The Lakhra anticline--An active feature of Pleistocene to recent age in southern Pakistan

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

1/ U.S. Geological Survey
2/ Geological Survey of Pakistan

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Abstract

The Lakhra anticline is a north trending breached structure west of Hyderabad in Sind Province, Pakistan. The Paleocene coal-bearing Bara Formation, exposed in the core of the anticline, is overlain by about 340 m of marine and non-marine, Paleocene to Recent strata. North-trending normal faults transect the anticline; some show recent vertical movement.

Lakhra Nala and Siph Nala were formed by a transcurrent intermittant stream system in the area of the anticline prior to uplift. The streams eroded the nalas (canyons, gullies, ravines, or watercourses) as the anticline rose and are now flowing on bedrock through the structure. The stream that formed Lakhra Nala deposited a large alluvial fan on the east side of the anticline as the structure rose and now flows onto the Indus River flood plain, which is accumulating about 6 m (20 ft) of alluvium per 1000 years. If the Lakhra anticline rose at an equivalent rate, it may not be older than 60,000 years.

Introduction

In 1985, the U.S. Geological Survey (USGS), under an agreement with the U.S. Agency for International Development (AID), and in cooperation with the Geological Survey of Pakistan (GSP), began a coal exploration project in southern Sind Province, Pakistan. Work started in the Lakhra anticline and extended as far south as Thatta. The Lakhra anticline is a north trending breached fold about 30 km wide and 100 km long whose highest elevations reach about 0.5 km above sea level. It is located along the Indus River west of Hyderabad (figs. 1, 2, and 3). The anticline has been

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Figures 1, 2, and 3 near here

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explored unsuccessfully for oil. Coal mining is the principal industry in the Lakhra area. Coal is mined from the Bara Formation, exposed at the core of the anticline Mine-mouth electric power generating stations are planned for the area, and they could be threatened by tectonic activity. This paper utilizes the data from the exploration drilling and the structural and stratigraphic studies by all members of the USGS and GSP that were involved in the project. However, the interpretations and conclusions are those of the authors and do not necessarily imply concurrence by all.

The earliest systematic geologic investigation in the region was that of Blanford (1879) who produced a geologic map showing the Lakhra anticline at a scale of 16 mi. to the in. Vredenburg (1909) established that the limestone mapped as Laki by Noetling (1904) was actually the younger Nari Limestone of Blanford (1879). Nuttall (1925) made a detailed study of the paleontology and stratigraphy of Tertiary units in the Meting area (fig. 2) and subdivided the Laki Formation into four members. He concluded, on the basis of stratigraphic and paleontologic studies, that the Lakhra anticline was already uplifted and eroding before the deposition of the Laki Formation and proposed that successively younger members of the Laki Formation extended unconformably northward over a laterite and older beds. Jones and others (1960),during the Hunting Survey, mapped the area on a scale of 1:253,440 (1 in. = 4 mi.) and found the laterite to be coal-bearing in the Meting area.

Structural and tectonic activity in Pakistan has been summarized by Farah and DeJong (1979). In general, the Indian plate, moving northward during Oligocene time, collided with the Eurasian plate. The process of collision between the plates is continuing and, the anticlines that approximately parallel the suture zone are consequences of the collision of. Another collision, among the Arabian, Eurasian, and Indian plates is also in progress, and the folding of some of the anticlines in southern Pakistan is attributable to it; among these is the Lakhra anticline. Nuttall (1925) considered the Lakhra anticline to have been formed during the Paleocene but our observations suggest that folding and uplift began more recently and is still continuing This paper uses stratigraphic and geomorphic data to interpret the tectonics and age of the anticline.

Figure 1. Index map showing location of the Lakhra anticline (modified from C. McA. Powell, 1979)

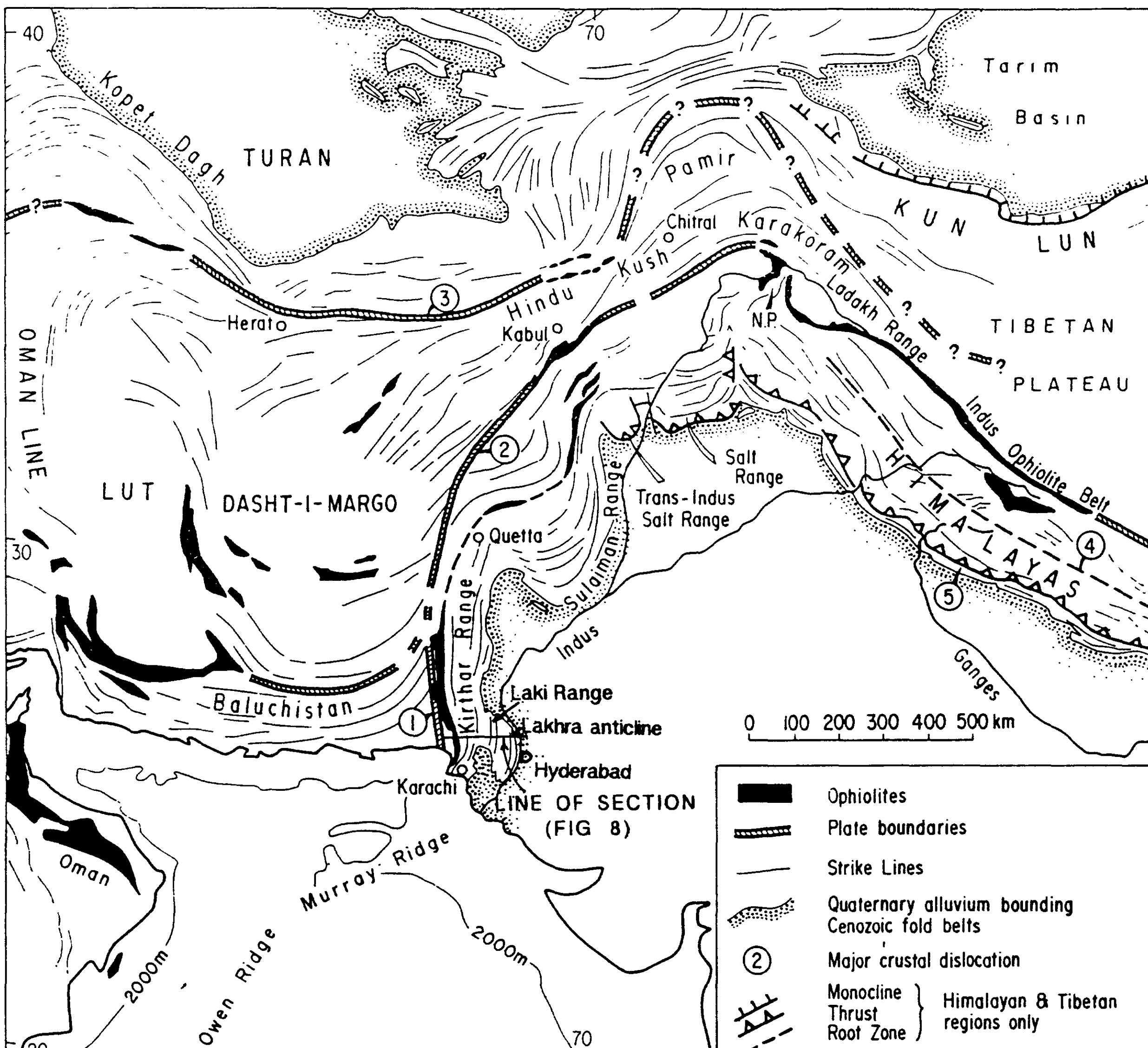


Figure 1. Tectonic sketch map of Pakistan and adjacent regions showing generalised strike lines and the limits of the Cenozoic fold belts rimmed by Quaternary alluvium. Circled numbers refer to major crustal dislocations as follows: 1, Ornach-Nal fault; 2, Chaman fault; 3, Herat-Hindu Kush fault zone; 4, Himalayan Central Crystalline Axis, and 5, Himalayan Main Boundary Fault. The two important plate boundaries, marked in part by ophiolite, separate three geotectonic regions *viz.* the *southern* Indo-Pakistani continental block, the *northern* Turan continental block, and *in between*, the Iran-Afghanistan belt (with a possible eastward extension into Tibet through Chitral by way of the Hindu Kush and Karakoram. N.P.=Nanga Parbat. Map based on Gansser (1964, Plate IB).

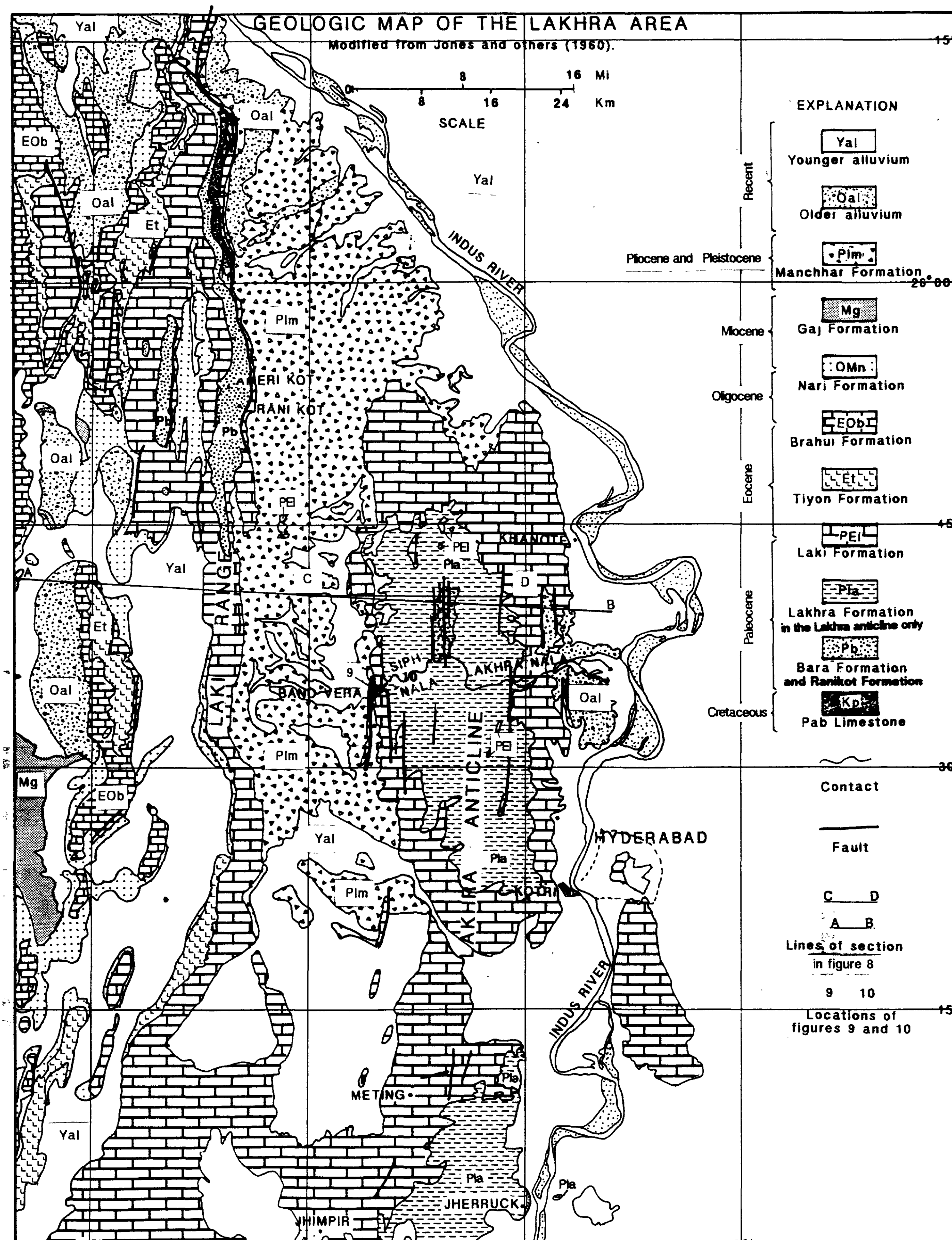

GEOLOGIC MAP OF THE LAKHRA AREA
Modified from Jones and others (1960).
0 8 16 Mi
0 8 16 24 Km
SCALE
EXPLANATION
Recent
Yal
Younger alluvium
Oal
Older alluvium
Pliocene and Pleistocene
Plm
Manchhar Formation
Miocene
Mg
Gaj Formation
Oligocene
OMn
Nari Formation
Eocene
EOb
Brahui Formation
Et
Tiyon Formation
PEl
Laki Formation
Paleocene
Pla
Lakhra Formation
in the Lakhra anticline only
Pb
Bara Formation
and Ranikot Formation
Cretaceous
Kp
Pab Limestone
Contact
Fault
C D
A B
Lines of section
in figure 8
9 10
Locations of
figures 9 and 10
INDUS RIVER
LAKHRA RANGE
LAKHRA ANTICLINE
RANI KOT
KHANOTE
SIPH NALA
LAKHRA NALA
BAND VERA
HYDERABAD
KOTRI
METING
JHERRUCK
JHIMPIR
15'
26°00'
45'
30'
68°00'

Figure 3. Structure contour map of the base of the Lakhra Formation

Interval 50 meters, dashed where approximately located

Grid is Pakistan 10 km grid.

Number at control point is elevation in meters of the base of the Lakhra Formation.

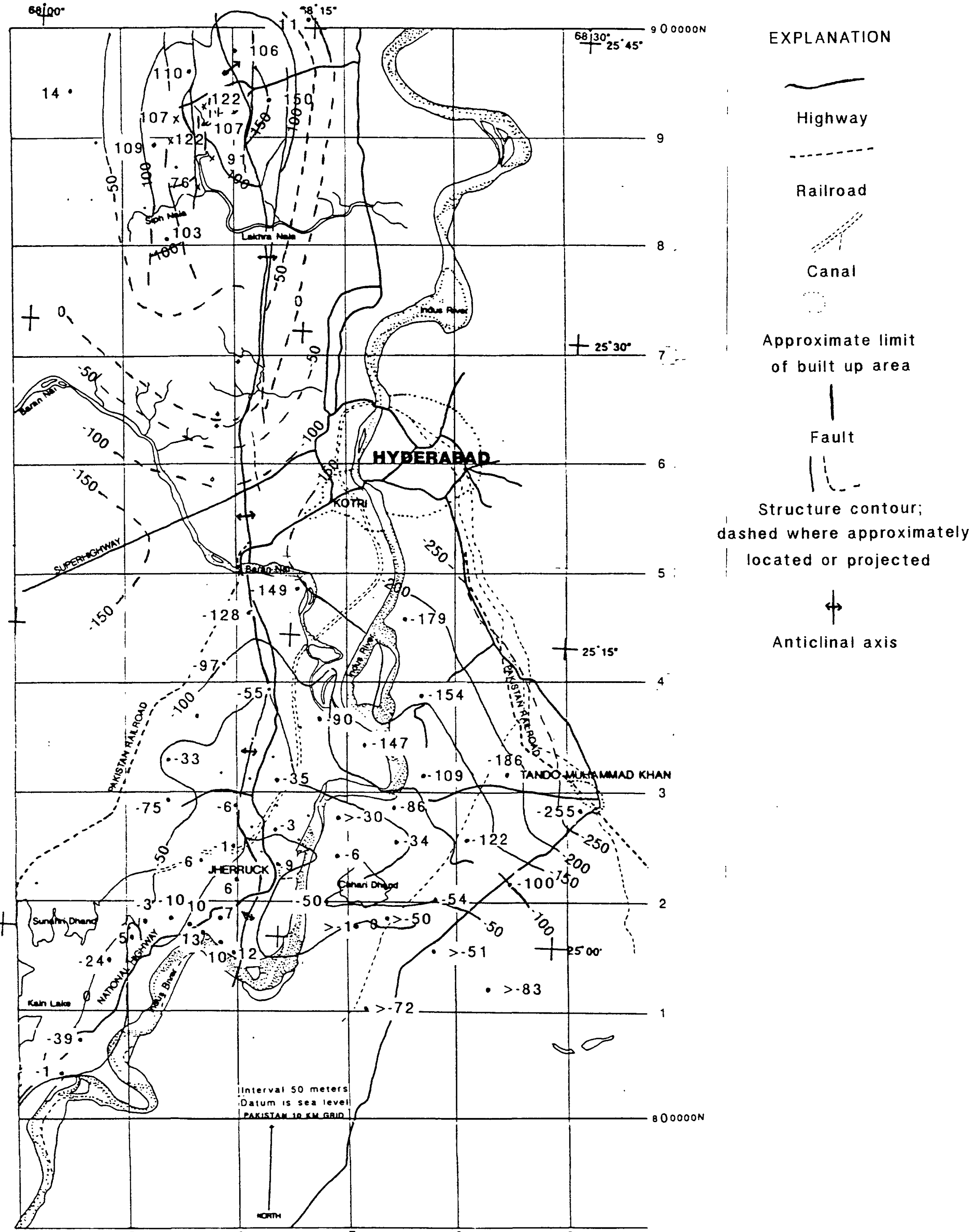
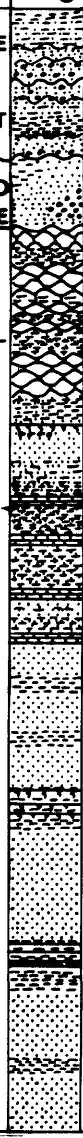


Figure 3. Structure contour map of the base of the Lakhra Formation

Figure 4. Stratigraphic nomenclature and general rock types exposed in the Lakhra anticline



AGE	LITHOLOGY	NAMES USED IN THIS REPORT		PREVIOUS NOMENCLATURE (FROM SHAH, 1977)	
PLEISTOCENE TO RECENT		YOUNGER ALLUVIUM OLDER ALLUVIUM		MANY NAMED UNITS. SEE KAZMI, 1984; SHAH, 1977.	
PLIOCENE TO PLEISTOCENE		MANCHHAR FORMATION		MANCHHAR OR SIWALIK GROUP	
EOCENE		LAKI FORMATION	LAKI LIMESTONE MEMBER	LAKI FORMATION	LAKI LIMESTONE
			METING SHALE MEMBER		METING SHALE
			METING LIMESTONE MEMBER		METING LIMESTONE
PALEOCENE			SOHNARI MEMBER		BASAL LAKI LATERITE
		LAKHRA FORMATION		RANIKOT GROUP	UPPER RANIKOT FORMATION
		BARA FORMATION			LOWER RANIKOT FORMATION

EXPLANATION OF LITHOLOGIC SYMBOLS

GRAVEL AND CONGLOMERATE
SAND AND SANDSTONE
CLAY AND SHALE
COAL
SEAT ROCK
CALCAREOUS CLAY AND SHALE
EVENLY BEDDED LIMESTONE
RUBBLY BEDDED LIMESTONE

Stratigraphy

Present and previous stratigraphic nomenclatureand the general rock types exposed in the Lakhra anticline are shown in Figure 4.

Figure 4 near here

Bara Formation

The Bara Formation of Paleocene age extends through southern Sind, mostly in the subsurface, and is reported to be 300 to 450 m (1000 to 1500 ft) thick (Jones and others, 1960). The basal contact is not exposed in the Lakhra anticline but it is conformable in the type area at Rani Kot in the Laki Range. The Bara is the main coal-bearing formation and is composed of thick to thin beds of clean, well sorted fine- to very coarse-grained, unconsolidated sand interbedded with silt, clay and shale, and coal. Redbeds were found in the lower part of the formation in drill holes. The Bara Formation was deposited in a complex of swamp, back barrier, sand bar, and lagoonal environments (C. Wnuk, USGS, oral communication).

Lakhra Formation

The Lakhra Formation is middle to Late Paleocene in age (Usmani, 1983). It is generally present west of the Indus River but appears to pinch out eastward (fig. 5). It is present in the outcrop

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Figure 5 near here

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area (Shah, 1977) but it was not mapped in the Laki Range. The basal contact is conformable on the Bara Formation. The Lakhra Formation is composed of sandstone, siltstone, claystone, and one or more distinctive fossiliferous sandy limestone beds. In drill cores, the lower and upper contacts of the Lakhra Formation are placed at the base of the lowest and at the top of the highest of these limestones, assuming that more than one limestone bed is present. If only one limestone is present, then the Lakhra Formation consists of only that limestone bed. The upper contact of the Lakhra Formation is locally disconformable; consequently the formation would include fossiliferous calcareous sandstone that cannot reasonably be included in the overlying Sohnari Member of the Laki Formation (C. Wnuk, USGS, oral communication). The Lakhra Formation is inferred to be a shallow shelf deposit. The Bara and Lakhra together constitute the Ranikot Group of established nomenclature. In the Lakhra area, the Ranikot Group increases in thickness westward from 700 m (2,300 ft) near the Indus River to nearly 1,000 m (3,300 ft) just west of the Lakhra anticline (Quadri and Shubai, 1986).

Laki Formation

The Laki Formation of Late Paleocene to Early Eocene age is divided into four members: the Sohnari, Meting Limestone, Meting Shale, and Laki Limestone.

The Sohnari Member of Paleocene age overlies limestone of the Lakhra Formation. The Sohnari Member is composed of sandstone, siltstone, shale, claystone, and coal. Some of the shale is extremely pyritic and weathers to red iron oxide impregnated rocks that have been called laterite. Isopach trends (fig 6) indicate that the Sohnari

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Figure 6 near here

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likely was deposited in a complex of swamp, back barrier, sand bar, and lagoonal environments, similar to those of the Bara Formation of which it may be a tongue.

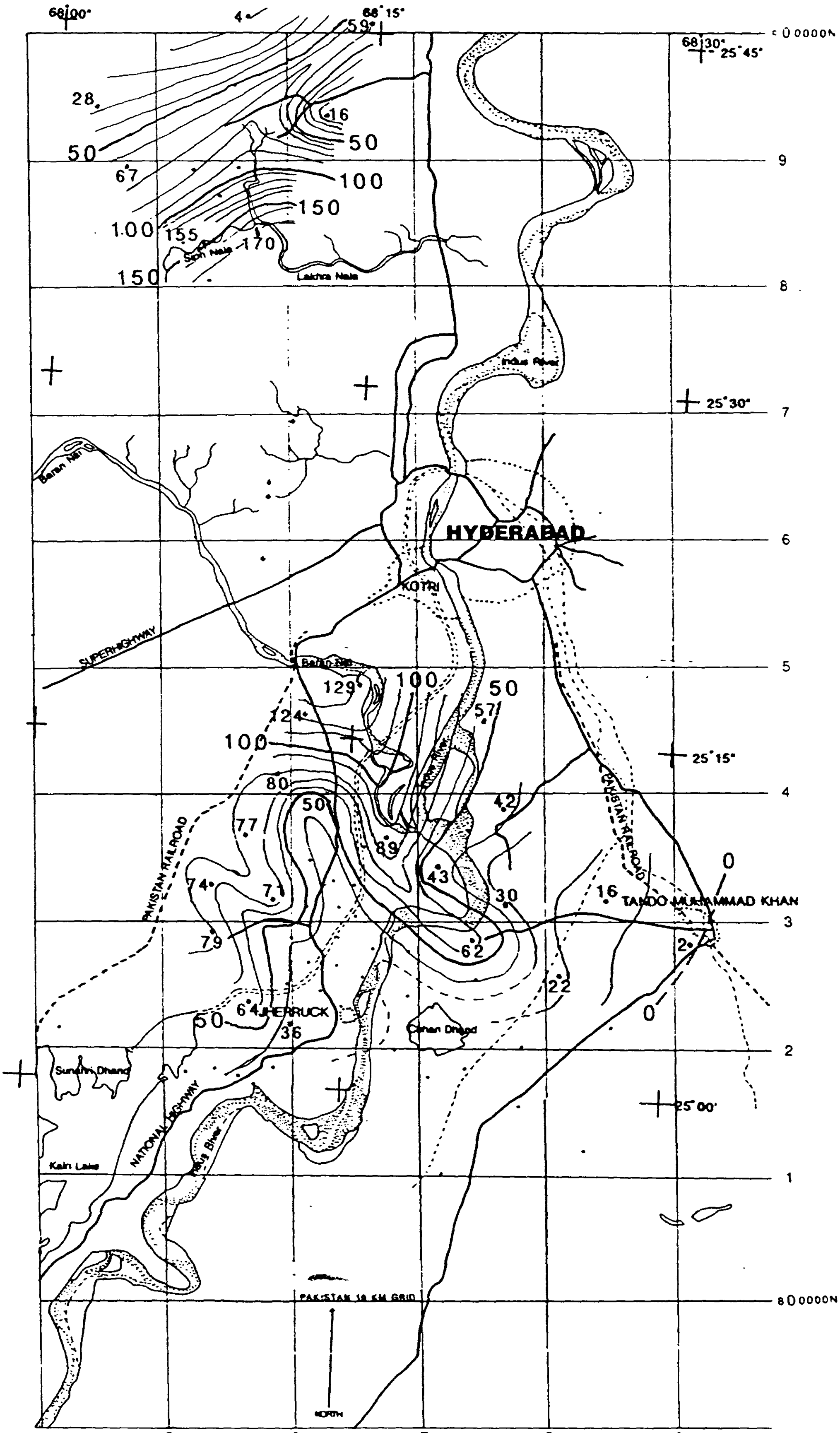
The marine members of the Laki Formation are the Meting Limestone, the Meting Shale, and the Laki Limestone. The Meting Limestone Member is of Paleocene to Eocene age, and the Meting Shale and Laki Limestone members are of Eocene age. The marine part of the Laki Formation is widespread throughout the Lakhra area (Fig. 2) and reaches thicknesses exceeding 76 m (250 ft), but the top is an unconformity. The basal contact of the Meting Limestone Member of the Laki Formation is sharp. The Laki Formation above the Sohnari Member consists of white to pale yellow orange, rubbly and chalky, fossiliferous limestone

Figure 5. Isopach of the Lakhra Formation

Interval 10 meters

Grid lines are Pakistan 10 km grid

Numbers at control point is thickness of the Lakhra Formation in meters.



EXPLANATION

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Drill hole showing thickness of Lakhra

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Measured section showing thickness of Lakhra

Isopach, interval 10 m

10 km

Scale

Figure 5. Isopachous map of the Lakhra Formation

Figure 6. Isopach of the Sohnari Member of the Laki Formation.

Interval 10 meters, dashed where approximate

Grid lines are Pakistan 10 km grid

Number at control point is thickness of the Sohnari Member in meters.

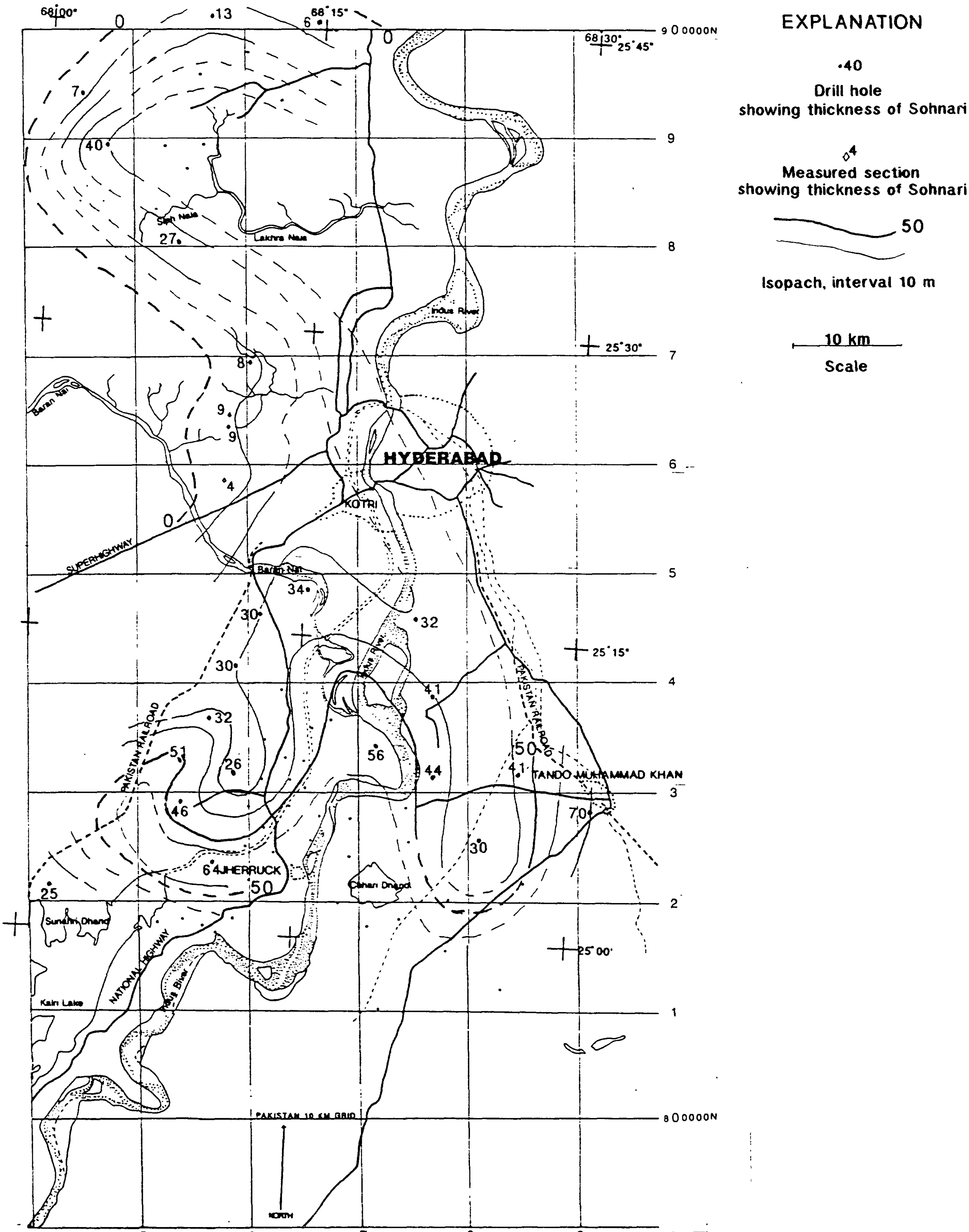

Figure 6. Isopach of the Sohnari Member of the Laki Formation

interbedded with moderate yellowish-brown, calcareous, fossiliferous clay. The marine strata in the Laki Formation apparently were deposited in an open lagoon or shallow marine environment.

The erosional interval

Based on stratigraphic descriptions and age designations that follow by Jones and others (1960), an interval of 50 million years time interval separates deposition of what remains of the Laki Formation in the Lakhra anticline and the onset of deposition of the unconformably overlying Manchhar Formation. According to them, four formations, the Tiyon, Brahui, Nari, and Gaj, were deposited between the Laki and Manchhar Formations in the Laki Range, about 26 km (16 mi) west of the junction of Siph and Laki Nalas on the Lakhra anticline.

The Tiyon Formation is Early to Middle Eocene in age, about 107 to 198 m (350 to 650 ft) thick, and has a gradational basal contact with the Laki Formation. The Tiyon Formation is composed of highly fossiliferous, even-bedded shale, calcareous claystone, and limestone. It is inferred to be a shelf deposit like the Lakhra Formation.

The Brahui Formation is of Middle Eocene to Early Oligocene age. It is widespread west of the Lakhra anticline and varies from 15 to 30 m (50 to 100 ft) in thickness near the anticline but is truncated by an unconformity. To the north, it is more than 1200 m (4000 ft) thick with the lower part concealed. Where exposed, the basal contact is gradational. The Brahui is composed of highly fossiliferous limestone, shale, and calcareous claystone. The limestone is nodular and suggests reef or very shallow-water deposition.

The Nari Formation of Oligocene to Early Miocene age is widely distributed west of the Lakhra anticline and is 900 to 1800 m (3,000 to

6,000 ft) thick. In the Laki Range, the Nari Formation rests unconformably on the Brahui, Tiyon, and Laki Formations. Near the lower contact is a thin conglomerate; above that the formation consists of sandstone, shale, and limestone, with sandstone the dominant rock type. Marine fossils are abundant in sandstone of the Nari Formation, and the formation appears to be entirely marine, but it marks the beginning of clastic deposition from the north and major clastic deposition between the suture zone and the Laki Range.

The Gaj Formation of Middle to Late Miocene age is widely distributed in western Sind, lying conformably on, and intergrading with, the Nari Formation. It is largely sandstone with lesser amounts of shale and limestone which mutually intergrade. The sandstone is locally conglomeratic. Marine fossils are present in most of the formation. Some fluvial beds are present in the upper part of the formation in the northern part of the range of the formation. Most of the deposition was between the Axial Belt and the Laki Range. The Gaj Formation generally is conformably overlain by the Manchhar Formation, but they may be locally unconformable.

Manchhar Formation

The Manchhar Formation, as it is called in Sind, or Siwalik Group as it is known in northern Pakistan, (Shah, 1977), is probably of Pliocene to Pleistocene age (Jones and others, 1960). It unconformably overlies the Laki and Lakhra Formations as erosional remnants up to 12 m (40 ft) thick in the core of the Lakhra anticline, and on its flanks and north end. The Manchhar Formation ranges from dark-brown silt to gravel or conglomerate and has abundant petrified angiosperm and gymnosperm wood and sparse bones and teeth of both reptiles and mammals. It is interpreted to be a southward prograding fluvial deposit (Shah, 1977) marking an eastward shift in the axis of deposition from the area between the Axial Belt and the Laki Range to the area of the Indus River flood plain north and east of the Laki Range. In some areas west of the Lakhra anticline, the Manchhar Formation as mapped by Jones and others (1960) (Fig. 2) is actually a quartz-rich lag deposit coated with brown desert varnish.

Older alluvium

Alluvial deposits are considered older if they are erosionally dissected and younger if they are being deposited, a distinction that is reasonably clear in the field. Absolute ages of the deposits are not implied. In the vicinity of the Lakhra anticline, terrace deposits along Siph Nala and Lakhra Nala and alluvial fan deposits along the east side of the Lakhra anticline are dissected. The terrace deposits may be as much as 9 m (30 ft) thick downstream from the junction of Siph and Lakhra Nalas, have unconformable contacts with the underlying bedrock, and consist of limestone gravel, sand, silt, and clay. The alluvial fans are thicker than the terrace deposits but otherwise have a similar composition. The environment of deposition then was probably the same as it is now; that is desert to semi-desert with torrential monsoonal rain.

Younger alluvium

Younger alluvium occupies wide areas of very low relief near the heads of intermittent streams, the beds and flood plains of intermittent streams, and the flood plain of the Indus River. Alluvium in intermittent streams is generally less than 1 m (3 ft) thick and is in transit downstream. Peripheral contacts are gradational with residual soils, and contacts with bedrock along central drainage lines are sharp. Younger alluvium in headwater areas is composed of clay- to sand- size grains; in the main streams, it is mostly sand- to gravel- size limestone clasts. Alluvium of the Indus flood plain is mostly gray silt.

Recent depositional history of the Indus flood plain

The head of the Indus River delta is reported to have been 55 km (35 mi) northeast of Hyderabad in historic time (Holmes, 1968). Historic time in Pakistan begins about 5,000 years ago. Lakhra Nala probably flowed directly into the sea. The flood plain now extends 160 km (100 mi) south of Hyderabad and the delta is an area of approximately 100 km^2 (39 mi^2) at the mouth of the Indus (Kazmi, 1984). The flood plain bordering the alluvial fan of Lakhra Nala is presently about 15 m (50 ft) above sea level. Deposits in the alluvial fan of Lakhra Nala interfinger with sediments of the Indus flood plain. Average grain size of the sediments of the Indus River increases sharply from silt to fine sand just south of the Lakhra Nala alluvial fan (Kazmi, 1984).

Structure

Regional tectonics

Jacob and Quittmeyer (1979) suggest that a triple junction joins the Indian, Arabian, and Eurasian continental blocks north of Karachi and west of Hyderabad where the Arabian block is moving toward the Indian block at a rate of about 1.8 cm/yr (fig. 7) Fold axes on the Indian plate are sub-parallel to the postulated plate boundaries.

Figure 7 near here

Progressively eastward from the Axial Belt (fig. 8) are 1), the Kirthar Range, 2), the Laki Range, and 3), the Lakhra anticline (figs. 1 and 8). The Kirthar Range is comprised of folded and faulted compressional ridges in a swath approximately 100 km (60 mi)

Figure 8 near here

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wide extending from Karachi to Quetta. The Laki Range (fig. 2) is a breached anticline that forms one or two ridges. It extends from the superhighway between Karachi and Hyderabad northward about 100 km (60 mi) to near Lake Manchhar, and its northern has a spectacular asymmetric fold, with a steep east limb, bounded on the east by a fault that separates the fold from flat-lying beds of equivalent formations.

The Lakhra anticline is a very gentle fold lying between the Laki Range and the Indus River (figs. 1, 2, 3, and 8). The length of the anticline is undefined but may be more than 100 km (60 mi). The Lakhra anticline appears to be the eastern limit of deformation associated with collision between the Indian and Arabian plates.

Structure contours drawn on the base of the Lakhra Formation (fig. 3) show a faulted asymmetric anticline with its axis nearer the east side. The anticlinal axis extends southward across a postulated saddle into a dome which has a crest near Jherruck. Trends of isopachs (fig. 5) suggest that the Lakhra Formation thickens greatly in the area of the saddle, thus the disparity between apparent structure at the surface and the structure shown by contours on the base of the formation is likely a function of that thickening. The anticlinal axis is not shown beyond the Indus River because of the lack of data. Dip slopes near Jherruck have varying strikes that generally follow the structural trends shown in Figure 3.

North trending faults displace strata in the core of the anticline near Lakhra to form a cluster of small grabens. Faults are less abundant in the Jherruck area and occur mainly west of the anticline. Surface expression of some faults suggests recent movement (fig. 9,10), probably

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Figure 9 near here

Figure 10 near here

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related to extension over the crest of the growing anticline. They interrupt stream gradients, block drainages (fig. 9), and leave traces across the landscape (fig. 10).

Regional vertical movement

The earliest vertical movement in the Lakhra area was the slow subsidence of the region as the Bara Formation accumulated. The rate of deposition balanced the rate of subsidence during accumulation of the Bara Formation, beds of which are characteristic of lagoonal, nearshore, beach, and swamp environments, then lagged behind the rate of subsidence during accumulation of most of the Lakhra Formation, which is characterized by marine shelf deposits. The rate of deposition was faster than the rate of subsidence as the Sohnari Member

Figure 7. Principal tectonic boundaries and slip vectors in southern Pakistan. Modified from Jacob and Quittmeyer, 1979.

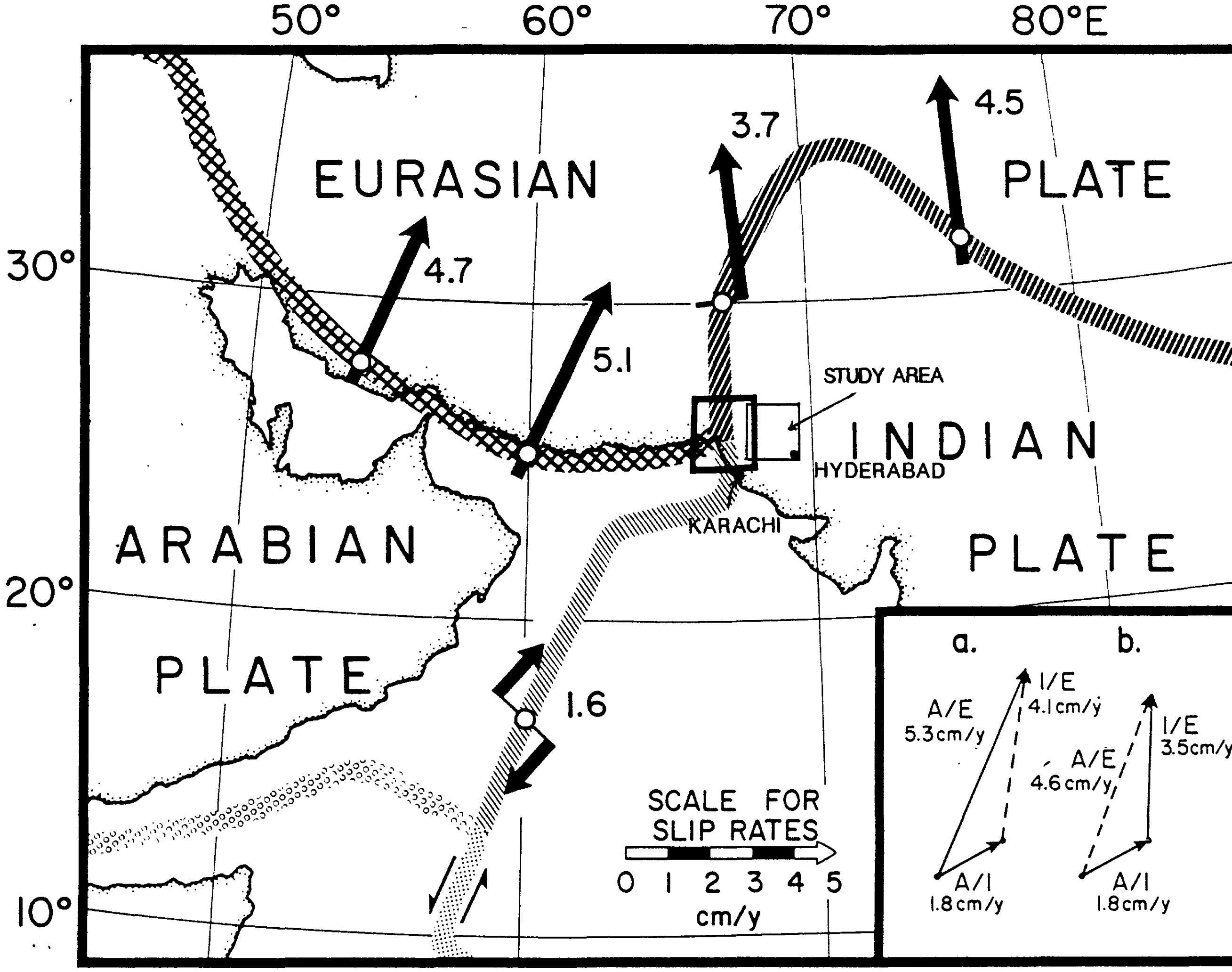
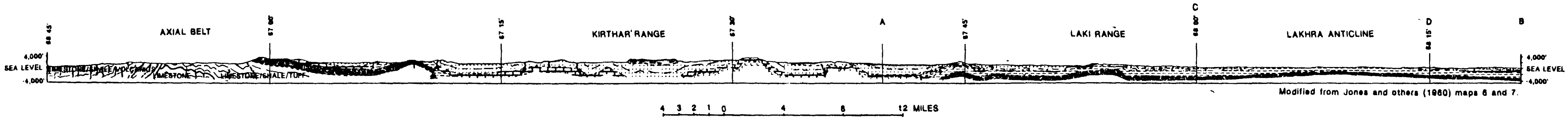


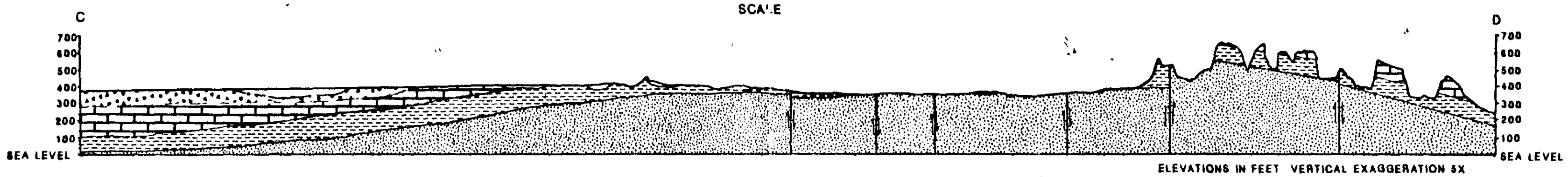
Figure 7. Highly simplified and schematic outline of the three major plates (India, Arabia and Eurasia) and estimates (in cm/ yr) of vectors for relative plate motions across the assumed plate boundaries computed after data from McKenzie and Sclater (1971), McKenzie (1972), and Minster *et al.* (1974).

The insert (lower right corner) shows two alternative vector diagrams, a and b, for the relative motions between the Indian (I), Eurasian (E) and Arabian (A) plates at the proposed triple junction (boxed area). Note that the computed slip vectors at the plate boundaries are valid only if the interior of plates are completely rigid.

Figure 8. Structural cross sections of the region from the Axial Belt to the Indus River and of the northern part of the Lakhra anticline. See Figure 2 for location of the sections.



Modified from Jones and others (1960) maps 6 and 7.



GENERALIZED SECTION ACROSS THE NORTHERN PART OF THE LAKHRA ANTICLINE, SIND, PAKISTAN

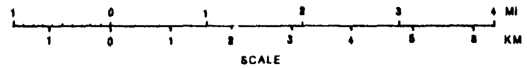


Figure 9. The Band Vera fault scarp. The Laki Formation of Paleocene to Eocene age forms a 1.3 to 1.7 m (4 to 5 ft) scarp. Beds in the foreground are Manchhar Formation of Pliocene to Pleistocene age. The Urdu word band or bund means dam, embankment, or levee.

Figure 10. Line of bruised rock showing fault line east of Band Vera

of the Laki Formation accumulated but lagged behind rate of subsidence during accumulation of the Laki Formation. The rate of deposition increased slightly, or sea level fell slightly, leading to the deposition of the Tiyon Formation, a shelf deposit like the Lakhra Formation and decreased again, or sea level rose slightly, leading to the deposition of the Brahui Formation, a lagoonal or shallow marine deposit like the Laki Formation. Regional uplift occurred, probably in the Middle Oligocene and probably as an early effect of the plate collision, which had its greatest effect east of the present Laki Range, and the Brahui and Tiyon Formations and part of the Laki Formation were eroded. Regional subsidence began again in the Late Oligocene and the marine Nari Formation was deposited. The Nari Formation is about 900 m (3,000 ft) thick in the Laki Range and very likely covered the site of the Lakhra anticline. The top of the Nari is absent west of the site of the Lakhra anticline and regional uplift after Nari deposition may have led to its erosion. The Nari is completely absent in the Lakhra anticline, undoubtedly because it was eroded, and the Manchhar lies on units as old as the Lakhra Formation. The Manchhar Formation was deposited over the entire region and is involved in recent folding and faulting.

Geomorphology

Low rounded hills and broad lowlands form on the nonresistant strata of the Bara Formation. Broad benches form on shale and sandstone of the Lakhra Formation; beds of limestone form ledges and underlie dip slopes. The generally nonresistant Sohnari Member of the Laki Formation crops out in low, rounded hills and in steep slopes of shale, siltstone, and sandstone under the scree of the overlying limestones. The limestone beds of the Laki Formation are cliff-formers where thick and ledge-formers elsewhere. They underlie extensive dip slopes that are interrupted by steep-walled gullies on the downhill side and shale slopes and ledges of thin limestone on the uphill side. No distinctive topography occurs on the Manchhar Formation. Dissected, generally level benches, terraces, and pediments and the large, gently sloping alluvial fan of Lakhra Nala are formed of older alluvium. Sediments in stream and river valleys and flood plains and most alluvial fans are composed of Recent alluvium.

Most streams on the Lakhra anticline flow down the dip slopes away from its topographic crest. An exception is the Lakhra Nala - Siph Nala drainage system. Lakhra Nala drains the breached crestal area and, along with Siph Nala, an extensive area to the west. Together they comprise the largest drainage basin associated with the Lakhra anticline.

Alluvial terraces are abundant in the breached area of the Lakhra anticline. They extend from near Band Vera in Siph Nala on the western side of the anticline into the Lakhra Nala gorge on the eastern side. At least three levels of terraces are present in the 9 to 12 m (30 to 40 ft)of exposure above the bed of the nala.

A large alluvial fan on the east side of the Lakhra anticline is extensively dissected by Lakhra Nala and the upper end of the fan has been largely eroded away. Where the stream emerges from its gorge through the anticline, it flows on bedrock but through a wide channel cut into the lower part of the fan, it flows on Recent alluvium. The most distal part of the alluvial fan is covered by Recent alluvium of the Indus River flood plain (fig. 2).

Small ridges, lines of broken and bruised rock, and lakes and ponds along blocked streams are formed by north-trending normal faults that are abundant in the northern part of the Lakhra anticline. A rock ridge uplifted by a fault crossing Siph Nala at Band Vera blocked the stream and formed a lake. The British improved the dam by building a wall to even out the crest of the ridge and by adding a spillway so that flow over the dam could be controlled (fig. 9). A ledge of rock along another fault blocks Siph Nala about 4 km (2.5 mi) below Band Vera, creating a pond about 0.5 km (0.3 mi) long above the fault and a dry stream below.

History of the Lakhra anticline

Evidence bearing on the history of the Lakhra anticline includes: 1) the characteristics of the Sohnari Member of the Laki Formation, 2) the change in thickness of the Lakhra Formation from place to place, 3) the stratigraphy of the marine section of the Laki Formation, 4) the ages of the units involved in the folding of the Lakhra anticline, and 5) the geomorphic evidence. The first person to consider any of these lines of evidence in detail was Nuttall (1925) and his interpretation has been followed ever since. New data makes another interpretation feasible and necessary.

Nuttall (1925) stated that the striking red unit at the base of the Laki Formation was a laterite, the Basal Laki Laterite (now called the Sohnari Member), and represented "a land period accompanied by erosion, between the marine deposition of the Upper Ranikot and that of the Laki series."

Core drilling by the GSP and the USGS has provided new evidence on the nature of the Sohnari Member. It is now thought to be a subaerial, coal-bearing unit, and the cores show an unbroken upward stratigraphic progression from limestone through shale, silt, sand, underclay, coal, shale, and limestone, with repetitions in the sequence. There is no evidence of erosion in the cores studied. The reddish colors on the outcrops probably are due to iron oxide that resulted from weathering of pyrite in the beds overlying the coal.

Nuttall (1925) stated that the hiatus represented by the Basal Laki Laterite is least near Thatta and increases northward and westward. The Upper Ranikot, or Lakhra of present usage, thins northward and northwestward from near Meting (Nuttall, 1925).

Interpretation of drilling data indicates that the Lakhra Formation thickens northward from near Jherruck and southward from the Lakhra area, and is thinnest near Tando Muhammed Khan (fig. 5). It appears to thin northwestward in the northern part of the Lakhra anticline. It is likely present and fairly thick between Baran Nai and Siph Nala (Fig. 5). The thickness data does not support Nuttall's hypothesis of erosional removal of the Lakhra Formation across the Lakhra anticline because the Lakhra Formation is thick where Nuttall claimed it should be thin.

Nuttall (1925) stated that successively younger units of the Laki Formation overlap successively older units of the Ranikot Formation northward from Thatta. This is based on the disappearance of the Meting Limestone and Shale northward, so that, in the Laki Range, Laki Limestone overlies Lower Ranikot. Nuttall used studies of larger foraminifera to support his finding of a hiatus between the two formations.

Our studies show that the Meting Limestone Member of the Laki Formation is thick and extends entirely across the Lakhra anticline. Usmani (1983) has studied the smaller foraminifera in cores from two drill holes in the Lakhra anticline and found that the lowest16.5 m (54 ft) of the Laki Formation is in the *Globorotalia pseudomenardii* planktonic foraminiferal zone of late Paleocene age. Her findings do not support a large hiatus between the Lakhra and the Laki Formations.

Geologic mapping by Jones and others (1960) and Rafiq Ahmed Khan (GSP, unpublished ms.) shows that the youngest pre-Recent unit involved in the rising of the Lakhra anticline is the Manchhar Formation or Siwalik Group of Pliocene to Pleistocene age. The Manchhar Formation is a widespread, partly marine unit, with many possible sources and environments of deposition but, in the vicinity of the Lakhra anticline, it is thought to be alluvium from one or more riverine systems (Jones and others, 1960).

After the Manchhar was deposited, the topography of the region probably was very much as it now is west of the Lakhra anticline. Low gradient streams drained the plains and flowed eastward. Much of the Manchhar Formation was eroded during this period. Erosion of the Manchhar suggests that uplift of the Lakhra anticline began in the middle to late Pleistocene.

The Lakhra anticline is considered to be the most distant of a series of folds resulting from the ongoing collision of the Indian, Eurasian, and Arabian plates (fig. 1). A source of the horizontal thrust, to which the Lakhra anticline is thought to be a response, is the ongoing collision of the Arabian plate with the Indian plate (fig. 7).

Several features suggest that the Lakhra anticline is still rising.

Most of the streams flowing across Lakhra anticline had very small drainage basins and were diverted as the anticline rose. The stream through Lakhra Nala maintained its course by eroding a gorge through the anticline as it rose. The streams that occupy Lakhra Nala and Siph Nala are still actively downcutting bedrock.

On the east side of the Lakhra anticline the stream that formed Lakhra Nala deposited an extensive alluvial fan that extends into the Indus flood plain. The stream is entrenched in the alluvial fan and is now cutting bedrock of the Lakhra Formation near the head of the fan. Erosion of an alluvial fan would be expected if the base level of the stream were lowered, but the level of the Indus River is the base level for the stream in Lakhra Nala and the Indus River, along with its flood plain is aggrading. A second alternative is to steepen the alluvial fan, which evidently is what is happening.

The northern part of the Lakhra anticline is replete with surface indications of faulting. Some of the traces are exhumed faults, but others are fresh surface traces (fig. 10). The faults crossing Siph Nala interrupt the gradient of the stream. If they had not occurred fairly recently, the stream would have restored its gradient.
Thus, if the faults are extensional features related to anticlinal growth, they clearly indicate continued movement.

Seismicity may indicate ongoing tectonic activity and appears to be active in the area of the Lakhra anticline. The strongest recorded earthquake in the vicinity of Hyderabad had an intensity of VI (Quittmeyer and others, 1979). Earthquakes of intensity II to III occur in the area every few weeks, based on reports from the earthquake observatory at the University of Sind, which is on the east side of the Lakhra anticline.

Conclusions

Beds of the Manchhar Formation of Pliocene to Pleistocene age were uplifted on the Lakhra anticline, indicating that movement on the anticline is Pleistocene or younger. A modern transcurrent stream on the anticline is currently dissecting its own alluvial fan. Fault scarps locally interrupt the gradients of streams in the area.

The amount and rate of folding and faulting of the anticline are estimated by making three assumptions: (1) that Siph Nala and Lakhra Nala formed after deposition of the Mahchhar Formation; (2) That the streams remain near grade; and (3) that total rise of the Lakhra anticline is the same as the combined thicknesses of the exposed formations plus the accumulated thickness of the Indus River alluvium and the amount of sea-level rise in the past 5,000 years.

The thicknesses involved are: 1) 15 m (50 ft) of Bara exposed along Siph Nala, 2) 170 m (560 ft) of Lakhra exposed along Siph Nala, 3) 40 m (130 ft) of Sohnari projected near Siph Nala from isopachs, 4) 100 m (330 ft) of Laki estimated from drill hole data, 5) 15 m (50 ft) of Manchhar estimated from present outcrops, and 6) 15 m (50 ft) of silt accumulation on the Indus flood plain above present sea level, for a total of about 355 m (1160 ft) of rise of the Lakhra anticline.

A rate of rise can be estimated assuming that the anticline has risen at least 30 m (100 ft) in the past 5000 years, based on 15 m (50 ft) of sea level rise (Imbrie, 1985) and 15 m (50 ft) of silt accumulation on the Indus flood plain. This rate of 6m / 1000 yrs is likely to be low because the place where it was estimated is about 16 km (10 mi) from the axis of the anticline, but, at that rate, it should have required about 60,000 years to raise the anticline to its present height.

Much more work needs to be done in this interesting area. In particular, a series of tilt meters on the east side of the anticline might show the current rate of tilting and rise of the anticline and a series of level lines surveyed across the anticline might document the movement of faults in the anticline. If the terraces along Lakhra Nala and Siph Nala were surveyed carefully, their levels might help document periods of movement on the anticline.

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