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THE STRUCTURE AND SEISMICITY OF A PORTION OF THE SOUTHERN SULAIMAN RANGE, PAKISTAN

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ABSTRACT

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The Sulaiman Range represents the northeast segment of the Baluchistan Arc portion of the Alpine—Himalayan Orogen. This study represents an analysis of structural geology based on the interpretation of satellite imagery and the analysis of seismicity data. The structure in the area is dominated by a north—south trending, left-lateral strike-slip fault, herein named the Kingri fault, which extends for a distance of approximately 200 km across the analyzed imagery. Smaller north—south strike-slip faults are also present. In addition, large curvilinear thrust faults have been inferred from the structural pattern. Evidence along the Kingri fault, such as stream offsets and the continuation of the fault trace through alluvial materials indicates Holocene movement.

The entire Baluchistan Arc is characterized by shallow focus earthquakes, generally less than 50 km in depth. The pattern of seismicity shows a distinct relationship to the geologic structure as determined from the satellite imagery. Earthquake epicenters exhibit a distinct alignment along the major north—south strike-slip fault as well as a clustering in the areas northwest of the inferred thrust faults. The hypocenter distribution as projected on a northwest—southeast profile indicates a northwest dipping seismic zone which correlates with the southeast direction of tectonic transport inferred from the regional structural pattern.

The tectonic setting is interpreted as indicating contemporaneous strike-slip faulting along a general north—south trend and thrust faulting along a plane dipping to the northwest. Published focal mechanism solutions agree in part with this interpretation.

INTRODUCTION

The main zone of intra-continental shortening in the Alpine—Himalayan Orogen in the Middle and Far East extends from Iran to the Himalayas to Burma and ends in the Java trench. Most of the movement within this zone is along the Zagros in southern Iran, the Baluchistan Arc in Pakistan and Afghanistan, and in the Himalayas (Fitch, 1970; Nowroozi, 1972). The zone is characterized physiographically by high mountains and plateaus to the north and a continuous linear depression to the south (Indo—Gangetic

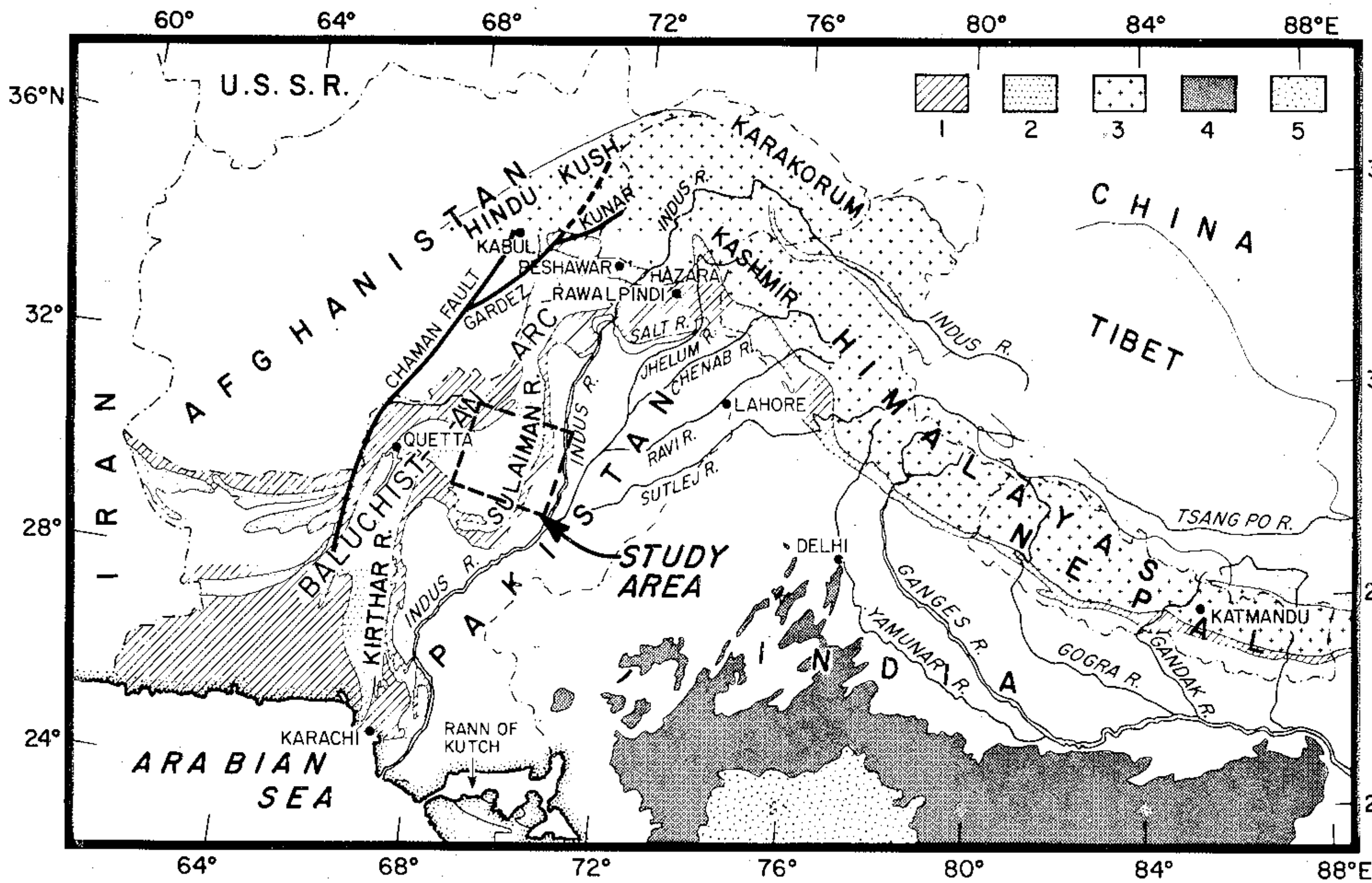

Fig. 1. Generalized geologic map showing major geologic units in the region of the Baluchistan Arc and Himalayas. *1* = Oligocene—Pliocene sedimentary foldbelts including the molasse-type Siwalik series; *2* = Jurassic, Cretaceous, and early Tertiary formations mostly of marine origin including occasional mafic ophiolite sequences; *3* = uplifted and overthrusted Triassic—Precambrian formations of the Himalayas often highly metamorphosed and intruded by Tertiary granite plutons; *4* = exposed Precambrian basement of the Indian shield; *5* = flood basalts (Deccan Traps) of mostly Paleocene age covering Precambrian basement of the Indian shield (modified from Menke and Jacob, 1976).

Trough). This paper deals with the Sulaiman Range in the eastern portion of the Baluchistan Arc (Fig. 1).

PLATE-TECTONIC SETTING

The current tectonic setting of the Middle East and Far East can be delineated by the distribution of earthquake epicenters in well defined belts of relatively high seismicity as opposed to the remaining areas which appear to be essentially aseismic. These areas of high seismicity are considered to mark the boundaries of large lithospheric plates that are undergoing deformation at their edges while the interiors of the plates are undergoing little, if any, appreciable deformation.

The Himalayan Orogenic Belt is the only region of the world where a large volume of continental lithosphere is being consumed. Although continental plates are easier to deform internally, they are difficult, if not impossible to be consumed by the subduction process of plate tectonics. This difficulty arises because of the lower density of the continental materials as opposed to

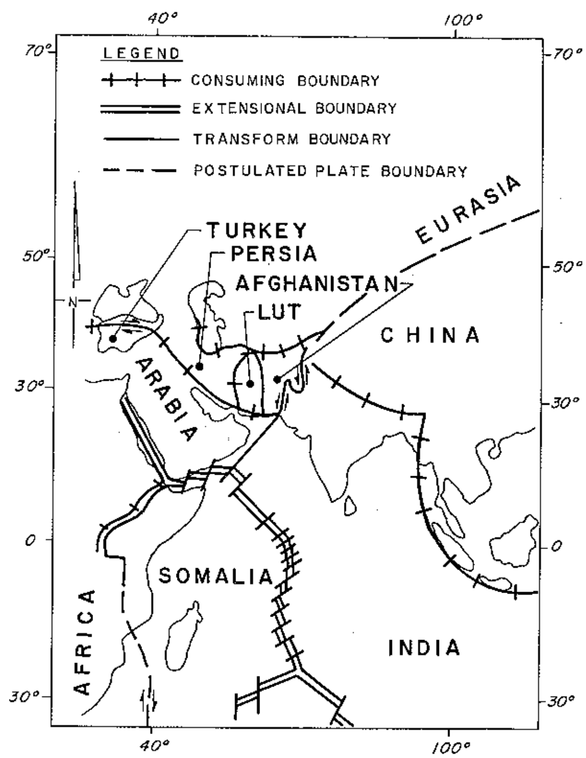

Fig. 2. Present plate-tectonic configuration of the Middle East (after Nowroozi, 1972; LePichon et al., 1973).

the denser composition of the oceanic crust. The presence of the lighter material results in an upward buoyant force that is greater than the downward force of subduction (McKenzie, 1972; LePichon et al., 1973).

Plate tectonic configurations of the Middle East (Fig. 2) have been proposed by McKenzie (1972), Nowroozi (1972) and LePichon et al. (1973) and primarily involves the north—south convergence between the Indian Plate and the Eurasian—China Plate or plates. The resulting consuming margin extends from the Baluchistan Arc to at least the Java trench. To the west of this collision zone, a consuming boundary is present between the Arabian and Persian plates. The Persian Plate, however, is probably composed of several microplates, such as the Lut Plate (Nowroozi, 1972) of eastern Iran and western Afghanistan.

This paper is concerned primarily with the area of the southern Sulaiman Range of the Baluchistan Arc, with the Indian Plate to the east and the Afghanistan Plate to the west. The western border of the Indian Plate is composed of a complex relationship between the Carlsberg Ridge, the Owen fracture zone, the Murry Ridge and the Kirthar—Sulaiman fault zone. Focal mechanism solutions of earthquakes indicate pure left lateral displacement along the Kirthar—Sulaiman fault zone (Nowroozi, 1972). In addition, Sykes (1970) obtained a left lateral faulting mechanism for an earthquake in the southern end of the Owen fracture zone. The general picture, however, is complicated by the presence of the Murry Ridge and a right lateral focal mechanism solution for an earthquake at the northern end of the Owen fracture zone (Banghar and Sykes, 1969).

There is, however, some general agreement in the pattern of relative plate motions in the continental portions of the plates. The Indian Plate is considered to be moving northward at a relatively faster rate than the Afghanistan Plate, which is also moving in a northerly direction. This differential movement is taken up by left lateral movement in the Kirthar—Sulaiman fault zone. This rate of movement for the Indian Plate has been estimated to range from 5 to 6 cm/year (LeFort, 1975).

The structure of the Baluchistan Arc is characterized by a complex pattern of wrench faults, thrust faults and folds (Fig. 1). In general, it represents a bend, or syntaxis, of the east—west trend of the Himalyas into a north—south orientation which remains relatively constant for a distance of approximately 880 km before making another east—west bend in the Makran mountains of southeastern Iran. Three areas within this general north—south trend are characterized by smaller syntaxial bends. The largest of these is the seismically active area near Quetta, another is west of Mianwali, and a third is northwest of Tank near the Bhittani Mountains.

The major structures of the Baluchistan Arc are large scale left-lateral strike-slip faults (Wellman, 1965; Abdel-Gawad, 1971; Nowroozi, 1972) associated with the collision of the Indian and Eurasian plates. The longest and best studied of which is the Chaman fault (Fig. 1), extending for a distance of at least 800 km from southern Pakistan to northeastern Afghanistan.

There is documented evidence for left lateral surface displacements along the Chaman fault as a result of the earthquake of December 20, 1892 (Griesbach, 1893; MacMahon, 1897) and West (1934) describes left-lateral surface displacements associated with the Quetta earthquake of 1931.

Abdel-Gawad (1971) suggested that the change in structural style within the Baluchistan Arc is dominated by a system of high angle wrench faults which trend north northeast—south southwest, parallel to the Kirthar and Sulaiman ranges, which he named the Kirthar—Sulaiman wrench zone. The presence of this zone was inferred from satellite imagery on which long, linear topographic lineaments transect the regional structural features for distances in excess of 200 km.

STRUCTURAL INTERPRETATION OF LANDSAT IMAGERY

Portions of the Sulaiman wrench zone have been analyzed in great detail by Abdel-Gawad (1971) and Eggenberger et al. (1975). The area analyzed in this study is north of the major syntaxial bend in central Pakistan. The general geology of this area (Fig. 3; Abu Bakr and Jackson, 1964) consists of a deformed sequence of Triassic to Quaternary sedimentary rocks which get progressively older from east to west. This portion of the Baluchistan Arc can be represented as three lithologic belts: the eastern and western belts are composed of Tertiary and possibly Quaternary sedimentary rocks and the central belt is composed of Mesozoic sedimentary and volcanic rocks.

The extreme eastern portion of the study area (Fig. 3) is composed of Quaternary alluvial and fluvial deposits associated with the Indus Basin which may be in excess of 2000 ft. thick in this area. To the west, the main portion of the Sulaiman Range is composed of Tertiary sedimentary rocks and range in age from Paleocene to Pliocene and possibly to Pleistocene. These rocks consist of limestones, sandstone, shale, siltstone and conglomerate, with the clastic sequence representing the largest volume of rock. Rocks in the western portion of the study area (Fig. 3) are composed primarily of limestone with minor amounts of sandstone and shale of Triassic, Jurassic and Cretaceous age. Interspersed throughout this area are deposits of Quaternary alluvium representing river deposits and alluvial fans (Abu Bakr and Jackson, 1964).

The structure of the Sulaiman Range is dominated by north—south oriented wrench faults (Abdel-Gawad, 1971) and southwest—northeast and north—south oriented thrust faults and folds (Hemphill and Kidwai, 1973). Tectonic transport of the rocks involved in the thrusting and folding is from the northwest and north. The following discussion will concentrate on the faults and folds within the southern Sulaiman Range.

Wrench faults

The most prominent feature located in this area is a nearly north—south fault which extends from the north-central portion of the imagery to the

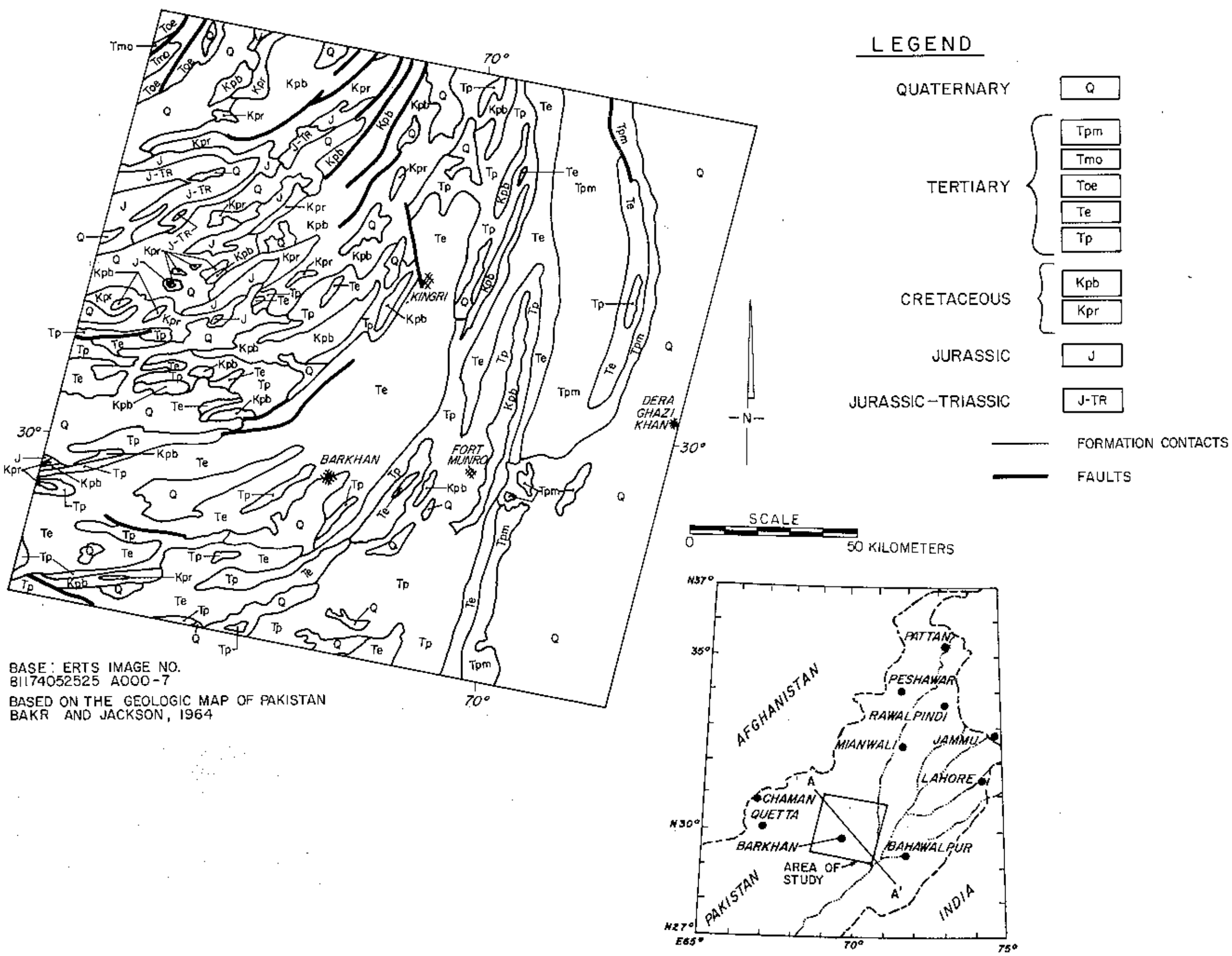

Fig. 3. Geologic map of the southern Sulaiman Range: *Q* = undifferentiated Quaternary deposits; *Tpm* = Pliocene and Miocene sedimentary rocks; *Tmo* = Miocene and Oligocene sedimentary rocks; *Toe* = Oligocene and Eocene sedimentary rocks; *Te* = Eocene sedimentary rocks; *Tp* = Paleocene sedimentary rocks; *Kpb* = Pab sandstone; *Kpr* = Park limestone; *J* = undifferentiated Jurassic sedimentary rocks, mostly limestone; *J—Tr* = undifferentiated Jurassic and Triassic sedimentary rocks.

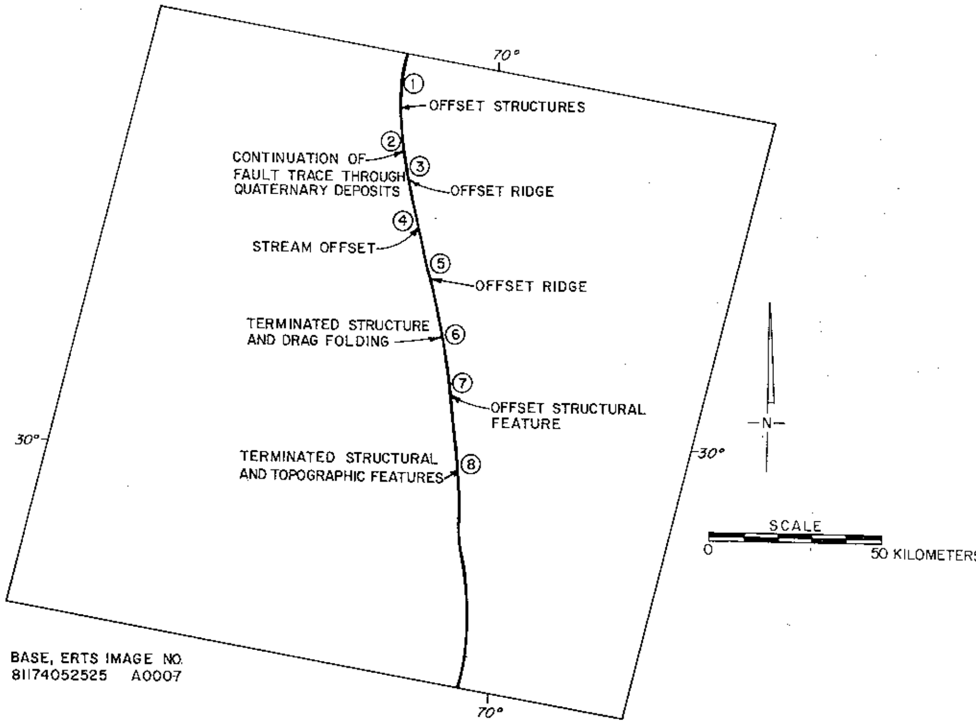

Fig. 4. Map showing the location of the Kingri fault and the geologic and geomorphic evidence for offset.

southeastern edge (Fig. 4). This fault passes through the town of Kingri and as a result has been herein named the Kingri fault. Eight areas (Fig. 4) exhibited distinct, well defined offsets of geologic structures or topographic features along this fault. Area *1* shows the distinct offset of both geologic structures and topographic ridges. Area *2* shows the continuation of the fault trace through Quaternary deposits. Area *3* exhibits distinct offsets of ridges. A pronounced stream offset is visible at location *4* and area *5* exhibits a distinct ridge offset. Area *6* shows the pronounced termination of both geologic structures and topographic features, as well as drag folding against the fault. Area *7* indicates the offset of a structural feature and area *8* shows the termination of both structural and topographic features. Although evidence is not conclusive along the entire length of the fault, most evidence, such as the offset of structures and drag folding, indicate that left-lateral strike-slip faulting is predominant. A small segment of this fault is shown on the Geological Map of Pakistan where it passes through the town of Kingri and Abdel-Gawad (1971) hypothesized its presence based on a single stream offset.

Detailed examination of satellite imagery of other areas to the north (Eggenberger et al., 1975; Rowlands, in prep.) indicates the presence of additional north—south oriented strike-slip faults. One of these extends from

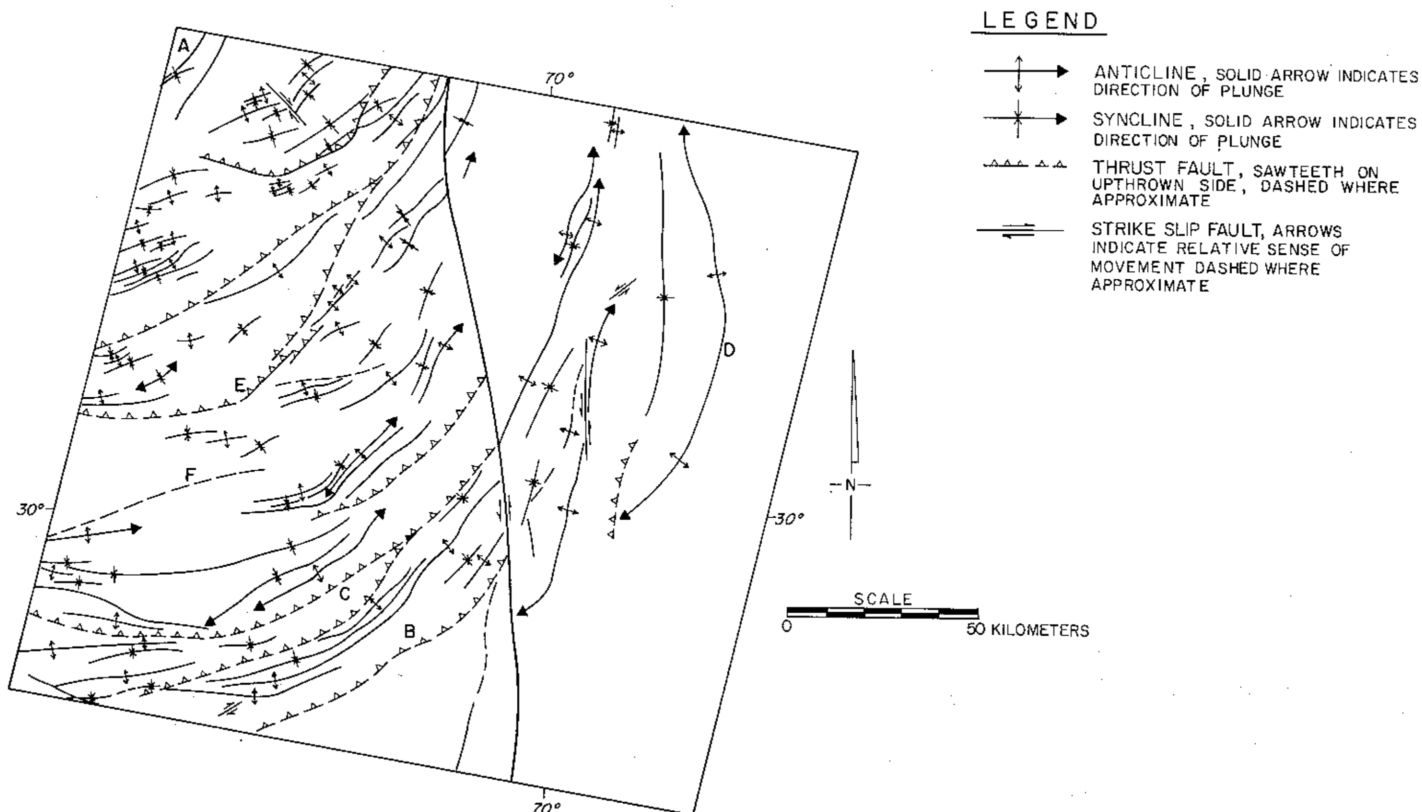

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Fig. 5. Structure map of the southern Sulaiman Range area.

point A in the northwest corner of the study area (Fig. 5) at least 200 km to the north, and to an as yet undetermined distance south. This second fault closely approximates the boundary between the central Mesozoic belt and the Tertiary rocks to the west.

Thrust faults

Thrust faults are generally difficult to locate on satellite imagery because they follow the general structural grain of the area. However, because of the sparse vegetation in this area and the generally rugged relief, it is possible to follow structures and stratigraphic units throughout the area. This ability to follow features for a considerable distance increases the likelihood of locating features indicative of thrust faulting. The presence of these thrust faults in speculative and awaits field verification, however, thrusting has been identified north of this area (Hemphill and Kidwai, 1973; D. Rowlands, unpubl. data).

The presence of thrust faults immediately north of the study area are documented by Hemphill and Kidwai (1973). Several large thrust faults have been interpreted in the present study. The two largest thrust faults are located in the area of curvature at the southern terminus of the mountain belt (points B and C, Fig. 5). The presence of these thrust faults is based on the irregular termination of structural trends, and the variations in curvature of the axial traces of several large folds (Fig. 5). Supportive evidence for this interpretation includes the long, narrow, pronounced valleys located immediately east and southeast of the fold terminations (point B, Fig. 5). These thrust faults represent only those observable at the scale of the imagery (1 : 1,000,000) and it is most probable that thrust faults could be mapped throughout this region at smaller scales.

Abdel-Gawad (1971) suggested that the boundary between the Sulaiman Range and the Indus basin may represent a wrench fault of major proportions. Even though this feature is represented by a distinct linear boundary, there is no distinct evidence for wrench faulting.

Folds

Folds can be mapped quite easily in this area at the scale of the LANDSAT imagery because of the generally rugged relief and the lack of vegetation. Inferred axial traces appear to be curvilinear throughout most of the area. Axes in the southwest portion of the study area appear to curve in a uniform manner from a predominantly east—west to a north-northeast—south-southwest orientation in the central area of the imagery and finally to a north—south orientation in the northern portion of the area. Most folds appear to be narrow, symmetrical, and doubly plunging, however, considering the degree of structural deformation, many of these may be overturned. The folds possess wavelengths ranging from approximately 30 km, such as the folds in the northeastern segment of the imagery, to less than one kilometer as exhibited by the tight spacing of folds in the northwest. The larger folds have discernable axial traces with lengths in excess of 100 km.

The most prominent fold is the large anticline at the eastern margin of the deformed belt where the Sulaiman Range is in contact with the Indus basin (Fig. 5, point *D*). The anticline exhibits a distinct curvilinear trend of the axial trace as well as the doubly plunging form that characterizes both anticlines and synclines throughout the area (Fig. 5). The doubly plunging and curvilinear nature of the folds are interpreted to be the result of re-orientation of stress rather than the result of multiple phases of folding. This anticline is cored with Paleocene sedimentary rocks (Fig. 3) and has a distinct termination at its southern end which is not expressed in the sedimentary rocks immediately to the west. This area has been interpreted to indicate the presence of a thrust fault between this anticline and the structures in the remaining part of the Sulaiman Range.

EVIDENCE FOR HOLOCENE SURFACE FAULTING

Evidence for historic surface faulting in other areas of the Baluchistan Arc has been presented earlier, especially for the Chaman fault in Pakistan and Afghanistan. Abdel-Gawad (1971) has identified several areas within the Kirthar Range showing evidence of stream offsets, lineaments in alluvium and faulted alluvial fans indicating Holocene surface faulting. The most distinctive evidence for Holocene surface faulting found in this area is shown at locations *2* and *4* (Fig. 4).

Location *2* shows the distinct continuation of the Kingri fault through recent alluvial deposits and a stream offset is apparent at location *4*. Holocene activity is also suggested between locations *7* and *8* (Fig. 4) where the fault marks the bundary between folded Tertiary rocks to the west and a plain of Quaternary deposits to the east.

Other evidence suggestive of Holocene faulting is evident at Location *E* (Fig. 6) where a distinct fault involving Jurassic and Cretaceous rocks continues through Quaternary alluvial deposits and the possible continuation of a fault through alluvial deposits at location *F* (Fig. 3).

SEISMICITY

The entire Baluchistan Arc is characterized by shallow earthquakes; most of which have depths less than 50 km and all having depths less than 70 km. This is true from the southern end of the Baluchistan Arc to latitude N34.5° where deeper earthquakes began to appear. These deeper earthquakes are probably caused by the influence on the Hindu Kush deep seismic zone at the northern terminus of the Baluchistan Arc.

All available instrumental data reported for the period 1905 through January 1975 for the Baluchistan Arc Region have been assembled from the fol-

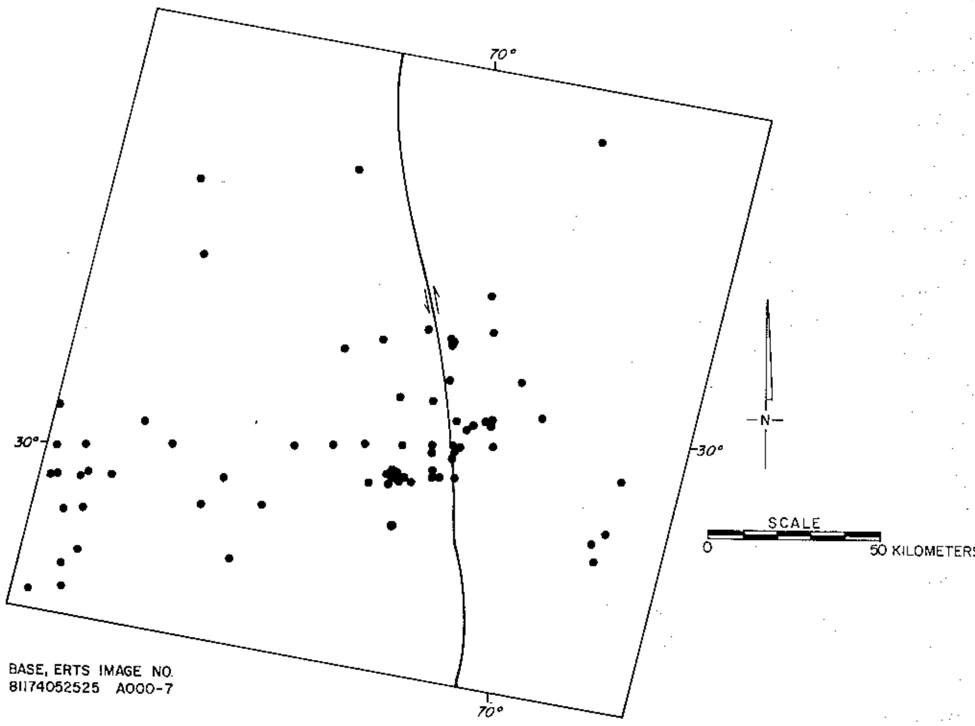

Fig. 6. Epicenter map of the southern Sulaiman Range area.

lowing sources: U.S. National Oceanic and Atmospheric Administration, the Preliminary Determination of Epicenters of the U.S. Geological Survey, the International Seismological Centre and the Pakistan Meteorological Department. All earthquakes having instrumentally determined epicenters within the field of the imagery have been used in the analysis and the distribution of epicenters plotted (Fig. 6). Of the earthquake data available, 80% is for the period 1950—1971 and 50% is for the period 1963—1974, and it should be emphasized that this earthquake data by no means represents all earthquakes that have occurred in this region.

RELATIONSHIP OF SEISMICITY TO STRUCTURE

Geologic evidence has been presented which indicates Holocene surface faulting at least along the Kingri fault. Additional evidence for recent activity is revealed through the analysis of seismic activity. The Kingri strike-slip fault shows a distinct linear alignment of epicenters along its central segment. At least twelve epicenters fall along, or very near the fault. Hypocenters for these earthquakes vary from 6 to 36 km. A relocation study of these earthquakes would probably reveal an even more pronounced relationship.

Current seismic activity appears to be concentrated along the central portion of this fault. However, considering the length of the fault and the relatively short period of detailed earthquake reporting, it is quite probable that earthquake activity should be expected along the entire length of this structure.

There appears to be no seismic activity associated with the trace of the southernmost thrust fault shown on Fig. 5, and very little activity along the trace of the next thrust fault to the north. It is suggested that the seismic activity found between these faults and to the north may indicate thrust movement at depth.

The earthquakes located at the eartern edge of the study area (Fig. 6) may be associated with faulting at the eastern edge of the Baluchistan Arc and if so may not be accurately located. They are shallow, 2—28 km and there is no distinct evidence within the alluvial deposits that suggests active faulting. These earthquakes could be associated wih the leading edge of the thrust fault that has been postulated as representing the eastern border of the Sulaiman Range. Such an interpretation is consistent with field studies conducted further to the north by the author. The fault in the extreme northwest corner (Fig. 5) appears to be traceable into the Quaternary deposits, thus suggesting that it has undergone recent movement, even though it is not known to have generated recent seismic activity within the area analyzed. It is the continuation of Fault F-4 of Abdel-Gawad (1971) and occurs at the contact of the central Mesozoic belt and the western Tertiary belt.

There is one epicenter which may be associated with a small left lateral fault located immediately east of the Kingri fault. There is no evidence of Quaternary offset along this fault and the location of the single epicenter is not considered sufficient evidence to indicate a distinct relationship.

HYPOCENTER DISTRIBUTION

A hypocenter profile has been constructed through this area (line $A—A'$, location map, Fig. 3). This profile (Fig. 7) clearly delineates a northwestward dipping zone of seismic activity which has been interpreted as a zone of thrust faulting directed from the northwest toward the Indus Basin and is probably composed of a number of thrust faults having similar orientations. The deformation, as indicated by the hypocenter distribution, clearly places all deformation within the crust and does not indicate deep subduction of this crustal material.

This restriction of earthquakes to the crust and the absence of deep subduction is probably the result of the buoyancy of the crustal rocks and is an indication of crustal thickening due to overthrusting.

Three focal mechanism solutions have been determined for two earthquakes located at 24.9°N 69.7°E (December 6, 1969) and 29.8°N 69.7°E (February 7, 1966) (Nowroozi, 1972; Banghar, 1974). Nowroozi's solutions for both earthquakes indicate pure left-lateral strike-slip faulting along vertical planes striking N14°E (Fig. 8). Since there is close similarity between

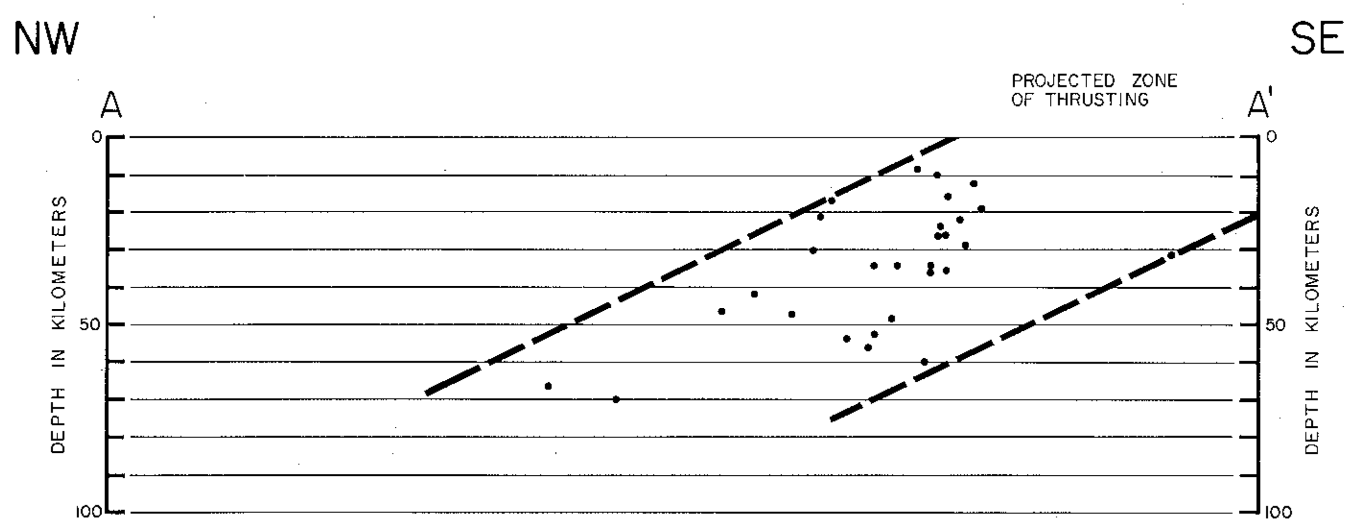

Fig. 7. Hypocentral profile through the southern Sulaiman Range.

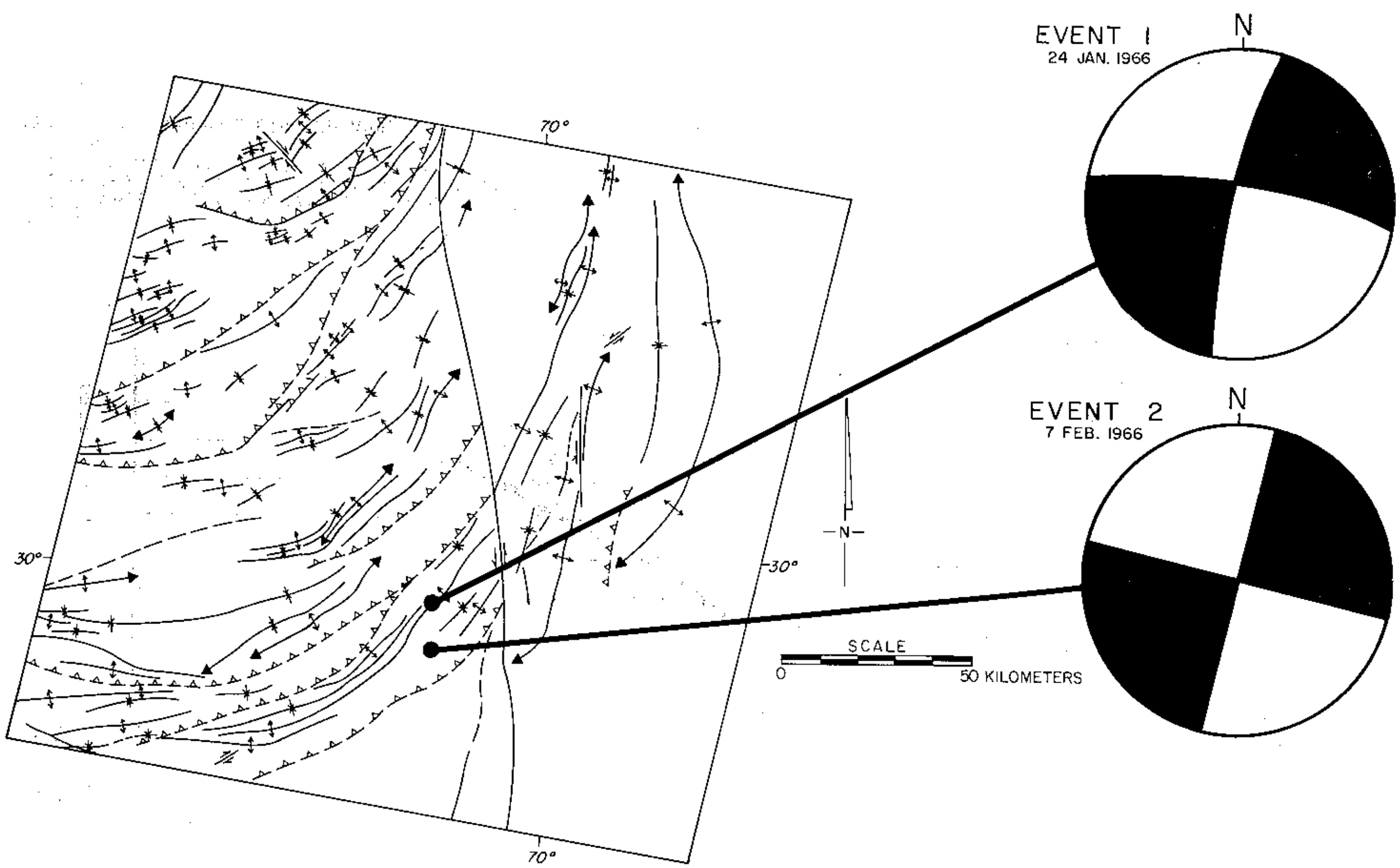

Fig. 8. Focal mechanism solutions for two earthquakes in the southern Sulaiman Range and their relationship to the local structural features. Solid area of focal mechanism solution equals compression; open area, dilatation (after Nowroozi, 1972).

the nodal planes and observed faults in this region, there is no ambiguity in choosing the correct fault plane. Banghar (1974), however, provides an additional focal mechanism solution for the earthquakes of February 7, 1966, which indicates pronounced components of both strike-slip and thrust fault motion. He chooses the N22°E plane as the fault plane based on a similarity in trend with that of the Sulaiman Range. The fault plane chosen, however, dips 54 degrees fo the southeast. Southeast dipping reverse (thrust) faults have been mapped to the north of this area in the Sulaiman Range (Hemphill and Kidwai, 1973) and thus there is some field evidence to support the selection of the N22°E (N12°E) trend.

Both Nowroozi (1972) and Banghar (1974) have determined similar directions for the axis of maximum compression. This compression is essentially horizontal (dips approximately eight degrees) in a N22°W orientation which is compatible with the direction of compression responsible for thrust faulting and folding in this area.

CONCLUSIONS

The analysis of the structural geology, as determined from LANDSAT imagery and the seismicity of this portion of the Sulaiman Range, shows sufficient evidence to indicate the presence of a large left-lateral strike-slip fault, the Kingri fault, that has been active during the Holocene. The seismicity pattern indicates a marked relationship with the location of the Kingri fault and to some extent with northwest dipping thrust faults. The hypocenter distribution indicates a northwest dipping zone which is consistent with the direction of thrusting and folding observed in the surface structural features. Focal mechanism solutions show left-lateral faulting with a northwest—southeast principal stress direction.

From the information generated during this study, it has been concluded that the present tectonic setting of the southern Sulaiman Range consists of large scale strike-slip faulting with concomittant thrust faulting. The strike-slip faulting is believed to penetrate the entire crust beneath the Baluchistan Arc and is related to the primary transcurrent faulting resulting from the continental collision of the Indian and Eurasian plates. The thrust faulting is interpreted to result from a secondary tectonic stress directed in a northwest—southeast direction.

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