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# PRIMARY AND SECONDARY FAULTING IN THE NAJD FAULT SYSTEM, KINGDOM OF SAUDI ARABIA

by

John McMahon Moore

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## ILLUSTRATIONS

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## ABSTRACT

The Najd fault system is a major transcurrent (strike-slip) fault system of Proterozoic age in the Arabian Shield. The system is a braided complex of parallel and curved en echelon faults. Complex arrays of secondary structures including strike-slip, oblique-slip, thrust, and normal faults, together with folds and dike swarms, are associated with some major faults, particularly near their terminations. The secondary structures indicate that compressional and extensional and dilational conditions existed synchronously in different parts of the fault zone. The outcrop traces of faults and syntectonic dikes have been used to interpret the configuration of principal compressive stresses during formation of parts of the secondary fracture systems. Second-order deformation was a series of separate events in a complex episodic faulting history. Comparison with model studies indicates that master faults extended in length in stages and periodically developed arrays of secondary structures. Propagation of the major faults took place along splay trajectories, which inter-connected to form a subparallel sheeted and braided zone. Interpretation of the aeromagnetic maps indicates that the Najd system is broader at depth than the outcropping fault complex, and that more continuous structures underlie arrays of faults at surface. The fault pattern is mechanically explicable in terms of simple shear between rigid blocks beneath the exposed structures.

## INTRODUCTION

The Arabian Shield is a complex of Proterozoic plutonic, metavolcanic, and meta-sedimentary rocks that was produced by multiple episodes of sedimentation, volcanism, and intrusive activity accompanied by deformation known as the Hijaz Orogenic Cycle (Brown and Coleman, 1972). The Hijaz tectonic fabric of the shield has a predominantly north-south or northeast-southwest trend, which is visible on aeromagnetic maps. Regional metamorphism has produced mineral assemblages of greenschist and amphibolite facies in various parts of the volcano-sedimentary complex. The Hijaz events culminated in dislocation of the complex by strike-slip faulting in late Proterozoic and early Phanerozoic times - designated the Najd Faulting (Brown and Jackson 1960).

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The Najd system of transcurrent strike-slip faults and related secondary structures traverses the shield northwesterly displacing the Hijaz metamorphic and igneous rocks. Najd deformation was mainly brittle but a penetrative tectonic fabric parallels the fault zone in the southeastern part of the shield. The outcropping Najd fault system is approximately 300 km wide and extends 1100 km inland from the Red Sea coast where it was truncated and locally re-activated by the Tertiary Red Sea rifts. The northwestern extensions are probably in the Eastern Desert of Egypt. Block movement in the basement along the line of the Najd has affected the Phanerozoic cover strata for more than 100 km southeast from the edge of the shield. Extrapolated to the southeast, the line of faulting coincides with structures in the south Yemen coast and in the bed of the Arabian Sea (Brown, 1972). This total possible length of more than 2000 km is similar to that of many of the world's major transcurrent fault systems, including the San Andreas (USA) and Alpine (New Zealand) Faults. The estimated displacement of 240 km (Brown, 1972), which accumulated during 50 million years, corresponds to an annual rate of movement of 0.5 cm (Fleck and others, 1976). This is comparable with the displacement rates of several currently active major strike-slip faults. Brown's estimate of displacement in the central parts of the system is based on correlation of displaced strings of basic and ultrabasic intrusions ('ophiolite belts') whose strike directions are parallel to the north-south Hijaz tectonic fabric.

Igneous intrustion associated with the Najd tectonics has produced small plutons and dike swarms. Radiometric ages obtained from small intrusions indicate that the faults were active from late Proterozoic into early Phanerozoic times, 580 - 530 m.y. ago (Fleck and others, 1976). Some of the alkaline and calc-alkaline intrusions and basalt-andesite-rhyolite dike swarms have been dislocated by continued fault movement after emplacement. Lavas are intercalated among the clastic sediments of the Jibalah (Jubaylah) group in fault-bounded grabens (Hadley, 1974b).

Hydrothermal activity was widespread and small ore deposits (mineralized quartz veins) occur in some areas (Moore and Al Shanti, in press). The widespread hydrothermal and igneous activity indicate that the fault zone was an area of anomalously high heat transfer in Proterozoic or Eocambrian, and possibly during Phanerozoic, times. The hydrothermal alteration is probably also a reflection of the mechanical importance of fluid pressure in the mechanism of faulting at this structural level (Phillips, 1972).

This paper is a preliminary review of the geometry of major structures in the Najd system and includes a description of second order and minor structures in selected parts of the system. There is also a discussion of time relationships, mechanisms of formation, and mechanical associations between structures of the first and second order and syntectonic dike swarms.

## ACKNOWLEDGMENTS

The Directorate General of Mineral Resources (DGMR) of the Kingdom of Saudi Arabia is acknowledged for kindly making available published maps and open-file reports of the DGMR, U.S. Geological Survey (USGS), and Bureau de Recherches Geologiques et Minieres (BRGM) missions, together with aerial photograph mosaics. Compilation of figure 1 would not have been possible without the maps of numerous DGMR, USGS, and BRGM geologists, whom I gratefully acknowledge collectively. (A complete list of the maps published by DGMR is available on request.) I offer my thanks to D.G. Hadley and R.J. Roberts for their assistance in supplying many of the maps from which several of my diagrams were compiled and for their helpful comments. I also thank my colleaques from the Institute for Applied Geology, Jiddah for their help in arranging the field work that complemented this study, and R. Urquhart and G. Thomas for their assistance in getting the paper to press.

## MAJOR FAULTS

The Najd system consists of parallel and en echelon master faults, the largest of which are more than 300 km in length. Many of the faults have curved outcrop traces and intersect or join to form braided zones.

The major fractures are susceptible to weathering and form wadi valleys that show clearly in aerial photographs and satellite images. Figure 1 is a compilation map prepared at 1:2,000,000 scale by interpretation of satellite imagery (ERTS and Landsat) and aerial photograph mosaics (scale 1:100,000). Additional information was provided by geological maps published by the Directorate General of Mineral Resources (GM and MI series). Unfortunately, published maps (scale 1:100,000) cover only a small part of the fault system, but they provide useful information for detailed studies of selected second-order fault systems. The first of a new series of 1:250,000 maps (Delfour, 1977) is better for regional interpretation. Much additional data is contained in numerous open-file reports of the Directorate General of Mineral Resources prepared by Directorate geologists and the U.S. Geological Survey and Bureau de Recherches Geologiques et Minieres missions.

Although incomplete, the compilation map illustrates the general form of the faulting. It shows the belt to be composed of many separate strands, without a unifying master structure. The outcropping zone is approximately 300 km in width and is dominated by several very important faults.

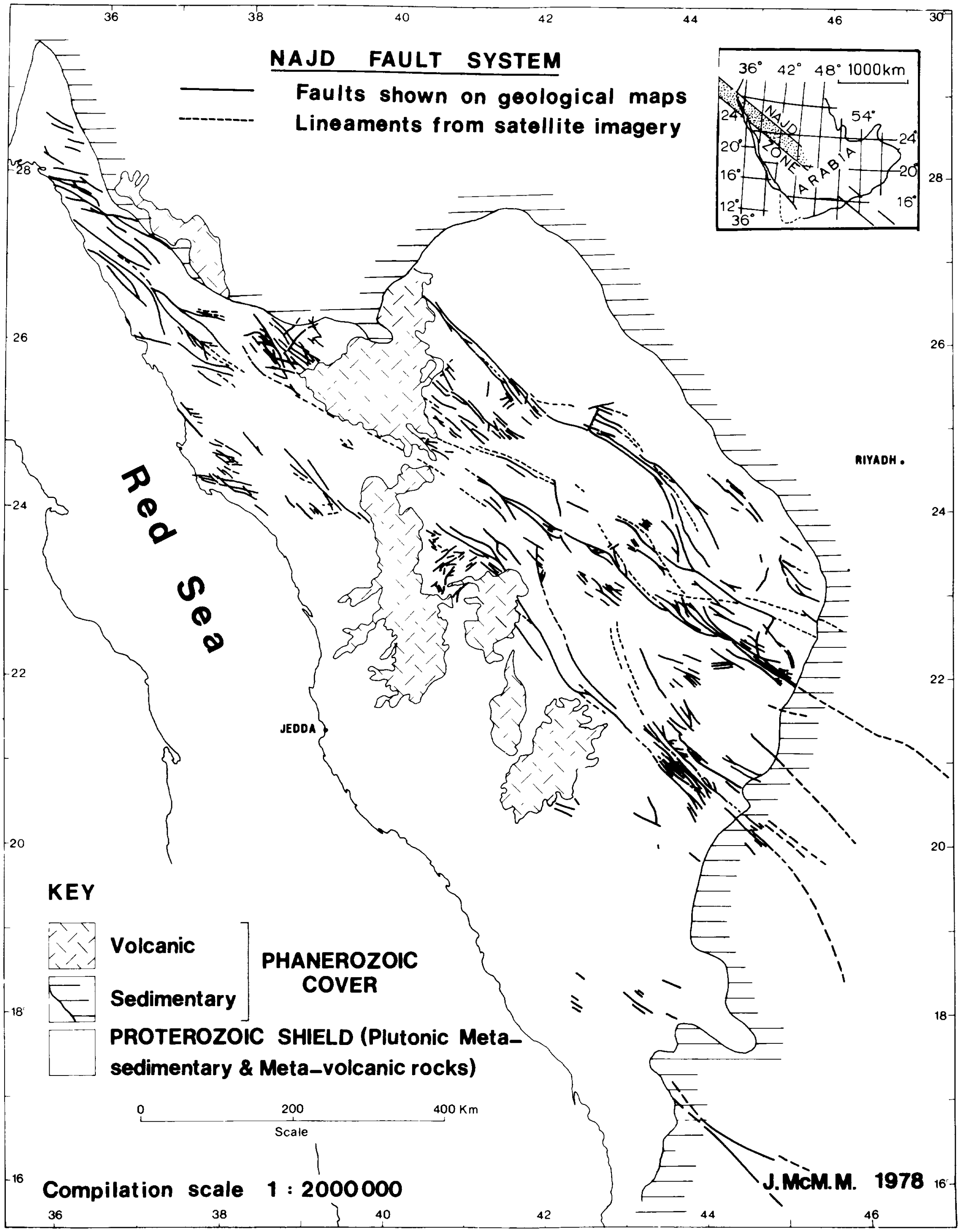


Figure 1. Outcrop traces of major faults of the Najd Fault system in the Arabian Shield. Inset: location map showing the Najd belt prior to Tertiary rifting in the Red Sea region. (From 1:100,000 and 1:250,000 geological maps and 1:100,000 photomosaics published by the Directorate General of Mineral Resources, and from satellite imagery).

Linear structures parallel to the fault zone (fig. 2) are visible on aeromagnetic maps as disturbances in the north-south or northeasterly 'Hijaz' magnetic fabric of the shield (Andreason and Petty, 1974 a,b,c,d,e, and f.). These magnetically defined lineaments commonly underlie areas that have disjointed and complex outcropping arrays of faults and are commonly seen on 1 : 100,000 - and 1 : 250,000 - scale maps; the Nuqra area shown in figure 3A is a typical example. Many of the magnetic lineaments defined by disturbances in the Hijaz tectonic and magnetic fabric coincide with major out-cropping faults but the presence of magnetically-defined dislocations parallel but south of the outcropping Najd system faults indicate a total width for the tectonic zone of 400 km. Interpretation of Andreason and Petty's maps gives a composite impression of fault geometry to some depth below the present surface. It is possible that magnetic lineaments that do not correspond to mapped faults may be an expression of shear zones whose movement has been accommodated at the structural levels currently exposed by displacements on older structures in the Hijaz tectonic fabric. The width of the fault system indicated by the aeromagnetic maps suggests that structures throughout the shield, in addition to those within the belt of outcropping faults, could have been affected by the Najd deformation. This would account for the widespread reactivation of Hijaz faults reported by workers in many parts of the shield (Schmidt and others, 1973). Unfortunately, aeromagnetic data are available for the shield area only and no interpretation of basement structure beneath the areas overlain by Phanerozoic cover has been possible in this study.

Deviatoric stress has been accommodated inhomogeneously in the fault system by simple shear on established fault surfaces and by brittle failure as new shear and extensional fractures formed. The larger faults have strike-slip displacements of tens of kilometers, generally with a sinistral sense. The most important are several hundred kilometers long but the majority are 50 km or less in length with displacements of a few kilometers. Maximum offset is generally in the central part of a fault trace and decreases laterally to zero at the terminations. In the Nuqra area there is a displacement of at least 40 km across a belt 60-70 km wide (Delfour, 1977). Individual faults at Nuqra have displacements up to 25 km.

Menard (1962) suggested that there may be a relationship between total length and offset displacement on large wrench faults. Although this relationship is not valid for major structures that terminate in transform faults, individual fractures in the Najd system whose terminations are known, appear to have maximum displacements (in the central part of the fault trace) proportional to outcrop length.

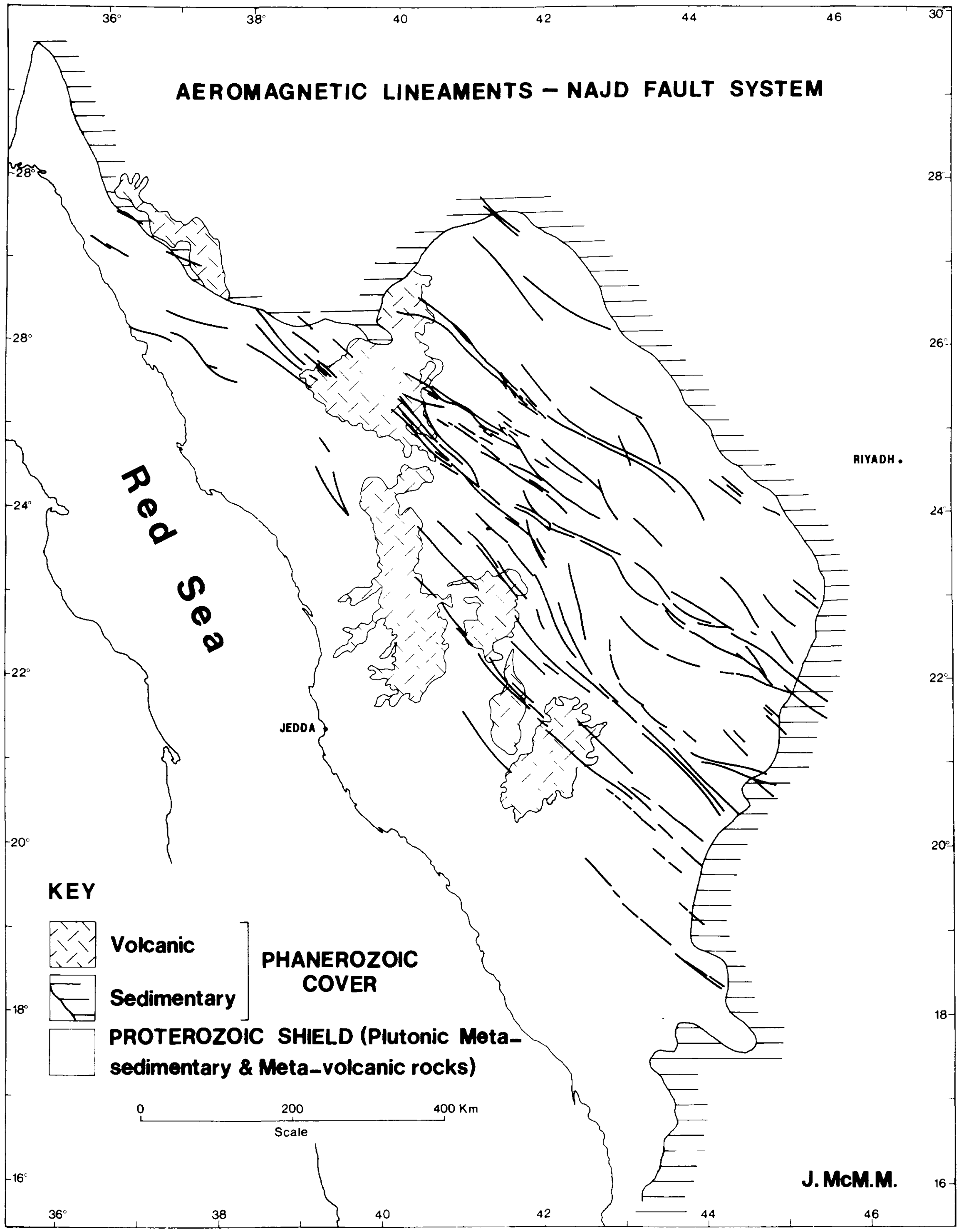


Figure 2. Aeromagnetic lineaments attributable to structures in the Najd Fault system. Interpreted from disturbance in the magnetic fabric on 1:500,000 scale maps (Andreason and Petty, 1974 a,b,c,d,e, and f.).

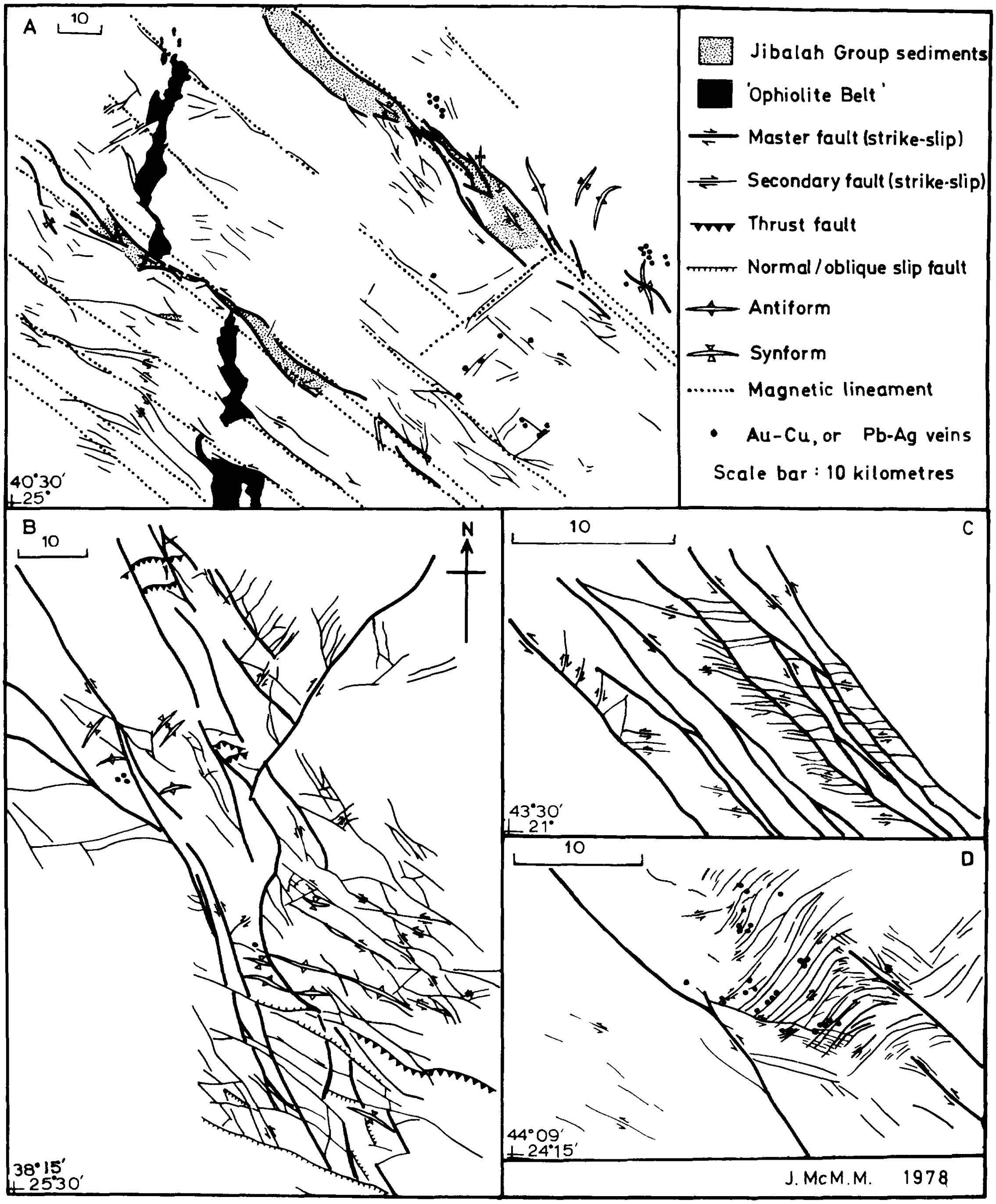


Figure 3. Simplified geological maps showing secondary structures in selected parts of the Najd Fault system: A, Faulting and folding in the Nuqra quadrangle. Fault displacement is shown by offset of the ophiolite belt . Simplified from Delfour, (1977). B, Faults and fold axial traces in the Wayban–Qal'at as Sawrah–Sahl al Matran district, northwest Hijaz. Simplified from Hadley (1973, 1974a, and 1975). C, Second-order faults in a pinnate array adjacent to sheeted master faults in the Bi'r Juqjuq quadrangle, southern Najd. Simplified from Hadley (1976). D, Primary and secondary faulting in the Ad Dawadami district. Simplified from Moore and Al Shanti (1973).

Parallelism between the regional penetrative fabric (schistosity and lithological banding) and major faults in the southern Najd (Hadley, 1976), indicates that part of the fault zone developed a penetrative schistosity prior to the widespread brittle deformations. The early ductile deformation caused transposition of lithological banding to an orientation sub-parallel to the major faults, together with widespread boudinage. This deformation has left many minor fold hinges isolated in the transposition fabric. The ductile deformation must have occurred at depths of several kilometres and was accompanied by greenschist-facies regional metamorphism. Field evidence shows that the ductile deformation was followed by brittle failure during the main faulting episodes. The currently exposed structural level in the Southern Najd was that of ductile to semi-brittle deformation in the earlier stages of the faults' history and of brittle deformation during the later events. The absence of widespread metamorphism during the brittle deformations indicate that the current erosion surface was a relatively high structural level at the time and that the older ductile structures had been brought several kilometers towards the surface before the onset of brittle deformation. The shallow origin of the later, brittle structures is confirmed by the presence of Jibalah group sediments in fault-controlled, graben basins in the braided zone, similar to those described by Kingma (1958) in the Alpine Fault Zone (New Zealand). It appears that perhaps 1 km or less of superstructure has been removed from the Najd system since the beginning of Phanerozoic times.

Most of the major faults, seen in plan, have similar geometry. Each has a sinusoidally curved outcrop trace with a northwest strike direction in the central part. The terminal sections of traces show a systematic tendency to change strike direction towards the north-northwest. Many of the major structures terminate in arrays of curved splays, some of which link separate strands. The total system consists of *separate* structures, some of which are inter-connected. Numerous uplifted, down-faulted, and tilted blocks occur in various parts of the belt, illustrating the vertical movements that accompanied the strike-slip motion on the master faults.

Several types of folds occur in the fault zone, including sets with axial traces parallel, transverse, and en echelon to the major faults. Open-to-close folds (Fleuty, 1964), with sigmoidally curved axial traces, occur in rock septa between major faults (fig. 3A and B). In some cases these may be Hijaz folds that have been re-activated and 'tightened' (fig. 3A). In others the orientations of the axial traces indicate that they could be the products of secondary deformations that caused thrusting nearby (fig. 3B). A separate and perhaps younger set of flexural folds occurs in the Jibalah group strata in fault-bounded graben and basins. The axial traces of these folds are parallel to the major faults or en echelon at a very acute angle. These folds appear to be the products of local secondary stresses generated during movement between lenticular blocks in the braided zone. Kingma (1958) demonstrated that dip and strike variations along curved fault surfaces can cause significant local variations in compressive stress conditions during movements in a wrench fault system.

The Najd system is dominated by faults striking northwest. Major dextral faults with a northeast strike, which would be the theoretical complements to the main system, are rare. It appears that the Najd fault system is the product of simple shear that allowed the Nubian and southern Arabian shield to move several hundred kilometers sinistrally with respect to northern Arabia. The ends of many of the world's currently active transcurrent fault systems terminate in transform faults and at ridges and trenches defining plate boundaries. Unfortunately, neither of the original ends of the Najd system is still visible and its significance in terms of Proterozoic and Eocambrian global tectonics remains enigmatic. The Najd movements, like those on the Great Glen Fault in Scotland, were the final events in a complex orogenic history.

## SECONDARY STRUCTURES

Susceptibility to weathering of the faults, associated extensional fractures, and dike swarms make the Najd one of the most clearly visible complexes of primary and secondary strike-slip faults in the world. The fault rocks are commonly obscured by wadi sediments but where visible they are schistose and fissile, commonly with granular cataclastic texture. Shear zones and slip surfaces range in thickness from a few centimeters to several hundreds of meters, depending on the tectonic style of the fault and nature of the host rocks.

Minor structures are of two types: those which pre-date or are independent of major faults, and those which are directly related to master structures. Among the most important in the first category are arrays of discontinuous, en echelon shears that occur along the projected lines of certain major faults. These structures, known as Riedel shears and conjugate Riedel shears (Tchalenko and Ambraseys, 1970) are sets of subordinate wrench faults that form in a zone of simple shear not marked by a continuous fault (fig. 6A).

The Riedel shears are complementary sets of faults, one of which, termed the synthetic set, is oriented at an acute angle (commonly about 15°) to the main shear direction, and has the same sense of movement. The conjugate Riedel shears, termed the antithetic set, have the opposite sense of movement and are oriented at 75-90° to the main shear direction.

The synthetic set is usually much better developed and widespread. Continued movement often causes dislocation of the antithetic shears while the synthetic shears increase in length to accommodate displacement until superseded by establishment of a master fault parallel to the main shear direction.

In the Najd system it is common to find only the synthetic Riedel shear set, with sinistral sense of displacement, oriented at an acute angle to the master fault direction, (master fault strike 140°, sinistral Riedel set strike 110-130°). The dextral antithetic shears (strike 000-050°) are rarer, shorter than their complements, and take the form of minor cross-faults or re-activated north-south Hijaz structures.

Geophysical evidence locally indicates the presence of continuous structures below outcropping assemblages of Riedel shears. It appears that the minor shears in some cases formed at higher structural levels above continuous structures (fig. 3A). In other cases Riedel shear formation was a precursor to establishment of a continuous major fault.

Sets of pinnate minor faults adjacent to one or both sides of a major structure are common in sheeted complexes. In the Juqjuq sheeted zone (fig. 3C), movement on the master faults has truncated sets of secondary fractures that could have originated as Riedel shears. Dislocation of a major fault by its own secondary structures, followed by renewed movement and reestablishment of the continuous master fault, is one of the factors responsible for formation of the sheeted or sub-parallel arrays of major faults. Many major faults in the northwest Hijaz district have been dislocated by related west-northwest trending secondary shears (fig. 3B).

Minor structures of the second group, related to established major faults, are numerous and varied. Complicated assemblages of secondary fractures occur around the terminations of major fault strands (figs. 3D and 4A). These arrays are found irregularly throughout the Najd system but are most noticeable in massive country rocks. Chinnery (1966) suggested that dissipation of anomalous stress concentrations around the terminations of shears could be achieved by propagation of the master fault along divergent splay faults, or by creation of arrays of secondary fractures. Both these mechanisms are thought to have operated on the faults that traverse the Ad Dawadami district (fig. 3D). The westernmost Ad Dawadami fault apparently once terminated in the map area but subsequently extended northwest along a splay trajectory that diverged from its earlier strike direction. A complicated assemblage of secondary fractures occurs around the termination of the most easterly fault where sets of arcuate complementary shears can be seen. Secondary fracture systems of this type occur at irregular intervals along major fault lines.

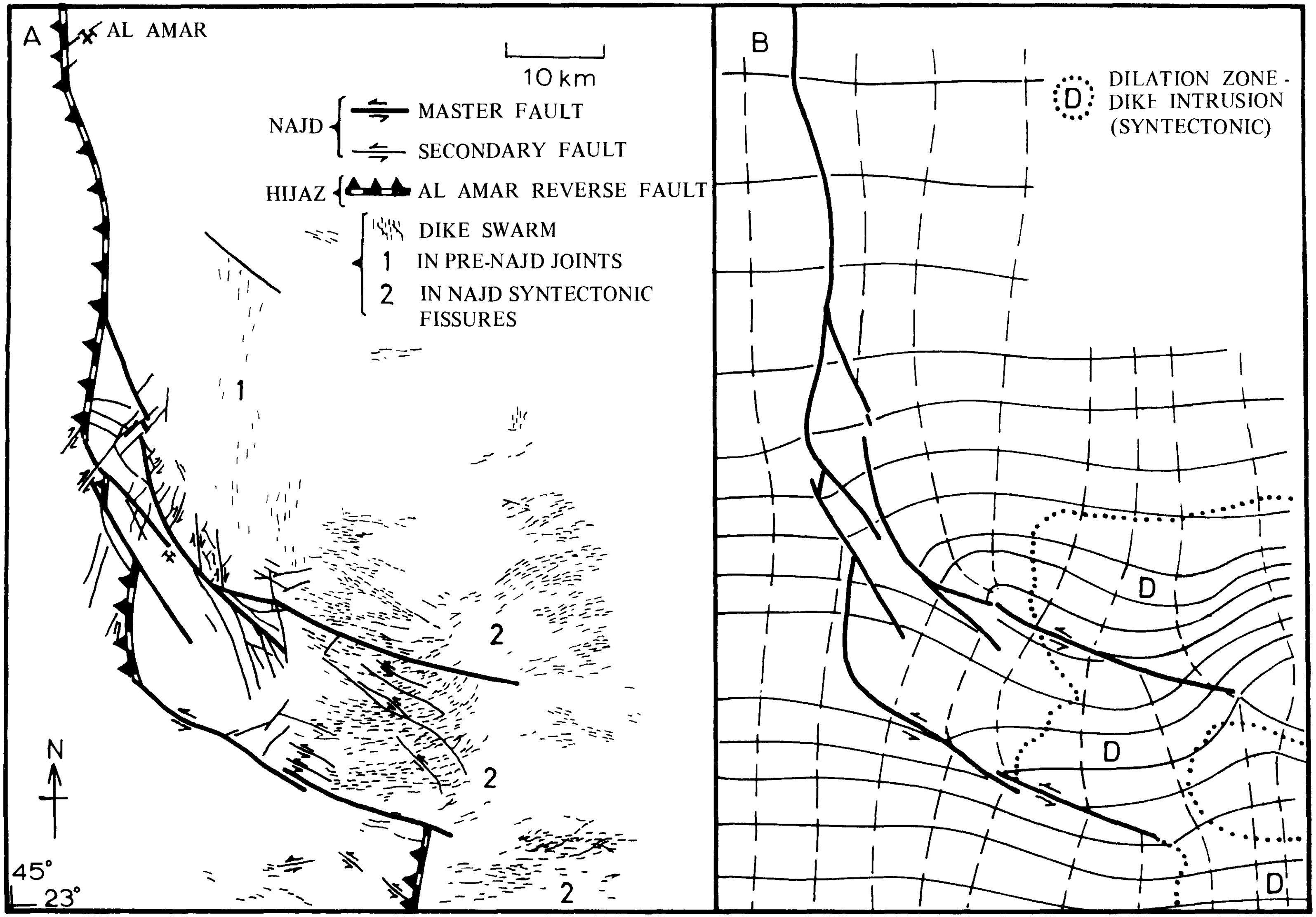


Figure 4. A, Simplified geological map showing faulting in the Idsas area. Prepared from aerial photograph interpretation and from Eijkelboom (1966). B, Stress trajectory interpretation of fault and syntectonic dike systems. Solid lines represent the orientation of maximum principal compressive stress ($\sigma_1$), broken lines, minimum principal compressive stress ($\sigma_3$).

The time relationships observed at Ad Dawadami and Juqjuq show that while some secondary faults cut and displace their parent structure, elsewhere the extension of a master fault can pass through its own secondary fracture system. It is a consequence of such a complex sequence of development that parts of a single fault may have different histories as well as varied amounts of displacement.

In addition to strike-slip movement, minor thrusting, oblique-slip faulting, and normal faulting have occurred in some areas. Thrust faults and folds adjacent to terrain containing normal faults can be seen in figure 3B. These unusual assemblages of minor structures define local areas of anomalous 'compression' or 'dilation' within the fault belt. The compressional regimes, in which thrusting and folding accompany second-order wrench faulting, occur on the northeast side of the northwest terminations and on the southwest side of southeast terminations and in the 'overlap' between en echelon major faults. The compressional regimes are complemented by 'dilation' on the opposite side of the master fault, marked by normal faulting and extension fissure formation. The dilational areas offer the most mechanically favorable loci for dike intrusion during the faulting events (syn-tectonically) and, subsequently, for hydrothermal vein emplacement. Somewhat similar phenomena associated with faulting at Owens Valley (USA) have been described by Pakiser (1960).

The juxtaposition of compressional and dilational conditions on opposite sides of a major fault means that normal faulting and dike intrusion could take place adjacent to part of a fault plane while, *simultaneously*, thrusting and folding could occur on the opposite side. The northwest Hijaz area contains excellent examples of the tectonic phenomena (fig. 3B) and the Idsas district illustrates dike intrusion adjacent to fault terminations (fig. 4A). Time relationships between dike intrusion and secondary faulting in the Ad Dawadimi district (fig. 3D) were investigated and described by Moore and Al Shanti (1973). Detailed study in that area demonstrated that intrusion of dikes associated with the secondary fault system took place while adjacent faults were subjected to tectonic stresses. The configuration of many dikes in the Idsas district (swarm 2, fig. 4A) indicates that they too may have been intruded into extensional and shear fractures during the tectonic events. Elsewhere (that is, dike swarm 1 in fig. 4A), the distribution of dikes is not consistent with the Najd stress field. These dikes cannot be explained in terms of syntectonic intrusion into extensional fissures in the $\sigma_1$-$\sigma_2$ principal plane. The alternative explanations for this discrepancy are: that swarm 1 consists of dikes emplaced before or after the Najd events, or that they may be syntectonic intrusions into older joint fractures. The second condition could result from magma fluid pressure finding it mechanically easier to dilute existing fissures normal to $\sigma_1$ than to create new fractures normal to $\sigma_3$.

Systems of secondary fractures can usually be attributed to a particular master fault. Although fractures may locally dislocate the major structure, renewed movement on the master fault generally restores its continuity. Secondary faulting in the Najd system is a composite of several generations of structures. Normal and reverse faulting with associated folding as separate events from secondary strike-slip movements can be seen in figure 3B.

Differing amounts of displacement on various parts of fault surfaces produce problems of accommodation, particularly in terminal areas. Some stress dissipation is achieved by reactivation of older structures. The Idsas area provides a good example of this where the northwest terminations of two Najd faults merge with the Al Amar fault (Al Shanti and Mitchell, 1976) an older structure which has been offset by Najd movements (fig. 4A). The Al Amar fault was reactivated as a high-angle reverse fault to accommodate stresses similar to those that generated splay and other secondary fractures at the southeast terminations of the Najd structures.

The need for secondary stress dissipation around active faults in the Najd system was particularly strong in parts of the braided zone where fault surfaces were non-planar. It was achieved by extension in length of the main fault along a splay fracture, creation of a secondary fracture complex, reactivation of older structures, or by vertical movement or tilting of fault blocks in the braided zone.

## FAULT MECHANICS

The mechanistic terminology I have used in this paper is from Wilcox and others (1973) and from Lajtai (1969), who states "Primary or first order state of stress refers to the condition under which faulting is initiated. It is the regional stress field in nature and the applied stress in the laboratory. Second-order state of stress refers to the readjusted stress field that develops during and after faulting and results in the formation of second order fractures." Chinnery (1966), considered stress conditions after movement on a master fault but experimental evidence shows that many arrays of en echelon minor structures (that is, Riedel shears) can form earlier than the master fault (Wilcox and others, 1973, Tanner, 1962). It appears from field evidence that some of the Najd secondary minor structures are explicable in terms of the conditions proposed by Chinnery but others conform to those discussed by

Lajtai. Lajtai states that fractures in an en echelon shear array are the product of anomalous conditions that do not bear a direct relationship to the regional stress field. Chinnery's models and the interpretation of field evidence presented below support this.

The outcrop traces of strike-slip faults, syntectonic dikes, and extensional fissures, together with their sense of displacement, can be used to construct diagrams showing the orientation of principal stress axes ($\sigma_1$-maximum, $\sigma_3$-minimum) within the stress system that related to the faulting. Stress trajectory diagrams, drawn by means of second-order shear, outcrop-trace interpretation, give an impression of the stress field around the master structure as it was during the secondary fracturing. This construction, made on geological maps, requires that the land surface should coincide approximately with a principal plane containing two of the principal stress axes. The best results are achieved when the construction is carried out on a regional scale, for an area of subdued topography. The requirements are met regionally in the Najd system but local thrusting, oblique-slip faulting, and normal faulting show that departures from plane stress conditions are not uncommon.

Regional-scale stress-trajectory construction shows that the stress field containing the main faults was relatively regular with the maximum principal compressive stress ($\sigma_1$) oriented approximately east-west. The main fault zone is oriented at 35-45° to the maximum principal compressive stress axis, and the system appears to have been subjected to stress approaching the uniaxial compressive condition.

The stress configuration around the Najd faults in the Idsas district is shown in figure 4B. Note the asymmetrical disturbance of stress-axis orientations adjacent to the southeast fault terminations. The array of splays and other minor faults adjacent to the Najd structures have been intruded by a dike swarm. The minor fault arrays are different on each side of the master structures but their geometry compares closely with that predicted on theoretical grounds (Chinnery, 1966).

The stress trajectory diagrams (figs. 4B and 5) have been constructed by the interpretation of secondary-fault geometry and represent conditions during second-order faulting. Continuing fault development has in some cases subsequently dislocated secondary faults, and it has only been possible to make a partial reconstruction of the secondary stress field (fig. 5A). The relationship between regional stress field and that related to secondary faulting is ambiguous in such cases, but elsewhere (fig. 5B) there appears to have been a regular regional stress field within which secondary conditions around the

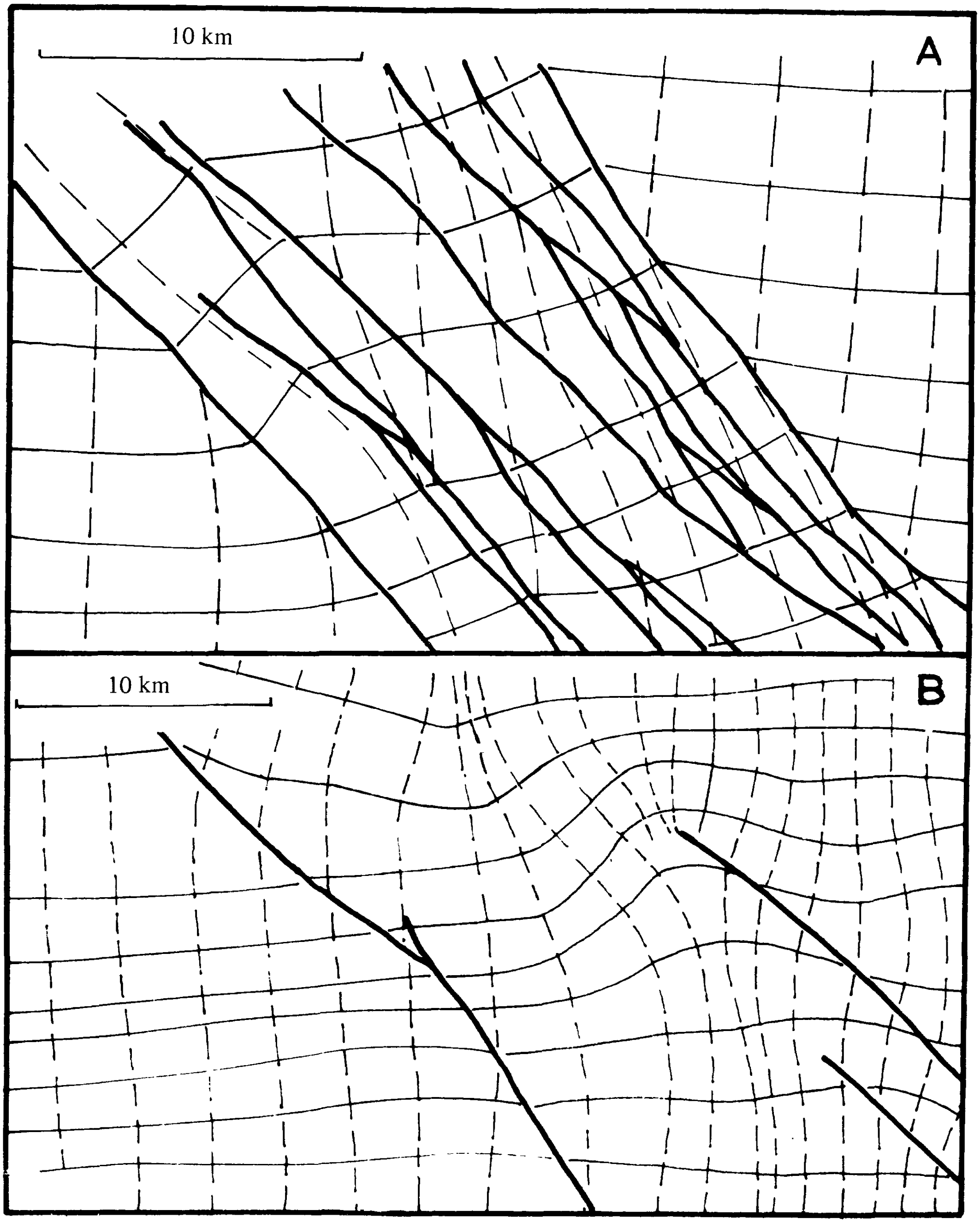


Figure 5. Stress trajectory diagrams showing orientation of principal stresses deduced from faults shown in figures 3C and 3D: A, Juqjuq. B, Ad Dawadami. Solid lines are the trajectories of maximum principal compressive stress ($\sigma_1$), and broken lines represent trajectories of minimum principal compressive stress ($\sigma_3$).

termination of a major structure were a local disturbance. It is important to appreciate that trajectory constructions represent very short periods of time during which perhaps only part of the composite fault system formed.

Figure 5 shows the trajectories of secondary principal compressive stresses constructed from geological maps of the Juqjuq and Ad Dawadami areas. These trajectories show stress-axis orientation interpreted from particular groups of secondary fractures. In the Juqjuq district, major faults, coinciding with the boundaries of the sheeted complex, mark discontinuities in the pattern of stress trajectories. The secondary fracture system appears to be the truncated remains of Riedel shears (fig. 6A) that have been cut by the sheeted master faults. The stress trajectory construction illustrates the pattern of stress as it was during secondary fault formation and movement. In some cases, for example, Juqjuq (fig. 5A), the trajectory construction illustrates the dislocated remains of the probably continuous stress field within which Riedel shear arrays formed prior to truncation by establishment of the sub-parallel master faults. The sub-parallel master faults apparently continued to move in response to the regional stress field oriented east-west (approximately 40° to their strike direction).

The Ad Dawadami trajectories (fig. 5B) are an interpretation of the secondary fracture array around the termination of the most easterly fault in the area; but detailed maps reveal another, older, and less well-developed fracture system adjacent to the most southerly of the three major faults (Moore and Al Shanti, 1974). Figure 5B also shows the localized nature of the stress-field disturbance around the termination of a major fault. Ad Dawadami is perhaps the most informative second-order fracture complex in the shield because of its mechanically isotropic host rocks and the precise time relationships that can be interpreted from study of structures related to the three major faults that traverse the area.

## DISCUSSION

Interpretation of aeromagnetic maps indicates that the Najd fault system is wider at depth than that shown on geological maps, and that the major structures below surface are better defined than the complex arrays of faults seen in outcrop. The width of the subterranean fault system suggests that the Najd movements could have been responsible for the reactivation of older structures noted in many areas of the shield.

The tectonic style of Najd primary and secondary structures is similar to that produced experimentally by Wilcox and others (1973) and Tanner (1962) in a brittle and semi-brittle 'cover'

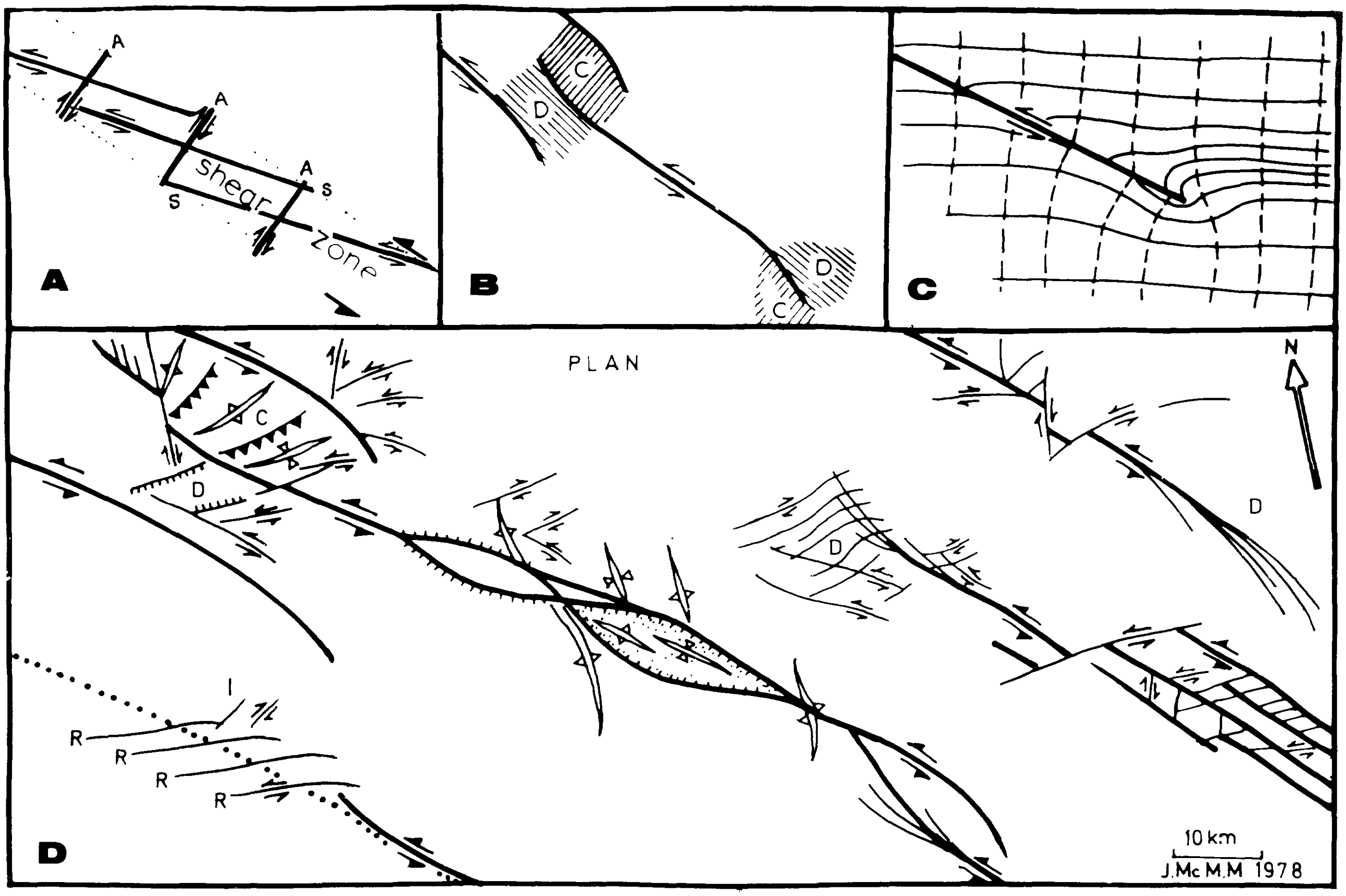


Figure 6. Generalized tectonic models (plan view) of Najd Fault system: A, Geometry of Riedel shears in relation to the shear direction that created them. Synthetic (S) and antithetic (A) conjugate Riedel shears. B, Generalized plan showing areas of convergence (anomalous compression (C)), characterized by thrusting, oblique-slip and secondary strike-slip faulting, and folding, and divergence between the master faults, (dilation and extension (D)) characterized by normal faulting and dike intrusion in relation to major faults. C, Trajectories representing the orientation of maximum and minimum principal compressive stresses around the termination of a fault after movement has occurred. Approximately one-eighth of total fault length is shown. After Chinnery (1966) based on models representing a fault under uniaxial compressive stress in plane stress condition. D, Secondary structures associated with major faults in the Najd Fault system. (C – compressional minor structures, D – dilational or extensional minor structures, R – synthetic Riedel shears). See figure 3 for explanation of symbols.

overlying a 'basement' comprising rigid blocks that can move laterally relative to each other. The well-defined linear structures revealed by the aeromagnetic maps may be the upper parts of the 'basement' fracture system.

Experiments indicate that major faults form in stages by shear-crack propagation. In some cases deformation began with establishment of Riedel shears (fig. 6A), which subsequently merged into continuous faults. Movement on a shear zone containing an array of Riedel shears changes the dihedral angle between the conjugate sets and modifies the angular relationships between the minor structures and major shear direction. In their experiments, Wilcox and others (1973) recorded an anticlockwise rotation of 3° and 15° for the synthetic and antithetic Riedel shears respectively in the course of one experiment on a sinistral shear zone. Dextral displacements, including reactivation of faults with north-northwest to northeast strike directions can therefore be explained in terms of the stresses that cause movement on rotated antithetic Riedel shears.

Strike-slip on intersecting faults that have differing dip angles and curved shears has created horst and graben structure and tilted blocks in the manner discussed by Lensen (1958) and Emmons (1969). These vertical movements in the braided zone have created the basins in which Jibalah group clastic sediments and volcanics were deposited.

Minor structures in the Najd system are of two types. The first type formed independently of the major faults, that is Riedel shears. The second type results from the disturbance of the orientation of the regional stress field and the value of normal confining stress caused by strike-slip movement on established master structures. Arrays of second-order faults characterize areas in which the stress acting normal to the major fault surface ($\sigma_n$) is unusually low for the fault system as a whole (Lajtai, 1969). Variations in strike direction among strike-slip faults can create these conditions.

Experimental evidence shows that variations in the angle between the regional shear direction and major fault strike (known as the angle of convergence or divergence, Wilcox and others, 1973), causes significant variations in the style of secondary structures. Structures characteristic of convergence or divergence are best developed adjacent to the arcuate terminal sections of Najd faults. Curvature on some faults is such as to create angles of convergence of as much as 30° relative to the shear direction for the belt as a whole. Compressional minor structures characterize areas of convergence, and extensional and dilational phenomena those of divergence (C and D in fig. 6B).

Commonly, there are differences between the orientation of the secondary stress field and that responsible for movement on the major faults. Secondary stress fields affect the orientation of regional principal stress axes for some distance from the major structure, producing minor structures in areas of several tens of square kilometers.

Figure 6C shows the asymmetrical configuration of principal stresses adjacent to the termination of a fault, based on theoretical considerations (Chinnery, 1966). It demonstrates how different patterns of secondary fractures can form on opposite sides of a major fault. Figure 6D is a summary in diagrammatic form of the minor structures associated with the Najd system.

Interpretation of field observations and the model experiments referred to above indicate that the sequence of development of secondary structures in the Najd system may have been as follows:

1) Riedel shear formation dominated by the synthetic set. This shear formation probably occurred simultaneously on several incipient shear zones in various parts of the proto-Najd system, accompanied by initiation of folding and local extension fissure formation.

2) Rotation of the Riedel shear sets and fold axial traces, accompanied by dislocation of the antithetic conjugate Riedel shears. The traces of antithetic shears may become sigmoidally curved by angular rotations of up to 15°.

3) Establishment and propagation of major faults approximately parallel to the main shear direction. The main faults may cut and dislocate both sets of Riedel shears.

4) More arrays of secondary faults develop around the terminations and in tectonic slices between major faults.

5) Continued propagation of the major faults creates the braided zone in which vertical movements produce tilting and horst and graben structure among the lenticular fault blocks.

6) Repetition of 1-5 and reestablishment of master faults earlier dislocated by their own secondary faulting create sheeted zones.

The Najd system displays many of the phenomena common to major strike- slip fault systems in many parts of the world, for example, the Transverse Ranges in the San Andreas system. The Arabian Shield is unique only in the clarity with which the plan view of the faults and associated fractures can be observed. This paper is a summary of preliminary compilations but much more information remains to be studied, and new data are accumulating as DGMR sponsored mapping programs progress.

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