THE GEOLOGY OF THE WESTERN LIMB OF THE HAZARA-KASHMIR SYNTAXIS, WEST PAKISTAN AND KASHMIR

by

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INTRODUCTION

Location of the Area Studied

The area studied lies on the western limb of the Hazara-Kashmir syntaxis in the Himalaya of northern Pakistan and western Kashmir, and it extends from Muzaffarabad in Kashmir westward to the Indus River (fig. 1). Detailed geological surveys occupy about 200 square miles in the eastern part of the area (fig. 1, areas A and B), and a special study of fracture traces occupies about 450 square miles in the western part of the area (fig. 1, area C).

Importance of the Present Study

One of the most remarkable large-scale features of the northwest Himalaya is the Hazara-Kashmir syntaxis, the great structural loop marking the western end of this mountain range (fig. 1). Very little previous work has been done in this area; therefore, the study of part of the western limb of the Hazara-Kashmir syntaxis is a contribution towards a better understanding of this unusual geologic feature.

General Statement of the Problem

The problem in general terms was to obtain detailed geologic information within a specific area on the western limb of the Hazara-Kashmir syntaxis, and, with this information as a basis, to generalize as far as possible on the development of the Hazara-Kashmir syntaxis as a whole.

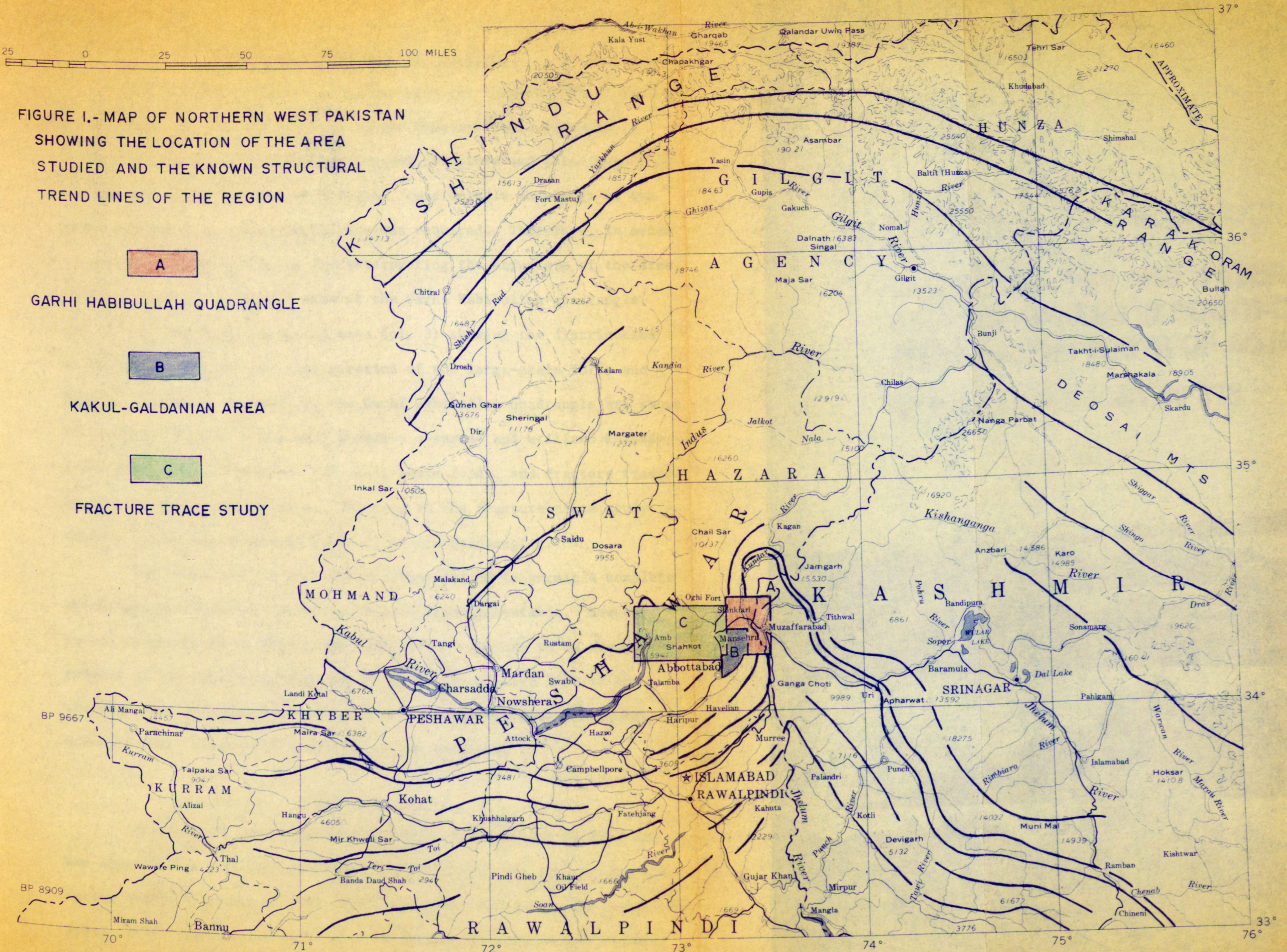

FIGURE 1.- MAP OF NORTHERN WEST PAKISTAN SHOWING THE LOCATION OF THE AREA STUDIED AND THE KNOWN STRUCTURAL TREND LINES OF THE REGION

Scope and Limitations of the Study

The work is concerned primarily with the large and small geologic structures along the western limb of the Hazara-Kashmir syntaxis. Because of the close relationship between structure and stratigraphy in the geological development of a region, considerable knowledge of the local and regional stratigraphy also was required. Therefore, in order to provide an adequate basis for interpreting the structure of the area, detailed geologic maps were made of the Garhi Habibullah quadrangle (pl. 1) and the Kakul-Galdanian area (pl. 3) showing the distribution of the rock units and the configuration of the large-scale folds and faults. Structure sections of the Garhi Habibullah quadrangle are shown in plate 2. Smaller structural elements observed and utilized include joint directions, lineations and small-scale folds, and fracture traces as seen on aerial photographs. The area of the fracture-trace study extends across approximately three 15 minute quadrangles.

The study area is not of sufficient extent to permit a complete structural synthesis of the entire Hazara-Kashmir syntaxis. However, enough is now known to allow some definite conclusions to be drawn with respect to the structural development along the western limb of the syntaxis, and to propose a tentative hypothesis regarding the overall movement which caused the formation of the syntaxis.

Schedule of Work

The present investigation was begun in the spring of 1962 and was completed in the fall of 1966. The field work was done during the spring and fall months of 1962, 1963, and 1964, and during the month of April, 1965. Laboratory work was done during the summers and winters of 1962-1965 while in Pakistan, and was completed in the United States in 1965 and 1966. The work was done as part of a cooperative geological survey program of the U.S. Geological Survey and the Geological Survey of Pakistan under the auspices of the U.S. Agency for International Development. The author was assisted on some field trips during 1962 by M. I. Durazzai, Geological Survey of Pakistan, and during June, 1963 by A. S. Abdul Matin, Geological Survey of Pakistan. Where possible the author operated out of Government Rest Houses located in the larger villages and in the Forest Reserve. In certain remote areas he lived in tents or in mountain villages.

The base map used for the field work in the Garhi Habibullah quadrangle was the Survey of Pakistan 15 minute topographic sheet 43-F/7 enlarged 50 percent to a scale of 1:31,680. In the Kakul-Galdanian area the base map was a special stereo-compilation at a scale of 1:12,000, made by the Photogrammetric Group, Geological Survey of Pakistan. The map of the fracture traces is a planimetric map constructed from aerial photographs.

Previous Work

Most of the previous knowledge of this area comes from studies of four members of the Geological Survey of India: Waagen, Wynne, Middlemiss, and Wadia. The earliest report is that of Waagen and Wynne (1872), who investigated an area of about four square miles just outside of Abbottabad (fig. 1). A more extensive report by Middlemiss (1896) was based upon a reconnaissance geologic survey extending from the Kunhar River westward to the Black Mountains on the west bank of the Indus (fig. 1). These early workers established the broad stratigraphic framework in the southern Hazara District, and named many of the rock units.

The only previous study of the Hazara-Kashmir syntaxis itself is the remarkable work of Wadia (1931), who recognized the continuity of the lithologic units around the periphery, and proposed a theory for its origin and development.

No geological work was done in the Hazara area during World War II. In 1948 to 1951 three members of the newly formed Geological Survey of Pakistan mapped the rock types in parts of several quadrangles, but this work was never finished.

More recently, a few geological reports relating to this area have been published by the Punjab University. These include: a brief account, with map, of the Mansehra quadrangle, 15 miles north of Abbottabad (Shams, 1961); a short report, and map, of a small area around Abbottabad (Marks and Ali, 1961); a study of the stratigraphy near Tarbela, 20 miles west of Abbottabad (Ali, 1962); a gravity study near Mansehra (Rahman, 1961); and several short but informative notes on the stratigraphy and paleontology of the region.

Specific Statement of the Problem

When the present investigation was begun, very little detailed information was available in the Hazara-Kashmir area. Limited reconnaissance work done prior to 1940 had established the broad geological outlines of the region and many of the rock units had been named, but no detailed information existed, and, although the shape of the syntaxis was known, structural information along the western limb was completely lacking.

The present study was undertaken in order to shed more light on the geology, especially the structural geology, of this little known part of the Himalaya. Contributions to the geologic knowledge of the area are offered on the following specific subjects:

1. Integration of the metamorphism and metamorphic structures into the geological development of the area.

2. The configuration and implications of the fold and fault systems on the western limb of the syntaxis.

3. The relation of the joints and fracture traces in the area to the structural pattern as a whole.

4. Hypothesis for the development of the syntaxis.

Culture, Accessibility and Climate[1]

Abbottabad (population, 75,000), just a few miles southwest of the area and 75 miles north of Rawalpindi, is the main town in the region, and the northernmost point in Pakistan where normal commercial activities are carried out. Headquarters for large contingents of the Army, political seat of the Hazara Political District, and home of the Army Cadet College, Abbottabad is surprisingly modern in aspect, and provides permanent residence for a few Western technicians and teachers, and accommodates many native tourists during the summer months.

Other small towns in and near the area studied are Mansehra, Garhi Habibullah, and Muzaffarabad. Muzaffarabad, located in the eastern part of the area, is the capital of Pakistani Kashmir (fig. 2). The innumerable small villages which dot the countryside are primitive clusters of mud huts connected by footpaths. Except for residents of Abbottabad and Mansehra, the people live a simple agrarian life centered around their individual villages and are little affected by outside

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1. Statements in this and the following section apply mainly to the area covered by the geologic maps of the Garhi Habibullah quadrangle (plate 1), and the adjacent Kakul area (plate 2).

Figure 2. VIEW OF MUZAFFARABAD, CAPITAL OF PAKISTANI KASHMIR

influences.

Despite the extremely mountainous terrain, the southern Hazara region contains a surprising number of roads, which provide a first approach to much of the area studied. Large rugged tracts between the roads, however, are accessible only by footpath, and require the packing in of tents and supplies. Paved roads in the area studied include the Hazara Trunk Road, connecting Abbottabad, Garhi Habibullah and Muzaffarabad; the Murree-Muzaffarabad road along the Jhelum River; and the parallel roads on both sides of the Siran River. Dirt roads follow the Kunhar and Kishanganga Rivers; another connects Abbottabad with the high village of Thandiani in the southern part of the area; and a fourth extends northward from the Hazara Trunk Road to the sheep farm at Jaba. In the intervening areas innumerable footpaths connect the villages and cross all mountain passes.

In general the climate is temperate with hot summers and mild winters, but it varies markedly with altitude, and is considerably modified by the summer monsoon. The early summer is hot and dry, with daytime temperatures reaching 110 degrees Fahrenheit below elevations of 2,000 feet. Above 7,000 feet, however, the summer days are cool and pleasant. During the summer monsoon, which begins in mid-July and ends in mid-September, temperatures moderate somewhat, but the humidity becomes uncomfortably high and the resulting climate is extremely unpleasant in the lower elevations.

Precipitation in the Abbottabad area is approximately 50 inches per year, half of it falling during the summer monsoon. Most of the remainder falls during January, February, and March. In Abbottabad most of the winter precipitation is rain, with only occasional light snow. Above 7,000 feet, however, deep snow accumulates, which lingers until April, May, or June, depending upon the altitude. In the higher mountains to the north, the permanent snow line is at an elevation of about 15,000 feet.

The generally mild and moist climate supports a forest of pine trees above 5,000 feet, although the stand of timber is not dense in most places because of the thin soil.

Topography and Drainage

Rugged mountains and deep V-shaped canyons characterize most of the area (pl. 1). Maximum topographic relief is about 7,500 feet between the highest elevation at Pir Chela (9,473 feet) in the north-eastern part of the area and the lowest elevation of 2,000 feet on the Jhelum River at the southeastern edge of the area. Local relief commonly exceeds 3,000 feet and in places is over 6,000 feet. Photographs showing the general nature of the terrain are shown in figures 3 and 4.

The area is drained by the Siran, Kunhar, Kishanganga, and Jhelum Rivers. The Kishanganga joins the Jhelum at Muzaffarabad and both rivers flow in deep canyons through the area (fig. 5a). The Kunhar River joins the Jhelum five miles south of Muzaffarabad, flowing the final six miles through a gorge (fig. 5b).

The ridges trend generally north or slightly west of north and form two topographic divides in the area. One divide is between the Kunhar and Kishanganga Rivers marking the boundary between Pakistan and Kashmir, and the second is an irregular and obscure divide separating the drainage eastward to the Kunhar and Jhelum Rivers from the drainage westward to the Siran River. This latter divide is obscured by extensive headward erosion of many second order streams which themselves

Figure 3a. TYPICAL TOPOGRAPHY IN THE MAP AREA

View looking northeast toward the high divide in the vicinity of the Sattu Resthouse

Figure 3b. MOUNTAINS OF THE SYNTAXIAL BEND

Mountains are 15 miles north of Mussafarabad

Figure 4a. RUGGED MOUNTAINS OF THE GALDANIAN AREA

Figure 4b. 1,200 FOOT CLIFF ALONG THE KISHANGANGA RIVER, THREE MILES NORTH OF MUZAFFARABAD

Figure 5a. CANYON OF THE KISHANGANGA RIVER, SIX MILES NORTH OF MUZAFFARABAD

Figure 5b. CANYON OF THE KUNHAR RIVER, NEAR ITS CONFLUENCE WITH THE JHELUM

have formed deep canyons and numerous secondary spurs oblique to the overall topographic trend. The ridges and secondary spurs commonly have rounded tops a few hundred feet wide which are favored sites for small villages.

Nearly all of the landscape is in slope. The only relatively flat areas are a few small terraces along the four main rivers, and the dissected eastern edge of an intermontane basin, called the Mansehra Plain, in the western part of the area. Slopes are uniform and in most of the area range from 20 to 33 degrees, averaging 28 degrees. In many places, particularly in the Kishanganga and Jhelum River drainage areas, many of the slopes are 38 to 40 degrees.

The four main rivers flow generally southward away from the Himalaya. The Kishanganga and Jhelum Rivers cut into bedrock over most of their courses. The scanty deposits of alluvium north and south of Muzaffarabad have been incised by these rivers, and remnants stand as boulder terraces 100 to 300 feet above the present river level. The lower part of the Kunhar River is cutting into bedrock, but north of Didal, the river flows in a narrow meander belt containing discontinuous deposits of Pleistocene and recent alluvium. The meander belt of the Siran River is somewhat wider and is bordered by continuous strips of alluvium.

The Kishanganga and Jhelum Rivers are extremely fast flowing and turbulent streams, and Kunhar less so. The Siran, being close to the local base level of the Mansehra Plain just west of the map area, is relatively mild by comparison. Figure 6 shows the Jhelum River at a cable crossing five miles south of Muzaffarabad. The gradient of the Kishanganga River above Muzaffarabad is 58 feet per mile, and that of

Figure 6. THE TURBULENT JHELUM RIVER

At a cable crossing, five miles south of Muzaffarabad: June normal flow the Kunhar River north of Garhi Habibullah is 38 feet per mile. Small side streams, unable to keep up with the rapid downcutting of the Kishanganga and Jhelum Rivers, form waterfalls as much as 150 feet high at their confluence with the main rivers; the larger creeks, however, enter the main rivers at grade. Most of these main creeks (second order streams) have flat sandy beds with gradients only slightly greater than the main rivers. The upper reaches of the main creeks, however, and many smaller side creeks, contain cascades, waterfalls, and huge boulders along their courses, and are difficult, in places impossible, to traverse.

In general the topographic trend reflects the structural trend. The overall northward trend of the ridges and the courses of the main rivers reflect the similar trend of the geologic structure. The Kishanganga River follows the bend of the syntaxis; the sharp bend in the Jhelum--from a northwest course as it enters the map area, to south along the eastern edge of the map area--is a reflection of a sharp kink in the regional structural trend. The Kunhar River also follows the structural trend across two thirds of the map area, but it cuts across the geologic structure in its lower course. Another notable exception to the correspondence between topography and geologic structure is the oblique angle at which the geologic units cross the main ridge in the northeast part of the area. Small side streams tend to flow directly downslope, and are apparently controlled more by gravity than by structure. Beyond the foot of the main steep slope, however, many of the larger creeks and segments of the main rivers follow joints, faults, and other lines of weakness in the rocks.

Acknowledgements

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GENERAL GEOLOGIC SETTING

The Indian region is made up of three distinct geologic and physiographic earth features: 1) the plateau of the Indian peninsula, composed of metamorphic and igneous rocks of the Precambrian shield, together with the Deccan Trap; 2) the mountainous region of folded rocks to the north, west, and east of the Indian peninsula, called the extra-Peninsula (Wadia, 1957); 3) the great Indo-Ganges Plain, an alluvial-filled structural depression separating the Indian Peninsula from the mountains.

The mountainous region of folded rocks was once a great marine trough called the Tethys Sea (Suess, 1904, Sollas translation), which existed, undisturbed by orogenic movements, from the Late Precambrian until the Middle Tertiary. Beginning in the Oligocene or Miocene and lasting to the present time, the marine and later continental deposits which filled the trough were folded into the present complex system of mountains, while the Precambrian shield of the Indian Peninsula was unaffected.

The mountainous region consists of many individual ranges, which together form a continuous chain 1,500 miles in length and 100 to over 200 miles in width across northern India and Pakistan. Well known individual ranges include the Karakoram, Hindu Kush, and Ladakh ranges, as well as the Great Himalaya itself. In the region of Hazara, the Gilgit Agency, and Hunza State (fig. 1), the mountain system describes a great arc, changing its trend from northwest across northern India to west and southwest across Afghanistan and the western frontier of Pakistan. This great arc of the Himalaya increases in curvature southward until in the Hazara-Kashmir region it becomes a tight, hairpin bend barely 10 miles in width, which is called the Hazara-Kashmir syntaxis. This structure was originally named "syntaxis" by Suess (1904, Sollas translation), and later the "Syntaxis of the northwest Himalaya" by Wadia (1931).

The area studied lies on the western limb of the Hazara-Kashmir syntaxis. The mountain ranges, rock units, and a system of boundary faults follow around this bend of 180 degrees, and then turn westward towards Peshawar and Kohat (fig. 1). The final development of the syntaxis was in post-Miocene time because the Murree formation (Miocene) is involved.

Within the area studied the rocks range in age from Precambrian to Tertiary, and include sedimentary, igneous, and metamorphic rocks. Regional stratigraphic correlation of many of the rock units has been established with nearly identical stratigraphic sections as far west as Peshawar and Kohat, and to a limited extent with stratigraphic sections in Simla, India, 200 miles to the southeast, and in Kashmir.

The rock units of Precambrian and Early-Paleozoic age are mainly clastic. A long interval primarily of carbonate deposition, extending from Carboniferous to Eocene time, is recorded in a sequence of rock units totaling over 5,000 feet in thickness. Beginning in Middle-Tertiary time detrital rocks again became dominant, reflecting the beginning of the Himalayan Orogeny, which ultimately deformed all rocks in the region.

Within the mapped area the geologic structure is divisible into three main areas or blocks separated by major boundary faults. The stratigraphy differs among these blocks and structural evidence indicates that they have moved as individual blocks relatively southward in a left-lateral sense along the main boundary faults.

The main episode of igneous activity within the mapped area took place in Late-Cretaceous and Early-Tertiary time, and resulted in the synorogenic intrusions of the Mansehra granite. These granite bodies are here considered to represent the southern fringes of the extensive granitic intrusions in the axial zone of the Himalaya. Pre-Tertiary igneous activity is recorded a few miles north of the mapped area, however, in a thick sequence of volcanic greenstones of Carboniferous and Permian age.

Regional metamorphism has affected the rocks of the stratigraphic sequence up to and including the Tanawal formation of Silurian-Devonian age. Although younger rocks display geometric and directional homogeniety of structure with respect to the metamorphic rocks, they have not been metamorphosed, perhaps because they were at too high a level in the crust during metamorphism. In general, regional metamorphism increases to the north and northwest. Slate, phyllite, and quartzose schists prevail in the map area, and less than 15 miles to the north sillimanite-quartz schist is found. A few miles to the south the Precambrian rocks are shales which are essentially unmetamorphosed. Stratigraphic information indicates that considerable tectonic activity took place in pre-Tertiary time, but it did not involve penetrative deformation associated with metamorphism. The structural homogeniety displayed between metamorphosed and unmetamorphosed rocks, the existence of essentially unmetamorphosed Precambrian rocks to the south, and the involvement of the Mansehra granite in the deformation, all indicate that regional metamorphism and deformation took place as a single event during the Himalayan orogeny. If an older period of metamorphism took place in this area, no indication of it was seen.

Contact metamorphism in the rocks adjacent to the Mansehra granite has been slight. In some places a narrow zone of cordierite and andalusite schist is present, but in other places virtually no contact effects are evident.

STRATIGRAPHY

Introduction

Because of the complex structure in this region, no single stratigraphic column gives a true picture of the stratigraphic arrangement for the area as a whole. The mapped area contains parts of three structural areas or blocks with different stratigraphy. These structural blocks are: the axial zone of the syntaxis, which lies east of the Jhelum fault; the Garhi Habibullah syncline between the Jhelum and Tarnawai faults; and the area west of the Tarnawai fault. Columnar sections showing the stratigraphic relations among the three structural areas are shown in figure 7.

The descriptions of the stratigraphic units in the following pages is based on the information from all three areas. The rock units shown on the explanations of plates 1 and 3 are composite sections arranged according to geologic age.

Hazarā Formation

The various names given to the thick and widespread sequence of black and brown slate, phyllite, and graywacke sandstone of Precambrian age that underlies large tracts between Kashmir and the Indus River include "Attock Slates" (Waagen and Wynne, 1872); "Slate Series of Hazara" (Middlemiss, 1896); and "Hazara Slate Formation" (Marks and Ali, 1961). In this report these rocks are called the Hazara formation.

The rocks of the Hazara formation crop out on both sides of a

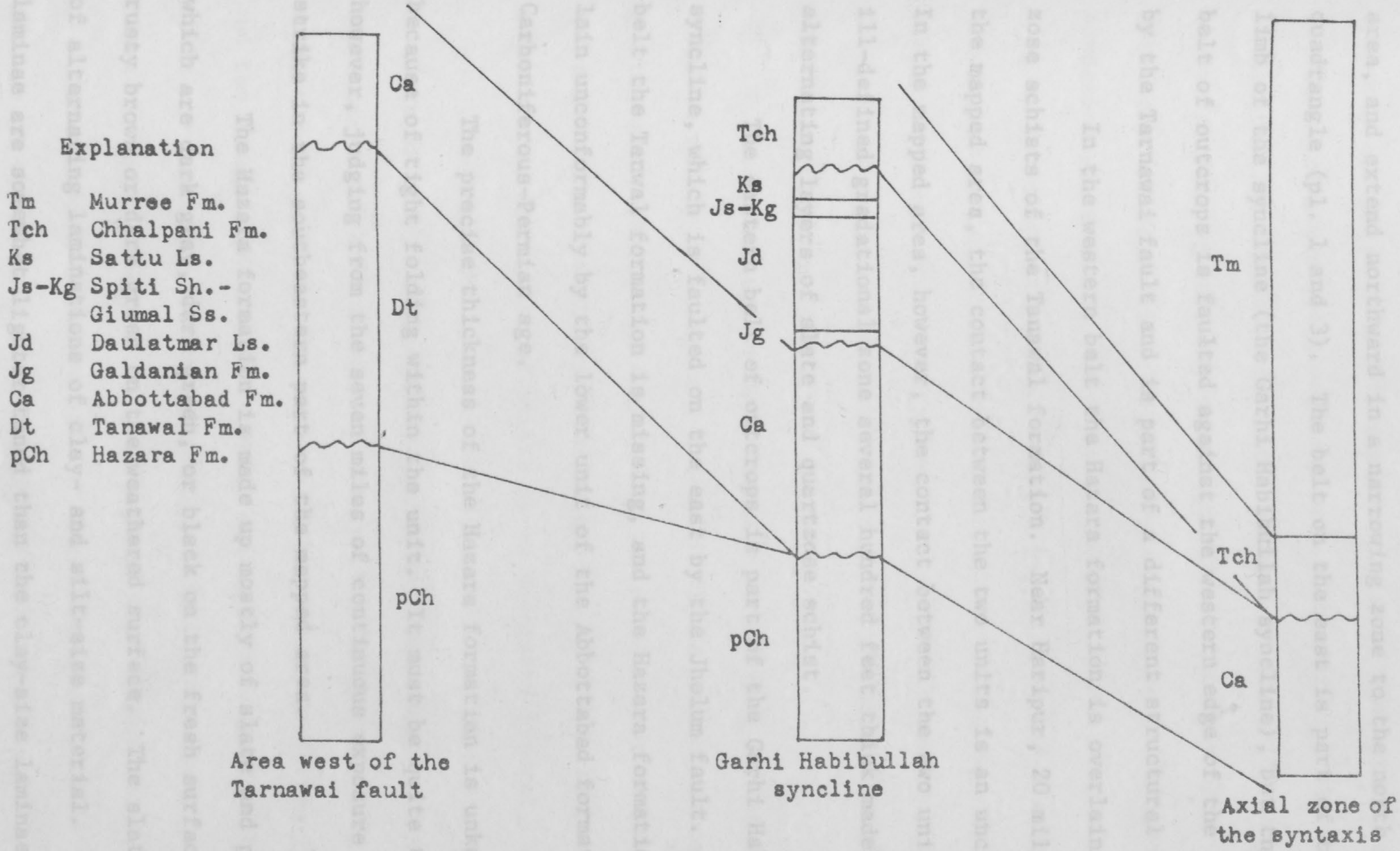


Figure 7.- Columnar sections in the three structural blocks of the Garhi Habibullah area, Hazara District, West Pakistan. Undulating lines represent regional unconformities.

synclinal trough of younger rocks in the southern half of the mapped area, and extend northward in a narrowing zone to the north edge of the quadrangle (pl. 1 and 3). The belt on the east is part of the east limb of the syncline (the Garhi Habibullah syncline), but the western belt of outcrops is faulted against the western edge of the syncline by the Tarnawai fault and is part of a different structural block.

In the western belt the Hazara formation is overlain by quartzose schists of the Tanawal formation. Near Haripur, 20 miles west of the mapped area, the contact between the two units is an unconformity. In the mapped area, however, the contact between the two units is an ill-defined gradational zone several hundred feet thick made up of alternating layers of slate and quartzose schist.

The eastern belt of outcrops is part of the Garhi Habibullah syncline, which is faulted on the east by the Jhelum fault. In this belt the Tanwal formation is missing, and the Hazara formation is overlain unconformably by the lower unit of the Abbottabad formation of Carboniferous-Permian age.

The precise thickness of the Hazara formation is unknown because of tight folding within the unit. It must be quite thick, however, judging from the seven miles of continuous exposure across the strike in the southeastern part of the mapped area.

The Hazara formation is made up mostly of slate and phyllite which are dark gray, dark green, or black on the fresh surface, and rusty brown or dark green on the weathered surface. The slates consist of alternating laminations of clay- and silt-size material. The silty laminae are somewhat lighter toned than the clay-size laminae, and occasionally display cross-bedding. The phyllite layers contain a higher percentage of mica and chloritic minerals than the slate and commonly are green. In thin sections, most of these rocks show well-developed alignment of elongate quartz blobs and clay minerals or micas in alternating laminae. Accessory calcite in disseminated grains is characteristic of some layers. Magnetite is the only other notable accessory. Beds of fine- to medium-grained thick-bedded graywacke sandstone are found in places, but sandstone is not common.

Two distinctive rock units, a gypsum unit and a limestone unit, are mapped as separate members of the Hazara formation. The two members extend northward from the southeast corner of the quadrangle to about three miles northwest of Muzaffarabad. West of Muzaffarabad the two members nearly merge (pl. 1).

The gypsum unit ranges from 100 to 400 feet in thickness and consists mainly of orange and green, thinly laminated, calcareous gypsum, and lesser amounts of thinly laminated contorted gray limestone and a few beds of white crystalline gypsum. The beds of pure gypsum contain scattered cubes of pyrite as an accessory mineral.

The limestone unit, which is as thick as 500 feet in places, consists of gray, shaly, thinly laminated limestones contorted into small-scale folds (crinkles) by penetrative deformation (fig. 8). The eastern contact of the limestone with the Murree formation is a fault, and the western contact is a normal sedimentary contact with black slate and phyllite. Another limestone bed, 10 feet thick and 200 feet above the main limestone unit, is exposed in a canyon two miles south of Muzaffarabad on the west side of the Jhelum River. This limestone also is in sedimentary contact with the adjacent slate.

The Hazara formation recently was considered to be a product of

Figure 8. LIMESTONE UNIT OF THE HAZARA FORMATION

Showing contortion into small-scale folds turbidity-current deposition, similar to the Alpine "Flysch," on the basis of graywacke layers, graded bedding, and sole marks (Marks and Ali, 1961). However, the presence of limestone, graphite schist, and even gypsum, certainly is unusual for a turbidite sequence. Most of the formation probably accumulated as an ordinary shallow-water marine argillaceous sequence.

The Hazara formation is thought to be Late Precambrain in age (Stratigraphic Commission, 1957), but as no fossils have been found, the age of this unit is uncertain. This age assignment is based upon its probable correlation with the Dogra Slate of Kashmir, which is overlain by fossiliferous Cambrian rocks (Fermor, 1931). In the mapped area, however, the thick interval of stratigraphic gradation with the overlying Tanawal formation indicates that the Hazara formation may range in age through the Early Paleozoic. In keeping with the present tentatively accepted age, however, the Hazara formation is considered to be primarily Precambrian in age.

On the basis of similar lithology and position in sequence, the Hazara formation is probably equivalent to the Attock Slates in the Peshawar area, the Dogra Slates of Kashmir, and the Simla Slate series of India. Taken together, the outcrop areas of these formations form a nearly continuous belt of slaty rocks along the Himalayan mountain front from the Peshawar area to beyond Simla, India.

Tanawal Formation

The Tanawal formation of Silurian-Devonian age was originally named "Tanol Group" by Wynne (1879) from exposures of the quartzose schists overlying the Hazara formation west of Abbottabad (pl. 1). The name comes from the former Tanol (Tanawal) tribal area north of Haripur, 20 miles west of the mapped area.

The rocks of the Tanawal formation, which are found only in the structural block west of the Tarnawai fault, occupy a belt one to two miles wide between the Mansehra granite and the Hazara formation. These rocks also crop out in small areas in the southwestern and northwestern corners of the mapped area.

Because of tight folding and the absence of marker beds, the exact thickness of the Tanawal formation is unknown. Near Haripur, 20 miles west of the mapped area, Ali (1962) estimates the Tanawal formation to be 5,000 feet thick. The lower contact in the mapped area is gradational with the underlying Hazara formation. The upper parts of the Tanawal formation are intruded by the Mansehra granite everywhere in the mapped area. Near Haripur, however, the Tanawal formation was found to be overlain unconformably by the Abbottabad formation.

The Tanawal formation consists mainly of thickly laminated low- to medium-grade, fine-grained schists containing quartz and mica as the major constituents, and accessory zircon, tourmaline and magnetite. Various combinations of the main minerals, and slight differences in metamorphic grade, from place to place result in a variety of quartzose and micaceous schists. The rocks range from pure white fine-grained quartzose schist with very little mica, to dark quartz-biotite schist containing only small amounts of quartz. Rock types between these two extremes include micaceous quartzite, micaceous quartzose siltstone, brown-weathering spotted biotite-quartz schist, quartzose muscovite or sericite schist, and other related rock types. Cross bedding is seen in a few places in the quartzose types.

Near the contact with the Hazara formation, rocks of the

Tanawal formation commonly contain layers of black slate, and, in places, pure sericite schist. A distinctive schistose type consists of augen of quartz in a matrix of chlorite and sericite which evidently is a metamorphosed conglomerate. Cordierite schist is found in a few places at the contact with the Mansehra granite, and in a few places andalusite occurs. A slight increase in degree of regional metamorphism is evident northward. North of Garhi Habibullah, the schists of the Tanwal formation are coarser grained, and the individual minerals are more fully developed than in the southwestern part of the mapped area, where fine-grained schist as well as essentially unmetamorphosed siltstone and fine-grained graywacke sandstone prevails.

The age of the Tanawal formation is uncertain because no fossils have been found in these rocks. The Tanawal formation overlies the Hazara formation of probable Precambrian or Early Paleozoic age, and underlies the Abbottabad formation of Carboniferous to Permian age. The lithology and stratigraphic position of the Tanawal formation suggest that it may be equivalent to the Muth quartzite of Kashmir whose age is believed to range from Late Silurian to Devonian. On this basis, the Tanawal formation tentatively is assigned a Silurian to Devonian age.

Abbottabad Formation

The Abbottabad formation of Carboniferous-Permian age was so named by Marks and Ali (1962) from the sequence of dolomite and sandstone exposed on Sirban Hill, one mile southeast of Abbottabad (fig. 1). This name supercedes the names "Infratrias" (Middlemiss, 1896), and "Below the Trias" (Waagen and Wynne, 1872).

The Abbottabad formation crops out in two main areas: the highly folded trough of the Garhi Habibullah syncline; and the core of the Muzaffarabad anticline (pl. 1). These two areas are in different structural blocks and exhibit different stratigraphic relationships. In the Garhi Habibullah syncline the Abbottabad formation overlies the Hazara formation unconformably, the unconformity being marked by a well-known boulder conglomerate. The Abbottabad formation is in turn overlain disconformably by the Galdanian formation of Jurassic age. In the Muzaffarabad anticline, Jurassic and Cretaceous rocks are missing, and the Abbottabad formation is overlain unconformably by the Chhalpani formation of Eocene age. The base of the Abbottabad formation is not exposed.

The thickness of the Abbottabad formation is different from place to place. It is about 2,000 feet thick at the type locality in Sirban Hill, four miles southwest of the mapped area (Marks and Ali, 1961); 2,500 feet in the Muzaffarabad area; and only 300 to 400 feet on the eastern limb of the Garhi Habibullah syncline.

In the mapped area, the Abbottabad formation is divided into three units: a dolomite unit, a black limestone unit within the dolomite unit, and a sandstone and conglomerate unit at the base of the formation.

The dolomite unit consists mainly of dense, fine-grained, light gray to black cherty dolomite which weathers gray to white. Some layers are distinctly pink, possibly owing to the presence of manganese carbonate. Bedding ranges in thickness from a few inches to two feet, and the beds themselves are made up of layers and laminae a fraction to a quarter of an inch thick. The rock is highly siliceous and brittle. Chert, which stands out in relief on weathered surfaces, is distributed in bands, lenses, and irregular patches. Chert bands are as long as ten feet. The rock is traversed by innumerable irregular hairline fractures filled with silica, as well as more regular closely spaced joints. For hundreds of feet upslope from the Jhelum and Muzaffarabad faults, the dolomite is shattered into small pieces, which collect into huge talus cones at the foot of steep slopes. Some beds contain rounded sand-size quartz grains disseminated throughout the dolomite, and in a few places thin beds and laminae of pure quartzose siltstone are seen. Beds of intraformational conglomerate occur uncommonly.

The black limestone unit is 400 to 450 feet thick, and is found only in the structural block east of the Jhelum fault. This unit, which is within the dolomite, extends from the east edge of the map northwest across the main divide to a point four miles north of Garhi Habibullah where it is cut off by the Jhelum fault. Its overall black tone stands out in strong contrast to the enclosing white dolomite.

The limestone unit is made up mainly of black, brown-weathering, partly dolomitized limestone; and dense, black, calcareous shale. A section, well exposed in a creek three miles north of Muzaffarabad, is shown in figure 9.

The transition zone at the top, although mainly dolomite, weathers dark gray instead of white and gives a slight effervescence in dilute acid. It is regarded as marking the change from dolomite to dolomitized limestone. A second section much like the first, is exposed in a double waterfall three miles northwest of Muzaffarabad. In this section, some of the limestone is intraformational conglomerate. The contact with the overlying white dolomite at this latter locality is a shear zone obscuring the stratigraphic nature of the contact.

Dolomite, weathering white and gray

20 feet -- Transition zone of dolomite, weathering dark gray

200 feet -- Alternating bands of black limestone and brown dolomite

100 feet -- Black shale, with numerous thin beds of limestone, some dolomitized

50 feet -- Quartzose sandstone with shale partings

Dolomite, weathering white

Figure 9. Stratigraphic section of the limestone unit of the Abbottabad formation

Whether the dolomite is primary or secondary is uncertain, but the abundance of black dolomite, indicating a high content of organic material, and the transition zone between the dolomite and limestone units suggest that most of the dolomite is secondary, that is, dolomitized limestone.

The lower unit of the Abbottabad formation consists of red and white, thin- and thick-bedded quartzose sandstone and siltstone containing a conglomerate at the base. Phyllite in small amounts is seen in places. The total thickness of this lower unit ranges from 200 to 600 feet. The conglomerate bed is a few feet to 50 feet thick, and in places is absent. Between Kalapani and Chure Gali (pls. 1 and 3) the bulk of the Abbottabad formation is missing, and only the lower unit is present. The conglomerate marks the unconformity between the Abbottabad formation and the underlying Hazara formation. It consists of flat elongate fragments of slate, phyllite, siltstone, and graywacke sandstone one inch to as much as two feet in length. The matrix is a green, chloritic, phyllitic material. Close study of this conglomerate in several different places provides information relating to the time of metamorphism of the area. Certain features discussed below suggest that the conglomerate did not come from a preexisting metamorphic terrain, but was metamorphosed at the same time as the slate and other metamorphic rocks of the area.

The fragments are slab-shaped, and lie parallel to the bedding in the overlying rocks. None were found to lie crosswise to the bedding, nor were any fragments seen with a second cleavage developed across the length of the fragments. Thus, the fragments themselves do not reveal when they were metamorphosed. Good exposures 1 1/2 miles south of Garhi Habibullah, however, provide stratigraphic information indicating that the conglomerate was metamorphosed after it was deposited. The section seen here is as shown in figure 10.

The presence of phyllite above the conglomerate, and the alternating sequence of phyllite and quartzite suggests that the conglomerate was metamorphosed after it was deposited, and after the deposition of the phyllite and quartzite. These observations tend to preclude a pre-conglomerate metamorphism, which leads to the conclusion that only one period of metamorphism has occurred in this area, namely, that connected with the Himalayan orogeny. No earlier period of metamorphism is recognized.

The age of the Abbottabad formation is not precisely known. In the mapped area it unconformably overlies the Hazara formation of Precambrian or Early Paleozoic age. Near Haripur, 20 miles west of Abbottabad, it unconformably overlies the Tanawal formation of Silurian-Devonian age. In the quadrangle north of the mapped area the Abbottabad formation is interbedded with volcanic greenstones, which farther east in Kashmir contain a fauna of Carboniferous- to Permian-age (Stratigraphic Commission, 1957). West of the Indus, however, rocks of similar lithology and stratigraphic position contain Conodonts no younger than Late Devonian (C. Teichert, personal communication).

Information perhaps more closely related to the Hazara area is given by A. N. Fatmi, Geological Survey of Pakistan (personal communication) who reports Early-Jurassic ammonites from the Datta formation of the Kala Chitta hills 50 miles southwest of Abbottabad. The geologic section in the Kala Chitta hills has been identified by the present writer as the southwestward continuation of the sequence of Hazara. Strata of identical lithology and sequential position are found in both

Covered

10 feet -- Clayey, coarse-grained quartzose sandstone

200 feet -- Alternating beds of phyllite, and pink and white quartzose siltstone

150 feet -- Brown phyllite

10 feet -- Pink quartzose dolomite

50 feet -- Boulder conglomerate

Phyllite of Hazara formation

Figure 10. Stratigraphic section at the contact between the Hazara and Abbottabad formations, 1 1/2 miles south of Garhi Habibullah

places. The Datta formation of the Kala Chitta hills is equivalent to the Galdanian formation of Hazara, and therefore, the Abbottabad formation, which underlies the Galdanian formation, must be pre-Early Jurassic in age.

On the basis of the present conflicting information the Abbottabad formation is tentatively assigned a Carboniferous- to Permian-age. It is equivalent to the Kingriali formation (formerly Kioto formation) of the Kala Chitta hills, and very likely also to the Swabi formation west of the Indus (Martin, 1962).

Galdanian Formation

The name "Galdanian formation" is here given to the thin but highly persistent and distinctive sequence of red and brown shales and quartzose sandstone beds which crop out in the Galdanian area and elsewhere in the Garhi Habibullah syncline (pls. 1 and 3). The formation is of Early Jurassic age. These rocks were noted earlier on Sirban hill near Abbottabad by Waagen and Wynne (1872), who included them in the upper part of their "Below the Trias" group (Abbottabad formation). The Galdanian formation not only provides the key to the stratigraphy and complex structure within the Garhi Habibullah syncline, but also is of interest as a source of low-grade sedimentary iron ore.

The Galdanian formation crops out as numerous narrow bands on the flanks of tight folds in the Garhi Habibullah syncline. It occupies the stratigraphic position between the Daulatmar Limestone and the Abbottabad formation; both upper and lower contacts are thin transition zones, probably representing disconformities. Because of numerous strike faults and tectonic lensing, the Galdanian formation is missing in many places. In the Kakul and Galdanian areas (pls. 1 and 3) the formation ranges in thickness from 90 to 200 feet, but westward near the Tarnawai fault the thickness exceeds 500 feet.

The Galdanian formation is here divided into three units; an upper quartzose sandstone unit, a middle shale unit, and a lower quartzose sandstone unit.

The middle shale unit of the Galdanian formation consists of red shales in the Galdanian, Chure Gali, and Kakul areas, but changes to brown shale along the western belt of outcrops. Sedimentary iron and manganese deposits of low- to medium-grade are found in several places in the Kakul and Galdanian areas, together with small showings near Chure Gali. In places they make up nearly the entire thickness of the Galdanian formation.

The iron-rich localities are 20 to 200 feet thick and consist of layers and lenses of red hematitic claystone and siltstone, and a few scarce layers of black hematite and brownish black manganese oxides. Some of the iron-rich lenses are siliceous. Lateral changes in lithologic character are pronounced, the iron-rich layers typically changing laterally into low-grade red shale. The claystones in the iron-rich localities contain a relatively high percentage of hematite, together with different amounts of brown and tan low-grade claystone and shale. Iron content ranges from 5 to 60 percent, averaging 22 percent for the iron-rich localities as a whole. The hematitic claystones exhibit several kinds of primary sedimentary structures, including oolitic, pelletal and nodular. Oolitic and pelletal hematite claystone alternate with the nodular type, and there is a complete gradation between the two. In some nodular claystone the hematite nodules are red in a black hematitic matrix; in others the nodules are black in a red hematitic matrix. In many cases, and perhaps most often, the matrix is low-grade brown claystone which reduces considerably the overall iron content of the rock. A photograph of the typical nodular rock is shown in figure 11. A detailed stratigraphic section (fig. 12), taken from the west side of Galdanian Creek, illustrates the lithology of the iron-rich localities.

In addition to hematite-rich beds, a few discontinuous layers and lenses of black manganese oxide are found near the base of the unit in the Galdanian area. They are 7 to 12 feet thick and 20 to 200 feet in outcrop length.

In the Chure Gali area, the shale unit of the Galdanian formation, although still retaining its overall red color, contains more yellowish-brown and gray siltstone and claystone than it does at Galdanian. Near Chure Gali this unit has numerous lenses of black manganese oxide near the top, some as long as 1200 feet.

The middle unit of the Galdanian formation nearly everywhere is bounded above and below by red and white quartzose sandstone and siltstone, and these have been mapped as an upper unit and a lower unit. The thickness of these units ranges from a few feet to several hundred feet. On Plates 1 and 3, they are shown in the Chure Gali area and northward; elsewhere they are too thin to show as separate units.

The Galdanian rocks are indicative of shallow water marine deposition of material eroded from a nearby tropical land mass. Quantities of finely divided detritus, including hematite, from the deep mantle of decayed rock were carried into the shallow agitated waters near the shore. During the early and late intervals of Galdanian

Figure 11. NODULAR HEMATITIC CLAYSTONE OF THE GALDANIAN FORMATION

Daulatmar limestone

\- -

6 feet -- Quartzose sandstone

5 feet -- White claystone

8 feet -- Nodular, pelletal, hematitic claystone

16 feet -- Hematitic claystone

26 feet -- Nodular hematitic claystone with a few thin beds of black hematite

10 feet -- Nodular hematitic claystone

2 feet -- Black hematite

16 feet -- Hematitic claystone

7 feet -- Nodular oölitic hematitic claystone

38 feet -- Nodular hematitic claystone

8 feet -- Purple quartzose siltstone

9 feet -- Manganese oxide lens

5 feet -- Quartzose sandstone and white claystone

\- -

Abbottabad formation

Figure 12. Stratigraphic section of the Galdanian formation, taken from the west side of Galdanian Creek

time fairly pure quartz sand and silt was deposited, some of it colored red by small amounts of hematite. Middle Galdanian time is represented by hematitic shale and mudstone, some of it oolitic, and by ordinary brown shale. Part of the hematite probably was detrital, but the oolites and nodules may have formed by precipitation of colloidal iron around a nucleus. Detrital hematite probably also contributed to the material of the oolites and nodules.

The Galdanian formation is the lowest (or earliest) formation in the area for which a definite age is established. Its age is Early Jurassic on the basis of Early-Jurassic ammonites found in 1965 by A. N. Fatmi, Geological Survey of Pakistan, in the equivalent unit, the Datta formation, in the Kala Chitta hills.

Daulatmar Limestone

The name "Daulatmar limestone" is given here to a sequence of limestones of Jurassic age which occupy Daulatmar peak and other parts of the Garhi Habibullah syncline. Because of the intensity of folding the thickness of the formation is uncertain. One apparently undisturbed section, two miles north of Kalapani is 1,100 feet in thickness. The lower contact with the Galdanian formation is a thin transition zone, although in many places it is a shear zone. The upper contact everywhere is a shear zone owing to the intense deformation of the overlying Spiti shale.

The Daulatmar limestone is essentially clastic. The rocks are black to dark gray, fine- to medium-grained, thick-bedded limestones that weather light gray and commonly are cross bedded. Petrographically, the most common type is a fine- to medium-grained pelletal limestone which has a matrix of microcrystalline ooze. Sparry cement makes up only a small part of the rock, but clear calcite is abundant as a secondary filling in cracks. Comminuted shell and algal debris is present in varying amounts, and is the major constituent in some beds.

Study of fossil specimens indicates that the Daulatmar limestone is Jurassic in age. A report on thin sections containing Dasyclad algae by J. Harlan Johnson of the Colorado School of Mines (written communication) is quoted in part as follows:

> Two of the Pakistan slides contain fairly well preserved fragments of Dasyclad algae. . . . these turn out to be new and undescribed species, possibly even a new genus. However, the genus is very close to one described years ago by Yabe which he named Neogyroporella. So far, this has been reported only from beds of Late Jurassic and earliest, i.e., pre-Aptian Cretaceous.

Thin sections of pelletal limestone studied by C. Teichert, University of Kansas (written communication), revealed several specimens of the gastropod Cossmanea, whose range is Jurassic-Cretaceous. Dr. Teichert's report is interesting because the specimens come from a bed that is only 300 feet stratigraphically above the Hazara formation (Precambrian), which suggests that no limestone of Triassic age is in this area, as was previously thought. Aftab Ahmad, Punjab University, reached this conclusion earlier from specimens of Cossmanea found in the limestones on Sirban hill near Abbottabad (Ahmad, 1962).

Probably the most precise age determination comes from A. N. Fatmi, Geological Survey of Pakistan, who has identified ammonites of Early-Jurassic age from the equivalent Sumana Suk limestone of the Kala Chitta hills. On the basis of the present information the Daulatmar limestone is considered to be Early to Middle Jurassic in age.

Spiti Shale and Giumal Sandstone

The Spiti shale (Late Jurassic) and the Giumal sandstone (Late

Jurassic-Early Cretaceous) are mapped together in this report because of their extreme thinness. The Spiti shale was named by Stoliczka (1865) for its exposure in the Spiti area of Kashmir. It is well known in Himalayan geology and is an important marker bed. The Giumal sandstone, also named by Stoliczka (1865) for the village of Giumal in Spiti, overlies the Spiti shale. In the Spiti area the Spiti shale and Giumal sandstone have a combined thickness of over 1,000 feet, but in the area of this report their combined thickness in most places is scarcely 200 feet.

The Spiti shale and Giumal sandstone form narrow outcrop bands extending northward from the vicinity of Kalpani to about one mile north of the Sattu Resthouse. These formations separate Jurassic limestone from Cretaceous limestone, and are a prominent marker horizon between them.

The Spiti shale is black, organic-rich, thinly laminated shale, and because of its soft, incompetent nature, has been thoroughly squeezed and contorted so that the stratigraphic nature of its contacts is not evident.

The Giumal sandstone is a medium-grained, soft, friable, glauconitic sandstone, containing rounded quartz grains in a black calcareous matrix. The calcareous matrix makes up about half of the rock. Fresh surfaces of the sandstone are black, and the rock weathers to a distinctive brownish orange (fig. 13). The upper contact is gradational with the overlying Cretaceous limestone the gradational zone being four feet thick.

The black carbonaceous unfossiliferous shales of the Spiti formation are indicative of a stagnant reducing environment, such as a

1 foot

Figure 13. GIUMAL SANDSTONE

Orange-brown weathering makes this unit a conspicuous marker bed. Ammonite in lower center partly closed basin. The organic-rich muds may have accumulated on the shoreward side of an upwarped linear landmass (geanticline), which supplied the detritus and at the same time acted as a barrier to ocean circulation. The change from black shale to glauconitic, calcareous sandstone containing ammonites probably indicates a shift to more open circulation, normal salinity and probably shallower water.

The Spiti shale was determined to be Late Jurassic in age by Waagen and Wynne (1872) on the basis of ammonites collected from Sirban hill near Abbottabad. No fossils were found by the writer. The Giumal sandstone is Late-Jurassic to Early Cretaceous in age. Several well preserved ammonites collected and identified by A. N. Fatmi from the Kalapani area include: Virgatosphinctoides sp., and Aulacosphinctoides sp., both of Late-Jurassic age; and Brancoceras, Subthurmannia, and Lyellceras, all of Early-Cretaceous age. Belemnites are abundant in certain beds.

The Spiti shale is equivalent to the Chichali formation, and the Giumal sandstone to the Lumshiwal formation of the Kala Chitta hills.

Sattu Limestone

The name "Sattu limestone" is given here to the limestone sequence of Late-Cretaceous age that overlies the Giumal sandstone in the vicinity of the Sattu Rest House (pl. 3). Limestones of Cretaceous age were noted in this area as early as 1872 by Waagen and Wynne (1872), but the rocks have never been named or mapped. Good exposures are seen on the high ridge north of Sattu, and along the steep footpath from Sattu to Galdanian.

The Sattu limestone forms a north-trending belt of variable width in the trough of the south-plunging Sattu syncline, which is a subsidiary fold within the Garhi Habibullah syncline. The northern limits of the formation can only be inferred because of the heavy timber and dense brush in the deep canyon northeast of the Sattu Rest House. The formation is overlain southward by Tertiary rocks. Along the east limb of the Sattu syncline the Sattu limestone is in gradational, and apparently conformable, contact with the underlying Giumal sandstone. The western limb of the syncline is faulted. In the Kakul-Kalapani area the formation is overlain unconformably by the Chhalpani formation of Paleocene-Eocene age, the contact commonly marked by a zone of laterite. One complete, apparently undisturbed, section of the Sattu limestone, one mile southwest of Kalapani, was 350 feet thick.

The Sattu limestone is light gray, fine grained, and thin bedded. It is distinguished from other limestone formations in the area by its aphanitic, nearly "lithographic," texture, and by the presence of <u>Globotruncana</u> (Foraminifera), visible on fresh surfaces under the hand lens. Clastic beds are rare, but under the land lens, minute brown colites, the tests of Foraminifera mentioned above, and other clastic items are seen in the matrix. The limestone commonly is stained in shades of red and brown owing to limonite and ankerite (?) in veins, streaks, patches, and along bedding planes and joints. A few brown rhomb-shaped crystals of dolomite and ankerite (?) also occur in rare partly dolomitized layers. Microscopically the rock is a fine-grained microcrystalline lithofied ooze containing scattered spherical foraminiferal tests, other tiny shell fragments and dolomite rhombs.

The assignment of Late-Cretaceous age to the Sattu limestone is based on the presence of the Foraminefer <u>Globotruncana</u>, visible in the hand specimen, and on the fact that it overlies the Giumal sandstone of

Early-Cretaceous age. More information is available from Latif (1962), who reports Foraminifera of Late-Cretaceous age including Globotruncana, Heterohelix, Rugoglobigerina, and Pseudotextularia from the Sattu limestone south of the mapped area.

The Sattu limestone is equivalent to the Kawagarh limestone of the Kala Chitta hills, and the Darsamand limestone of the Kohat area (fig. 1). The Sattu limestone probably also is equivalent to the Chikkim limestone of the Spiti area in Kashmir (Stoliczaka, 1865), and according to Latif (1962), the Sattu limestone may be equivalent to the Parh limestone of Baluchistan.

Chhalpani Formation

The name "Chhalpani formation" is given here to the sequence of limestone of Paleocene and Eocene age that crosses the canyon of the Kishanganga River at Chhalpani village, four miles north of Muzaffarabad (pl. 1). This name supercedes the descriptive term "Nummulitic formation" of Waagen and Wynne (1872).

The Chhalpani formation crops out in two different structural blocks, and the stratigraphic relations in the two blocks are somewhat different. The first area of exposure is near Kalapani in the Garhi Habibullah synclinal block. In this area the Chhalpani formation overlies the Sattu limestone unconformably. The second area of exposure is east of the Jhelum fault in the axial zone of the syntaxis. In this latter area the Chhalpani formation crops out on both limbs of the Muzaffarabad anticline. Jurassic and Cretaceous rocks are missing, and the Chhalpani formation rest unconformably directly on the Abbottabad formation. The Chhalpani formation is overlain conformably by the Murree formation of Miocene age. The contact is a transitional zone ranging in thickness from 60 feet at Chhalpani, to 1,200 feet on the high ridge north of Sirikot.

The thickness of the Chhalpani formation, computed from the map, is about 1,300 feet where it crosses the Kishanganga River, and about 2,000 feet on the high ridge north of Sirikot. Northwest of Sirikot the formation thins rapidly to about 150 feet at the northern edge of the map.

The Chhalpani formation consists of gray, poorly-bedded, generally nodular limestone, and dark-gray, calcareous shale. The shale commonly contains nodules of clayey limestone. Foraminifera are abundant in the formation, especially in the shale beds. They are visible in every outcrop and serve to distinguish this limestone from other limestone formations in the area. Rock specimens collected by C. Teichert, University of Kansas, and the writer from outcrops one mile east of Muzaffarabad contained corals and hydrozoans, in addition to Foraminifera.

The basal parts of the Chhalpani formation are different in the two structural areas. In the Kalapani area the unconformable contact with the overlying Cretaceous limestone is a laterite zone ranging in thickness from as little as six inches, to 20 feet. The zone consists of irregular layers and lenses of limonite and hematite intercalated with limestone beds. Ferruginous, calcareous quartzose sandstone also is present in places. In the Kalapani area, rocks younger than the Chhalpani formation are absent.

In the Muzaffarabad anticline, which is in the axial zone of the syntaxis, the base of the Chhalpani formation is marked by a zone of quartzose sandstone; high alumina, blue-gray shale, in places pisolitic; and black carbonaceous shale which is coal bearing. These rocks always are present at the base of the Chhalpani formation in the structural block east of the Jhelum fault, even towards the north where the formation thins markedly.

The Chhalpani formation is dated as Paleocene and Eocene. Foraminifera collected from Chhalpani village and identified by E. Fritz, U.S. Geological Survey, include the following: ~~Lepidocyclina,~~ Operculina, and Miscellanea of Paleocene age; and Lockhartia, Abveolina and Assilina of Eocene age. The Chhalpani formation is equivalent to the Lockhart limestone (Paleocene) and Kohat limestone (Eocene) of the Kohat area; the Kala Chitta group (Paleocene to Eocene); and the Kirthar limestone (Eocene) of the Quetta-Baluchistan region.

Murree Formation

The first recorded name for the widespread sequence of red shales and sandstones of Miocene age found along the foothills of the Himalaya is from Wynne (1874), who called these rocks the "Mari Group" after the "Mari Hill Station" 35 miles northeast of Rawalpindi. Mari is now spelled Murree. Subsequent designations for this sequence have been "Murree beds" (Lydekker, 1876), and "Murree Series" (Pilgrim, 1910; Wadia, 1928). The unit is now called the Murree formation. In Kashmir it has been divided into two units, but is considered only as one unit in this report. The Murree formation crops out only in the structural block east of the Jhelum fault, which is the axial zone of the syntaxis.

The thickness of the Murree formation is uncertain because of tight folding in the region. Wadia (1928), estimated a thickness of 6,000 feet. On the spur east of Lachi Khan, eight miles north of

Muzaffarabad (pl. 1), a longitudinal section totaling 5,000 feet can be seen. In the International Stratigraphic Lexicon the formation is estimated as more than 8,000 feet thick (Stratigraphic Commission, 1957). The lower contact is gradational into the underlying Chhalpani formation of Eocene age. The transition zone consists of beds of marl alternating with green and red shale. The upper contact is nowhere exposed in the map area, but southward, near Rawalpindi, the Murree formation is overlain by the Siwalik Series (Wadia, 1928).

The Murree formation is made up of red, thinly laminated siltstone and shale, massive red mudstone, and subordinate green to gray, fine- to medium-grained graywacke. Some graywacke is dark maroon. Most of the Murree rocks contain enough interstitial carbonate to effervesce in dilute acid. Graywacke beds are 2 to 20 feet thick and commonly contain cross-bedded laminations (fig. 14). In places, the graywacke beds are lenses that range in length from 100 to 300 feet. Beds of calcareous sandy conglomerate in places are intercalated with the sandstone. The pebbles are calcareous, and for the most part oval in shape, but some are flattened and squeezed into various shapes, some even tapering to a point on one end. Evidently these pebbles originally were soft calcareous mud balls formed at the site of deposition, not detrital items brought in from the outside.

In thin section the sandstone is a fine- to medium-grained graywacke containing remarkably angular sand-size grains of quartz, chert, volcanic rock fragments, and feldspar, in a matrix of finely comminuted quartz, some chloritic material, and discrete flakes of micaceous clay. Clear calcite cement occupies the interstices. Quartz and chert make up approximately 40 to 50 percent of the rock; rock fragments and

Figure 14. CROSS-BEDDED SANDSTONE OF THE MURREE FORMATION

Two views of the same ourcrop taken from 18 and 8 inches feldspar each 5 to 10 percent; matrix 25 percent; and cement 15 percent. The maroon color is hematite, present in flakes, patches, and as a stain in many of the grains. The ratio of sandstone to shale is not known quantitatively. In the profile view of the spur east of Lachi Khan, a longitudinal section 5,000 feet thick is estimated to contain 15 percent sandstone, 85 percent shale.

The environment of deposition and the source of the Murree rocks has been much discussed. In order to explain the red color of the Murree, Wadia (1931), concluded that the source area was from the iron-bearing Cuddapah and Dharwar rocks far to the south in the Indian peninsula. It does not seem reasonable, however, to postulate a basin receiving sediments from the south at a time when the rising Himalaya immediately to the north must have been shedding great amounts of detrirus southward. The present existence of red soils and much decayed red rocks in the Indian Precambrian peninsula does not prove a source area from that direction. The rising mountains to the north must also have been subjected to intense chemical weathering under warm humid conditions, and the resulting red soil would provide the coloring material for the Murree rocks. A much shorter transport than from the Indian peninsula is indicated by the marked angularity of the grains in the sandstone.

The Murree formation is regarded as Early to Middle Miocene in age on the basis of leaf impressions (Feistmantel, 1882), and on stratigraphic grounds (Pilgrim, 1910). However, the gradational contact with the underlying Eocene limestone indicates that the lower part of the Murree formation may be Oligocene in age.

Quaternary Deposits

Quaternary deposits consist of sand, gravel, and boulders in the stream beds, slope wash, reworked loess interlayered with older stream gravels, and terrace and old fan deposits. Quaternary deposits along the Kunhar River (pl. 1) have been subdivided, but elsewhere they are undivided.

The lowlands around Shinkiari (pl. 1) form the eastern edge of an upland plain which extends for eight miles west of the mapped area. These lowlands are developed on brown, partially consolidated reworked loess interlayered with sand and gravel beds. The streams have deeply incised these deposits forming steep gulleys as much as 300 feet deep in places.

In the Muzaffarabad area (pl. 1), the alluvial deposits along the Kishanganga and Jhelum Rivers consist mostly of stream-laid boulder and gravel deposits which stand as terraces high above the present river level. In most places, the rivers cut into bedrock and have exposed long narrow bedrock outcrops along the river banks.

The Quaternary deposits along the Kunhar River have been studied with the aid of aerial photographs, supplemented by a reconnaissance traverse along the road that parallels the river. Elevation readings during field traverses were taken with a Taylor aneroid barometer, and the closest vertical measurements are within 25 feet.

Three systems of terraces are evident along the Kunhar River; all gradually increase in elevation upstream in conjunction with the present stream gradient. The terrace material is crudely stratified and ranges from sand-size to huge boulders five feet in diameter. The elevation of the highest terraces (Qt 1 of Pl. 1) gradually increases from 3,000 feet at Garhi Habibullah (fig. 15) to 3,250 feet at the northern border of the quadrangle. The highest terraces stand 200 to 250 feet above the middle terraces and about 300 feet above the river level. The elevation of the middle terraces (Qt 2 of Pl. 1) gradually increases upstream from an elevation 2,700 feet at Garhi Habibullah to 3,000 feet at the northern edge of the map. The middle terraces stand 20 to 40 feet above the low terraces and 30 to 50 feet above river level. The lowest terraces (Qt 3 of Pl. 1) form narrow banks along both sides of the river and stand about 10 feet above the river level. They are difficult to distinguish from the numerous step-like terraces made in the present river alluvium, and in many places they grade into these present deposits.

Old alluvial fans at the mouths of a few west flowing creeks (fig. 16) can be distinguished on aerial photographs. These old fans cut through the middle terraces and in turn are cut by the lower terraces. The fans consist mainly of large flat fragments of slate and occupy positions 20 feet above the present younger fans.

Summary of the Depositional History

Regionally, the area studied was once part of a great marine trough, called the "Tethys Sea" by Suess (1904, Sollas translation) which existed, undisturbed by orogenic movements, from the late Precambrian until the middle Tertiary. By combining the information obtained from the three structural blocks of the mapped area, a nearly complete stratigraphic record of this trough is obtained, which extends from the Late Precambrian to the Miocene. Clastic deposits predominate during the early history of the trough. Marine carbonate deposits occupy the middle interval, and the onset of the Himalayan orogeny, which closed

Figure 15. HIGH TERRACE ON THE KUNHAR RIVER

High terraces stand 300 feet above river level

Figure 16. OLD ALLUVIAL FAN (WITH GROWTH OF TREES) CUT BY RECENT DRAINAGE

Jhelum fault visible in background

the trough, is marked by continental sediments of Tertiary age.

During the Late Precambrian, and probably extending into the lower Paleozoic, a thick accumulation of generally fine-grained clastic sediments is recorded in the slates, phyllites, and unmetamorphosed shales and graywackes of the Hazara formation. Limestone and gypsum beds within the slates indicate shallow water conditions. In the area west of the Tarnawai fault, the Silurian and Devonian is represented by the equally thick accumulation of quartzose silts, now the quartzose schists of the Tanawal formation. Deposition during the Silurian and Devonian evidently did not extend into the Garhi Habibullah block, for Tanawal rocks are missing in this block, and the top of the Hazara formation is an erosional unconformity. The juxtaposition of two areas so radically different stratigraphically indicates that one area underwent considerable tectonic transport with respect to the other.

The long interval from the Carboniferous to the Eocene is characterized largely by carbonate deposition totaling over 5,000 feet in thickness. This thick sequence is indicative of a long period of relative stability and low relief, during which time carbonates were being deposited in a slowly subsiding shallow trough. The depositional environment was by no means constant and unchanging, however, nor was the depositional history the same over the whole area. The presence of red beds, black shale, and glauconitic sandstone at various places in the stratigraphic section, as well as marked differences in the limestone formations themselves, record differing conditions of sedimentation during this long interval. In addition, considerable warping and epirogenic movement on a regional scale are recorded in two erosional unconformities; one at the top of the Tanawal-Hazara surface, and the other at the top of the Abbottabad formation.

The dolomite of the Abbottabad formation was laid down on the Tanawal formation in the area west of the Tarnawai fault (west of the mapped area), but in the Garhi Habibullah block it rests directly on the Hazara formation. Therefore, a period of emergence must have existed prior to the deposition of the dolomite, during which time, the Tanawal formation was being eroded west of the Tarnawai fault while the Hazara formation was being eroded in the area now represented by the Garhi Habibullah block. The stratigraphic relations in the axial zone of the syntaxis during this time are not known because the base of the Abbottabad formation is not exposed.

As far as is known, the Triassic is not represented in the study area. The Jurassic to Cretaceous interval, present only in the Garhi Habibullah block, is represented largely by carbonate deposition, interrupted by intervals of detrital influx, first at the base of the Jurassic by the Galdanian red hematitic shales, and again at the top of the Jurassic by the Spiti black shales and the Giumal glauconitic sandstones. The clastic, cross-bedded limestones of the Daulatmar limestones, indicative of deposition in shallow agitated water, are in marked contrast to the fine-grained, nearly "lithographic" limestones of the Cretaceous Period, the latter indicating slow accumulation in quiet water.

Following a period of weathering and erosion represented by a lateritic zone, a sequence of nodular, argillaceous limestones rich in Foraminifera was deposited during the Paleocene and Eocene. In the axial zone of the syntaxis, Jurassic to Cretaceous strata are missing and the Eocene limestone rests unconformably on the Abbottabad formation.

The first stratigraphic indications of the Himalayan orogeny are recorded in the red sandstones and shales of the Murree formation. The great marine trough called the "Tethys Sea" ceased to be the site of marine deposition after the Eocene, but along the flanks of the rising mountains to the north, it continued to receive thousands of feet of continental red sediments of the Murree formation, and to the south of the mapped area by the similar sediments of the Siwalik formation. The total thickness of these clastic rocks exceeds 18,000 feet, which indicates that the Tethys trough subsided a greater amount during the Middle and Late Tertiary than it did throughout the entire Paleozoic and Mesozoic.

IGNEOUS ROCKS

Mansehra Granite

The Mansehra granite of Late-Cretaceous to Early-Tertiary age was named by Shams (1961) for the nonfoliated prophyritic granite around Mansehra, four miles west of the mapped area (fig. 1). Shams also distinguished a foliated type and a tourmaline type, but in this report these three varieties are mapped together. The granites studied by Shams extend eastward from Mansehra into the northwestern part of the Garhi Habibullah quadrangle (pl. 1).

The Mansehra granite is well foliated in the mapped area except for a few square miles on both sides of the Hazara Trunk road in the west-central part of the quadrangle.

The granite is white to gray on weathered or fresh surfaces, medium- to coarse-grained, and is characterized by large phenocrysts of twinned microcline, some as long as five inches (fig. 17). It is composed mostly of microcline, oligoclase, and quartz, with small amounts of biotite and muscovite. The quartz content ranges from 15-20 percent, feldspar 65-70 percent, and biotite and muscovite 5-10 percent. Accessory minerals include black tourmaline, magnetite, and sphene. Penetrative deformation during regional metamorphism has resulted in alignment of phenocrysts, mica flakes, and quartz grains to provide a well-developed foliation. Along the foliation surfaces the mineral components, especially mica, generally also exhibit a prominent mineral lineation.

Figure 17. MANSEHRA GRANITE, SHOWING CHARACTERISTIC PHENOCRYSTS OF FELDSPAR

The contact between the Mansehra granite and the adjacent rocks is sharp and essentially concordant with the foliation of the adjacent rocks. In a few places the contact is a shear zone. The intrusive nature of the granite is easily seen in many places along the contact. Intrusive relations include irregularities along the knife-edge contact, seams and stringers of granite cutting into and across the adjacent rocks, and inclusions of the adjacent rocks in the granite (fig. 18).

Contact metamorphic effects are feeble and in places virtually absent. In general, the country rock is very little altered, but in a few places, for example at Batrasi Gali (pl. 1), a narrow zone of corierite schist is developed. The configuration of the granite body at depth is not known directly. However, the absence of a gravity anomaly over it (Rahman, 1961) suggests that it does not extend downward as a vertical pluton. The fact that the metamorphic rocks dip under the granite in many places suggests that it is sheet-like in form.

The age of the Mansehra granite is not known with certainty, because the youngest rocks intruded belong to the Tanawal formation of probable Silurian to Devonian age. Similar granite intrudes rocks of Cretaceous age in the Astor-Burzil area in Kashmir (Wadia, 1937). An age determination of a sample of granite collected at Mansehra by R. Davies, Punjab University, was 80 million years, which is Late Cretaceous. The Mansehra granite probably is Late-Cretaceous to Early Tertiary in age, synchronous with the early phases of the Himalayan orogeny. It probably represents the southern fringes of the extensive granitic intrusions in the axial zone of the Himalayas, which have been called the "Central Himalayan gneiss" (Stoliczka, 1865).

Figure 18. CONTACT BETWEEN TANAWAL QUARTZ SCHIST AND THE MANSEHRA GRANITE

Pegmatites, Quartz Veins, and Basic Dikes

A few pegmatites, quartz veins, and basic dikes cut the Mansehra granite and, in places, the Tanawal formation. They represent the latest phases of intrusive activity in the area. The pegmatites, which rarely are greater than 10 feet thick and 50 feet long, consist of quartz, microcline, muscovite, and accessory tourmaline. At two localities northwest of the mapped area, the pegmatites have been mined for beryl, but none was observed in the mapped area. A system of en echelon quartz veins are located at Chitta Batta on the Hazara Trunk Road at the western edge of the quadrangle (pl. 1). They are 10 to 40 feet thick and cut the Mansehra granite and the Tanawal formation. No feldspar was seen in these veins. Thin, medium-grained basic dikes are found in the Mansehra granite and the Tanawal formation. They are oriented generally parallel to the foliation, but in some cases at right angles to it.

STRUCTURE

Regional Setting

The mapped area (pls. 1, 3) lies on the west flank of the Hazara-Kashmir syntaxis, and the geologic structure, therefore, is closely related to this large feature. Originally called the "syntaxial bend of the northwest Himalaya" by Wadia (1931), the Hazara-Kashmir syntaxis is the sharp bend of nearly 180 degrees exhibited by the mountain ranges and geologic structures at the western end of the Northwest Himalaya.

After following a northwesterly course for 1,000 miles in a gentle unbroken arc across northern India, the major faults and most of the geologic units abruptly turn 180 degrees at Paras, 20 miles north of the mapped area, and then follow a southeasterly course to Muzaffarabad. Beyond Muzaffarabad the structural trend lines gradually fan out to the southwest through the mapped area (fig. 1).

The axis of the syntaxis is oriented slightly west of north, and the axial zone, which is occupied mainly by rocks of the Murree formation, is barely 10 miles wide. The Murree formation in the eastern part of the mapped area lies in the axial zone of the syntaxis. Not only are the outer (southern) ranges of the Himalaya inflected, but a similar bend in the tectonic trend is evident 150 miles to the north, beyond the central axis of the inner Himalayas, and in the Pamirs, 200 miles to the north. As shown by the structural trend lines of figure 1, the mapped area lies close to the pivot point of a great regional bend that involves the entire width of the Himalayas.

Large Structural Features

Within the mapped area the geologic structure is divisible into three main areas or blocks: the area east of the Jhelum fault which is part of the axial zone of the syntaxis; the Garhi Habibullah syncline between the Tarnawai and Jhelum faults; and the area west of the Tarnawai fault (pl. 1). The Tarnawai and Jhelum faults are main boundary faults separating these three areas, and although the three areas have similar structural patterns, there is evidence that they have moved as individual blocks relatively southward in a left-lateral sense along the Tarnawai and Jhelum faults.

The Jhelum Fault

The Jhelum fault is a main boundary fault separating the younger rocks of the axial zone of the syntaxis from generally older rocks to the west. This master fault has been traced continuously from the Kunhar River southeastward to Muzaffarabad, and then south along the Jhelum River. The Jhelum fault is easily seen in the field because of the strong color contrast of the rocks on either side of it. Along the mountain front north and northeast of Garhi Habibullah white dolomite of the Abbottabad formation lies against the gray and black slate of the Hazara formation (fig. 19). Farther south, the edge of the Murree red beds marks the position of the fault. In the northern part of the quadrangle near the Kunhar River the Jhelum fault forms a complicated horsetail structure 2 1/2 miles long and half a mile wide, within which a system of anastimosing faults separate slices of the Abbottabad, Chhalpani and Murree formations. At all other points along its course

Figure 19. JHELUM FAULT EXPOSED ALONG THE MOUNTAIN FRONT NORTHEAST OF GARHI HABIBULLAH

the Jhelum fault forms a relatively narrow zone of breccia and gouge 50 to 150 feet in width, although the brittle dolomite commonly is broken and fractured for many hundreds of feet upslope from the actual fault zone. The dip of the Jhelum fault is directly measurable in many places because of the strong relief and good exposures in the area. Northwest of Muzaffarabad the Jhelum fault dips 50 to 70 degrees east; south of Muzaffarabad it steepens to 80 degrees east, and in places is vertical.

The Tarnawai Fault

The Tarnawai fault is the master fault separating the Garhi Habibullah syncline from the rocks to the west (pls. 1 and 3). The slates and quartzose schists of the Hazara and Tanawal formations abut the younger rocks in the trough of the Garhi Habibullah syncline. The fault is marked by a breccia and gouge zone 100 to 200 feet in width. North of Garhi Habibullah village the Tarnawai fault is inferred to follow the valley of the Kunhar River, and to join the Muzaffarabad fault near the northern edge of the quadrangle. The Tarnawai and Jhelum faults, combined into a single master fault, reappear beyond the alluvium four miles north of the quadrangle boundary. The intersection of the Tarnawai and Muzaffarabad faults marks the apex of the Garhi Habibullah block.

In the vicinity of Garhi Habibullah the Tarnawai fault dips steeply east; southwestward, along Sangar Katha, the dip is 50 degrees southeast. At Hazira the Tarnawai fault turns south and steepens to vertical, and near Ratri Gali it changes into a pair of thrust faults which dip 20 to 25 degrees north. Along these thrust surfaces quartzose schists of the Tanawal formation have been displaced southward over dolomite of the Abbottabad formation, and the dolomite in turn has moved southward over the Daulatmar limestone. Five miles west of the map area these thrust faults are known by the writer to change back to a single, nearly vertical master fault which continues southwest to the Haripur Plain, 10 miles southwest of Abbottabad.

Structures East of the Jhelum Fault

East of the Jhelum fault the Abbottabad, Chhalpani, and Murree formations form a single structural unit or block which is part of the axial zone of the syntaxis. These rocks are folded into a large anticline, the Muzaffarabad anticline, which trends northwest across the map area (pls. 1 and 2), and is sharply overturned to the southwest. The southwest overturned limb is faulted against the Jhelum fault. At Jabri the anticline is disrupted by the horsetail structure of the Jhelum fault, and north of this point another fold system begins, which continues into the adjacent quadrangle. The Muzaffarabad anticline plunges southeast, and the older rocks in the core plunge under the Murree rocks two miles southeast of the map area.

On the overturned southwestern limb of the Muzaffarabad anticline, a second fault, the Muzaffarabad fault, separates the Abbottabad formation from younger rocks. The fault dips 20 to 50 degrees to the northeast, and along the fault plane, the rocks of the Abbottabad formation have moved southwest over the Chhalpani and Murree rocks. Direct dip measurements taken at two points along the steep slope two and three miles northwest of Muzaffarabad are shown in figure 20. Northwest of Muzaffarabad, the Eocene and Murree rocks on the overturned southwest limb are sandwiched between the Jhelum and Muzaffarabad faults, and for a distance of two miles are cut out entirely. Two miles northeast of

Figure 20. THE MUZAFFARABAD FAULT

Two views of the Muzaffarabad fault separating the Abbottabad formation from the Murree formation, two and three miles northwest of Muzaffarabad

Garhi Habibullah the Muzaffarabad fault joins the Jhelum fault; to the southeast, beyond the map area, it decreases in displacement and disappears. In the Muzaffarabad area the Muzaffarabad fault is located at the base of the Chhalpani formation, which consists of incompetent coal and pisolitic claystone. The larger remnants of the Chhalpani rocks along the fault are shown on the map (pl. 1). The outcrops of coal one mile east of Muzaffarabad have been converted in rank from sub-bituminous to semi-anthracite as a result of the extreme granulation along the Muzaffarabad fault.

Superimposed upon the Muzaffarabad anticline and other northwest-trending structures is a system of subsidiary folds trending northeast (pl. 1). These subsidiary folds are most evident north of Muzaffarabad where they have refolded the Muzaffarabad anticline and the Muzaffarabad fault. However, they also occur in the Murree rocks along the Jhelum River south of Muzaffarabad, and in fact represent the only observed fold direction in this latter area. These subsidiary folds are open and symmetrical and range in wave length from over two miles to a few hundred feet. Along the spur two miles south of Muzaffarabad the Murree rocks display nine symmetrical folds belonging to this later fold system in slightly more than a mile of outcrop width (fig. 21). These folds tend to turn parallel to the Jhelum fault, as indicated by the strike of the Murree beds adjacent to the fault. On a reconnaissance trip up the Kishanganga River to Tithwal (fig. 1) on the east side of the axial zone of the syntaxis, these subsidiary folds were found to be horseshoe-shaped so that they follow approximately the curve of the apex of the syntaxis, and, as on the west side, they turn into parallelism with the boundary fault on the east side of the axial zone.

Figure 21. OPEN, SYMMETRICAL FOLDS IN THE MURREE FORMATION

View from hills east of Muzaffarabad looking southwest

The Garhi Habibullah Syncline

In the Garhi Habibullah block, lying in the area between the Jhelum and Tarnawai faults, the Hazara formation and younger rocks outline a south-plunging synclinal structure, called the Garhi Habibullah syncline, which is generally overturned westward and contains Carboniferous to Eocene rocks in its trough (pls. 2 and 3). The trough opens southward and becomes very complex internally, essentially losing its identity as a synclinal trough except in gross aspect. The west limb of the syncline is truncated by the Tarnawai fault. The basal unit of the Abbottabad formation marks the east edge of the synclinal trough, and is little deformed as compared to the rocks within the trough. Deformation in the Hazara slates on the east limb has been more penetrative than the sedimentary rocks of the trough, and this situation, together with the general lack of marker beds, effectively masks the large fold pattern in the slate belt. Some information is available, however, from an analysis of small-scale structures, discussed in a later section.

On the eastern margin of the slate belt two prominent marker beds--the gypsum unit and the limestone unit--follow a remarkably straight course throughout their extent. The straight rather than sinuous course and the lack of repetition of these units, suggests that, in a gross way at least, the order of superposition of the beds in the slate belt has remained intact, from younger on the west to older on the east.

The faults within the Garhi Habibullah syncline are closely spaced, quite numerous, and tend to parallel for considerable distances the strike and dip of the beds, as well as the strike and dip of the axial planes of minor folds. Two of the more continuous faults within the trough are called the Kakul and Galdanian faults (pl. 3). The Kakul fault branches off from the Tarnawai fault and follows a somewhat sinuous course to Kakul Cantonment where several faults converge. Southward to the vicinity of Galdanian, the Kakul fault dips vertically or steeply west. South of the point where it turns southwest the Kakul fault decreases in dip to 40-50 degrees west, parallel to the strike and dip of the beds along the west side of a creek valley. One mile north of the alluvial plain near Kakul, the dip becomes vertical again.

The Galdanian fault follows a northward course from Kakul village through Galdanian valley to a point one mile west of Sattu Rest House where it is lost in the monolithologic rocks of the Daulatmar limestone. The Galdanian fault is steeply dipping throughout its extent as is indicated by its relatively straight trace across the rugged terrain. One measurement half a mile south of Galdanian gave a dip of 90 degrees. Near Kakul the fault forms a breccia zone having a maximum width of 600 feet.

Near Hazira, in the zone between the Tarnawai and Kakul faults, are a series of subsidiary faults which dip 30 to 60 degrees to the southeast. The slices of strata between the faults are upside down and represent the overturned remnants of folds with east-dipping axial planes. As the fold and fault system turns southward the faults and fold axes become vertical and the folds more nearly symmetrical.

A similar imbricate structure is found along the steep slope west of the Kalapani Rest House. In this case, however, the beds and the faults dip westward instead of eastward, and the beds are generally right side up. The base of this imbricate structure is a fault separating Jurassic from Eocene rocks. Upslope to the west, the stratigraphic section is repeated by a fault localized along the incompetent Spiti shale, and the beds as well as the fault dip 40 to 45 degrees west. On the east side of the creek valley the stratigraphic section dips east and is sharply overturned westward. The Cretaceous rocks at Kalapani Rest House mark the highly compressed trough of a syncline overturned westward with Cretaceous rocks dipping 60 to 70 degrees eastward under older rocks.

Two other faults having low to moderate dips to the west occur just west of Maira and form fault boundaries on both sides of a narrow strip of the Galdanian formation (pl. 3). The strip of Abbottabad dolomite, flanked on both sides by the Galdanian red-bed unit forms the core of a highly compressed anticline which is recumbently overturned eastward. The beds and the faults dip about 20 degrees west and in places are flat. Northward the faults and the beds become vertical, and east of Galdanian they dip steeply eastward.

Northeast of Kakul village in the zone between the Kakul and Galdanian faults, the stratigraphic section is broken up into fault slices by two nearly vertical faults, and large folds in most of this zone are not recognizable. Small-scale folds, however, are sharp-crested and symmetrical with vertical axial planes (fig. 22).

The largest subsidiary fold in the trough of the Garhi Habibullah syncline is the south-plunging Sattu syncline (pl. 3), which is faulted along the west limb, and contains Cretaceous rocks in the trough overlain southward by Eocene rocks. This synclinal structure appears simple, but actually is as complex internally as the area

Figure 22. SHARP-CRESTED, SYMMETRICAL FOLDS IN DOLOMITE AND LIMESTONE, NORTHEAST OF KAKUL VILLAGE

around Galdanian. The complexities are not apparent because marker beds, needed to define the smaller folds, are not present. The tight folding in areas of single noncontrasting rock units can be seen from certain vantage points, for example across deep canyons (figs. 22, 23) and also is indicated by the disordered orientation of dip and strike symbols on the map. The internal deformation within the Sattu syncline also is revealed northeast of Sattu Rest House where the Galdanian red beds and associated rock units on the nose of the syncline form seven recognizable south-plunging folds, some of which are symmetrical and some overturned slightly towards the west.

Tight folds also are outlined in the area between Galdanian and Rihala villages. The outcrop pattern of the rock units in this area reveals ten conspicuous north-plunging folds in slightly more than one mile of outcrop width. They are highly compressed and most of them are slightly overturned westward (fig. 23). The beds and the axial planes of the folds dip from 70 degrees eastward to vertical. West of Rihala the shale of the Galdanian formation on the nose of a syncline is drawn out into a long string 3,000 feet long and only 200 feet wide. In a similarly shaped but smaller syncline northeast of Galdanian village, the Galdanian unit is 1,000 feet long and 50 feet wide, and the tip of the nose tapers to a point along a minor shear zone. The fold system 1 1/2 miles south of Galdanian proper reverses its plunge, plunging gently southward instead of northward.

Area West of the Tarnawai Fault

The area west of the Tarnawai fault consists of low-grade metamorphic rocks and granite, and the structural trend in this area is parallel in general to the trace of the Tarnawai fault (pls. 1, 2, and

Figure 23. FOLDS IN THE GALDANIAN AREA

Upper photograph shows Jurassic limestone on steep slope just north of Galdanian. Long limbs overturned westward (towards left of picture), short limbs flat. Lower photograph shows syncline at Galdanian village, overturned westward.

3). From a north-south direction in the northern part of the area, the structural trend fans out to the west and southwest in the southwestern part of the area.

Adjacent to the Tarnawai fault the Hazara slates and overlying Tanawal schists outline a south-plunging anticlinal structure. The existence of this anticline is based upon the outcrop pattern of the younger Tanawal rocks around the older Hazara slates.

The eastern and southern margin of the Mansehra granite follows the structural trend of the area. At Batrasi Gali, the configuration of the contact outlines a northward-projecting salient of metamorphic rocks and a southward-projecting salient of granite. This configuration, together with the fact that the metamorphic rocks in most places dip under the granite, suggests that the granite is sheet-like in form, and that it has been folded with the metamorphic rocks. On this basis the northward-projecting salient of metamorphic rocks may represent the core of a north-plunging anticline, and the adjacent salient of granite represent the trough of a north-plunging syncline. Both the granite and metamorphic rocks have been affected by penetrative deformation and these folds are considered to be passive flow folds.

Fault Displacements

The Tarnawai and Jhelum faults are major structural discontinuities and the displacements along these and other faults provide information on the structural development of the area. In general, most faults show reverse fault movement (pl. 2); the faults and the folds tend to be parallel, and together they point to the same sense of structural asymmetry in a given area. In addition, there are indications and some direct evidence that strike-slip movement in the left-lateral sense has taken place along some faults. A few faults show a combination of strike-slip and reverse-fault movement.

The Tarnawai fault provides the most direct evidence of combined strike-slip and reverse movement. Basically, the block on the west side of the Tarnawai fault is upthrown relative to the block on the east side. The stratigraphic displacement is equal to the thickness of the stratigraphic section above the Tanawal formation, which amounts to about 11,000 feet, assuming that these rocks formerly existed west of the Tarnawai fault.

Superimposed upon this reverse movement is the present westward asymmetry of the Garhi Habibullah syncline and the eastward dip of the Tarnawai fault. These latter relations indicate that a westward countermovement of younger-over-older rocks took place during the later development of the area, but the amount of this later displacement is unknown.

Direct evidence also points to strike-slip movement along the Tarnawai fault. At Ratri Gali the change from a vertical fault to a pair of thrust faults dipping north calls for strike-slip movement along which the Tanawal and Hazara rocks on the west have moved relatively southward past the rocks of the Garhi Habibullah syncline. The thrust faults at Ratri Gali represent a southward breakout of the rocks in the western block.

Another indication of left-lateral strike-slip movement along the Tarnawai fault is the inferred offset of the Hazara slate in the northern part of the mapped area (pl. 1). The Hazara slate west of the Tarnawai fault is interpreted to be truncated by the Tarnawai fault and the continuation of the slate east of the fault implies a left-lateral offset of four miles. This offset cannot be proved, however, because the inferred northward extension of the Tarnawai fault is covered by valley alluvium. Another possible interpretation is that the outcrop belt of the Hazara slate represents the unfaulted compressed nose of the Garhi Habibullah syncline. This alternative interpretation is unlikely, however, in view of the known movement of the Tarnawai fault farther south.

Strike-slip movement along the Jhelum fault is not directly evident, although the horsetail structure at Jabri and the variation in dip along the fault are features commonly associated with strike-slip movement. It is possible that no lateral displacement has occurred along the Jhelum fault. As with the Tarnawai fault, a large component of vertical displacement has raised the rocks west of the fault relative to the rocks of the axial zone east of the fault (pl. 1). Vertical stratigraphic displacement is about 11,000 feet. And like the movement along the Tarnawai fault, a similar westward countermovement of younger rocks over older rocks took place during the later development of the syntaxis.

The westward countermovement is the only evident displacement shown by the Muzaffarabad fault, along which the Tertiary rocks on the southwestern limb of the Muzaffarabad anticline are partly or completely overridden by the rocks of the Abbottabad formation.

The system of smaller faults in the Kakul-Galdanian area (pls. 2 and 3) are mainly steeply dipping, reverse faults associated with folds. Some of them are associated with recumbent folds and have low to moderate dips. Vertical stratigraphic displacement along the smaller faults is small, ranging from the thickness of the Galdanian formation (140 to

300 feet) to the thickness of the Galdanian and Daulatmar formations (1,500 feet).

Strike-slip movement of these smaller faults may be more significant than the available information shows. Left-lateral strike-slip movement amounting to 3,000 feet is indicated by the offset of the Galdanian formation along a northeast trending fault one and one half miles north of the Sattu Rest House. The syncline half a mile northwest of Rihala does not reappear east of the Kakul fault, which would indicate two miles of left lateral movement along the Kakul fault. Finally, the southward convergence of several faults near the Kakul Cantonment seems best explained by strike-slip movement.

Small-scale Structures

Small-scale structures are those seen in the outcrop or hand specimen and include foliation, bedding, cleavage, minor folds, and various kinds of lineations. Data from small-scale structures, when reduced to usable form on equal-area projections, provide additional information on the structural development of the area. In metamorphic terrain where marker beds are absent and it is not possible or practical to determine the configuration of the folds, equal-area projections of small-scale structures serve to identify the general trend and plunge of fold systems within areas of homogeneous deformation, and provide indirect information on the shape of the folds. Equal-area projections also supplement the information obtained on a larger scale and in some cases reveal certain structural relations that were not previously evident.

Foliation in the Mansehra granite is produced by the parallel orientation of micas, elongated quartz, and subparallel feldspar grains. In the quartzose schists of the Tanawal formation foliation is largely subparallel to relict bedding. The original beds are isoclinally folded and therefore the limbs tend to be parallel to each other and to the axial planes of the folds. This is the "transposition foliation" of Sander (in Turner, 1963). In the slates of the Hazara formation bedding and axial-plane cleavage are the main planar features; cleavage has the same structural meaning as foliation in this area and is plotted as foliation on the projections and on the geologic maps. Many outcrops of slaty rocks exhibit both bedding and cleavage, but in most cases cleavage is the better developed. As in the Tanawal rocks, cleavage in the slate tends to be subparallel with bedding, but because the crests of minor folds are seen more frequently, cleavage is seen to transect the beds more frequently also. Axial-plane cleavage also is common in the red shales of the Murree formation.

Minor folds range from tiny crinkles on foliation surfaces to folds as much as 50 feet across. Most of the larger minor folds are found in the sedimentary and slaty rocks; in the granite and highly schistose rocks easily observable minor folds are generally restricted to tiny crinkles on foliation surfaces. In general the larger minor folds approach the isoclinal shape, even in the sedimentary rocks, but still retain rounded, rather than V-shaped crests. The fold style in the sedimentary rocks can be seen in cross-section in certain good exposures in the deep canyons of the Galdanian area. The limbs of the folds extend for hundreds of feet up canyon walls, and yet the limbs, which are parallel, are only a few feet apart. These tight isoclinal folds are accompanied by innumerable bedding shears. The minor folds in the Galdanian area actually are replicas in miniature of the large fold system of the Kakul-Galdanian area shown in plate 3.

Lineations are of three main types; minor-fold axes (crinkles) on foliation surfaces, linear orientation of minerals, and the intersection of bedding and cleavage. Mineral lineations are almost entirely limited to the granite, although a few were observed in the Tanawal rocks. The slaty rocks are too fine grained for mineral lineations to be visible megascopically. Mineral lineations as utilized in this report do not exist in the sedimentary rocks because the fabric of these rocks has not been affected by penetrative deformation.

For the analysis of small-scale structures the map area of the Garhi Habibullah quadrangle (pl. 1) has been divided into five main subareas of similar rock types and similar structural trend, in order to approach homogeneity of structure. The data for each subarea is summarized on equal-area projections (pl. 4). Areas 3 and 5 of plate 4 are further subdivided into still smaller areas in order to obtain structural homogeniety. Projections of the poles to foliation, bedding, and cleavage (pole diagrams) are shown for all subareas, and the direction and plunge of lineations are shown as separate diagrams for some subareas. The isopleths (called "contours" on plate 4) are lines of equal density of observations expressed as a percent of total number of points per one percent of the projection area (for example: five percent per one percent of total area).

In Area 1 of plate 4 in the northwestern part of the map area the pole diagram indicates folding around nearly north-south axes with a gentle plunge to the south. The fold limbs dip steeply and are essentially symmetrical. The lineation diagram shows a doubly plunging set, plunging gently north (12 degrees, N. 10° E.), and gently south (10 degrees, due south).

Area 2 reflects the swing in tectonic strike to the southwest. The pole diagram indicates assymmetrical folding around axes which trend N. 44° E. and plunge 10 to 20 degrees northeast. The northwest-dipping limb is represented more frequently than the steeper southeast-dipping limb, which may mean that the northwest-dipping limb is the longer, in which case, the fold system is assymmetrical toward the southeast.

The lineation diagram shows high dispersal with two maxima. One maximum plunges 20 degrees N. 46° E., corresponding to the main axis of folding shown in the pole diagram. The other maximum plunges 40 degrees nearly due west and may represent the local swing to the west of the main fold system near Chitta Batta; or it may be a second lineation direction. Inasmuch as 2 and even 3 fold-axis lineations have been measured on a single outcrop, at least 2 main lineation directions must be present, but much more data and detailed study are needed to define the meaning of a second or third set more completely. In some cases both lineations are fold crinkles representing slightly different orientations of the main fold system. In other cases one fold crinkle plunges in the general strike direction of the foliation and a second plunges down the dip of the foliation. However, some double lineations plunge in opposite directions halfway between the dip and strike direction of the foliation.

In Area 3a the bedding surfaces are somewhat dispersed and inconclusive, but do demonstrate definite folding around axes oriented slightly east of north. From the data available the concentration in the northeast quadrant is interpreted as belonging to the northeast-trending fold system. On this basis an approximate pole circle can be constructed which defines a fold system plunging 30 degrees, S. 18° W., with nearly vertical axial planes. The limbs are approximately symmetrical and dip from 50 degrees to vertical.

Area 3b shows a distinct grouping along a pole circle which defines a fold axis oriented N. 40° E., reflecting the bend in the main synclinal structure. The fold system plunges 15 degrees southwest and is slightly assymmetric with the axial plane dipping 70 to 80 degrees southeast.

In Area 3c, a sharply defined pole circle indicates a fold axis plunging 10 degrees N. 25° E. The single main grouping of poles in the northwest quadrant correlates with observed nearly isoclinal folds overturned westward with axial planes dipping steeply eastward. This pole maximum represents the nearly isoclinal limbs striking N. 25° E. and dipping 70 to 80 degrees east. The weak maximum in the southeast quadrant correlates with the observed short limbs of drag folds 15 to 20 feet in length found on the isoclinal limbs.

In Area 4 the pole diagram fails to show a clearcut pattern, which indicates either that the area is not structurally homogeneous, or more than one direction of folds are present. In spite of the dispersed pattern, however, the diagram indicates a definite fold axis, or axes, in the northeast-southwest direction. When the pole diagram is compared with the lineation diagram some additional inferrences can be made. The lineation diagram shows two sets of maxima representing two sets of doubly plunging fold systems. One set plunges 20 degrees N. 32° E., and 10 degrees S. 32° W.; and the second set plunges about 20 degrees N. 20° W., and 15 degrees S. 16° E. On the pole diagram two likely pole circles are drawn, along which most of the pole maxima occur. The first pole circle (PC_1) defines a fold axis plunging 26 degrees N. 24° E. and the second pole circle (PC_2) defines a fold axis plunging 10 degrees S. 32° W. It is seen that the northeast-southwest set of lineation maxima corresponds to the two fold axes inferred from the pole diagram. Therefore, the majority of foliations in this area are interpreted to represent a doubly plunging fold system trending northeast and southwest. The second set of lineations trending N. 20° W. and S. 16° E., and the remaining two pole maxima on the pole diagram represent additional fold directions the significance of which is unknown.

The pole diagram of Area 5a shows a strong concentration of bedding attitudes striking northwest and dipping northeast, reflecting the fact that most of the area lies on the northeast limb of the Muzaffarabad anticline. The pole diagram fails to show the known northeast-trending subsidiary folds, but the lineation diagram of bedding-cleavage intersections shows this latter direction clearly. The lineation diagram indicates a fold system plunging 50 to 70 degrees northeast. These folds, being located on the limb of the Muzaffarabad anticline, have a plunge equal to the dip of the limb of the anticline.

In Area 5b the bedding pole distribution is indistinct, indicating only a general trend to the northeast and southwest.

The total-area summary of the mineral lineations shows a strong concentration trending north and south, and plunges from 0 to 20 degrees. Most of the mineral lineations are found in the granite and hence this diagram resembles the lineation diagram of Area 1.

Summary and Conclusions

The conclusions presented here relate for the most part only to the local mapped area, and therefore are limited in scope. Further discussion of the mapped area in the context of the Hazara-Kashmir syntaxis as a whole is presented in a later section.

The structural pattern in the map area is the result of deformation during the Himalayan orogeny, which began with the granite intrusions of Late-Cretaceous or Early-Tertiary time, and has lasted to the present. The deeply buried rocks (Hazara and Tanawal formations as well as the granite itself) were affected by penetrative deformation; rocks less deeply buried (Carboniferous to Eocene rocks) were not affected by metamorphism or penetrative deformation in the map area, but nonetheless were strongly deformed, and in the Garhi Habibullah syncline they were isoclinally folded. In the mapped area the youngest rocks involved in the deformation are those of the Murree formation; farther south, near Rawalpindi, rocks of the Siwalik formation (Plio-Pleistocene) are folded. The change from metamorphosed to unmetamorphosed rocks is transitional, occurring near the top of the Hazara formation along the east limb of the Garhi Habibullah syncline, and in the Tanawal rocks in the southwestern part of the mapped area. As far as is known the Tertiary orogeny is the only major period of deformation and metamorphism in this region.

Structurally the mapped area contains parts of three structural blocks: the area east of the Jhelum fault, which is part of the axial zone of the syntaxis; the Garhi Habibullah syncline between the Tarnawai and Jhelum faults; and the area west of the Tarnawai fault. These structural blocks are identified by the major boundary faults separating them, and by the different stratigraphic relationships among them.

The pattern of folds and faults together provide evidence of differing and opposed movements during the structural development of the area. Direct and indirect evidence indicates that during the early stages of deformation, the Tarnawai and Jhelum faults underwent combined reverse-strike-slip movement. The blocks west of these faults were raised and moved to the east and southeast over the neighboring block east of the faults, and at the same time the structural blocks moved past one another relatively southward in a left-lateral sense. The net result was a general southward movement of the rocks west of the Jhelum fault, combined with a strong component of movement to the east and southeast towards the axial zone of the syntaxis.

Vertical stratigraphic displacement along the Tarnawai and Jhelum faults is about 11,000 feet. Strike-slip movement along the Tarnawai fault is shown by the change from a vertical fault to a pair of northward-dipping thrust faults at Ratri Gali. A possible left-lateral offset of 4 1/2 miles is indicated by the inferred offset of the Hazara formation along the fault. Strike-slip movement along the Jhelum fault is inferred as direct evidence is lacking. The horsetail structure at Jabri and the variations in dip along the fault are believed to be indications of strike-slip movement.

JOINTS

Introduction

As part of the study of the geologic structure in the syntaxial area, it was thought desirable to analyze the joint pattern in the Garhi Habibullah quadrangle, with the objectives, first, of determining if the joint directions have a systematic arrangement, and second, of establishing, if possible, an apparent relation or independence between joints and other structural elements of the area. If the joints formed as a result of the Tertiary mountain building episode, then their pattern would be expected to relate in some way to the present structure. If the joint pattern formed prior to the Himalayan orogeny, or by some general and long continuing process which is independent of the Himalayan orogeny, then the joint pattern would very likely show no relation to the present structure.

This area affords an excellent opportunity to find out if systematic joint patterns exist in a mountain chain so recently developed and so complexly folded as the Himalaya.

Although joints are not usually dealt with in routine field work, they have been the subject of discussion and special studies since the early 19th century. Previous investigations reveal that joints basically are caused by tensional or shear (compressional) forces, but there is no general agreement on the relative importance of these forces, nor on the causes behind them. Patnode (unpub.) thinks that as a general rule joints are tensional, whereas Harris (1960) thinks that shear joints are more important except over passive uplifts. In compressive folds both tension and shear joints have been observed, and these are geometrically related to the folds (De Sitter, 1959; Parker, 1942). In domes and other folds due to passive uplift, tension joints dominate (Patnode, unpub.; Gilke, 1953; Duschatko, 1953). In little folded areas the joint pattern commonly bears no relation to the folds (Hodgson, 1961a), and are thought to be inherited from the structures of pre-existing rocks (Hodgson, 1961, a, b). The control of joints on topography and drainage is pointed out by Hobbs (1911), Verstappen (1959), and Patnode (unpub.). The relation of joints to fracture traces, lineaments, and to the local and regional structure is discussed in several recent articles by Lattman (Lattman and Nickelson, 1958; Lattman and Segovia, 1961; Lattman and Matzke, 1961).

Summary of Method

Information on joint directions was taken at 139 outcrops distributed throughout the Garhi Habibullah quadrangle (pls. 1, 5). In an effort to obtain a representative sample at each outcrop, joint directions were taken at four stations equally spaced within the outcrop, each station being about eight feet square. The method used in establishing the four equally spaced stations is as follows:

1. Determine the length of the outcrop by pacing (for example 100 feet).
2. Divide the outcrop length by 5 (which in the example would be 20 feet).
3. Set off four stations at intervals of one fifth the length of the outcrop (in the example the stations would be 20, 40, 60, and 80 feet along the length of the outcrop).

4. If a station cannot be established at one of the intervals, because of cover or for some other reason, then an alternate station is located by moving to the nearest accessible bedrock along a line at right angles to the main traverse.

At each station the strike and dip of several individual joints are measured, taking care to include all joint directions, not just prominent ones. The attitudes of those joints belonging to the same set are averaged for each station and for the outcrop as a whole, which in the present study resulted in a total of 352 observations from 139 outcrops. From these data a rosette diagram of joint directions is constructed for each outcrop. The attitude of the bedding or foliation, and the rock type were also noted at each outcrop. The locations of the outcrops with their accompanying rosettes are shown in plate 5.

Additional information noted at each station includes certain physical features of the joints and the relations among them, such as the continuity of joints, degree of separation of opposing joint faces, which set in an outcrop was most prominent, and joint spacing.

Using the data from the individual rosettes, analyses of the joint directions are made for the area as a whole and for sub-areas of different rock types. In one set of analyses the strike directions of the joints are compared among themselves for evidence of systematic trends, and in the second analysis the strike directions of the joints are compared to the strike of the beds for indications of a geometric relation to the folds.

Physical Features and Spacial Relations of Joints

Joints are best developed in the thick massive sandstone beds of the Murree Formation. In this rock type the joints are clearly defined, evenly spaced, and the joints of a given set are closely parallel. Joints are most poorly developed in the massive mudstones of the Murree Formation. In this rock the joints are short, discontinuous, and irregular. Some joints which occur in sandstone also appear in the adjacent shale and mudstone, but in the latter rocks they are short and discontinuous. Joints are difficult to deal with in the thin-bedded dolomite of the Abbottabad formation primarily because of the confusing array of directions present and because they are very closely spaced and usually short and discontinuous. Spacing in the dolomite ranges from as little as a quarter of an inch to two inches, and the length of the joints from 3 to 10 feet.

Joints in granite usually are widely spaced, ranging from one to three feet, and are less abundant but more regular than most other rock types. Joints as long as 20 feet have been noted in granite. In the nodular limestone of the Chhalpani formation, joints are few in number, irregular and curving, and widely spaced. The metamorphic rocks, including the Hazara slates, usually display well developed, clearly defined joints, commonly in only one or two directions.

One of the interesting features of the joints is the almost total absence of visible lateral movement along the opposing faces, which is surprising in this area. In only four cases were there signs of movement, these being chatter marks, and scalloped surfaces. In addition, the joints are commonly open, as much as half an inch and filled with calcite, although tight hairline cracks also are numerous. In the sandstone and mudstone rocks of the Murree formation, joints open to a half inch and filled with calcite commonly taper within five feet to thin hairline cracks. In rare cases the calcite filling is smeared showing that lateral movement has taken place.

Another general feature of the joints is the absence of offsetting or displacement of one set by another. Commonly a weak, discontinuous set terminates against a stronger set, but no offsetting is observed. The existence of a strong, throughgoing set at one place does not mean it is dominant everywhere; in fact, one set may be dominant at one station of an outcrop and a second set at the next station, the dominant set of the first station being weakly developed or absent entirely.

Most joints dip steeply--from 60 to 90 degrees--and no systematic relationship was noted between the dip of the joints and the dip of the beds.

Analysis of Joint Directions

Introduction

In the following analyses the joint directions are divided into 18 classes of 10 degrees each, thus covering 180 degrees. In one analysis the data are grouped into 9 classes of 20 degrees each because of a shortage of data in this case. The frequency of occurrence of the joint directions falling into each class is represented by histograms (figs. 24, 25).

Analyses are made on two kinds of data: (1) the strike of the joints (fig. 24); and (2) the angular divergence between the strike of the joints and the strike of the bedding or foliation (fig. 25). Each of these analyses includes a total area summary, and subarea summaries of the sedimentary terrain and the granite-metamorphic terrain. In addition, the six resulting groups of frequency-distribution data are

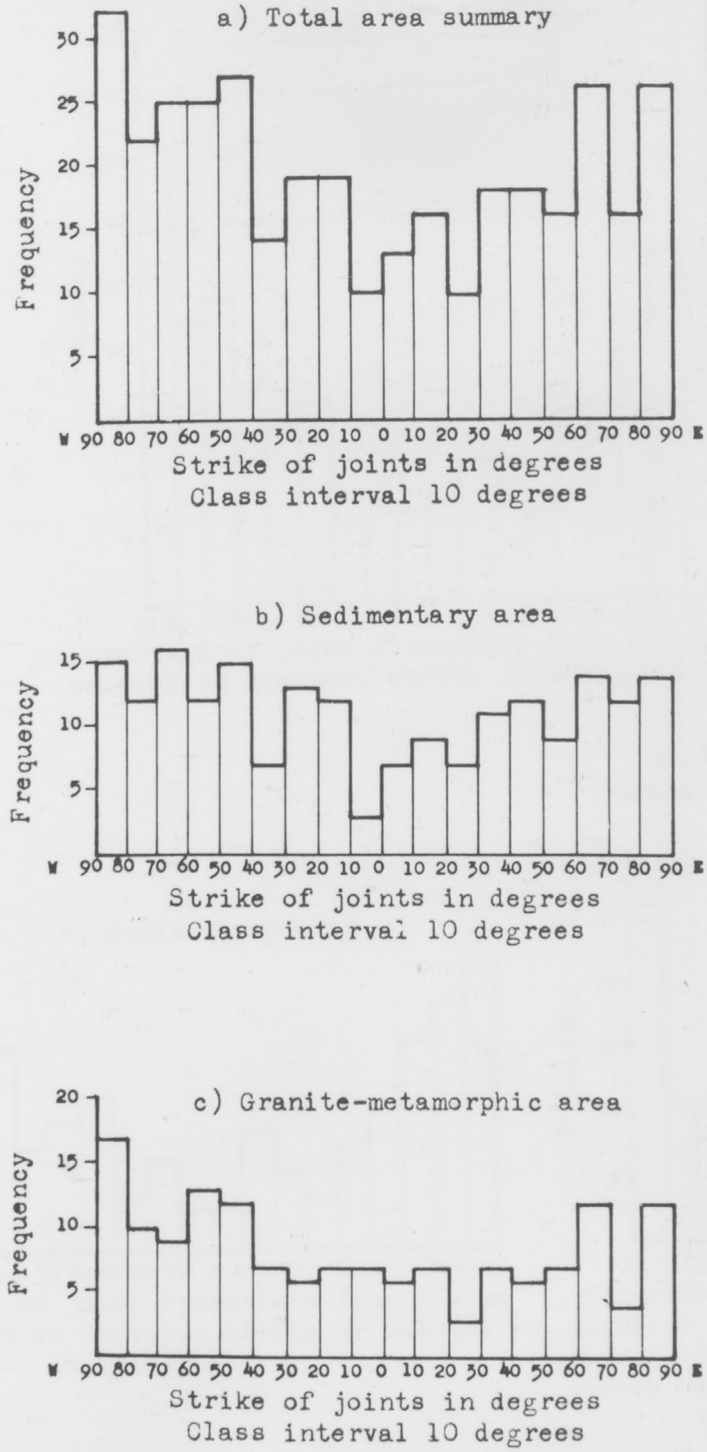


Figure 24. Frequency distribution of joint directions, Garhi Habibullah quadrangle, Hazara District, West Pakistan: a) total area summary; b) sedimentary area; c) granite-metamorphic area.

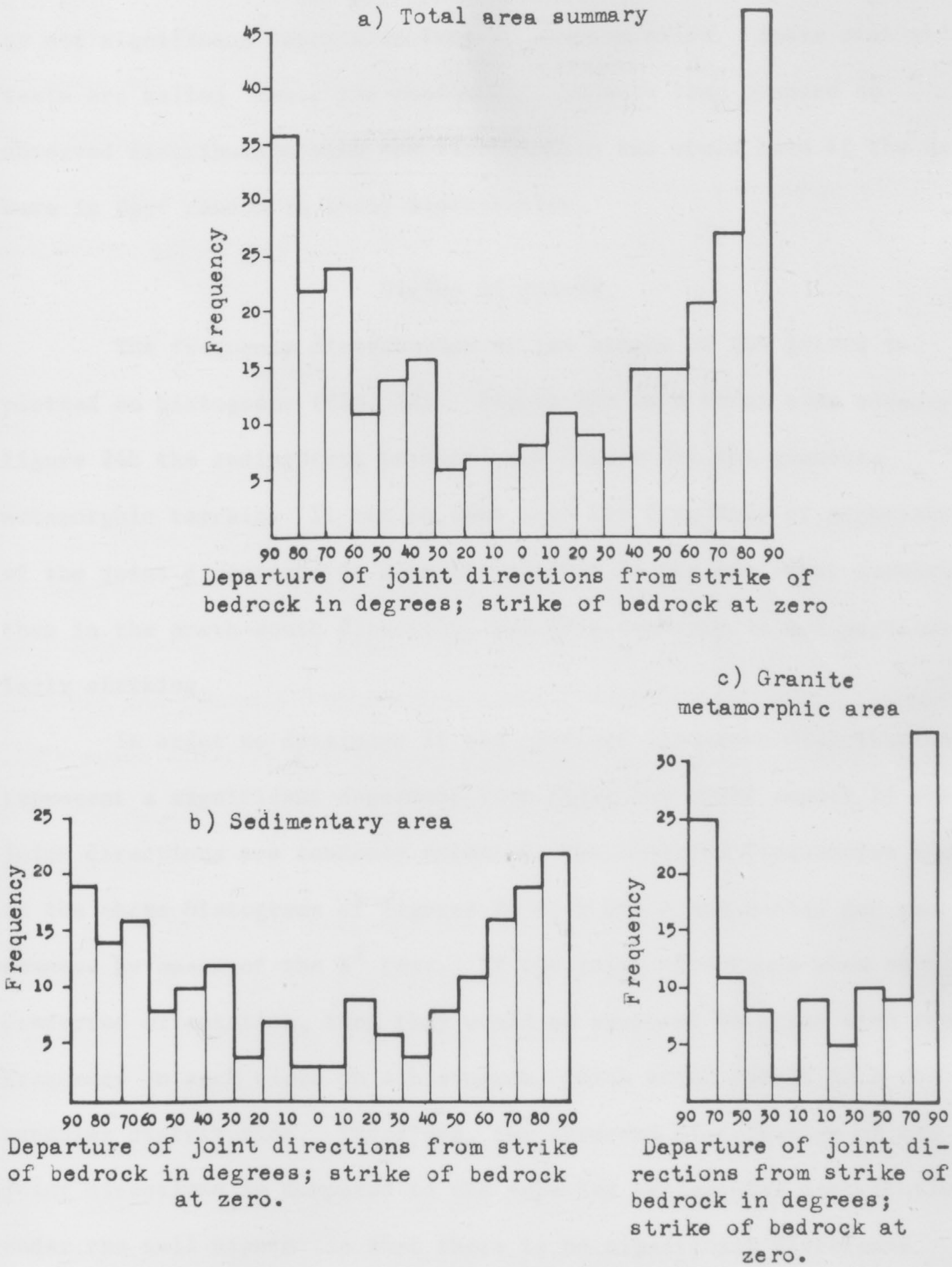


Figure 25. Frequency distribution of divergence between joint directions and strike of bedrock, Garhi Habibullah quadrangle, Hazara District, West Pakistan; a) total area summary; b) sedimentary area; c) granite-metamorphic area.

tested by the X^2 test as a means of determining statistically whether or not significant departures from randomness exist. These statistical tests are called "tests for randomness" because they compare an observed distribution with the distribution one would have if the data were in fact random in their distribution.

Strike of joints

The frequency distribution of the strike of the joints is plotted on histograms (fig. 24). Figure 24a is a total area summary; figure 24b the sedimentary terrain; and figure 24c the granite-metamorphic terrain. It can be seen that the frequency of occurrence of the joint directions is somewhat greater in the east-west direction than in the north-south direction, but this tendency is not particularly striking.

In order to determine if the observed frequency distributions represent a significant departure from those one would expect if the joint directions are randomly oriented, the observed frequencies shown on the three histograms of figures 24 a, b and c are tested for randomness by means of the X^2 test. If the joint directions show no preferred orientation, then they would be expected to occur with equal frequency in each class on a histogram, which would result in a rectangular distribution. Therefore, the observed distribution of the joint directions is compared to the expected rectangular distribution under the null hypothesis that there is no significant difference between the observed distribution and the expected rectangular distribution.

The data for the three areas tested are arranged for the X^2 test in Table 1 (appendix). The X^2 value is computed as follows:

$$X^2 = \sum^{K} \frac{(O-E)^2}{E}$$ where O = observed frequencies; E = expected frequencies; and $\sum^{K}$ directs one to sum over all categories.

The computed X^2 values for the three areas and the probability statements associated with them are as follows:

Total area:	$X^2 = 33.54$	$.001 < P < .01$
Sedimentary area:	$X^2 = 18.40$	$.30 < P < .50$
Granite-Metamorphic area:	$X^2 = 25.50$	$.05 < P < .10$

Thus, the observed differences for the total area summary would be expected to occur less than one time in every 100 trials under the null hypothesis that no significant differences exist between the observed and expected frequencies. For the sedimentary area the observed differences would be expected to occur between 30 and 50 times in every 100 trials, and for the granite-metamorphic area between 5 and 10 times per 100 trials.

The frequency diagrams and the X^2 tests indicate that the joint directions in the granite-metamorphic area have a greater tendency for a preferred orientation than those in the sedimentary area, although neither are significant statistically. However, when the two subareas are combined into a single total-area summary, the maxima in the east-west direction is pronounced on the frequency diagram (fig. 24a) and the X^2 test indicates a significant departure from a random distribution.

The significant result for the total area as opposed to the non-significant results for the subareas is attributed to the greater amount of data available for the total area. The ability of some statistical tests, including the X^2 test, to detect significant differences between samples depends in part upon the size of the samples. If the differences between samples of two different populations are small, a large sample is required to detect them.

Divergence between strike of joints
and strike of bedding or foliation

In a similar manner, analyses are made of the divergence between the strike of the joints and the strike of the bedding or foliation. Histograms showing the total area summary, the sedimentary area, and the granite-metamorphic area are shown in figures 25 a, b, and c. It is readily apparent that the joint directions in all three histograms show a strong preferred orientation perpendicular to the strike of the bedrock. X^2 tests (table 2) all yield significant X^2 values with probabilities associated with their occurrence of less than .001 ($P < .001$) indicating a significant departure from a random distribution.

Conclusions

In view of the complexity of the structure in this area, one might expect a thorough scattering of joint directions. However, in spite of the fact that as many as six joint directions are recorded in a single outcrop, it is clear from the analyses that the joints bear a geometric relationship to the folds. All three frequency diagrams of the divergence between the strike of the joints and strike of the bedding or foliation (fig. 25), as well as the X^2 tests (table 2), indicate a strong preferred orientation perpendicular to the strike of the bedrock, i.e., in the dip direction. This is equivalent to a direction perpendicular to the folds, inasmuch as most of the area studied is occupied by the limbs of folds rather than the noses, because of tight folding.

When the joint directions are compared among themselves for indications of a regional trend the results are mixed (fig. 24). Joint directions in the granite-metamorphic subarea may have greater preferred orientation than those in the sedimentary subarea, but neither are significant statistically. The total area summary, however, does exhibit a significant excess of joint directions in the wide interval between N. 40° - 90° W. and N. 60° - 90° E., and a deficiency in the interval between N. 40° W. - N. 60° E. These excesses and deficiencies are not particularly striking on the frequency diagram (fig. 24a) but the X^2 test (table 1a) indicates a significant departure from a random distribution.

The preferred orientation in the total area summary is interpreted as a reflection of the curving geologic strike of the area rather than as a regional trend independent of the geologic structure. The geologic strike, including the trends of the fold axes in the area, is generally northward, ranging from N. 30° W. in Kashmir to N. 50° E. in the southwestern part of the area. The complimentary directions, or dip directions, include the zones of joint maxima in figure 24a. Therefore, it is concluded that the broad zones of joint maxima represent an indistinct reflection of joints oriented preferentially at right angles to the folds.

Not enough data are available to analyze the joint directions in individual rock types. However, analyses for the larger rock groups indicate that the joint directions in the granite-metamorphic area may show a higher degree of preferred orientation than the joint directions in sedimentary rocks.

The joints are believed to be primarily tensional, and tensional joints oriented perpendicular to folds have been noted elsewhere (Melton, 1929; Patnode, unpublished). In highly folded rocks the main direction of relative tension (minimum principal stress) is parallel to the fold axes, and therefore jointing of a tensional nature would be expected to occur perpendicular to the fold axes. Another main source of relative tension parallel to fold axes is a doubly plunging fold system, with its resulting flexing of the fold axes.

The joint pattern throughout the syntaxial region is not known. It probably may be assumed that the joint pattern would maintain a preferred orientation perpendicular to the bedding or foliation, as was found in the local study. On this basis the joints may be among the latest structural elements of the area, having formed after folding, or during the later stages of folding, and therefore a regional trend independent of the local geologic structure would not be expected.

FRACTURE TRACES

Introduction and Definition of Terms

Knowledge of the natural linear features seen on aerial photographs is still scanty, and no study of them has ever been made in the Himalaya. Although it is generally believed that these linear features represent some type of localized fracturing on the earth's surface, few "on the ground" field studies have been made to verify this causal relationship. In an effort to shed more light on this subject, a study of fracture traces seen on aerial photographs was made of an area of about 450 square miles on the western limb of the syntaxis. The area occupies most of three 15 minute quadrangles and extends from Garhi Habibullah westward across the Indus River (fig. 1). The study included 74 stero models (photo-pairs) across slightly more than four flight lines. A total of 757 fracture traces mapped on these photographs constitutes the basis of this study. The pattern displayed by these lines is analyzed for the area as a whole and for individual sub-areas. Field examination in certain well exposed localities provided information on the nature of these linear features. With these data, consideration is given to the possible relationship between these linear features and the local and regional structure.

The air photography in this area was done in 1954 by Hunting Surveys under Canadian Colombo Plan auspices at a flying height of 25,000 feet above sea level, using a six inch lens. The scale therefore ranges from 1:45,000 at a ground elevation of 2500 feet, to

1:30,000 where the ground elevation is 10,000 feet. Such great changes in scale exist on several of the photo pairs because of the extreme relief. Because the area was flown between January and May, some of the photographs are of poor quality owing to snow and long northward shadows.

Natural linear features seen on aerial photographs, aerial mosaics, and topographic maps have been called lineaments (Hobbs, 1904, 1911; Kaiser, 1950); linears and topographic linears (Gross, 1951); fractures (Blanchet, 1957); and airphoto linears (Brown, 1961). The term lineament was coined by Hobbs in 1904 and was defined as "a generally rectilinear earth feature," which included crests of ridges, coast lines, drainage lines, boundary lines of geologic units, and joints and faults. In a later paper on the subject Hobbs (1911) redefined lineaments as "significant lines in the earth's face," and he narrowed the meaning of the term to include only lines of fracture which he suggested were to be found over the whole earth as a worldwide fracture system.

In an effort to clarify and standardize the nomenclature relating to these features Lattman (1958) has proposed the following definitions:

a) Photogeologic fracture trace (or simply fracture trace):

> . . . a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs, and expressed continuously for less than one mile. Only natural linear features not obviously related to outcrop pattern of tilted beds, lineation and foliation, and stratigraphic contacts are classified as fracture traces. Included in this term are joints mapped on aerial photographs where bare rock is exposed.

b) Photogeologic lineament (or simply lineament):

> . . . a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs or mosaics,

and expressed continuously for at least one mile, but which may be expressed continuously or discontinuously for many miles. The restrictions placed on the term "fracture trace" as regards origin apply equally to the term "lineament."

Lattman's definitions of fracture traces and lineaments are adopted here, with the exception that certain natural linear features accepted by the definitions are excluded. These are as follows:

1. In areas of extreme relief, the innumerable gulleys which drain directly down the maximum slope are not mapped. These are attributed to erosion by runoff traversing straight downslope by gravity.
2. Only those straight stream segments are mapped which are part of linear features seen in bedrock along their continuation. This excludes many straight stream segments.

As a general rule only those linear features that cut across natural drainage lines and structural trend lines are considered as fracture traces and lineaments.

In addition, all the linear features are called fracture traces in this report because most of them fall into this category.

Summary of Method

The examination of the stereo models was carried out using both the portable 2 1/2 power stereoscope and the "Old Delft" stereoscope, a sophisticated office model with variable magnification to 4 1/2 power. The natural linear features considered to be fracture traces were drawn directly on the photographs with a sharp grease pencil.

The high relief in many places causes the azimuths of lines drawn on the photographs to vary considerably from their true values. This situation, together with the planimetric errors on the existing topographic maps (except for established control points), made it impossible to transfer accurately the lines on the photographs to the existing topographic maps.

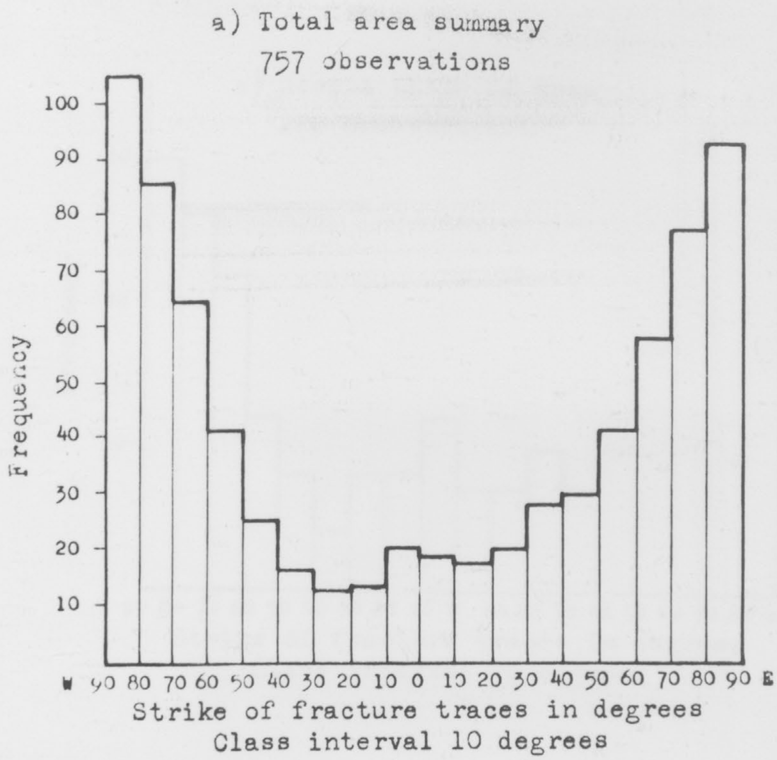
Therefore, a special planimetric base map at a scale of 1:48,000 was constructed from the photographs using the slotted template method, and the lines drawn on the photographs were transferred to the planimetric base map in their true direction by means of the Kail Radial Line Plotter. The planimetric error of the base map, measured in nine places, is a maximum of 25 feet per mile. The use of 17 control points scattered over the area assured a reasonably accurate scale solution. This map, reduced to a scale of 1:96,000, is shown in plate 6.

Analysis of Fracture Traces

As with the analysis of joints, the directions taken by the fracture traces are divided into classes of 10 degrees each, ranging from 90° west to 90° east, making a total of 18 classes. The frequency of occurrence of the fracture traces in each class is counted and represented by histograms (fig. 26). Tests for randomness are carried out using the X^2 test. In addition to a total area summary, analyses are made for the western third, the middle third, and the eastern third of the area. In the X^2 tests the western third of the area has been grouped into 15 classes and the eastern third into 17 classes because of lack of data for certain classes in these subareas.

The absolute lengths of individual lines is not considered nor is the density of lines per unit area, because both these factors are highly influenced by the degree of bedrock exposure, the type of bedrock, and the quality of the photographs.

The data of the four areas tested is arranged for the X^2 tests



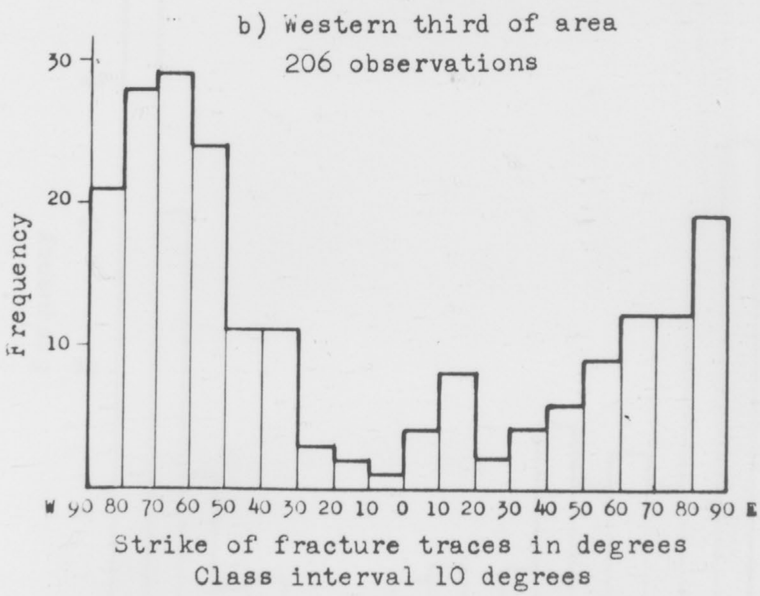
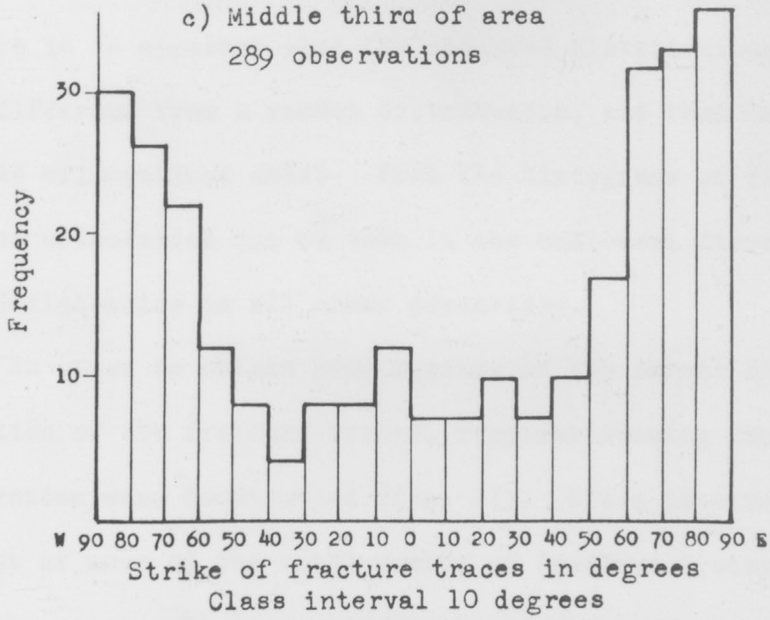


Figure 26. Frequency distribution of fracture trace directions in part of the Hazara District, West Pakistan: a) total area summary; b) western third of area; c) middle third of area; d) eastern third of area.



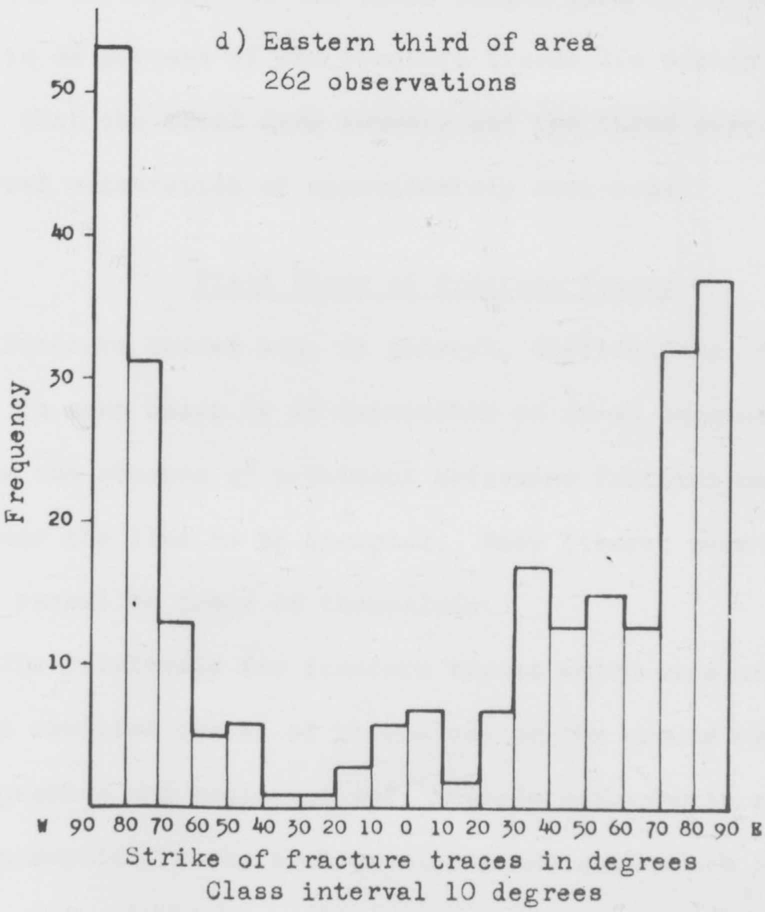


Figure 26 (Contd)

in Table 3. As shown in Table 3, the computed X^2 values for all four areas have associated probabilities of less than .001 ($p < .001$). Therefore it is apparent that the observed distributions are significantly different from a random distribution, and that one or more preferred orientations exist. From the histograms of figure 26 a preferred orientation can be seen in the east-west direction with marked deficiencies in all other directions.

In order to obtain some measure of the extent of preferred orientation of the fracture traces, diagrams showing cones of maximum concentration were constructed (fig. 27). Class intervals containing 9 percent or more of the total number of fracture traces are included within the cones. It is seen from the diagrams of the four areas that the angular divergence of the cones ranges from 40 to 50 degrees. From 47 to 58 percent of the fracture traces lie within the cones. It is clear that the total area summary and the three subareas all exhibit a preferred orientation of approximately east-west.

Field Study of Fracture Traces

Fracture traces are, in general, difficult to occupy on the ground. In many cases it is impossible to do so because of heavy timber or the absence of prominent reference features on the photographs near the line to be occupied. Many others, when occupied exactly, reveal no trace of themselves.

The relatively few fracture traces which were occupied exactly and which revealed traces of themselves on the ground were in well-exposed granite and resistant medium-grade metamorphic rocks. Relatively incompetent rocks such as slates and shales are poorly exposed and hence not suitable for the study of fracture traces on the ground.

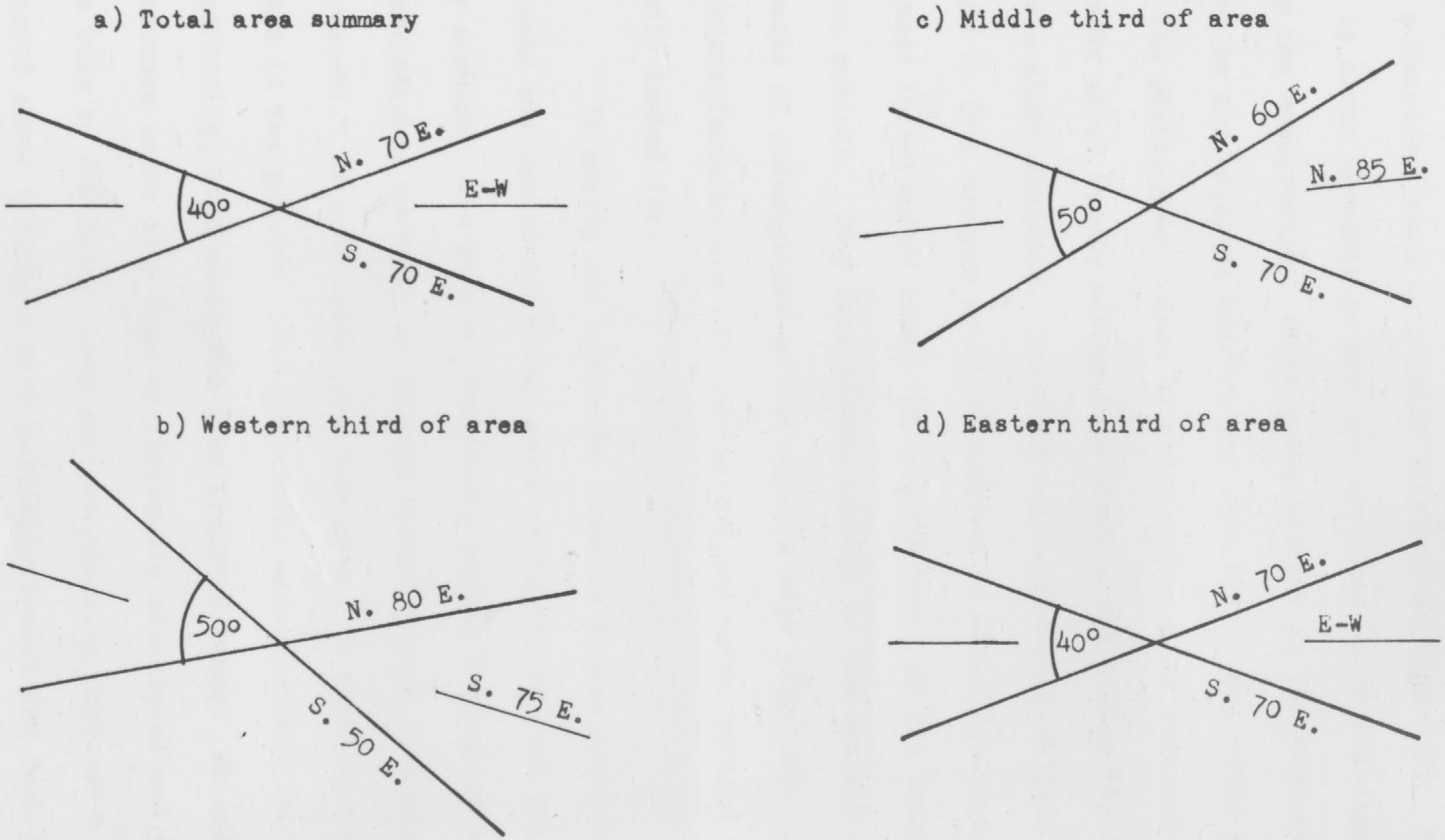


Figure 27. Diagrams showing zones of maximum concentration of fracture trace directions, Hazara District, West Pakistan: a) total area summary; b) western third of area; c) middle third of area; d) eastern third of area.

Fracture traces in granite commonly form shallow linear depressions 2 to 8 feet deep and 15 to 200 feet wide (fig. 28). A close view of a fracture trace in granite is shown in figure 29. When occupied, it is often possible to see the continuation of the depression traversing the countryside. Grass grows thicker in the depressions than it does on the adjacent bedrock and this helps to provide a tonal contrast on the photographs. Some of these topographic depressions cross small creeks which nearly always turn sharply and follow the fracture trace for a short distance. Fracture traces trending oblique to the ridges tend to form notches or small saddles at the ridgecrests. The fracture traces investigated along the bedrock banks of the Indus are in garnet mica schists. They form narrow notches in the bedrock as well as a series of indentations at the water's edge (fig. 30). All of these surface features are very subtle and are never noticed unless specifically looked for.

In nearly all cases the fracture traces investigated on the ground are caused by linear zones of fractured rock which are excavated by erosion. The kind of fracturing ranges from shear zones involving considerable movement to closely spaced joints involving little or no movement. In some cases, the fracturing is parallel to a crude foliation in the granite. All gradations exist between the two kinds of fracturing, even along the same fracture trace. At one extreme the fracture trace is a zone of thoroughly brecciated and ground up rock as wide as 200 feet. Less intense shearing produces a series of closely spaced shear stringers with partially brecciated rock in between. The next stage consists of a series of closely spaced joints with only scattered shear stringers, the rock as a whole being largely intact.

Figure 28. FRACTURE TRACES IN GRANITE, NEAR BARIARI, TWO MILES NORTHWEST OF MANSEHRA

Figure 29. CLOSE VIEW OF A FRACTURE TRACE IN GRANITE

Fracture trace consists of parallel fractures with partially crushed granite in between. Wall of unfractured more resistant granite on left forms boundary of fracture trace

Figure 30. FRACTURE TRACE TEN FEET WIDE IN SCHIST ALONG EAST BANK OF THE INDUS RIVER

Fracture trace is formed by weathering along closely-spaced joints

Finally, at the other extreme, the fracture trace consists solely of closely spaced joints along which no visible movement has taken place.

One fracture trace, 10 miles northeast of Mansehra (J190b, table 4), exhibits the two extreme kinds of fracturing. This observation lies at the intersection of two fracture traces, one trending N. 5 E., and the other trending N. 85 W. At this intersection the granite is cut by both North-South and East-West joints, and the granite between the joints is only slightly crushed. 500 feet to the east, the East-West fracture trace is marked by a zone of intense brecciation 200 feet wide which forms a natural depression in the bedrock.

The fracture traces in the narrow belt of metamorphic rocks along the Indus form deep notches as narrow as 5 feet wide and 5 to 20 feet deep. They are oriented N. 60 to 70 W. approximately at right angles to the foliation. One wall of the notch often projects into the river and in one case forms a straight line indentation on the east bank. These notches show as thin black lines on the photographs because of their shadow.

With one exception these fracture traces consist of a series of closely spaced joints along which only occasional shearing movements are evident. On the photographs some of them are seen to extend eastward across the gravel terrace for as much as 1000 feet, but no trace of their extension could be seen on the ground.

Widely spaced joints of the same orientation are common throughout this area, and it is likely that these fracture traces are the result of slight movements along pre-existing a-c tension joints.

The one exception mentioned above which was marked as a fracture trace on the photographs, proved to be a line parallel to the foliation of the metamorphic rocks.

The field investigation brought to light a few unusual reasons for the existence of straight lines seen on photographs. One straight line, 500 feet long in unfoliated granite, consisted of a granite ledge 30 feet wide standing 5 to 10 feet above its surroundings. The granite ledge was flanked on both sides by thick basic dikes, and the more rapid weathering of the basic dikes with respect to the granite caused the granite to stand out in relief.

Another fracture trace 200 feet long in granite was a single joint along which bedrock on the south side jutted 15 feet above the rock on the north side. The shadow formed by this arrangement showed distinctly on the photographs as a short straight line.

A fracture trace in granite, which consists of a series of closely spaced joints, is associated with numerous aplite dikes and stringers. The line seen on the photographs is not due to the joints, but to the aplite dikes, which exhibit a lighter tone than the granite. The concentration of joints in the midst of the aplites probably is due to slight differences in competency between the two rock types during slight tectonic movements.

A summary of the data collected from field investigations of the fracture traces and lineaments is given in table 4.

Tension Fractures and Shear Fractures

Tension fractures are those formed under tensile stress, that is, when the minimum principal stress is negative (Seigel, 1950).

Field observations indicative of the tensional nature of the fracture traces in this area are the absence of shearing along some of them, and the east-west directions taken by the soapstone veins and basic dikes, which are taken as indicators of dilation.

Tension fractures resulting from compressional deformation may form (a) parallel to the maximum principal stress during the main deformation, or (b) perpendicular to the principal stress as a result of elastic release after the compression vanishes (deSitter, 1959). When plotted on a rose diagram a single sharp maximum concentration would be expected to occur (a) parallel, or (b) perpendicular to the direction of maximum principal stress. In a paper on the fracture of materials, Seigel (1950) states that failure by tension should occur in the region from 0° to 22.5° on either side of the maximum principal stress, and failure by shear from 22.5° to 45°. On this basis the frequency diagrams and the cones of maximum concentration (fig. 27), which show only single maxima in the east-west direction, are indicative of tension fractures.

Shear fractures are inclined to the direction of maximum principal stress at angles ranging from 22.5° to 45° (Seigel, 1950). Therefore, rose diagrams would be expected to display two sharp maxima, one for each set, which are bisected by the direction of maximum stress.

Field observations in favor of the shear origin of the fracture traces are the visible shears along them, although the maximum movement cannot be great because they are known to change along their strike from well-defined breccia zones to a concentration of fractures showing no visible movement.

The diagrams of figures 26 and 27 show only one maximum of concentration instead of two, and therefore the fracture traces probably are not shear fractures. The evident shearing along them is attributed to later movements.

Conclusions

It has been established in this area that the fracture traces are for the most part linear zones of fracture which are expressed on aerial photographs as narrow furrows, straight stream segments, tonal alignments, and lines of trees.

A summary of the observed data on fracture traces in this area is as follows:

1. They exhibit a preferred orientation from N. 60° E. to S. 50° E., averaging N. 85° E.
2. The topographic expression of these features indicates that they dip steeply.
3. They are fractures of various kinds--breccia zones, fracture concentrations, or single joints. They may change along strike from breccia zones to fracture concentrations of no visible movement. At least some movement took place as shown by the breccia zones, but it cannot be much.
4. The preferred orientation of these linear features cuts across present structural trends, which vary from north-south to east-west over the area.
5. Soapstone veins are oriented east-west, as are most basic dikes.

The information obtained from the present study, although not clear cut, favors the conclusion that the fracture traces are tensional rather than shear fractures. The total area summary and the three subareas all show only one maxima, with cones of maximum concentration between 40 and 50 degrees (figs. 26 and 27). Two maxima spaced 45 to 90 degrees apart would be expected if the fracture traces were shear fractures. Therefore the distribution of the fracture traces indicates the existence of tension fractures oriented approximately east-west, with a spread of 20 to 25 degrees on either side of this direction. The visible shearing evident along many of the fractures is attributed to later movement. The soapstone veins, some of which are over 50 feet thick, and some basic dikes, have been sheared by these later movements.

The constant east-west direction maintained by the fracture traces across an area so variable in structure is taken to indicate that the fracture traces are not directly related to the structure of the immediate area.

Information on the relation of fracture traces to joint directions is contradictory. Many fracture traces are composed of closely-spaced joints, and even single joints. The fracture traces themselves, some of which contain joints, show no relation to the local structure they pass through. On the other hand, the joints studied in the Garhi Habibullah quadrangle show a definite geometric relationship to the structure. Evidently the joints present in the fracture traces are caused by regional stresses, whereas those not associated with fracture traces are caused by local stresses related to folding.

In an article on the geological significance of fracture traces, Lattman and Matzke (1961) proposed the hypothesis that fracture traces in folded rocks are not affected by local folds, but rather are governed by the regional structure. In strongly folded rocks, therefore, the local structures give rise to joints not related to the regional pattern, whereas the fracture traces do show a relation to the regional pattern. The findings of the present study tend to verify the first part of this hypothesis; the area of the present study is not large enough to verify or disprove the second part of the hypothesis.

The source of the tension that caused the fracture traces is not revealed by the present study, although it still remains as a possibility that the late phase of compression from the east, which is responsible for the westward sense of overturning in the Garhi Habibullah quadrangle, could also have caused the tension fractures. More likely, however, the cause is more regional in extent. It may be that fractures in the Precambrian (Archean) basement have been propagated upward to the surface, but this seems unlikely in this area.

As with the joint pattern, the fracture-trace pattern throughout the syntaxial region is not known. Information from the local study, however, indicates that the fracture traces would not bear a relationship to the local structure. If Lattman's hypothesis is correct, the fracture traces would be expected to follow in general the regional trend of the Himalaya across northern India.

HYPOTHESIS FOR THE DEVELOPMENT OF THE HAZARA-KASHMIR SYNTAXIS

The mapped area is an integral part of the Hazara-Kashmir syntaxis and cannot very easily be studied in isolation. Therefore, in this chapter, the structural interpretation within the local mapped area is presented as part of a general proposal for the development of the syntaxis as a whole. No simple movement picture accounts for all aspects of the Hazara-Kashmir syntaxis; present structures provide evidence of contradictory movements, which took place at different times in a continuum of structural development.

Deformation in its early stages is pictured as a general southward movement away from the central axis of the rising Himalayas. On the assumption that tectonic transport was perpendicular to the great regional arc of the Hindu-Kush-Himalaya mountain system, it is seen from figure 1 that the lines of tectonic transport converge on the present position of the Hazara-Kashmir syntaxis, which lies at the pivot point of the arc. Such movement, focusing on the present location of the Hazara-Kashmir syntaxis from the northeast, north, and northwest, eventually would cause the geologic structures and rock units to wrap around a core zone, compress the younger rocks within the core zone, and a structure such as the present syntaxis would be the natural result.

Southwestward tectonic transport along the eastern limb of the syntaxis is demonstrated by the known system of thrust and reverse faults in the Pir Panjal range southwest and west of Srinagar (Wadia, 1931). Southwestward assymmetry also was noted by the present writer at Tithwal (fig. 1) on the eastern limb of the syntaxis, where Carboniferous rocks have moved southwestward over the Murree rocks of the axial zone along a nearly vertical fault.

In the mapped area, which is on the shorter western limb of the syntaxis, the present structural pattern was developed in two principal phases of deformation, successive and related parts of the overall picture of the tectonic convergence as postulated above. In the first phase tectonic transport was generally southward, together with a strong component of pressure to the east and southeast as the southward-moving rock masses impinged against the axial zone of the syntaxis. Southward transport in the map area is inferred from north-trending mineral-streak lineations, left-lateral movement along the Tarnawai fault, and the north-dipping pair of thrust faults near Ratri Gali. Mineral-streak lineations parallel to fold axes in the granite and metamorphic rocks are taken as evidence of extension and flow folding parallel to the direction of tectonic transport, which initially was generally southward. In keeping with the picture of southward translation of rock masses, left-lateral displacement also is inferred along the Jhelum fault, although direct evidence of this is lacking. On this basis, the Jhelum fault developed in response to shearing stresses set up between the relatively stationary rocks of the axial zone and the southward-moving rocks on the west.

A second strike-slip fault, the Tarnawai fault, developed when the eastern part of the southward-moving rock mass lagged behind the western part. Thus the mapped area became divided into three structural areas, or blocks, separated by strike-slip faults. In the southern part of the mapped area, left-lateral movement along the Tarnawai fault changed to southward movement along a pair of north-dipping thrust faults.

General southward movement was accompanied by a strong component of pressure directed southeastward in the mapped area, particularly in the southwestern part where the tectonic trend fans out to the southwest. This southeastward component resulted in significant vertical movement along the main strike-slip faults, with the west side upthrown relative to the east side. The Tarnawai and Jhelum faults thus are combination strike-slip-reverse-faults.

The second phase of deformation was a southwestward and westward movement of rocks in the axial zone, manifested in the westward overturning of major folds in the mapped area, and east-over-west displacement of younger-over-older rocks along the Tarnawai, Jhelum, and Muzaffarabad faults. It is the most evident phase of deformation in the mapped area and tends to mask the earlier phase. On the scale of the Hazara-Kashmir syntaxis as a whole, this westward assymmetry is a local development restricted almost entirely to the segment of the western limb covered by the mapped area. The second phase is interpreted as an extrusion upward and westward of the highly compressed rocks in the axial zone of the syntaxis in response to continued southward and southwestward movement of rocks on the longer eastern limb of the syntaxis. Westward movement also was accompanied by continued southward movement of the rocks along the western limb of the syntaxis, which accounts for the changes in dips along the major faults. The continued squeezing together of the limbs of the syntaxis completed the horseshoe-shaped fold pattern within the axial zone and refolded the Muzaffarabad anticline and the Muzaffarabad fault. These are the latest folds recorded in the mapped area.

Two other hypotheses for the origin of the syntaxis have been proposed: one by Wadia (1931), and the other by Carey (1958). Wadia, who was the first to work in the syntaxial area, proposed that great thrust sheets ("orogenic wave fronts") moving southward from the main Himalayan orogenic axis impinged upon a buried projection of the peninsular Precambrian basement, called the Punjab wedge. Unimpeded southward movement down both sides of the projection caused the rocks to wrap around the point of impingement producing the syntaxis. Wadia's idea of a basement buttress may be true, but cannot be proved or disproved at present. Under the hypothesis proposed in the present report a buttress is not required. The presence of Late Tertiary rocks (Murree formation) throughout the axial zone where topographic relief exceeds 8,000 feet would seem to indicate a deep structural trough in the axial zone rather than a basement "high." Moreover, three additional large reentrants, similar in shape to the Hazara-Kashmir syntaxis, occur in the mountain ranges of Pakistan, and under the basement buttress idea, each of these also would call for the presence of a buried prong of the Indian peninsula at their apex.

A more recent hypothesis which approaches the problem from a continental scale has been offered by Carey (1958). Carey proposes that the Himalayan mountains and the east-west-trending mountains of Iran and southern Pakistan underwent sinistral rotation with respect to one another (left-lateral couple). This rotation presumably is around a vertical axis or series of axes and thus in plan view the large reentrants connecting the two mountain systems resemble large-scale drag folds. Certain details of the four reentrants, however, are at variance with this movement picture. The syntaxis appears at first sight to display sinistral assymmetry, but detailed work shows that rotation around a vertical axis is not a factor in its development. The Kalabagh reentrant is symmetric. The remaining two (Tank and Quetta) have short eastern limbs implying dextral assymmetry (right lateral couple). Thus the hypothesis of Carey, although attractive at the scale of whole mountain chains, is in conflict with recently obtained information on the individual mountain ranges.

GENERAL SUMMARY AND CONCLUSIONS

The area studied lies on the western limb of the Hazara-Kashmir syntaxis, in the southern Himalayas of northern Pakistan and western Kashmir. Geological surveys were made of about 200 square miles, and fracture traces were mapped from aerial photographs over an area of 450 square miles. The work is concerned mainly with the geologic structure along the western limb of the Hazara-Kashmir syntaxis, including separate studies of joints and fracture traces. With the detailed information of the study area as a basis, a hypothesis is presented for the development of the Hazara-Kashmir syntaxis as a whole.

The rocks in the area range in age from Precambrian to Tertiary, and include sedimentary, igneous, and metamorphic rocks. The area was once part of a great marine trough called the Tethys Sea, which existed, undisturbed by orogenic movements, from the Late Precambrian until the Middle Tertiary. The rock units of Precambrian and Early-Paleozoic age are mainly clastic in origin. A long period mainly of carbonate deposition, lasting from Carboniferous to Eocene time, is recorded in a sequence of limestone and dolomite totaling over 5,000 feet in thickness. Lithologic differences in the limestone, variations in thickness and disappearances of some rock units in short distances, together with the presence of some clastic units, provide evidence of nonorogenic crustal movements prior to the Himalayan orogeny. Beginning in the Middle Tertiary detrital rocks became dominant, reflecting the beginning of the Himalayan orogeny, which ultimately deformed all rocks in the region.

Intrusive granite bodies of Cretaceous-to-Tertiary age are considered to represent the southern fringes of the extensive granitic intrusions in the axial zone of the Himalaya. The granite is foliated and folded with the adjacent rocks.

The conclusions to the four specific problems as enumerated in the introductions are summarized in the following pages:

1. Integration of the metamorphism and metamorphic structures into the geological development of the area.

Regional metamorphism in the area studied has affected the rocks as young as Silurian-Devonian age. Younger rocks have not been metamorphosed, presumably because they were at too high a level in the crust during metamorphism. In general, regional metamorphism increases northward and to the northwest. North of the mapped area rocks as young as Permian are metamorphosed. Slate, phyllite, quartzose schist and dolomite give way northward to higher-grade metamorphic rocks, and a few miles to the south the slates of the map area are unmetamorphosed shales. The metamorphic rocks, as well as intrusive granite of Cretaceous-to-Tertiary age, are deformed by penetrative deformation. The sedimentary rocks are not so deformed, but nevertheless are strongly folded and are nearly isoclinal in places.

The structural homogeniety between metamorphosed and unmetamorphosed rocks, the presence of unmetamorphosed Precambrian rocks to the south, and the involvement of the Mansehra granite in the deformation, all indicate that regional metamorphism and the deformation took place as a single event late in geologic time, that is, during the Himalayan orogeny. If an earlier period of metamorphism affected the rocks in addition, no indication of it was seen.

2. Configuration and implications of the fold and fault systems on the western limb of the syntaxis.

Parts of three structural areas separated by major faults occupy the mapped area: the area east of the Jhelum fault, which is part of the axial zone of the syntaxis; the Garhi Habibullah syncline between the Jhelum and Tarnawai faults; and the area west of the Tarnawai fault. These structural areas are recognized by the boundary faults separating them and by differing stratigraphic relations within them. The general structural trend across all three structural areas is generally north-south, fanning to the southwest in the southwestern part of the area, and to the southeast in the axial zone.

The Jhelum and Tarnawai faults are combination reverse-strike-slip faults which have had west-over-east displacement in conjunction with left-lateral strike-slip displacement. Later countermovement resulted in east-over-west displacement of younger-over-older rocks and produced the present eastward dips along the faults. This later countermovement also is evident in the major folds, which are overturned westward, away from the axial zone of the syntaxis. Vertical stratigraphic displacement along the Tarnawai and Jhelum faults is about 11,000 feet. Strike-slip displacement along the Tarnawai fault is a possible 4 1/2 miles; that of the Jhelum fault is unknown. Northeast-trending secondary folds in the axial zone have refolded the Muzaffarabad anticline and the Muzaffarabad fault.

3. Relation of joints and fracture traces to the geologic structure.

A study of joint directions from 139 outcrops in the Garhi Habibullah quadrangle was made in order to determine their possible relationships with the structure of a young and complex mountain range. Joint directions were determined at each of five stations of an outcrop, and the results incorporated into a rosette for each outcrop. Frequency-distribution diagrams and X^2 analyses for the total area, the sedimentary area, and the granite-metamorphic areas show a significant preferred orientation in a direction perpendicular to the strike of the bedrock. This direction is equivalent to a direction perpendicular to fold axes, inasmuch as most of the area studied is occupied by the limbs of folds rather than the noses, because of tight folding. A weak regional direction of preferred orientation is revealed on the total-area summary. This direction ranges from N. 60° E. to S. 40° E. and is complimentary to the regional swing of the strike of the bedrock. Therefore, the apparent regional trend is considered to represent a somewhat veiled reflection of the swing in tectonic strike of the area, rather than a regional trend independent of the structure. The joints are primarily tensional, and tensional joints oriented perpendicular to folds in tightly folded rocks have been noted before by other workers.

A study of fracture traces as seen on aerial photographs, and accompanied by a ground survey, was made of about 450 square miles between the Garhi Habibullah quadrangle and the Indus River. A total of 757 fracture traces were mapped of the photographs. Frequency diagrams and X^2 tests for the total area and three subareas all show a preferred orientation ranging 20 to 25 degrees on either side of the east-west direction. The fracture traces studied on the ground were mainly narrow linear zones of fractured rock excavated by erosion. The kind of fracturing ranges from shear zones of thoroughly brecciated and ground up rock, to closely-spaced joints. All gradations are found between these two kinds of fracturing, even in the same fracture trace.

The fractures are considered to have originated by tensional stresses rather than shearing stresses, although the information bearing on this question is not clear-cut. The fracture traces show only one maxima on the frequency diagrams. Two maxima would be expected if the fracture traces were due to shear. The visible shearing along many fracture traces is attributed to later movement. Soapstone veins and basic dikes, which are taken as evidence of dilation, also have been sheared by later movements. The nearly constant direction of the fracture traces across the variable structure indicates that the fracture traces are not directly related to the local structure. Whether or not they may follow the regional strike of the Himalayas is unknown.

4. The development of the syntaxis.

No simple movement picture accounts for all aspects of the Hazara-Kashmir syntaxis; differing and contradictory movements took place at different times during the development. On the assumption that tectonic transport was perpendicular to the great regional arc of the Himalayan mountain system, the lines of tectonic transport converge on the present position of the Hazara-Kashmir syntaxis, which occupies the pivot point of the arc. With such a movement picture a structure such as the present syntaxis would be the natural result.

Southwestward transport along the eastern limb of the syntaxis has been demonstrated by Wadia. In the mapped area, which is on the shorter western limb of the syntaxis, the present configuration was developed in two phases of deformation, successive parts of the Himalayan orogeny.

The first phase was a general southward movement, together with a strong component of pressure to the east and southeast as the rock masses impinged against the early axial zone area. Southward transport is inferred from the north-trending mineral streak lineations, left-lateral movement along the boundary faults, and the north-dipping thrust faults. The southeastward component of movement resulted in significant vertical movement along the main strike-slip faults, with the west side upthrown.

The second phase of deformation was a westward and southwestward countermovement of the rocks in the axial zone, manifested in the westward overturning of major folds in the mapped area, and east-over-west displacement of younger-over-older rocks along the Tarnawai and Jhelum faults. The second phase is interpreted as an extrusion upward and westward of the highly compressed rocks in the axial zone in response to continued southwestward movements on the longer eastern limb of the syntaxis. The continued squeezing together of the limbs of the syntaxis completed the horseshoe-shaped fold pattern within the axial zone and refolded the Muzaffarabad anticline and the Muzaffarabad fault.

Wadia's hypothesis that southward-moving rock masses wrapped around a basement buttress is doubted, because the axial zone, occupied nearly throughout by Late Tertiary rocks, would seem to indicate a structural trough rather than a basement high.

Carey's hypothesis that a left-lateral couple between the Himalayas and the mountain system of Iran produced the syntaxis also is doubted, because other large reentrants in the system do not have the required sense of rotation.

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APPENDIX

Table 1. Chi square tests for randomness of joint directions, Garhi Habibullah quadrangle, Hazara District, West Pakistan: a) total area summary; b) sedimentary area; c) granite-metamorphic area.

a) Total area summary

W 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 E

EXP	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	
OBS	32	22	25	25	27	14	19	19	10	13	16	10	18	18	16	26	16	26	352
x^2	7.8	0.2	1.5	1.5	2.8	1.6	.02	.02	4.7	2.2	0.7	4.7	0.1	0.1	0.7	2.1	0.7	2.1	33.54

$.001 < P < .01$; df = 17

b) Sedimentary area

W 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 E

EXP	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	
OBS	15	12	16	12	15	7	13	12	3	7	9	7	11	12	9	14	12	14	200
x^2	1.4	.07	2.2	.07	1.4	1.5	.32	.07	5.9	1.5	0.4	1.5	.01	.07	0.4	.76	.07	.76	18.40

$.30 < P < 50$; df=17

c) Granite-metamorphic area

W 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 E

EXP	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	
OBS	17	10	9	13	12	7	6	7	7	6	7	3	7	6	7	12	4	12	152
x^2	8.8	.31	.04	2.5	1.5	.24	.69	.24	.24	.69	.24	3.5	.24	.69	.24	1.5	2.3	1.5	25.5

$.05 < P < .10$; df=17

Table 2. Chi square tests for randomness of divergence between joint directions and strike of bedrock, Garhi Habibullah quadrangle, Hazara District, West Pakistan; a) total area summary; b) sedimentary area; c) granite-metamorphic area.

a) Total area summary

W 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 E

EXP	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	
OBS	36	22	24	11	14	16	6	7	7	8	11	9	7	15	15	21	27	47	303
x^2	22.0	1.6	3.1	2.0	.45	.04	6.1	5.7	5.7	5.7	2.0	3.7	5.7	0.2	0.2	1.0	6.2	54.8	125.7

$P < .001$; df=17

b) Sedimentary area

W 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 E

EXP	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	
OBS	19	14	16	8	10	12	4	7	3	3	9	6	4	8	11	16	19	22	191
x^2	6.6	1.1	2.7	0.7	.03	0.2	4.1	1.3	5.4	5.4	.24	2.0	4.1	0.7	.02	2.7	6.6	12.2	45.89

$P < .001$; df=17

c) Granite-metamorphic area

W 90 70 50 30 10 10 30 50 70 90 E

EXP	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	
OBS	25	11	8	2	9	5	10	9	33	112
x^2	12.4	.16	1.55	8.7	.93	4.4	.47	.93	34.0	63.54

$P < .001$; df=8

Table 3. Chi square tests for randomness on orientation of fracture traces in part of the Hazara District, West Pakistan: a) total area summary; b) western third of area; c) middle third of area; d) eastern third of area.

a) Total area summary

	W 90–80	80–70	70–60	60–50	50–40	40–30	30–20	20–10	10–0	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90 E	
EXP	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	
OBS	104	85	64	41	25	16	12	13	19	18	17	19	28	29	41	57	77	92	757
X^2	88	42	10.5	0.1	7.4	17	22	21	13	14	16	13	5,1	4.5	0.1	4.7	27	58	363

P< .001; df 17

b) Western third of area

	W 90–80	80–70	70–60	60–50	50–40	40–30	30–10	10–10	10–20	20–40	40–50	50–60	60–70	70–80	80–90 E	
EXP	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
OBS	21	28	29	24	11	11	5	5	8	6	6	9	12	12	19	206
X^2	3.9	15	17	7.7	0.5	0.5	5.5	5.5	2.4	4.3	4.3	1.3	0.2	0.2	2.0	70

P<.001; df 14

c) Middle third of area

	W 90–80	80–70	70–60	60–50	50–40	40–30	30–20	20–10	10–0	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90 E	
EXP	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	
OBS	30	26	22	12	8	4	8	8	12	7	7	10	7	10	17	32	33	36	289
X^2	12.2	6.2	2.2	1.0	4.0	9.0	4.0	4.0	1.0	5.0	5.0	2.2	5.0	2.2	0.1	16	18	25	122

P<.001; df 17

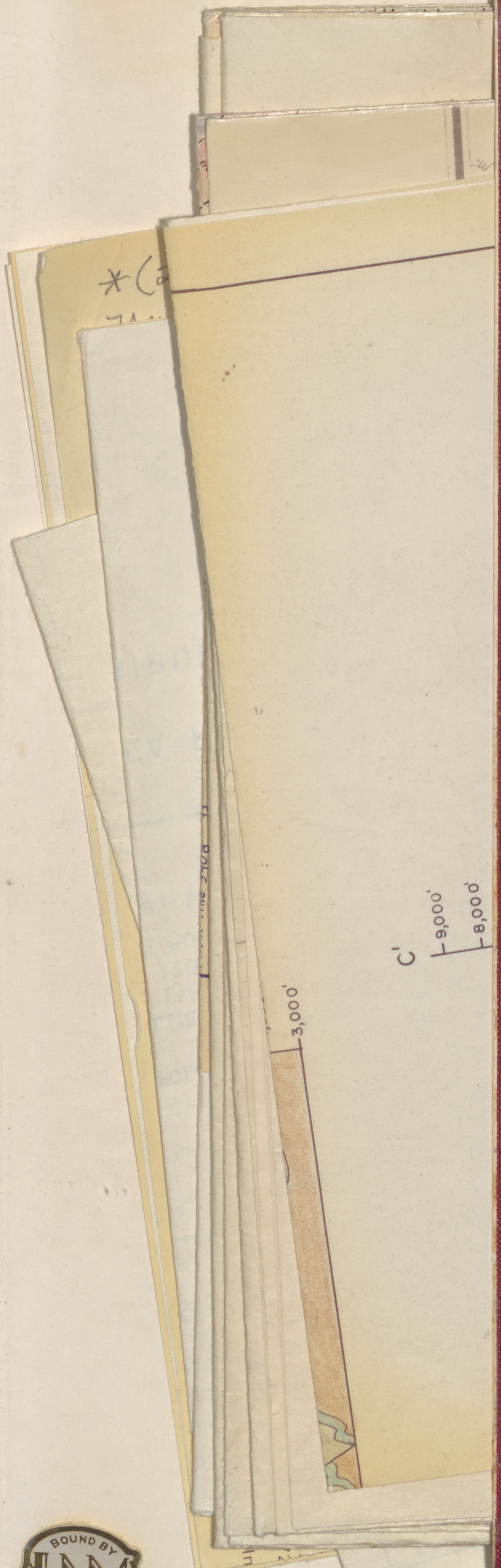
d) Eastern third of area

	W 90–80	80–70	70–60	60–50	50–40	40–20	20–10	10–0	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90 E	
EXP	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	
OBS	53	31	13	5	6	2	3	6	7	2	7	17	13	15	13	32	37	262
X^2	90	15.5	0.4	7	5.8	11.5	10	5.8	4.6	11.5	4.6	0.4	0.4	.06	0.4	17	30	215

P< .001; df 16

Table 4. Summary of data collected from field investigation of fracture traces

Field no.	Direction	Width	Cause
Low hills 3 miles north of Mansehra in porphyritic, generally unfoliated granite			
J330, 331	N. 61° E.	15 feet	shear zone parallel to crude foliation
J332	N. 83° E.	12 feet	slightly crushed zone parallel to crude foliation
J334	N. 73° W.	15-20 feet	closely spaced joints plus small shear zones and shear stringers
J335	N. 25° E.	6-20 feet	breccia zone
J336-337	N. 77° E.	15 feet	breccia zone
Low hills 10 miles northeast of Mansehra in prophyritic, generally unfoliated granite			
J190a	N. 1° W.	50 feet	widely spaced joints parallel to crude foliation
J190b	N. 5° E.	30 feet	closely spaced joints with partial crushing of rock between joints
J190b	N. 84° W.	30-100 feet	closely spaced joints; eastward the zone is strongly brecciated
J190d	N. 38° W.	50 feet	closely spaced joints
J190f	N. 75° E.	100 feet	closely spaced joints associated with aplite dikes and stringers



C'
9,000'
8,000'
3,000'