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The Najd fault system revisited; a two-way strike-slip orogen in the Saudi Arabian Shield

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Abstract—The Najd strike-slip fault system extends over the northeastern Arabian Shield in a zone >1200 km in length and >300 km wide. Faults trend NW–SE with strike lengths >500 km but small sinistral displacements of <25 km. Cumulative displacement across the zone is >240 km. Najd faults were active in the late Proterozoic and post-date cratonization of the Shield. Associated secondary structures include grabens, thrust faults, folds and dike swarms. In the southwest of the Najd system, near Zalm, initial faulting was dextral and began earlier than formerly thought. Emplacement of a plutonic complex was controlled by Najd fractures of dextral geometry and displacements. The same fractures were active before and after deposition of a group of volcanosedimentary rocks in grabens orientated consistently with development in a dextral strike-slip regime. Graben deformation was controlled by sinistral motion along the same fractures responsible for graben development and also by younger fractures of sinistral geometry and displacement. Dike swarms in the area are also consistent with early dextral and later sinistral shear of Najd trend. Structures in the Zalm area occur throughout the Najd system and the consistent chronology of older dextral structures dislocated and deformed by younger sinistral faults suggests a reversal in the sense of motion of the Najd system as a whole.

INTRODUCTION

THE ARABIAN Shield comprises a series of Proterozoic island arc terranes in the south and west (Greenwood *et al.* 1976, 1980, Camp 1984) sutured to a continental microplate, The Afif terrane, in the northeast (Fig. 1, Agar 1985, Stacey & Agar 1985, Stacey & Stoeser 1983, Stoeser *et al.* 1984). An active N–S trending magmatic arc bounded the continental microplate to the west before collision with the accreted island arc terranes of the western Shield and subsequent orogeny and suturing along the Nabitah mobile belt at around 660 Ma (Stoeser *et al.* 1984). The eastern margin of the continental microplate is defined by the Al Amar suture (Fig. 1), dated at around 640 Ma (Stacey *et al.* 1984). These two orogenic events effectively ended accretion of the Shield and were followed by widespread post-orogenic granite emplacement and the development of the Najd fracture system (Fig. 1).

The Najd fracture system is defined as a NW–SE trending group of left-lateral strike-slip faults which traverse the northeastern part of the Shield (Brown & Jackson 1960, Delfour 1970, Moore 1979). Displacements across individual faults are 2–25 km, with cumulative displacements of ophiolite belts in excess of 240 km, always in a sinistral sense (Brown 1972). The period of activity of the faults was thought to be 580–530 Ma (Fleck *et al.* 1976) but has recently been shown to have commenced earlier at around 630 Ma (Stacey & Agar 1985). This longevity and the strike length of the fault zone of over 1200 km and possibly as much as 2000 km (Moore 1979), makes the Najd a major transcurrent fault system. Secondary structures recognized in association with the Najd fault system include strike- and oblique-slip faults, normal and reverse faults, graben structures, thrusts and folds (Moore 1979). Igneous and hydrothermal activity are associated with the faults and small ore deposits are known in some areas (Moore & Al-Shanti 1980).

The Najd has been studied in some detail by Moore (1979), who stated that the faults have a generally sinistral sense. However, both Howland (1979) and Moore (1979) observed that the ends of the master faults change strike in the opposite sense to that expected for

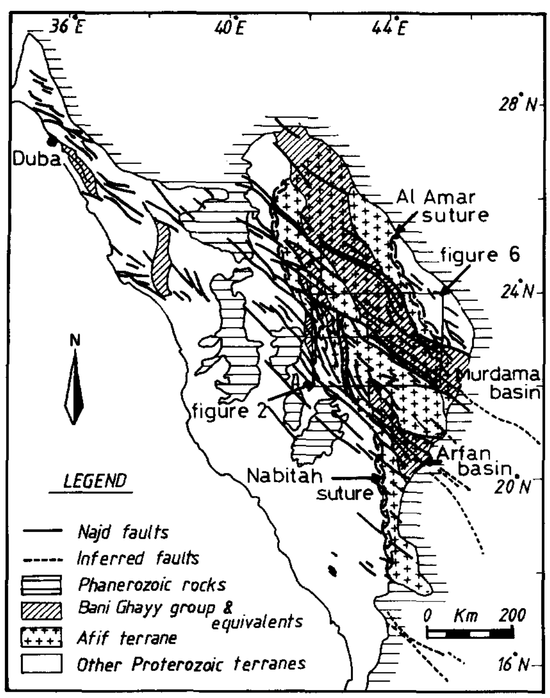

Fig. 1. Generalized map of the Arabian Shield showing major Najd faults as defined by mapping, satellite imagery and aeromagnetic data (after Moore 1979), principal geological features, places referred to in the text, and location of Figs. 2 and 6.

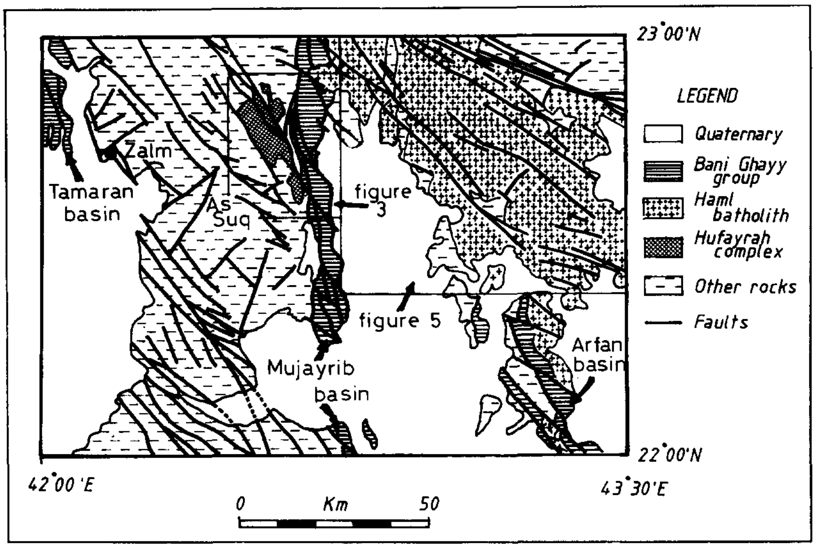

Fig. 2. Generalized geological map of the Zalm quadrangle showing major Najd faults, geological features and places referred to in the text, and the location of Figs. 3 and 5.

propagation during sinistral shear. Furthermore, Moore (1979) noted that the degree of offset varied along the length of Najd faults and that some show dextral displacements. More recently, Davies (1980) has reported dextral displacements along Najd faults in the northwestern part of the Najd zone. This paper presents a study of Najd structures in part of the central Shield. The evidence indicates that Najd faulting began earlier than first thought and that initial motions were dextral, not sinistral.

REGIONAL SETTING

The Zalm quadrangle, the area of this study, is situated close to the southwestern limit of the Najd system and along the western boundary of the Afif terrane (Fig. 1). The geology of the area comprises three volcanosedimentary successions, of which the two older pre-date the Nabitah orogeny (Agar 1985, Stacey & Agar 1985). The youngest group, known as the Bani Ghayy, lies unconformably over deformed older rocks, truncating structures associated with the Nabitah orogeny (Agar 1984, 1986). The Bani Ghayy is equivalent in age to the Murdama group (Delfour 1980a,b) and sequence A of Roobol *et al.* (1983) which have been dated at 612–608 Ma (Darbyshire *et al.* 1983). In the Zalm area, U–Pb zircon geochronology dates both older volcanosedimentary successions as >720 Ma, brackets the Nabitah orogeny between 690 and 640 Ma and deposition of the Bani Ghayy group between 640 and 620 Ma (Stacey & Agar 1985).

All primary and secondary structural features of the Najd, described by Moore (1979), can be seen in the Zalm quadrangle (Fig. 2). The longevity of Najd fractures extends from the emplacement of the Hufayrah gabbro–diorite–granite complex, which truncates Nabitah structures, through deposition of the Bani Ghayy group, which lies unconformably upon the Hufayrah complex, to the intrusion of post-Bani Ghayy plutonic rocks, the Haml batholith. The evolution of the Najd in this area can be traced by looking in turn at structures within these three rock groups.

THE NAJD STRUCTURES OF THE ZALM AREA

The Hufayrah complex

Igneous contacts in the Hufayrah complex are vertical and orthogonal, NW–SE and NE–SW, and some of those parallel to the Najd trend extend into major faults (Fig. 3). Emplacement of the gabbro was by a form of

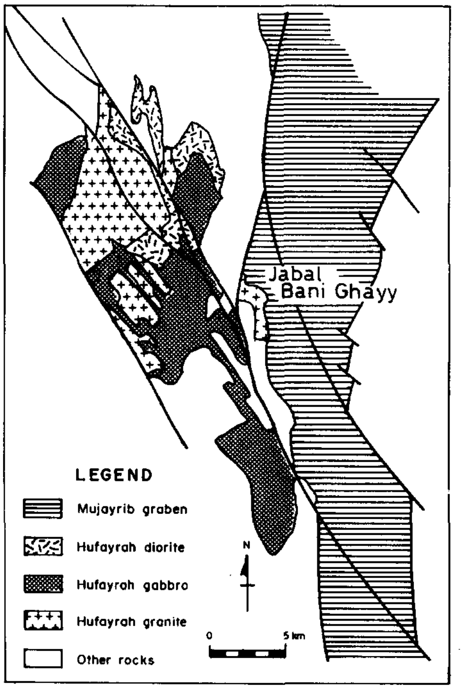

Fig. 3. The Hufayrah complex and Mujayrib graben showing Najd trending faults of dextral geometry with net dextral displacements of vertical contacts within the Hufayrah complex.

cauldron subsidence controlled by these vertical Najd and Najd-normal fractures. Rectangular blocks of older granite, defined by these fractures, were enveloped by and, locally, became a floor to the younger gabbro (Agar 1984). Vertical plutonic contacts within the complex are displaced in a dextral sense by those Najd fractures which extend into faults (Fig. 3). Displacements of older rocks by the same faults are also dextral but younger rocks, including the Bani Ghayy, show sinistral offsets only.

The faults which displace the Hufayrah complex are also of interest for their geometry. Theoretically, the ends of propagating fractures curve towards the direction of maximum compressive stress (Chinnery 1966). In fractures of Najd orientation, this would be E–W for sinistral shear and N–S for dextral shear. Although the termini of the Hufayrah faults are not seen in the area, their sinuosity (Figs. 2 and 3) is typical of Najd master faults within the Shield as a whole (Fig. 1), trending NW overall but swinging locally into a NNW or N trend. This sinuosity is in the opposite sense to that expected for sinistral shear, and this was recognized by both Howland (1979) and Moore (1979).

The Bani Ghayy Group

The Bani Ghayy group crops out in the Zalm area in three elongate, N–S trending belts (Fig. 2). Although each belt is largely fault bounded, the unconformable relationship between the Bani Ghayy rocks and older basement is locally preserved. The same general rock types are present in each belt although the respective stratigraphic sequences are very different (Fig. 4, Agar 1986). Thus, each belt was isolated from the others during sedimentation and represents a single depositional basin. In the Mujayrib belt at Jabal Bani Ghayy, the group lies unconformably upon a granite of the Hufayrah complex, emplacement of which was influenced by Najd fractures. Some of the Hufayrah fractures extend into and offset the Mujayrib rocks and other Najd fractures within the Mujayrib belt swing northward and become the boundary faults of the belt itself (Figs. 3 and 4). There is, therefore, evidence that Najd faults were active both before and after deposition of the Bani Ghayy and also were influential in defining its sedimentary basins (Agar 1986).

Fault bounded sedimentary basins within strike-slip fault regimes may be of two types, either ramp valley basins associated with compression or pull-apart extensional grabens. There is no evidence, within the stratigraphy of the Bani Ghayy group, of progressive deformation and sedimentation as one might expect in a series of ramp valley basins. Unconformities or disconformities within individual Bani Ghayy sequences are rare and the only evidence for compressional tectonics is post-depositional; the basins and their contents are deformed as a whole (Agar 1984). All Bani Ghayy basins are characterized by extreme length and thickness of sediments relative to width, rapid deposition, deep-water graywacke deposits along the axis of the basin with coarse fanglomerate deposits along the margins, bimodal volcanism typical of extensional regimes, and the presence of highly deformed ultramafic rocks along fault planes within and marginal to the basin (Agar 1986). All are typical features of strike-slip, pull-apart basins.

The volcanic rocks comprise basaltic andesites and rhyodacites which occur together throughout thick volcanic intervals with no units compositionally intermediate between the two. Such rocks are geochemically typical of extensional tectonic regimes such as the Basin and Range Province (Ewart & Le Maitre 1980, Agar 1986). Ultramafic rocks are widespread within the Arabian Shield but mostly occur in narrow belts or tectonic suture zones such as the Nabitah suture (Stoeser & Camp 1985). Others occur within older, pre-Nabitah rocks in the Zalm area and are associated with extension in a continental marginal basin in pre-Nabitah times and are confined to the west of the area (Agar 1985). The ultramafic rocks within faults associated with Bani Ghayy basins might be considered remnants of older bodies. However, there are no blocks of older basement within these faults and ultramafic rocks occur in Bani Ghayy basins within the Afif continental terrane, to the east of the limit of such rocks within the basement. Thus, it is more likely that the Bani Ghayy ultramafics are genetically associated with their sedimentary basins and represent the deformed floor of original pull-apart grabens (Agar 1986).

The grabens developed after the emplacement of the Hufayrah complex. The N–S trending graben boundary faults swing into or become NW–SE oriented Najd faults (Fig. 4). In the Mujayrib graben, both boundary and associated Najd faults have been related to the sequential south to north development of the basin through observed northward younging in the faults and a parallel transgression in the stratigraphy (Agar 1986). The almost N–S orientation of the grabens is consistent with their development in a dextral strike-slip regime. If the Najd faults responsible for the grabens were sinistral then the grabens should be oriented more or less E–W, as indeed are grabens of the Jibalah group, a much younger sedimentary sequence of the Najd fault zone (Delfour 1970). The shape of the Bani Ghayy grabens, in the Zalm area and elsewhere in the northeastern Shield (Fig. 1), is the 'lazy Z'-shape typical of dextral strike-slip, pull-apart basins (Mann *et al.* 1983).

Deformation of the Bani Ghayy rocks was entirely post-depositional and involved the closing up of their depositional grabens. Boundary faults evolved from normal to reverse as the basement was thrust over the Bani Ghayy volcanosedimentary sequences, although their relationship to the Najd fracture system remained intact. The thrust faults extend into and become part of the older Najd-trending fractures with dextral geometry (Fig. 4). Thus, the compressional tectonics relate to renewed movements of the same fracture system. Progressive changes from extensional to compressional tectonics within a continuing strike-slip regime are to be expected as the cross-over fault (in this case the normal

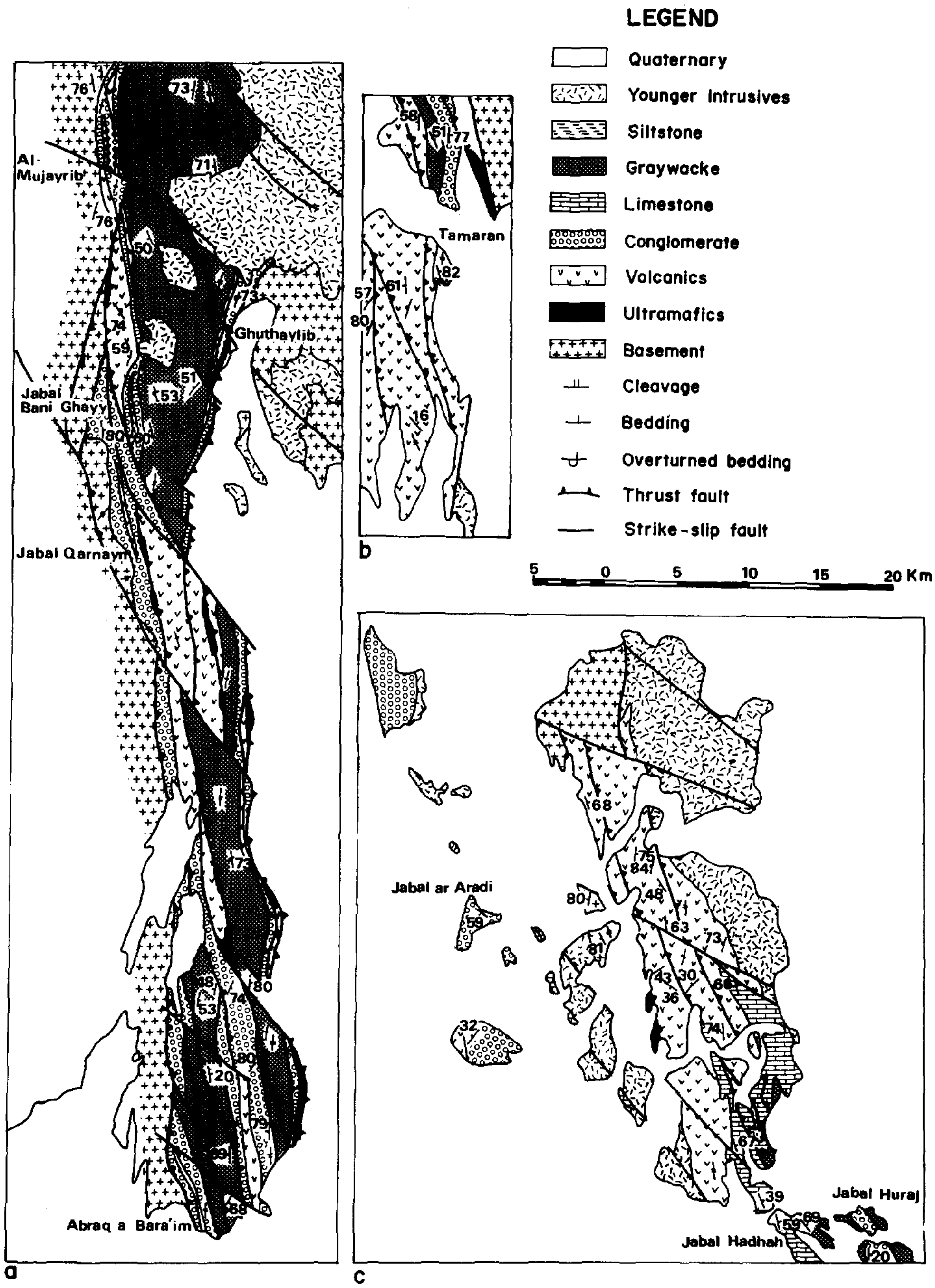

Fig. 4. Detailed geological maps of the Mujayrib (a), Tamaran (b) and Arfan (c) belts of the Bani Ghayy group in the Zalm area.

graben boundary fault) rotates more nearly parallel to the Najd master faults (Mann *et al.* 1983). However, in the Bani Ghayy grabens, the orientations of cross-over faults are N–S or NNW–SSE and at a high angle to the Najd master faults (Figs. 1 and 4). Thus, if the grabens were the product of dextral strike-slip, there can have been little or no rotation of the cross-over fault and the change to compressional tectonics must be explained in some other way. The cross-over faults are themselves displaced sinistrally by a younger generation of Najd faults which show a sinistral geometry (Fig. 4). These faults and the overall sinistral displacement of the Najd fault system as a whole (Moore 1979) are evidence that the final movements along Najd faults throughout the Shield was sinistral strike-slip. Thus, in the Zalm area, it is proposed that the Bani Ghayy group was deposited in pull-apart grabens developed in an early dextral phase of the Najd but later deformed by sinistral strike-slip along the same faults.

The Haml Batholith

Faults of sinistral geometry and displacement occur throughout the eastern part of the Zalm area and displace fold structures in Bani Ghayy rocks and the intrusive contacts of the Haml batholith (Fig. 5). Emplacement of the Haml batholith began before deposition of the Bani Ghayy rocks and continued for a long time after

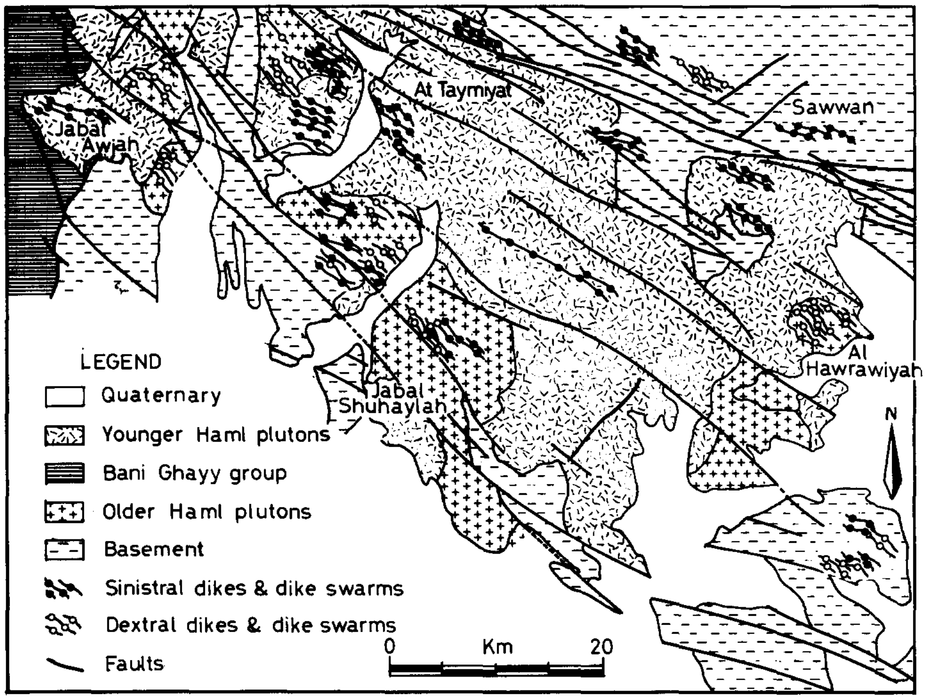

Fig. 5. The Haml batholith in the Zalm area showing dextral ('lazy Z'-shaped) and sinistral ('lazy S'-shaped) dikes and dike swarms relative to plutons older and younger than the Awjah pluton.

their deformation (Stacey & Agar 1985). The oldest post-Bani Ghayy pluton truncates the Mujayrib graben boundary fault at Jabal Awjah (Fig. 5). This pluton and subsequent intrusives are grouped as younger Haml plutons but preceding plutons are regarded as older Haml. Dike swarms of Najd trend are associated with many of the Haml plutons but although present offsets across Najd faults are sinistral, the geometry of many dike swarms is consistent with emplacement during dextral shear. Significantly, those dikes within older Haml intrusions and basement, as seen north of Jabal Shuhaylah and west of At Taymiyat, may be 'dextral' or 'sinistral' whereas younger Haml plutons, at Jabal Awjah and At Taymiyat, contain only sinistral dikes or dike swarms (Fig. 5).

In the north-east of the area, Najd faults of sinistral geometry and displacement post-date another set of sinistral fractures trending approximately E–W (Fig. 5). Similar fractures have been described elsewhere in the Najd zone and are examples of Riedel shears produced at an early stage of NW–SE directed sinistral shear (Moore 1979). These shears are clearly older than the major Najd sinistral faults of the Zalm area but their relationship to the Najd faults of dextral geometry and displacements is not seen directly. Antithetic dextral Riedel shears in the west of the area, near As Suq (Fig. 2), truncate dextral faults and represent the first Najd structures produced by sinistral shear.

THE NAJD FAULT SYSTEM IN THE NORTHEASTERN SHIELD

The Najd fault system is confined to the northern and eastern parts of the Arabian Shield (Fig. 1). The outcrop traces of its major faults are sinusoidally curved and trend from NW–SE towards NNW–SSE. The latter direction is particularly common towards the termini of major fractures (Fig. 1). This feature of the faults was discussed by both Howland (1979) and Moore (1979) in terms of the theoretical models of Chinnery (1966). These models are based on small amounts of elastic strain within an homogeneous medium and, although the Arabian Shield is not homogeneous, displacements across Najd faults are small relative to their strike lengths. Howland (1979) noted that the change in trend of the fault traces was opposite to what would be expected in a sinistral regime and considered that it was due to either rotation or local modification of a daughter stress field at the ends of the faults. Moore (1979) argued that such a pattern of curvature could be explained by asymmetrical stress variations around fault termini (Chinnery 1966) coupled with the influence of the underlying N–S regional fabric. The possibility of fracture propagation by dextral shear was not considered.

None of these explanations account for observed dextral displacements or the fact that some Najd faults have dextral and others sinistral geometry. If the regional tectonic fabric was a major influence then its effects should be seen in all faults. Also, if rotation or modification of a daughter stress field at fault termini is involved it must have had variable degrees of influence both regionally and temporally. The faults developed episodically (Moore 1979), and it is reasonable to assume that the master faults were the earliest fractures to develop and also the longest lived planes of movement. It is significant that the majority of these master faults display a sinuosity consistent with propagation by dextral shear (Fig. 1) but record sinistral displacements;

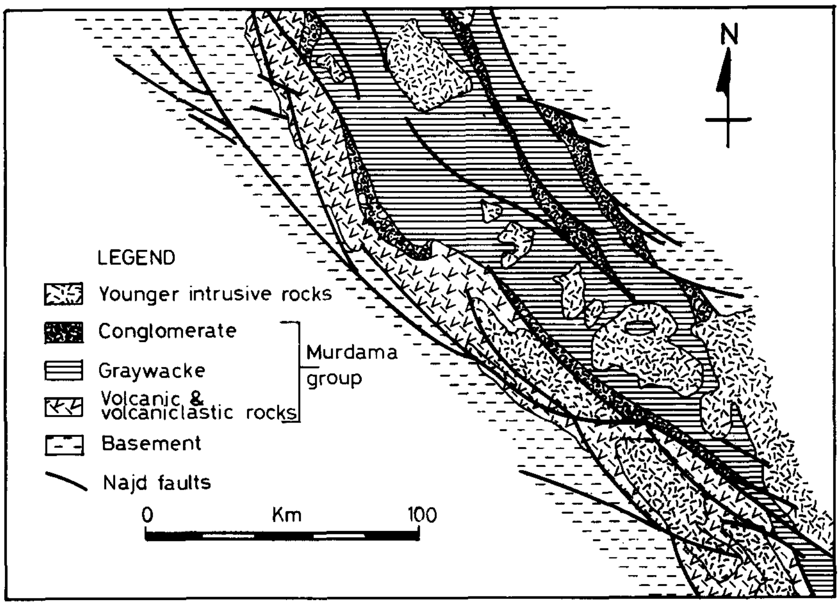

Fig. 6. The southern part of the exposed Murdama basin showing its fault bounded nature, the dextral geometry of the boundary faults and the linear disposition of sedimentary and volcanic rocks within the basin.

whereas other faults, probably younger, show evidence for sinistral shear and offsets only.

Dextral displacements and variable offsets along individual faults have been recognized in Najd faults other than in the Zalm area and have been attributed to varying degrees of scissor movement or dismissed as local reversals (Moore 1979, Davies 1980). However, in view of the noted dextral geometry of many master faults throughout the Najd zone, perhaps some of the dextral offsets are the net result of initial dextral and subsequent lesser sinistral displacements. In the Duba area, Najd faults of dextral displacement are truncated by synthetic sinistral Riedel shears oriented approximately E–W (Davies 1980). The latter are considered to be the forerunners of major Najd sinistral faults (Moore 1979) which suggests that at Duba, as at Zalm, dextral movements preceded sinistral. Moore (1979) also considered that other apparently anomalous aspects of Najd fault displacements could be the result of rotation of associated ENE-trending antithetic dextral Riedel shears. Although anticlockwise rotation of such shears of up to 15° has been observed (Wilcox *et al.* 1973), very much greater rotation would have been required to bring such shears at Duba into a NW–SE orientation. Antithetic Riedel shears showing dextral displacements are preserved in the Zalm area and maintain their original theoretical orientation (Figs. 2 and 5).

In the northeastern Shield, rocks equivalent in age and lithology to those of the Bani Ghayy group, also occur in elongate N–S or NNW–SSE fault bounded belts with the typical 'lazy Z'-shape of dextral strike-slip, pull-apart grabens (Fig. 1, Mann *et al.* 1983). The largest of these belts, the Murdama (Fig. 6), shows a close association with Najd faults which, in detail, is very similar to the Mujayrib graben of the Zalm area (Fig. 4). Boundary faults trend NNW but curve into NW-trending Najd faults and are offset by younger Najd faults with a clear sinistral geometry. Furthermore, the Murdama volcanic rocks are also bimodal (Roobol *et al.* 1983) and sedimentary units show the same type of facies distribution as in the Mujayrib graben, with coarse boulder conglomerates and volcanics along the margins of the belt and predominantly proximal graywackes along the axis (Fig. 6). Deformation of the Murdama group also entirely post-dates deposition (Delfour 1980b) and the relationship between the Murdama basin and Najd faulting is also best explained by graben formation during dextral strike-slip. The Arfan basin (Fig. 1), of the same age as both the Bani Ghayy and Murdama groups (Darbyshire *et al.* 1983, Stacey & Agar 1985), contains bimodal volcanic rocks (Roobol *et al.* 1983) and has been interpreted as a depositional graben (Thieme 1984). Thus, graben formation during the early stages of the Najd strike-slip orogen was not local to the Zalm area but occurred throughout the northeastern Shield.

Dike swarms of Najd age are numerous throughout the northeastern Shield, and are of both dextral and sinistral configurations. However, the detailed relative chronology of their host plutonic rocks is at present insufficiently established to determine whether or not the relationship of dike emplacement to faulting established in the Zalm area holds for the Najd system as a whole.

DISCUSSION

In the Zalm area and the northeastern Arabian Shield as a whole, there is considerable evidence in favour of two distinct episodes of Najd faulting. Najd master faults and an apparently older set of fractures show a sinuosity consistent with propagation during dextral shear according to the models of Chinnery (1966). These models are applicable to the Najd fault system in as much as offsets are small relative to strike lengths of faults; but the inhomogeneity of the terrane reduces their validity. Nevertheless, it must be noted that in the Zalm area, the Murdama basin and the Arfan graben (Thieme 1984), faults with both dextral and sinistral geometry occur within the same media and that the dextral ones are older. This observation suggests that lithological variations within the terrane in fact had little influence upon fracture propagation and that the models of Chinnery (1966) are valid. Whether this is the case or not, the same observation indicates that the influence of the older Nabitah (formerly named Hijaz) tectonic fabric was not as important as suggested by Moore (1979). Similarly, local rotation of daughter stress fields at the ends of propagating fractures, as suggested by Howland (1979), does not explain why it is consistently the older fault traces that are curved in the opposite sense to that predicted for sinistral strike-slip motion.

Dextral displacements might easily be explained as local reversals within the Najd fault system of overall sinistral movement, much in the manner described by Sengor *et al.* (1983). However, both at Zalm and at Duba (Davies 1980), dextral strike-slip faults of Najd orientation have a dextral geometry and pre-date Riedel shears associated with sinistral strike-slip. It seems unlikely that local fault reversals would take place at such an early stage in the development of a large strike-slip fault system such as the Najd or that the dextral offsets in faults of dextral geometry are purely coincidental.

Volcanosedimentary rocks of the Bani Ghayy group and its equivalents are widespread throughout the northeastern Shield and occur in NNW to N-trending 'lazy Z'-shaped fault-bounded belts (Fig. 1). The boundary faults to these belts curve into NW-trending Najd faults and, in the Zalm area at least, faults of Najd orientation existed before deposition of the Bani Ghayy. Throughout the northeastern Shield, there exists close spatial and temporal relationships between these sedimentary basins and the Najd. Both the orientation and shape of the belts are consistent with either ramp valley basins produced during progressive sinistral strike-slip motion or pull-apart grabens formed during dextral strike-slip motion. The ramp valley model is not favoured due to the lack of evidence for progressive deformation with sedimentation. Furthermore, the stratigraphy of the basins, their bimodal volcanic suites and fault-associated ultramafic rocks are more consistent with an extensional regime, and thus the pull-apart graben model is favoured.

Within the Haml batholith, dike swarms in older plutons and basement appear to have been emplaced during both dextral and sinistral shear, whereas dike swarms in younger bodies were only emplaced during sinistral motion. Net displacements across all faults within the batholith are sinistral but the repeated association of older fractures with dextral shear and younger fractures with sinistral shear remains significant.

Younger Najd fractures throughout the northeastern Shield show both sinistral geometry and offsets and, with the net displacement across the Najd fault zone as a whole being sinistral, there is no doubt that the final and greatest overall movements were sinistral. The final movements deformed the Bani Ghayy grabens and their contents. Compressional structures within these rocks entirely post-date deposition and are orientated consistently with deformation during sinistral strike-slip. There is no evidence for rotation of the boundary faults with time, and the transition from extensional to compressional tectonics is best explained by reversal of motion along the entire Najd fault system.

Evidence for an early phase of dextral strike-slip movement within the Najd fault system is not restricted to the Zalm area and occurs in a variety of structural features. These are dextral fracture configurations, some with net dextral offsets, graben formation consistent with dextral strike-slip and dike emplacement during dextral shear. It cannot be coincidental that these features all occur in older rock units and pre-date clear sinistral structures. A two-phase model for the Najd fault system involving a reversal of motion is, therefore, required.

Reversals of movement on strike-slip faults have rarely been reported, but that they can occur during continental collision has been demonstrated in the case of the Red River fault of southeast Asia (Tapponnier *et al.* 1982). In this case, sinistral movements were initiated by the collision of the Indian sub-continent with Asia, and evolved to become dextral strike-slip movement during the same collisional event. In the Arabian Shield, the onset of the Najd fault system followed not one but two continental collisions. The explanations for dextral geometry suggested by Howland (1979) assumed that the regional stress system during the Najd was the result of "two plates moving past each other" and was non-compressive. However, continental collisions took place along both the Nabitah and Al Amar sutures around 660 and 640 Ma, respectively (Stoeser *et al.* 1984, Stacey *et al.* 1984), immediately prior to the inception of the Najd fault system (Stacey & Agar 1985).

The total longevity of the Najd fault system is significant. Two separate plutons in the Zalm area show emplacement structures which were influenced by the Najd and both yield U–Pb zircon ages of >630 Ma (Stacey & Agar 1985). Ages of the Bani Ghayy and its equivalents range from 620 to 608 Ma (Darbyshire *et al.* 1983, Stacey & Agar 1985). Thus, the Najd fault system began very soon after the Nabitah and Al Amar orogenies, between 640 and 630 Ma, and was dextral in sense until about 600 Ma. In the Shield as a whole, the Najd fault system is known to have been active until 530 Ma (Fleck *et al.* 1976), and possibly until 507 Ma (Delfour 1977), a total longevity of >100 Ma.

In terms of longevity, strike length, displacements and secondary structures, the Najd fracture system ranks among the major transcurrent fault systems of the world and is an example of a major strike-slip orogen. Associated extensional and compressional features, including dike swarms and grabens, plutonic activity, folding and thrusting, have all well-documented equivalents in both ancient and modern strike-slip systems such as the Hercynides and the western Cordillera of North

America (Badham 1982). The role of large scale strike-slip movements in orogeny and large-scale transcurrent fault systems are being increasingly used to explain problems in ancient orogenic belts which defy solution by simple plate tectonics (Dewey 1982, Badham 1982). That the Najd fault system reversed its sense of motion is unusual but not unique; a similar reversal has been shown to occur during progressive continental collision (Tapponnier *et al.* 1982). Two such collisions played a major role in the cratonisation of the northeastern Arabian Shield and immediately preceded the onset of Najd faulting. Thus, the two-way Najd strike-slip orogen was probably the direct response of a continental micro-plate to compression caused by progressive continental collision on both sides.

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