries. Fortunately, magmatic rocks retain critical information on the age and nature of their source regions. In the case of Sm–Nd decay, model Nd ages can be calculated for igneous or sedimentary rocks which constrain when the rock or its crustal precursor was extracted from a mantle reservoir. If, for example, a magma formed directly from mantle melting the model Nd age will equal the emplacement age. In general, the model Nd age is somewhat older than the emplacement age reflecting the time of crust generation. The importance of Nd model ages rests on the fact that Sm and Nd, unlike Sr and Rb, are not readily fractionated by crustal processes but are fractionated between the crust and mantle. Thus Nd model ages record the time when the rock was extracted from the mantle (usually taken to be a depleted upper mantle) irrespective of subsequent periods of crustal reworking or sedimentary cycles. If several sources are involved, the Nd model age provides a weighted average of the ages of the contributing sources. Model Nd ages, therefore, provide direct information on the source of the magma, whether that is in the mantle or the continental crust.

Regional Nd-isotope studies map out isotopic variations in the basement, and sharp changes in such trends may reflect terrane margins where crust generation in adjacent terranes has occurred at different times. Pb isotopes also provide information on the source of the magma although Pb and Nd isotope studies offer distinct geochemical information because of the

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different behaviour of U:Pb, Th:U and Sm:Nd in different geological environments. In general, Sm:Nd is strongly fractionated between mantle and crust, whereas U:Pb is affected by intra-crustal fractionation and Th:U by sedimentary recycling. U:Pb ratios show much more variation in crustal rocks than do Sm:Nd, so that, whereas Pb isotopes studies are commonly successful in distinguishing between different crustal processes, periods of crustal growth are better identified through Nd isotopes.

Where areas of strongly contrasting periods of crust generation are juxtaposed by terrane tectonics, isotope geochemistry may reveal inter-terrane boundaries. For example, in southern California, approximately north–south isopleths of initial Sr ratios have been mapped in the Sierra Nevada batholith, where the rapid variation between 0.704 and 0.706 is correlated with Pb isotope and trace element variations within the batholith, and with a major fault zone (Kistler & Peterman 1973). This shift in initial isotopic ratios has been recognized as a suture between oceanic and continental basement terranes (Saleeby 1981).

For pre-Phanerozoic terranes, isotope geochemistry may provide the only available criteria distinguishing terranes, but caution is required if isotopic provinces are to be correlated with discrete terranes. Far less is known about the growth and tectonics of the Proterozoic of the western United States than of the Mesozoic of the North American Cordillera. However, isotopic basement trends in the western United States have been mapped for both Nd and Pb isotopic ratios. Nd model ages are found to conform to a general pattern (figure 1*a*) that reflects a systematic decrease in model age away from the Archaean nucleus in the north (Bennett & DePaolo 1987). The data are consistent with crustal growth at a continental margin, active between 1.7 and 1.5 Ga. The lack of sharp boundaries in the isotopic characteristics of the basement and the lack of correlation between basement geochemistry and major faults or shear zones argue against their distribution being controlled by tectonic boundaries.

Early Proterozoic outcrop is not extensive. Magmatic ages in the region range from 1700 to 60 Ma and their distribution shows no simple trends (figure 1*a*). The importance of model Nd

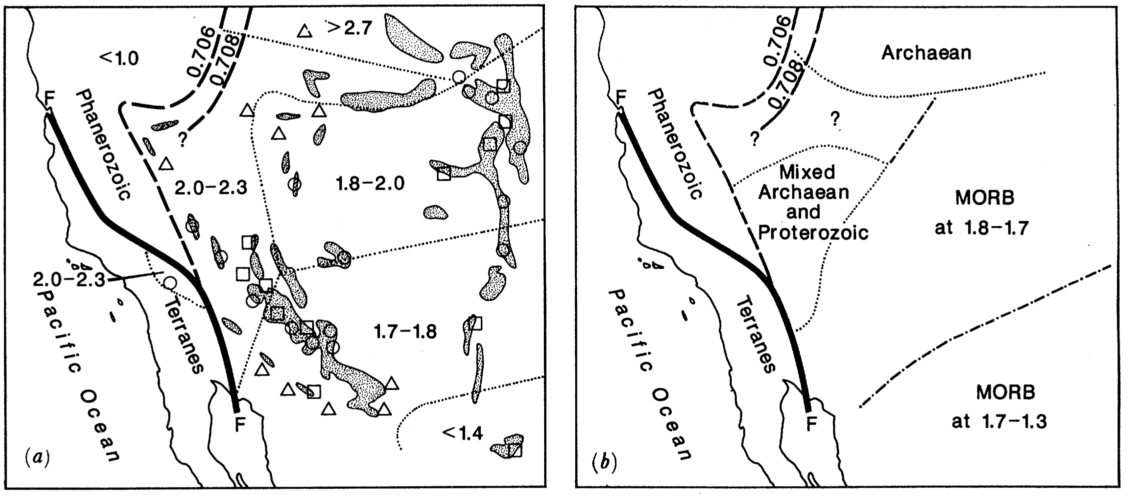

FIGURE 1. Isotopic provinces from the Proterozoic basement of the western United States. (*a*) Nd isotope provinces (Bennett & De Paolo 1987) with characteristic model Nd ages in Ga. Dotted lines delimit model Nd age provinces (initial $^{87}Sr:^{86}Sr$ isopleths at 0.706, 0.708 taken from Kistler & Peterman (1973)). Stippled areas, early Proterozoic outcrop. Symbols indicate sample locations with the following crystallization ages: ○, 1.7 Ga; □, 1.4 Ga; △, 0.06 Ga. (*b*) Pb isotope provinces (dotted line from Wooden *et al.* (1986); dot-dash from Oldow *et al.* (1989)).

age trends is that they reflect the character of the basement, and effectively 'see-through' subsequent intra-crustal processes such as post-accretion magmatism.

The boundaries between Archaean and Proterozoic Pb isotope provinces are consistent with Nd isotope mapping (figure 1*b*), but within the region of Proterozoic basement, the distribution of Pb provinces is more equivocal. These were initially explained as three or more terranes of different characteristics that had accreted during a period of rapid crustal growth 1.8–1.6 Ga ago (Wooden *et al.* 1986). A terrane model is favoured by Condie (1986) partly on the basis of irregular age distributions for felsic eruptions between 1.7 Ga and 2.3 Ga. The redrawing of some of the boundaries between Pb isotopic provinces (Oldow *et al.* 1989) suggests a systematic shift of less radiogenic lead outwards from the Archaean nucleus (figure 1*b*). As for the Nd data, this pattern is consistent with a model of crustal growth at a continental margin rather than a random accretion of allochthonous terranes.

Terrane accretion is a mechanism of lateral growth for continents. Since continental lithosphere is not vertically homogenous, it cannot be assumed either that variations in initial isotopic ratios of crustal melts indicate a terrane boundary (they may reflect a lateral change in depth from which magma is derived) or conversely that lack of variation rules out a terrane boundary. For example, in one study across a known Archaean–Proterozoic boundary in Wyoming, Proterozoic Nd model ages were obtained from granitoids on both sides of the boundary (Geist *et al.* 1988). The implication is that the Archaean continental crust had been underplated near the suture during Proterozoic magmagenesis. What is important in relating isotopic provinces to terrane accretion is the pattern of their distribution and their correlation with major tectonic features.

Nd model ages are also of value for sedimentary rocks. In fine-grained clastic sediments, Nd model ages provide an average age of their source regions: that is a weighted average of the times at which contributing sources to the detritus were extracted from the mantle. Consequently, where terranes of contrasting basement ages are brought together, a marked shift in model ages should be observed in sediments deposited after the docking of the terranes. This has been observed in northern Britain where sediments deposited south of the Iapetus suture, which represents closure of a major ocean, show an increase in Nd model ages for deposition younger than about 500 Ma (Davies *et al.* 1985; Miller & O'Nions 1984). This is persuasive geochemical support for a tectonic model that argues for the arrival of an older terrane as a consequence to ocean closure. Unfortunately, such an elegant technique requires well-constrained deposition ages which are seldom available in Precambrian shields.

3. The Afro-Arabian Shield

The late Proterozoic crystalline basement of the Afro-Arabian shield is now separated into Arabian and African segments by the late Tertiary opening of the Red Sea, and is onlapped to the East and West by Phanerozoic sediments. The exposed geology of the Shield (figure 2) is dominated by granitic intrusions (greater than 66%) and calc-alkaline volcanics with relatively minor volcanoclastic sediments, all of Pan-African (900–600 Ma) age. Mafic-ultramafic complexes occurring therein have been identified as ophiolitic sequences (Bakor *et al.* 1976; Al Shanti & Mitchell 1976; Gass 1977). Moreover, a growing body of geochemical data identifies the great majority of magmatic rocks as originating in an arc (supra-subduction zone) environment and consequently the subparallel ophiolite zones have been interpreted as

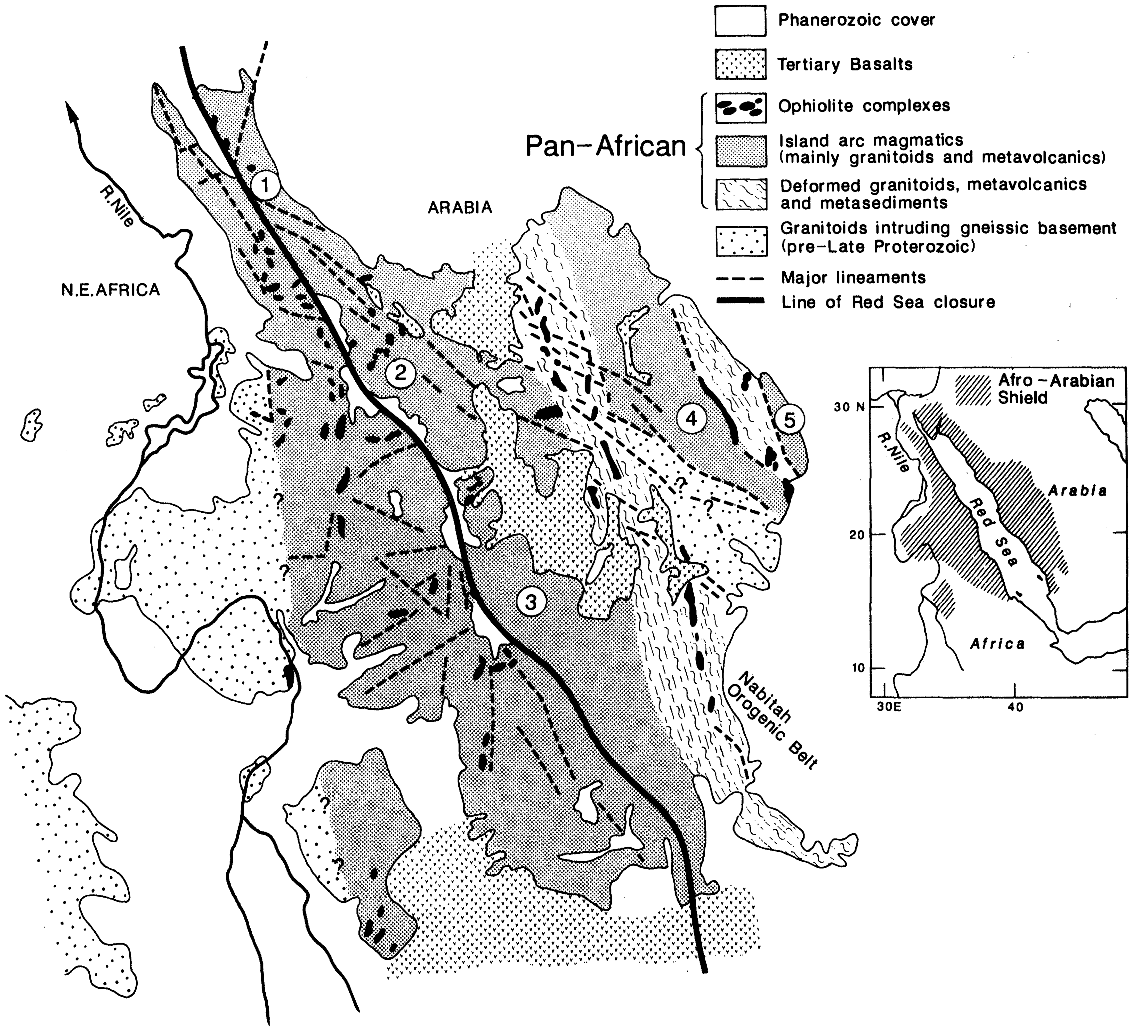

FIGURE 2. Sketch geological map of Afro-Arabian shield. Insert shows present distribution of basement outcrops. Arabian 'terranes' after Stoeser & Camp (1985); 1, Midian; 2, Hijaz; 3, Asir; 4, Afif; 5, Ar Rayn.

marking inter-arc sutures. In this model, the arcs accreted to the African craton by the end of the Pan-African to form the Afro-Arabian Shield (Greenwood *et al.* 1976; Gass 1977).

Analogies have been drawn between the terrane accretion of the North American Cordillera and the tectonics of the Afro-Arabian Shield (Kroner 1985). Ophiolite-decorated sutures are identified as the boundaries between geologically discrete terranes. Indeed, a hierarchy of terranes has evolved in the literature for the Arabian segment of the shield; Johnson & Vranas (1984) recognized 10 terranes, which were bound by major faults and ophiolite 'lineations' referred to as sutures. Each terrane was described as a coherent sedimentary and volcanic environment, and igneous suites within each terrane shared petrologic and chemical affinities. Stoeser & Camp (1985) provided a simpler model of five terranes in Arabia separated by four sutures. This terrane hierarchy was further subdivided by Stoeser & Stacey (1988). However, all subdivisions of the shield recognize the importance of the Nabitah orogenic belt; a 200 km wide zone of syn-orogenic granite plutons separated by regions of amphibolite grade metasediments and metavolcanics (Droop & Al-Filali 1989). This separates western terranes,

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which are unequivocally oceanic in character, from eastern terranes, which include at least some pre-Pan-African continental material. The Stoeser & Camp model defined a period of island arc evolution (950–715 Ma) followed by terrane accretion (715–630 Ma) and finally by within plate magmatism (630–550 Ma).

Unfortunately, with crust of early Phanerozoic–late Precambrian age the matching of faunal provinces to identify terranes is not possible. Moreover, palaeomagnetic reconstructions, used so successfully in identifying allochthonous terranes in North America, have not been successful in Arabia. The only detailed palaeomagnetic study of the area (Kellogg & Beckman 1984) was undertaken in the southeastern Arabian Shield; this concluded that pre-600 Ma magnetic signatures were destroyed by the widespread Pan-African granite plutonism. By this time, the apparent polar wandering path of Arabia is indistinguishable from that of Africa. There is, therefore, no palaeomagnetic information on the relative positions of different terranes in the shield before 600 Ma and their recognition rests almost entirely on geochemical criteria.

(*a*) *Ophiolites and inter-terrane sutures*

The ophiolite sequences of the Afro-Arabian shield include ophiolitic melanges, serpentinite thrust melanges and fault-bounded inliers. To interpret the outcrop distribution of ophiolite fragments as terrane boundaries or sutures, it must be assumed that the ophiolites have not been displaced significantly from the suture during obduction or post-obduction collisional processes.

There are several lines of evidence that suggest that the present-day distribution of many of the ophiolite fragments from the Afro-Arabian Shield do not mark ancient sutures. Afro-Arabian ophiolites form detached masses with tectonic contacts and there is no evidence for primary obduction such as the metamorphic sole of ocean floor basalts to the Tethyan Oman ophiolite (Lippard *et al.* 1986). Detailed structural studies of ophiolites from the Eastern Desert of Egypt recognize the ophiolite fragments as allochthonous ophiolitic melanges, possibly displaced from their suture zone by several hundred kilometres (Ries *et al.* 1983). Moreover, in the Arabian Shield the ophiolite distribution has been rearranged by the Nadj fault system; a left-lateral shear zone with 200–300 km offsets which evolved between 630–550 Ma (Davies 1984) and clearly post-dated all obduction.

Perhaps one criterion for associating ophiolites with sutures is their virtual continuity over many hundreds of kilometres as in the Tethyan suture zone of southern Tibet. The only linear zone of ophiolitic fragments in the Afro-Arabian shield that may be traced over such distances is in the Nabitah orogenic belt (figure 2). Moreover the Pan-African ophiolites are smaller and more widely spaced than their Tethyan counterparts. This may simply be an erosional effect for virtually all the Semail ophiolite of Oman would disappear if the area were eroded to a depth of 5 km (Lippard *et al.* 1986). Maximum depths of erosion in the Afro-Arabian Shield as measured in the Nabitah Orogenic belt are about 10 km (Droop & Al Filali 1989) although much of the southern portion of the shield has only been subjected to about 5 km of erosion (Gass *et al.* 1990).

As well as indicating the site of former oceans, ophiolites identify the composition of that oceanic lithosphere and, thereby, its tectonic setting. Trace elements from the basic eruptive components together with their field associations suggest that most of the ophiolites in both northeast Africa and Arabia were generated in a supra-subduction zone tectonic setting as, for example, in Jebel al Wask (Bakor *et al.* 1976), Jebel Thurwah (Nassief *et al.* 1984), and the

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Halieb ophiolite NE Sudan (Price 1984). Ophiolites of the Al Amar zone in eastern Arabia have boninitic characteristics, again indicating a supra-subduction zone setting (Al Shanti & Gass 1983). Furthermore, precise single zircon studies of ophiolites from the Egypt–Sudan border dated at 740–750 Ma are generally younger than the oldest magmatic arc sequences (850–870 Ma) and may therefore derive from intra-arc basins (Kroner & Todt 1989). It appears, therefore, that these ophiolites probably do not mark the closures of wide ocean basins but those of several small marginal basins such as are found presently in the western Pacific.

(*b*) *Crystallization ages and terranes*

Of the many Rb–Sr whole rock isochrons published from the Afro-Arabian Shield, few reliable isochrons have been recorded outside the range 850–550 Ma. Spatially related age trends are not apparent within the shield although a general trend of younging of arc-related magmatism from north to south in the western terranes has been suggested (Stoeser & Camp 1985). Variations of initial (^{87}Sr:^{86}Sr) ratios are virtually restricted to between 0.707 and 0.702 throughout the shield and any spatial trend within this range is masked by analytical uncertainties. Stoeser & Camp (1985) record a slightly higher range (0.707–0.7035) east of the Nabitah orogenic belt compared with values of 0.7035–0.702 to the west. However, a detailed study of volcanics from the south eastern shield provided no initial ratios in excess of 0.7036 (Darbyshire *et al.* 1983). Therefore, neither Rb–Sr crystallization ages nor initial Sr isotope ratios provide unequivocal evidence for discrete terranes within the Afro-Arabian shield.

Numerous zircon studies also reveal a general age span of 870–550 Ma within the shield (Stoeser & Stacey 1988 and references therein). There are, however, some interesting examples of pre-Pan-African ages, which have been reviewed by Harris *et al.* (1984) and Kroner *et al.* (1988). In the south of the eastern terranes of Arabia, three upper intercept zircon ages from magmatic rocks lie in the range 1800–1600 Ma indicating the presence of some pre-Pan-African basement. In Africa, early Proterozoic zircon ages are found in sedimentary rocks from the Eastern Desert of Egypt and to the southeast of Lake Nasser. There is no doubt that a pre-Pan-African source region is required for some sediments, which must lie west of the Nile. An Archaean craton of unknown size certainly exists in the Uweinat inlier on the Egyptian–Libyan border where Rb–Sr isochrons of 2600 Ma have been obtained (Klerkx & Deutsch 1977). Much further south, ion microprobe ages of 1000–2700 Ma from zircons in the Sabaloka basement north of Khartoum (Kroner *et al.* 1987) confirm the presence of a mid-Proterozoic or Archaean source region in western Sudan.

Crystallization ages indicate the presence of pre-900 Ma ages in the southeastern Arabia and west of the Nile but do not define discrete age provinces within the Afro-Arabian shield. There remain two isotopic techniques that provide information not on the periods of magmatism but on the age and geochemistry of the underlying basement.

(*c*) Pb–Pb *isotopic data*

Pb isotopic data may be plotted on two evolution diagrams (figure 3). For initial ratios, the upper plot (^{208}Pb:^{204}Pb against ^{206}Pb:^{204}Pb) reflects variations in Th:Pb and U:Pb and hence the Th:U ratio in the source. The Pb isotope evolution through time of average upper mantle, as modelled by Zartman & Doe (1981), is also plotted. The growth curve for average crust is not indicated since crustal Th:U ratios are extremely variable but, in general, sedimentary recycling will result in elevated Th:U, resulting in fields above the mantle growth curve for

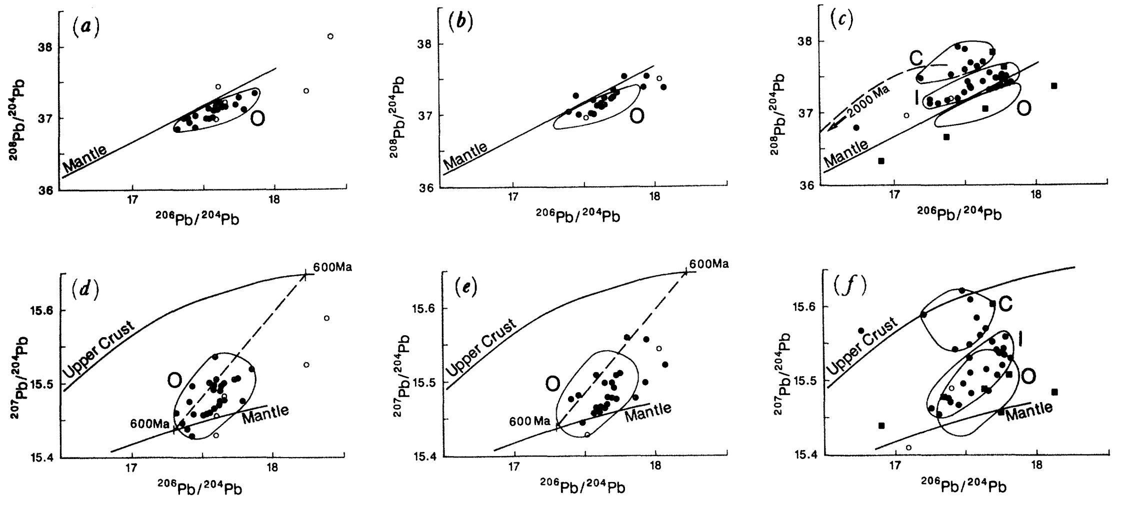

FIGURE 3. Pb isotopic characteristics of the Afro-Arabian shield with modelled upper mantle and upper crust evolution from Zartman & Doe (1981). Closed symbols indicate data from sediments and intermediate-acid magmatic rocks. Open symbols, ophiolites. (*a*), (*d*) The western terranes of Arabia. Dashes indicate mixing line between upper crust and mantle at 600 Ma. (*b*), (*e*) The Nabitah orogenic belt. (*c*), (*f*) Eastern terranes of Arabia. Squares indicate samples from NE Africa. Dashed line indicates evolution line for crust (U:Th = 4.0) extracted from mantle at 2000 Ma. Empirical fields indicated by O (oceanic Pb), I (intermediate Pb) and C (continental Pb). (Data from Stacey *et al.* 1980; Stacey & Stoeser 1983; Gillespie & Dixon 1983; Pallister *et al.* 1988; Stoeser & Stacey 1988; Ellam *et al.* 1990.)

mature continental crust (Ellam *et al.* 1990). For the lower plot ($^{207}Pb:^{204}Pb$ against $^{206}Pb:^{204}Pb$), mantle and crustal reservoirs are better constrained since fractionation of crust from upper mantle results in at least a slight increase in U:Pb, and modelled evolution curves for both average upper mantle and average upper crust are given from Zartman & Doe (1981). Also shown is a dashed line linking the isotopic ratios of the model crust and mantle at 600 Ma. Interpretation of Pb isotope ratios is often equivocal since there is considerable variation in both mantle and crustal sources. The upper mantle is not only heterogeneous but, at island arcs, $^{207}Pb:^{204}Pb$ ratios in particular can be elevated by small components of subducted sediment.

Data from the Afro-Arabian Shield are from galena and feldspar separates which record the initial Pb isotope ratio at the time of crystallization. In the western Arabian terranes (figure 3*a*) samples cluster just below the mantle growth curve suggesting that the crust has primitive or oceanic isotopic ratios (field O). For the Nabitah orogenic belt (figure 3*b*) samples generally lie in the same field, but for the eastern Arabian terranes samples have a higher initial $^{208}Pb:^{204}Pb$ suggesting elevated Th:Pb and Th:U in their source (figure 3*c*) and therefore that mature continental material has contributed to their source regions. These data have been divided empirically into field I (intermediate) and field C (continental) and the spatial distribution of samples with O, I and C characteristics are plotted on figure 4*a*. In figure 3*c* a two-stage model is illustrated where crust is extracted from the upper mantle at 2000 Ma with an increased Th:U ratio of 4, compared with a typical mantle value of 3.5 (2000 Ma is chosen because it represents a typical model Nd age for samples in field C). Field I could represent either mixed sources of O and C type or a discrete terrane of pre-Pan-African age of less than 2000 Ma. In either event, the data identify an older continental fragment in the south of the eastern Arabian terranes and, although Pb data from Africa are sparse, there is some evidence for a pre-Pan-African continent in southwestern Egypt (figure 4*a*).

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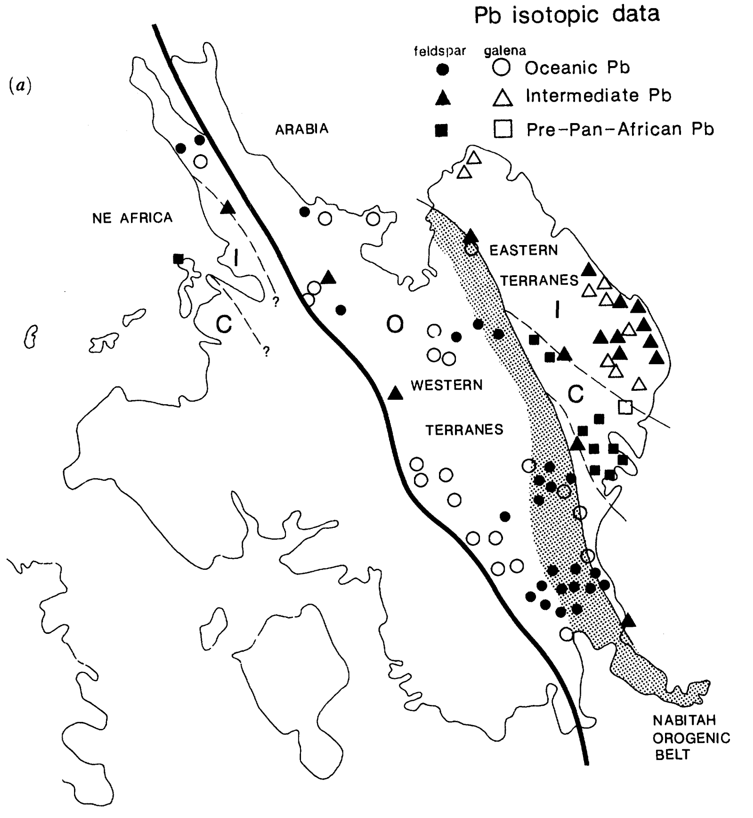

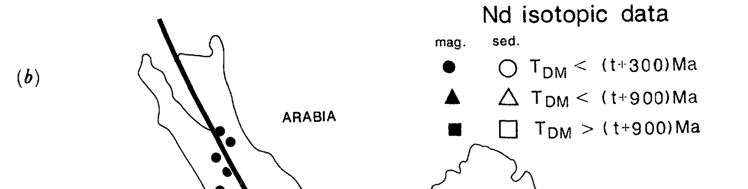

FIGURE 4. Isotopic data for Afro-Arabian shield. (*a*) Distribution of Pb data from galena (open symbols) and feldspar (closed symbols). ○, Oceanic (MORB) Pb at 600 Ma; △, intermediate Pb; □, continental Pb (as defined in figure 3). (*b*) Distribution of Nd initial ratios from magmatic rocks (closed symbols) and sediments (open symbols). ○, Oceanic Nd; △, intermediate Nd; □, continental Nd (as defined in figure 5).

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In figure 3*d* and *e*, field O samples from the eastern Arabian Terranes and the Nabitah orogenic belt scatter above the mantle growth curve at 600 Ma, with some evidence for subducted sediment in the source region seen from samples with elevated $^{207}Pb:^{204}Pb$ ratios. It is proposed that such oceanic isotopic ratios resulted from intra-oceanic arcs between 900 and 600 Ma ago. However, in eastern Arabia, there is a significant shift to more crustal values (figure 3*f*), and these confirm a Lower Proterozoic crustal fragment in the south-east of the Arabian Shield. However, it can be seen from comparing figures 2 and 4*a*, that, if the I and C isotopic provinces do mark discrete terranes, their boundaries only coincide with those determined from ophiolite-decorated sutures along the eastern margin of the Nabitah Orogenic Belt.

In general, Pb isotopic ratios from ophiolite samples lie in the fields defined by samples from the adjacent terranes. In other words, ophiolites from the western Arabian terranes lie below the mantle growth curve in the $^{208}Pb:^{204}Pb$ against $^{206}Pb:^{204}Pb$ plot (figure 3*a*, *b*) but from the western Arabian terranes lie above the mantle growth curve (figure 3*c*) which is consistent with the generation of ophiolites in a supra-subduction environment. The Pb isotope ratios of ophiolites from the eastern Arabian terranes probably have been affected by subduction of some pre-Pan-African sedimentary material.

(*d*) Nd *isotopic data*

Model Nd ages (T_{DM}) from the Afro-Arabian shield are plotted in figure 5 against their emplacement age (t). t represents the crystallization age for igneous rocks and deposition age for sediments. The majority of samples from Arabia have emplacement ages approximately equal to their model Nd ages ($T_{DM}-t$) < 300 Ma. This suggests a short time interval between extraction of the melt from the mantle and its emplacement. However, for samples from eastern Arabia and Africa, there is a wider interval between model Nd age and emplacement age. Unfortunately, Pb and Nd isotope data are rarely available on the same samples, but Nd data can also be divided into three fields, O, I and C with increasing ($T_{DM}-t$) (figure 5) and their spatial distribution is plotted in figure 4*b*. They exhibit an E–W variation in Nd isotopic characteristics across NE Africa. On the Red Sea coast, sedimentary and plutonic samples essentially have 'oceanic' characteristics with Nd model ages less than 1100 Ma. To the west of this belt, both plutonic and sedimentary rocks have increased model Nd ages (1700–1000 Ma) and fall in field I defined by ($T_{DM}-t$) lying within the range 300–900 Ma. The eastern boundary of samples with these characteristics, roughly coincides with the river Nile. These can be interpreted either as representing a discrete continental terrane of Proterozoic age, or a continental margin to which both juvenile and Archaean continental sources contributed. A detailed study of interlayered metavolcanics and metasediments from southern Egypt (Wust *et al.* 1987) reveals much older Nd model ages for the metasediments (1700 Ma) than for the metavolcanics (*ca.* 800 Ma) suggesting that the sediments are derived from an ancient distal source, probably an Archaean craton to the west.

The presence of a North African craton is well-documented by samples from western Egypt and central Sudan which define a third group of continental character (field C, figure 5) in which model Nd ages range from 2500 to 1600 Ma. Further west Archaean model Nd ages of over 3000 Ma are obtained (Harris *et al.* 1984). The size of this craton is unknown, although it certainly extends westwards for several hundred kilometres and north–south for at least the length of the Afro-Arabian Shield (1200 km). What is important about the pattern of Nd

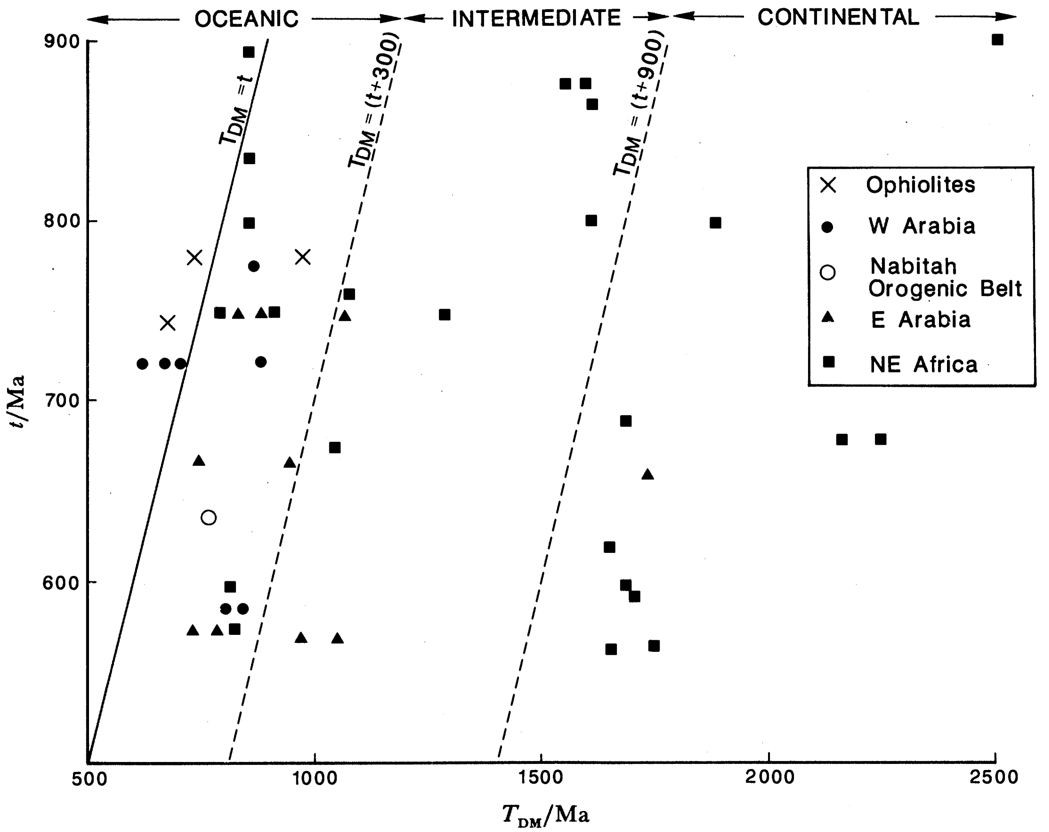

FIGURE 5. Model Nd ages (T_{DM}) plotted against emplacement ages (t) for samples from the Afro-Arabian shield. (Data from Bokhari & Kramers 1981; Duyverman *et al.* 1982; Claessons *et al.* 1984; Stacey & Hedge 1984; Harris *et al.* 1984; Reischmann *et al.* 1986; Kroner *et al.* 1987; Wurst *et al.* 1987; Schandelmeier *et al.* 1988.)

results in Northeast Africa is that it records a transition between cratonic and oceanic characteristics which probably reflects a continental margin, but the spatial distribution of Nd model ages has no relation either to major lineaments or to the present-day distribution of ophiolite fragments (figure 2).

For the Arabian Shield, there are fewer Nd data but the distribution of available Nd data essentially mimics the pattern better defined by the Pb isotope data. Samples with oceanic Nd signatures characterize the western terranes of Arabia, including the Nabitah orogenic belt. East of the Nabitah orogenic belt, intermediate model ages occur in the centre of the exposed shield but more oceanic characteristics are located further east and north. In the south, a single early Proterozoic model age has been published although more samples with older model Nd ages have been obtained both from this region and from North Yemen (J. S. Stacey, personal communication).

In general, there is not a strong correlation between the distribution of Pb and/or Nd isotopic provinces and the distribution of ophiolite fragments. The only unambiguous example in the Afro-Arabian shield of ophiolite outcrops coinciding with the boundary between age provinces lies along the eastern margin of the Nabitah orogenic belt. Elsewhere in the shield, terranes may exist but if, as seems likely from major and trace element geochemistry, the shield results from accreted island arcs, their similar periods of formation prevents their being resolved isotopically.

(*e*) *Crustal evolution of the Afro-Arabian Shield*

The Afro-Arabian Shield is continental crust of normal thickness with geochemical characteristics indicative of crustal growth by late Proterozoic subduction processes. It is possible to calculate the rate at which continental crust was generated in this area and to compare it with contemporary rates at active subduction zones (Reymer & Schubert 1982, 1984; Duyverman *et al.* 1982; Dixon & Golombek 1988). However, such calculations are poorly constrained because of large uncertainties in both the surface area of the Pan-African crust and in the length of arcs active over the 300 Ma period. The area of Pan-African crust, if restricted to known outcrop of Pan-African age, is approximately 1.2×10^6 km^2, equivalent to a volume of 4.8×10^7 km^3 (assuming an average crustal thickness of 40 km) which implies an average growth rate of 0.16 km^3 a^{-1} over 300 Ma. Present-day global rates are 1.0 km^3 a^{-1}, or 20–40 km^3 Ma^{-1} per kilometre of arc length (Reymer & Schubert 1984). If we assume similar growth rates per kilometre of arc operated in the late Proterozoic (geothermal gradients were only about 10% greater 900 Ma ago compared with current values) then 4000 km of arc are required to account for the exposed Afro-Arabian island arc terranes during the Pan-African event.

Over 1200 km of arc can be inferred by adding the lengths of ophiolite sutures in Arabia alone (Stoeser & Camp 1984) and a value of 3600 km has been obtained from identifications of liner granitic zones throughout the Afro-Arabian shield (Gass 1982). The 4000 km of arc implied by crustal growth rates, based on isotope systematics, is a reasonable estimate and is broadly consistent with arc lengths estimated from field studies.

The total area of Pan-African crust is probably much greater than is presently exposed. The presence of calc-alkaline granitoids of Pan-African age with low initial (^{87}Sr:^{86}Sr) ratios in the Oman suggest much of the Phanerozoic sediment of Arabia may be underlain by Pan-African basement (Gass *et al.* 1990). In NE Africa, the Pan-African crust extends at least as far south as Ethiopia and possibly into northern Somalia (Kroner *et al.* 1989). Overall, the total area of Pan-African crust in the Afro-Arabian shield may be as large as 3.5×10^6 km^2 although the proportion of older terranes within this extensive area remains unknown. This larger area implies a crustal growth rate of 0.47 km^3 a^{-1}, which is almost 50% of that generated globally at the present time. The total length of arc required for this increased volume is about 12000 km considerably less than the 23000 km active in the SW Pacific over the past 200 Ma (Reymer & Schubert 1986).

High crustal growth rates in a relatively small area are powerful evidence for a terrane-based tectonic model. A terrane collage as exposed in the North American Cordillera, or as presently being accreted in Southeast Asia will provide high crustal production rates because only in such a setting will arcs formed across wide oceans become juxtaposed. In contrast, crustal growth by magmatic accretion at an active continental margin is restricted to an arc length equivalent to the length of the margin. Moreover a significant proportion of magmatism will include a recycled component (*ca.* 20% according to Bennett & DePaolo (1987)) thus reducing growth rates calculated from isotopic criteria. A recent Nd study of the Canadian Cordillera identified five large terranes of oceanic affinity which indicate a crustal growth rate of 0.13 km^3 a^{-1} (Samson *et al.* 1989), similar to the minimum calculated rate for the Afro-Arabian Shield. If the distribution of isotopic provinces has not provided conclusive evidence for terrane tectonics in the Afro-Arabian Shield, the high crustal growth rate is difficult to explain by any other process.

4. Conclusions

Geochemical techniques can provide important constraints on terrane accretion, particularly where palaeomagnetic and faunal evidence are not available.

Trace element studies of both ophiolite fragments and more evolved magmatic rocks can identify the tectonic régime in which oceanic lithosphere and continental crust has formed. Isotopic analysis of sedimentary rocks can identify the geochemical characteristics of sedimentary source regions and thereby the timing of docking between terranes provided that uplifted regions in adjacent terranes are isotopically distinct.

In Precambrian shields it is commonly not possible to determine the age of sedimentation with sufficient accuracy for this technique to be of value, but here isotopic provinces defined by Pb and Nd isotope ratios can provide information on the chemical characteristics of the basement. Where sharp isotopic variations coincide with structural discontinuities then a terrane boundary may be established, as across the eastern margin of the Nabitah belt in the Arabian shield. Such studies will not determine distances over which adjacent terranes have been displaced but that they have evolved in distinct tectonic environments.

Terrane accretion can lead, locally, to unusually high crustal growth rates if the collage incorporates a high proportion of island arc fragments. In the Afro-Arabian shield, high crustal generation rates are broadly similar to those calculated for some juvenile terranes from the North American Cordillera. Along such continental margins, a high proportion of the global crustal growth rate may appear to have occurred across distances of a few hundred kilometres although, at the time of crustal generation, the island arcs responsible for crustal growth may have been widely separated.

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Discussion

J. R. VAIL (*Portsmouth Polytechnic, U.K.*). The application of geochemical techniques to the classification of geological units within Proterozoic basement areas has been a major factor in distinguishing and characterizing these features. In particular, the sophisticated application of trace element and isotopic ratios for metamorphosed and tectonically disturbed rocks has been most successful in understanding the nature and distribution of geological units. The points raised by the speaker, and the case study of northeastern Africa and adjacent areas are well taken and provide a clear example of how geochemistry can support investigations of the geology of this, and similar, complex areas.

There has been much discussion and some strong criticism on the merits and appropriateness of the terrane concept. There is no doubt, however, that in the Pan-African Afro-Arabian Shield this concept has been useful. It is true that the application so far has been largely geographic, and that names are proliferating and liable to cause confusion, yet in this vast area too little is known of the detailed geology, the age, or the boundary conditions to adopt initially anything other than a simplistic approach. True, the interpretation of boundaries and of dismembered ophiolite remnants as suture zones has been too hasty and will need to be modified as data accumulate; nevertheless the overall regional pattern strongly supports the concept of a continental crustal terrane against a plate margin island-arc oceanic terrane, with

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internal subterranes all with strongly deformed bounding margins. The paper as presented may have given an erroneous impression as to extent of these features (Vail 1987, 1988).

N. B. W. Harris. I agree with Professor Vail that the terrane concept has been useful in interpreting the evolution of the Afro-Arabian shield, although the identification of terrane boundaries through joining up ophiolite fragments across hundreds of kilometres has been, in the main, a fruitless pursuit. On the other hand the identification of continental regions within the island arc collage has been successful, though whether these represent far-travelled terranes or near *in situ* fragments of continental margins remains a matter of speculation.

P. F. Hoffman (*Geological Survey of Canada*). Rates of crust formation estimated from Nd model ages tend to be too fast because these ages give only the mean age of crust formation, thereby underestimating the duration of crust-forming episodes.

N. B. W. Harris. In the case of juvenile magmas, crystallization ages and model Nd ages are similar. In all other cases mixed sources may contribute to magmatism so that Dr Hoffman's point is a valid one. For the Afro-Arabian shield we have estimated that maximum age span for the *crystallization* of juvenile Pan-African magmas. Hence crustal-growth rates are minimum estimates.

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