Stratigraphy, structure, petrology and local tectonics, Central Ladakh, NW Himalaya

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Stratigraphy, Structure, Petrology and Local Tectonics, Central Ladakh, NW Himalaya

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Abstract

This paper summarizes results of traverses in central Ladakh, NW India, in the platform sediments of the northern Indian sub-continent (Zanskar Platform), an allochthon including discrete blocks of basic volcanic rocks and ultramafic rocks (Spongtang Allochthon), a major tectonic zone bounding the section of Indian platform sediments on the north (Indus Zone), and a composite batholith north of that tectonic zone (Ladakh Batholith). Sediments in the Zanskar Platform range from Lower Eocene (or younger) sandstones and shales through Triassic limestones. Three major phases of deformation are distinguished: Late Cretaceous isoclinal folding around SW verging axial planes, post-Lower Eocene open folding about almost vertical axial planes, and brittle deformation of this later structure during emplacement of the Spongtang Allochthon. The basal thrust of the Allochthon is nearly flat and undeformed. The Spongtang Allochthon includes isolated blocks of ultramafic, volcanic and sedimentary rocks in a large scale matrix of sheared serpentinite. The volcanic rocks may be correlative to the island-arc type Dras Volcanics of the Indus Zone. The ultramafic rocks, predominantly harzburgite but including dunite, orthopyroxenite, and lherzolite, host numerous gabbroic to tonalitic dikes. The Indus Zone consists of fault-bounded volcanic rocks which include agglomerate and rhyodacitic pyroclastic rocks; the volcanic rocks may be correlative to bimodal volcanics intruded by the Ladakh Batholith. The Ladakh Batholith is lithologically complex, with a varied suite of intrusive rocks ranging from pegmatite, aplite and granophyre to harzburgite and lherzolite, with hornblende-biotite monzodiorite predominating. The ultramafic rocks of the Ladakh Batholith contain phlogopite, plagioclase and spinel, distinguishing them from more refractory rocks of the Spongtang Allochthon. Gradational contacts were observed between gabbronorite and clinopyroxene-bearing granite. A bimodal volcanic suite is found within the Batholith at Teah, in which basic volcanics are intruded by a granite, while dacitic dikes intrude other members of the Batholith. These volcanics are correlative to the Shyok Volcanics north of the Ladakh Batholith.

Keywords: tectonics, areal geology, stratigraphic columns, continental shelf, ultramafic nappes, batholites, Ladakh

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Introduction

Many geologists have visited the district of Ladakh, in northwestern India, to study the Indus Zone or Indus-Tsangpo Suture Zone, first proposed to be a major intercontinental lineament by GANSSER (1964). The ESE-WNW trending portion of the Indus Zone in Ladakh, marked by steep fault zones including ophiolitic mélange, separates the northernmost expression of the platform sediments of the Indian subcontinent (Zanskar Platform) from volcanic rocks and a major batholith to the north (Ladakh Batholith). A large body of literature on the Indus Zone has recently been summarized by SHARMA and KUMAR (1978), KLOOTWIJK et al. (1979), and SRIKANTIA and RAZDAN (1980). However, little information is available on the Ladakh Batholith or the Zanskar Platform.

The authors made several traverses across the Zanskar Platform (Fig. 1). Previous work on the area is limited to reconnaissance by LA TOUCHE (1888), LYDEKKER (1883), FUCHS (1977, 1979), BASSOULLET et al. (1978a) and SRIKANTIA and RAZDAN (1980). We were also able to make brief visits to the southern margin of the Ladakh Batholith. Geologists studying the Indus Zone have previously described the general lithology of the Batholith (SHAH et al., 1976; SHANKER et al., 1976; FRANK et al., 1977; SRIKANTIA and BHARGAVA, 1978; KLOOTWIJK et al., 1979). SHARMA and GUPTA (1978) report on a traverse made across the Ladakh Batholith.

The age of emplacement of the Ladakh Batholith is controversial. SHANKER et al. (1976) report Upper Cretaceous sediments transgressive onto the southern margin of the batholith. HONEGGER et al. (1982) report a U/Pb zircon age of 103 ± 3 m.y. for granodiorite near Kargil (western Ladakh), a Rb/Sr biotite - whole rock isochron of 80 ± 3 m.y. for granodiorite intruding the Dras Volcanics of the Indus Zone near Kargil, and a Rb/Sr whole rock isochron for samples from the batholith near Shey Gompa of 60 ± 10 m.y. They note that K/Ar ages on biotite from the same samples are 45–50 m.y. BROOKFIELD and REYNOLDS (1981) determined a K/Ar age of 60 m.y. for a member of the batholith near Kargil. DESIO et al. (1963) report an Rb/Sr age of 48 m.y. for a sample from the western extension of the batholith in the Deosai Plateau. KLOOTWIJK et al. (1979) summarized numerous K/Ar and fission track ages for members of the batholith and concluded that a grouping between 49 and 45 m.y. indicates sudden Middle Eocene cooling. However, LAL and NAGPAUL (1975) report apatite annealing ages ranging up to 15 m.y. SHARMA et al. (1979) report a K/Ar age of 38 m.y. from the "core zone" of the Batholith near Hemiya in eastern Ladakh. SHARMA and KUMAR (1978) conclude that the Batholith represents a continuous Lower Cretaceous to Lower Miocene intrusive suite.

South of the Ladakh Batholith lie a series of Upper Cretaceous to Pliocene sedimentary rocks transgressive onto the intrusions (SHANKER et al., 1976; PAL et al., 1978; BAUD et al., 1981). We refer these as the Indus Molasse in our field

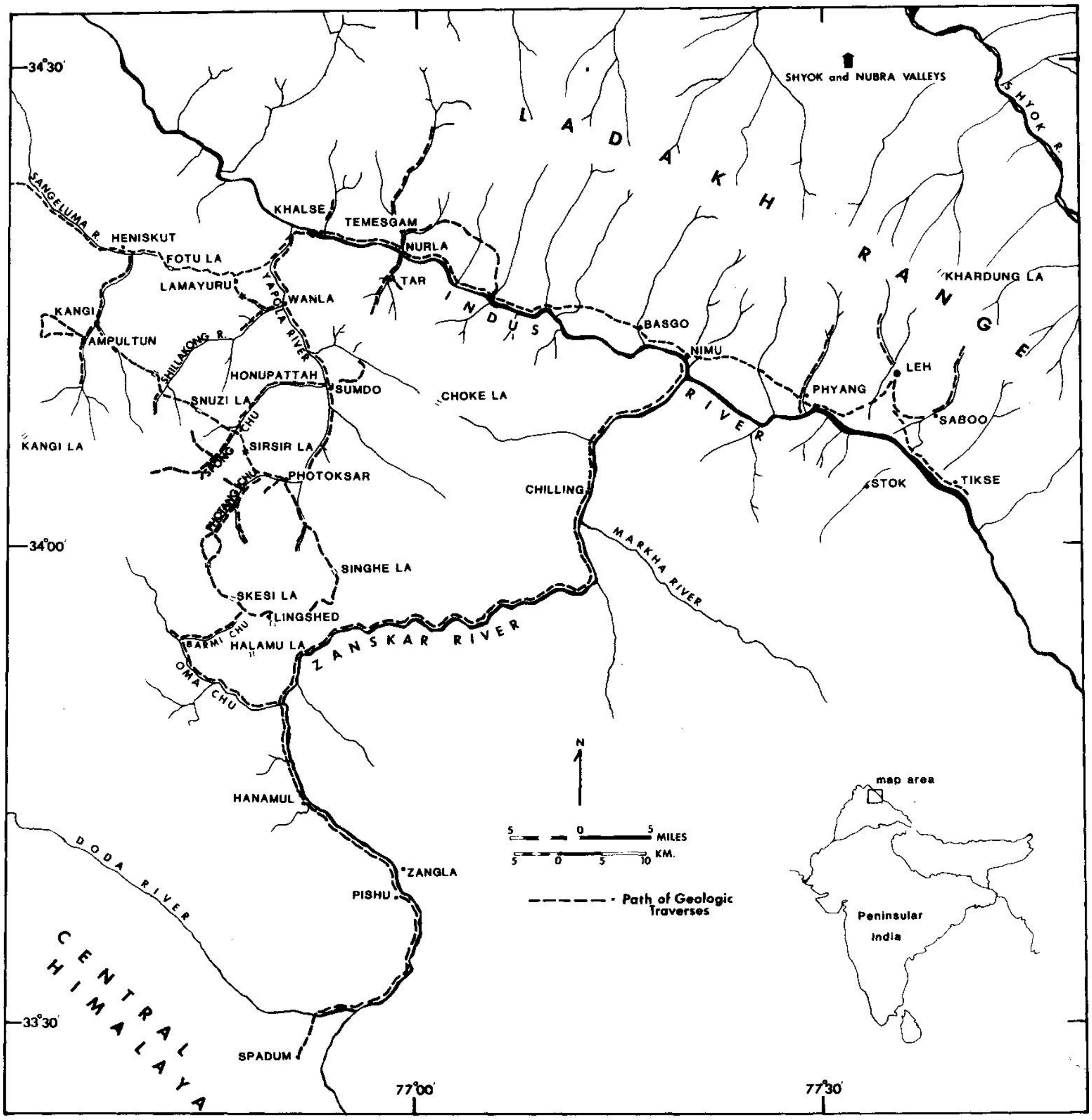

Fig. 1 Geography of central Ladakh and Zanskar, with geologic traverses (August-October, 1980).

area. The Indus Molasse is separated by a fault from a volcanoclastic and sedimentary unit, the Indus Flysch, as reported by FUCHS (1977, 1979) who found Middle Cretaceous fauna in intercalated limestones. A major fault zone including ophiolitic mélange separates the Indus Flysch from the Dras Volcanics and Flysch. WADIA (1937) and GUPTA and KUMAR (1975) report Mid-Cretaceous ages for limestones intercalated with the Dras Volcanics. Eocene limestones overlie the Dras Volcanics in the vicinity of Dras (MIDDLEMISS, 1919, cited in WADIA, 1937). The Dras Volcanics are bounded to the south by another fault zone including ophiolitic mélange. The fault-bounded Indus Flysch and Dras

Volcanics and Flysch, together with ophiolitic mélange, comprise the Indus Zone. Geochemical studies of the Dras Volcanics (KLOOTWIJK et al., 1979; HONEGGER et al., 1982) indicate that they include island arc type volcanics and are not, strictly speaking, part of the ophiolite suite in Ladakh. Paleomagnetic data obtained by KLOOTWIJK et al. (1979) suggest convergence between the Indian subcontinent and the Ladakh Batholith continued until a Paleocene or Lower Eocene "final closure" of the Indus Zone (approx. 50 m.y. ago).

South of the Indus Zone, in the western portions of our field area, lies the Lamayuru Formation, a thick sequence of flyschoid black shales, phyllites, marly shales, sandstones, and narrow horizons of sandy limestone. FRANK et al. (1977), FUCHS (1977, 1979) and STERNE (1979) report Middle and Upper Triassic fauna in the Lamayuru Formation. However, FUCHS (1979) hypothesizes that the Lamayuru Formation includes post-Triassic rocks on the basis of belemnites discovered near the village of Lamayuru. BASSOULLET et al. (1981, cited in BAUD et al., 1982) report Lower Jurassic microfauna from limestone lenses in the Lamayuru Formation. This unit is bounded to the south and truncated to the east by an extensive fault named the Zanskar Thrust by FRANK et al. (1977).

South of the Zanskar Thrust lies a more or less conformable sequence of Mesozoic and Lower Tertiary sediments of the northern Indian sub-continent (Zanskar Platform). In this region we followed FUCHS' (1977, 1979) stratigraphy, with a few necessary departures. The Zanskar Platform extends south to the Permian Panjal Trap, which passes downward into crystalline metamorphic rocks of the Greater Himalayan Range. Fuchs described a complete succession of platform sediments younger than the Panjal Trap and extending to the Eocene, southwest of our field area near the village of Rangdum. The eastward extension of this stratigraphic and structural work was the focus of our traverses in the Zanskar Platform, which included investigation of the previously undescribed section beneath the Spongtang Allochthon and of the structure of Mesozoic rocks along the lower Zanskar River (Spadum to Nimu).

The Spongtang Allochthon, identified as allochthonous by FUCHS (1977), is emplaced over the sedimentary rocks of the Zanskar Platform. We were able to identify and map the major structural units of the allochthon and conduct a preliminary petrographic study of the igneous rocks present there.

Stratigraphy and Petrology

ZANSKAR PLATFORM

Red and Green Shale

Directly beneath the basal thrust of the Spongtang Allochthon lies a red and green shale and sandstone unit several hundred meters thick. Graded beds are locally present in rhythmic sequences with intercalations of green shale, red sandstone, and coarse green sandstone and conglomerate. These colorful upper units are replaced by dark green grey shales lower in the formation. FUCHS (1977, 1979) found similar colorful shales in synclines near Kangi La to the west of the Spongtang Allochthon.

Lingshed Limestone

Beneath the shales is a thick bedded limestone, with a few shaley horizons, more than 100 m thick. It contains Alveolina, Flosculina and Nummulites, giving an Upper Paleocene to Lower Eocene age. This is the "Eocene limestone" described by LA TOUCHE (1888) above Singhe La and Lingshed, and appears to be laterally continuous, though time transgressive, with Upper Cretaceous to Paleocene limestones near Rangdum, noted by FUCHS (1977, 1979) and described by GAETANI et al. (1980). Its presence establishes a lower limit for the age of the Red and Green Shales and the emplacement of the Spongtang Allochthon. Beneath the Lingshed Limestone is a very continuous narrow horizon of brown to tan-weathering quartzite intercalated with black calcareous shales. These units locally overlie a horizon of cream, tan and red calcarenites which rarely exceeds 10 m in thickness. The quartzite and calcarenite are included with the Lingshed Limestone on our geologic map (Fig. 2).

Kangi La Flysch

Below these units are tightly folded, tan-weathering black shales with a few intercalated silts and sands, showing well-developed axial plane cleavage. The sands and shales include many fucoids, including fragments of Rotalidae (?). This unit is correlative to FUCHS' (1977, 1979) Kangi La Flysch. GAETANI et al. (1980) question FUCHS' assertion that the Kangi La Flysch is more than 1000 m thick, reporting a thickness of 400 m near Rangdum. We believe that the unit thickens to the northeast and, although tight folding of incompetent shales makes estimation difficult, propose that the unit extends more than 1000 m in the vicinity of Lingshed and Skesi La.

FUCHS (1977, 1979) proposed a narrow NW-SE trending allochthonous belt of the Lamayuru Formation extending from Kangi and Ampultun to the Sirsir La. This hypothesis was based on the lithology of flyschoid black shales of this belt, which is similar to that of the Lamayuru Formation. However, these shales may be followed in continuous outcrop from Kangi across the Singhe La to Lingshed. Throughout this area they lie between the Mid (?) to Upper Cretaceous Multicolored Formation and the Upper Paleocene-Lower Eocene

Lingshed Limestone, and represent a slightly more distal facies of the Kangi La Flysch. Similarly, "allochthonous Triassic limestones" shown by FUCHS (1977, 1979) in the Kong drainage south of Kangi are continuous in outcrop with the Lingshed Limestone, and form conformable synclines in the Kangi La Flysch. Anticlines of the Multicolored Formation comprise the "exotic limestones" reported by FUCHS at Sirsir La and Snuzi La.

Multicolored Formation

This unit, a series of red, green, cream and grey calc-arenites, slates, phyllites and calc-schists, with intercalations of lithographic limestone, was originally identified by FUCHS (1977, 1979) who mistakenly assigned it a Triassic age. BASSOULLET et al. (1978b) found microfauna of Campanian age in the Multicolored Formation just south of the Zanskar Fault above the Fotu La. The Formation grades upward into the Kangi La Flysch between Dumbur and Kangi, and along the Kong drainage between Kangi and Ampultun. Along the lower Kong drainage between Kangi and Heinskut, it grades downward into a thick sequence of massive grey limestone and dolomite, eventually passing downward into the Lower Jurassic Kioto Limestone. In the southeast, along the Oma Chu and Zanskar Rivers the Multicolored Formation grades laterally and downward into the Lower Cretaceous Guimal Sandstones. Further west along the Oma Chu drainage a lateral facies change is observed between the Multicolored Formation and the Middle to Upper Cretaceous Chikkim Limestone. At the confluence of the Barmi Chu and the Oma Chu, the Multicolored Formation is not present at all, and the Kangi La Flysch conformably overlies the Chikkim Limestone. In summary, the Multicolored Formation is a distal facies of the Zanskar Platform, thickening to the north and grading into more proximal facies to the south and southwest.

Chikkim Limestone, Giumal Sandstone and Spiti Shales

Conformably below the Kangi La Flysch along the Barmi Chu drainage is a nodular, light grey limestone some 100 m thick, with very abundant but poorly preserved belemnites and stromatolitic algal mats. This is FUCHS' Chikkim Limestone (1977, 1979). Along the Oma Chu east of the Barmi Chu, the upper beds of the Chikkim Limestone grades laterally into the Multicolored Formation (described above). This stratigraphy is in accord with BAUD et al. (1981), who report multicolored marly limestones, green quartzarenite and dark grey marly limestones overlying the Lower Cretaceous Giumal Sandstone in the Zanskar Platform east of the Zanskar River.

Along the Barmi Chu the Chikkim Limestone occurs in three distinct intercalations with upper members of the Guimal Sandstone. This unit is composed of dark green to black greywackes and shales weathering dark red. Lower members include greenish shale and green calcarenite, coarse-grained channelized sandstones and conglomerates in local unconformity with the surrounding shales and sands, and dry ground boreholes in some of the finer shaley overbank deposits. The lowest member is rich in black concretions and angular, trachytic lithic fragments. All three members include sequences of graded beds and locally show cross-bedding. Eastward, down the Oma Chu drainage, the lower two of the nodular Chikkim Limestones grade laterally into sandstones and shales. Further east, the greywackes are consolidated, forming a massive, resistant bed beneath the upper member of the Chikkim Limestone and overlying a thick sequence of black shales full of black lithic clasts and concretions. This appears to be the lateral continuation of the Upper Jurassic Spiti Shales, identified in the Zanskar Platform beneath the Giumal Sandstone by FUCHS (1977, 1979) and BAUD (1981).

Kioto Limestone

Along the Oma Chu, the Giumal Sandstone and the Spiti Shale overlie a great wall of massive limestone with occasional shaley beds, in isoclinal and tight chevron folds with axial planes dipping NE. These are the Kioto Limestone and older formations representing the proximal Jurassic (?), Triassic and Permian of the Zanskar Platform, stretching uninterrupted to the Oma Chu-Doda River divide to the southwest. We made no attempt to differentiate the Kioto Limestone from older limestone and dolomite in the field, and they are shown together on our geologic map.

SPONGTANG ALLOCHTHON

The allochthon is structurally complex, with many discrete blocks of volcanic and volcaniclastic rocks, ultramafics, rodingites, clastic sediments and limestone in a large scale matrix of sheared serpentinite and chlorite schist. The volcanic rocks do not form a horizon beneath the major peridotite block as shown by FUCHS (1977, 1979). Volcanic blocks predominate along the north, northeast and estern margins of the allochthon but are quite secondary to the south and southwest. One volcanic block is well over 1 km thick and 10 km long, forming a gigantic scarp striking NNW along the east side of the allochthon, underlain by a cataclastic breccia of reworked basalt and sandstone above the basal thrust. In general, blocks larger than 1 km in diameter are common, although smaller slices to 5 m in diameter are found in melange near the southern edge of the allochthon. Here, clastic sedimentary and limestone blocks approach or exceed the volcanic blocks in volume.

The volcanic rocks resemble the Dras Volcanics of the Indus Zone and we have tentatively correlated the two, following FUCHS (1977, 1979) and SRIKANTIA and RAZDAN (1980). We noted reddish brown and green submarine flows, intercalated with green pyroclastic rocks; green shales (ash beds?); red and green siltstones, sandstones and conglomeratic sandstones; abundant red, green and white jasper and chert; and a striking multicolored agglomerate with angular clasts of brightly colored siltstone, chert, basalt, pyroclastics and limestone in a matrix of fine clastic material. The basaltic flows, with iddingsite, calcite and sericite replacing olivine, pyroxene and plagioclase phenocrysts, often show well preserved pillow structure and, in larger flows, a gradation from vesicular, glassy material at the top, down to columnar jointed, massive basalt at the base. As noted by BASSOULLET et al. (1978a) limestones are intercalated with basic volcanics in an outcrop west of Photoksar. These limestones are light grey to pink and yield indeterminable crinoids and ammonites. A large, isolated block of massive light grey to pink limestone with abundant corals and crinoids forms a prominent peak on the southern margin of the allochthon. Particularly relevant in correlating the volcanic rocks with the Dras Volcanics is the abundance of bright red jasper, considered diagnostic in distinguishing the Dras Volcanics from the Panjal Trap by WADIA (1937), who also reported ammonites in the Cretaceous Orbitolina limestone intercalated with the Dras Volcanics in the Burzil Valley. However, HONEGGER et al. (1982) propose that some of the volcanic rocks represent an alkaline volcanic series. Because volcanic rocks occur in isolated blocks throughout the allochthon, systematic sampling will be necessary to distinguish geochemically distinct volcanic series.

Relatively fresh ultramafic rocks form discrete, tectonically coherent blocks, one more than 1 km thick, within the Spongtang Allochthon. They grade through partially serpentinized rocks showing pyroxene into sheared serpentinite over 10 to 50 m. The ultramafic rocks vary in composition, including lherzolite, dunite and orthopyroxenite as well as abundant harzburgite. These varieties are juxtaposed within 50 m and probably are not regionally zoned as shown by SRIKANTIA and RAZDAN (1980). Harzburgite samples are seriate porphyritic, with enstatite or bronzite phenocrysts to 1 cm in diameter including abundant clinopyroxene exsolution lamellae. Anhedral, interstitial forsteritic olivine crystals, ranging from 1 mm to 1 cm in longest dimension, are usually elongate with banding normal to the direction of elongation. Spinel is occasionally present in these rocks, while plagioclase, phlogopite and primary amphibole are absent in our samples. FUCHS (1979) gives a petrographic description of lherzolite, with colorless amphibole replacing pyroxenes, sampled from float near the Allochthon. Dunite and orthopyroxenite are coarse grained, with forsteritic olivine and enstatite to 5 cm in maximum dimension.

Intrusive dikes and rodingites are abundant in the allochthon, occurring as isolated blocks in sheared serpentinite, but more commonly within tectonically coherent ultramafic rocks. Near the basal thrust these dikes are mylonitized and show sharp contacts with the surrounding serpentinized harzburgite. Within the large ultramafic block at the center of the allochthon, between the Photang and Spong drainages, dikes and rodingites intrude the ultramafic rocks. Intrusive features along the contacts include stoping of bronzitic pyroxene megacrysts into leucocratic rondingites, and narrow apophyses of sericitized albitic plagioclase with sharp contacts in unaltered ultramafic rocks. A sample of such a contact zone shows interesting metamorphism. The plagioclase is heavily altered to sericite, smectite (perhaps sapponite), and possibly cryptocrystalline hydrogrossular. At the contact is a narrow blackwall of chlorite 3-5 mm wide, followed by a broader zone of tremolite in acicular aggregates 5-10 mm wide. The tremolite zone passes into another monomineralic zone of anhedral bronzite with narrow clinopyroxene lamellae, cut by veinlets of tremolite. This zone, about 1 cm wide, terminates with the appearance of relict olivine poikiloblastically included in orthopyroxene crystals with dramatic reaction rims. At irregular distances from the contact, but within a few mm of the first appearance of olivine, the rock grades into virtually pure dunite with a tectonic fabric, containing a few modal percent bright green spinel.

In general, rodingites show characteristic lithologies, ranging from dense, white cryptocrystalline rocks probably containing hydroglossular + diopside + rutile to coarse grained rocks with anhedral pyroxene xenocrysts in a matrix of prehnite + diopside + green amphibole + pennine or clinochlore. A few of our samples contain albite corroded by prehnite. One seems to have escaped calcium metasomatism. It is composed of cataclastically deformed, xenoblastic albite and large quartz crystals (to 40% by volume) with sutured grain boundaries, in quartz mortar including minor chlorite, actinolite and rutile.

Bassoullet et al. (1978a) believe that some of the rodingites are derived from gabbroic dikes intrusive into the ultramafic rocks. They sampled dolerite and gabbro from the allochthon. Fuchs (1979) describes a sample of mylonitic hornblende diorite, containing andesine (50% by volume) and 2% quartz collected from float near the allochthon. Clearly, some of the rodingites within the Spongtang ultramafic rocks have a more felsic protolith, a tonalite or trondjemite. These felsic rocks are probably not "plagiogranites" of the ophiolite suite, since plagiogranites occur as gabbroic differentiates high in the cumulate section and are not known to intrude tectonised peridotites.

Serpentinite

Serpentinite with small associated blocks of limestone and basic volcanics was observed in discrete lenses overlying Kangi La Flysch. These are similar to those identified by FUCHS (1977, 1979) in the Lamayuru Formation south of Lamayuru and near Heniskut. In the Kangi La Flysch north of Sirsir La, east of Snuzi La, along the Shillakong-Chomo drainage divide, and southeast of Dumbur, these lenses are found on topographic highs in regions with good exposures and high relief. They are not overlain by the surrounding sediments. No serpentinite outcrops were observed on or near the Kangi-Naerung fault west of Dumbur or east of the Sirsir La. Similarly, no serpentinite was found on or near the Zanskar Thrust at Heniskut, Shilla, Phenjila, Chahari La or Chilling. Where they overlie the Kangi La Flysch, the serpentinite lenses almost certainly represent outliers of the Spongtang Allochthon.

INDUS ZONE

As noted above, a voluminous geologic literature exists on the Indus Zone. We have summarized a few pertinent observations here. Serpentinite crops out north of Khalse, on the fault zone separating the Indus Flysch and Indus Molasse, confirming FUCHS' (1977, 1979) assertion that the Indus Flysch is tectonically distinct from the Molasse, at least in the vicinity of Khalse.

A new traverse was made across the Indus Zone along the Yapola gorge from Khalse to Wanla. A few marked beds of agglomerate in the Dras Volcanics include rounded clasts to 5 cm in diameter in a matrix of volcanoclastic material. These agglomerates are similar to those noted by WADIA (1937) in the Dras Volcanics of the Burzil Valley. In the Burzil area, he noted clasts of feldspar porphyry and hornblende granite, while in one such agglomerate in the Yapola gorge are clasts of rhyolite, dacite and basalt. These occurrences invite correlation of the Dras with the bimodal Shyok Volcanics associated with the Ladakh Batholith (SHARMA and KUMAR, 1978) and add to the growing body of evidence that the Dras Volcanics are an island arc type volcanic series.

LADAKH BATHOLITH

Traverses were made into the Ladakh Batholith above Saboo, Leh, Phyang and Teah. Topographic control was poor during this reconnaissance and we often had to sample talus blocks. For these reasons we have not presented a geologic map of the region. We distinguished a wide variety of rock types: pegmatite, aplite, granophyre and graphic granite, biotite-hornblende granodiorite to diorite, norite, gabbronorite, hornblende gabbro, hornblendite, orthopyroxenite, and plagioclase-hornblende peridotites, as well as melanocratic doleritic to dacitic dike rocks. Intrusive relations indicate that the mafic rocks are oldest, and that intermediate rocks are generally older than granites, aplite, pegmatite and melanocratic dikes.

All the rock types appear to be evenly distributed, albeit in varying quantities, throughout the southern margin of the batholith. We found all of them in the drainages above Saboo, Phyang and Teah; above Leh we found no ultramafic rocks. The most common intrusive type is hornblende-biotite granodiorite to monzodiorite. Gabbroic and ultramafic types appear to be primarily restricted to the topographic crest of the Batholith, although there is an outcrop of melanocratic intrusive rocks near Likir along the Kargil-Leh Road (possibly gabbro, SHARMA and KUMAR, (1978).

Gabbros and ultramafic rocks all contain bytownite or anorthite. The peridotites include bright green spinel, which is apparently in equilibrium with coexisting bytownite, phlogopite, and patchily zoned amphibole ranging from pargasite and kaersutite to pargasitic hornblende. In the peridotites, phlogopite, amphibole, bronzite, augite and bytownite enclose rounded, embayed olivine (about Fo_{80}). Phlogopite is quite subordinate, and is itself enclosed in amphibole. Augite is uncommon in our samples, and is apparently replaced by amphibole. Plagioclase, orthopyroxene and amphibole occur as poikilitic crystals to several cm in maximum dimension, with plagioclase the most subordinate and amphibole the most common. Where plagioclase encloses olivine, amphibole locally forms a reaction rim to 1 mm wide separating the two phases. Spinel and an opaque oxide occur in anhedral to subhedral crystals to 1 mm in maximum dimension scattered throughout the rock. Hornblendite includes subhedral relicts of olivine and anhedral crystals of green spinel. In all the ultramafic rocks, pale pargasitic hornblende shows fractures which very closely mimic pyroxene cleavage, and has thin trains of opaques which resemble schiller structure in orthopyroxene. However, reaction textures between amphibole and orthopyroxene were not observed in ultramafic samples.

In gabbroic samples, plagioclase often occurs as euhedral crystals poikilitically enclosed in euhedral orthopyroxene and, especially, hornblende. As plagioclase content increases, plagioclase crystals interstitial to hornblende impinge on the amphibole crystal boundaries. Phlogopite is absent from most gabbros. However, one gabbro sample, intruded by a granitic dike, contains about 50% green to brown phlogopite or biotite corroding hornblende, concentrically zoned pyroxenes and plagioclase. Another sample of a granite-gabbro contact shows complete gradation between gabbro and granite over a few inches. The rock contains no amphibole, biotite, or chlorite. Relict clinopyroxene in the coarse grained granite is corroded by plagioclase and potassium feldspar.

Above Teah, we discovered a suite of volcanic rocks just north of the transgressive contact between the Indus Molasse and the Ladakh Batholith. These included porphyritic augite-plagioclase basalt, seriate prophyritic rhyodacite, and porphyritic rhyolite. The latter is cut by melanocratic dacite dikes, as are many surrounding intrusive rocks. The basalt, on the other hand, is intruded by a granitic member of the Batholith. This bimodal volcanic suite is probably correlative to the bimodal Shyok Volcanics, described by SHARMA and GUPTA (1978) and SHARMA and KUMAR (1978), overlying the Ladakh Batholith on the north.

Structure

Major structure in the Zanskar Platform is outlined on our geologic map and cross sections (Fig. 2 and 2a). The axis of the Zanskar Synclinorium plunges to the NNW from Zangla in the southeast through Kong in the northwest. The synclinorium is bounded on its northeastern limb by the Kangi-Naerung Fault, between the Multicolored Formation and the underlying Kioto Limestone. To the northeast lies the Honupattah Anticlinorium, exposing Jurassic and older platform sediments along NNW to NW trending axes. The Anticlinorium is cut along its northeast margin by the NW to WNW strike of the Zanskar Thrust. The Zanskar Thrust separates Triassic, Jurassic and Cretaceous rocks of the Zanskar Platform on the south from the Triassic (and younger?) Lamayuru Formation to the north. It is probable that the platform sediments were originally underthrust beneath the flyschoid rocks of the distal slope and rise along a fault parallel to northward subduction postulated by KLOOTWIJK et al. (1979) and many others.

There were at least three major phases of deformation in the sediments of the Zanskar Platform during Late Cretaceous and Tertiary tectonic events. The first is represented by tight to isoclinal, SW verging, overturned to recumbent folds (F1). F1 folds are exceptionally well displayed in the Kioto Limestone and Multicolored Formation along the Zanskar River from Zangla to Naerung, where fold amplitudes exceed 0.5 km. However, the "megafolds" often lack infolded older or younger rocks; isoclinal folding must have been accompanied by extensive decollement along shale horizons.

The Paleocene to Lower Eocene Lingshed Limestone, on the other hand, shows upright to slighly overturned open folds which are strikingly different from isoclines in the Mesozoic sediments. We believe that F1 folds were formed prior to the deposition of the Lingshed Limestone. Folding probably occurred throughout the Late Cretaceous, contemporaneous with deposition of the Kangi La Flysch and underthrusting of parts of the platform to the NE or NNE along the Zanskar Thrust and, to a lesser degree, the Kangi-Naerung Fault.

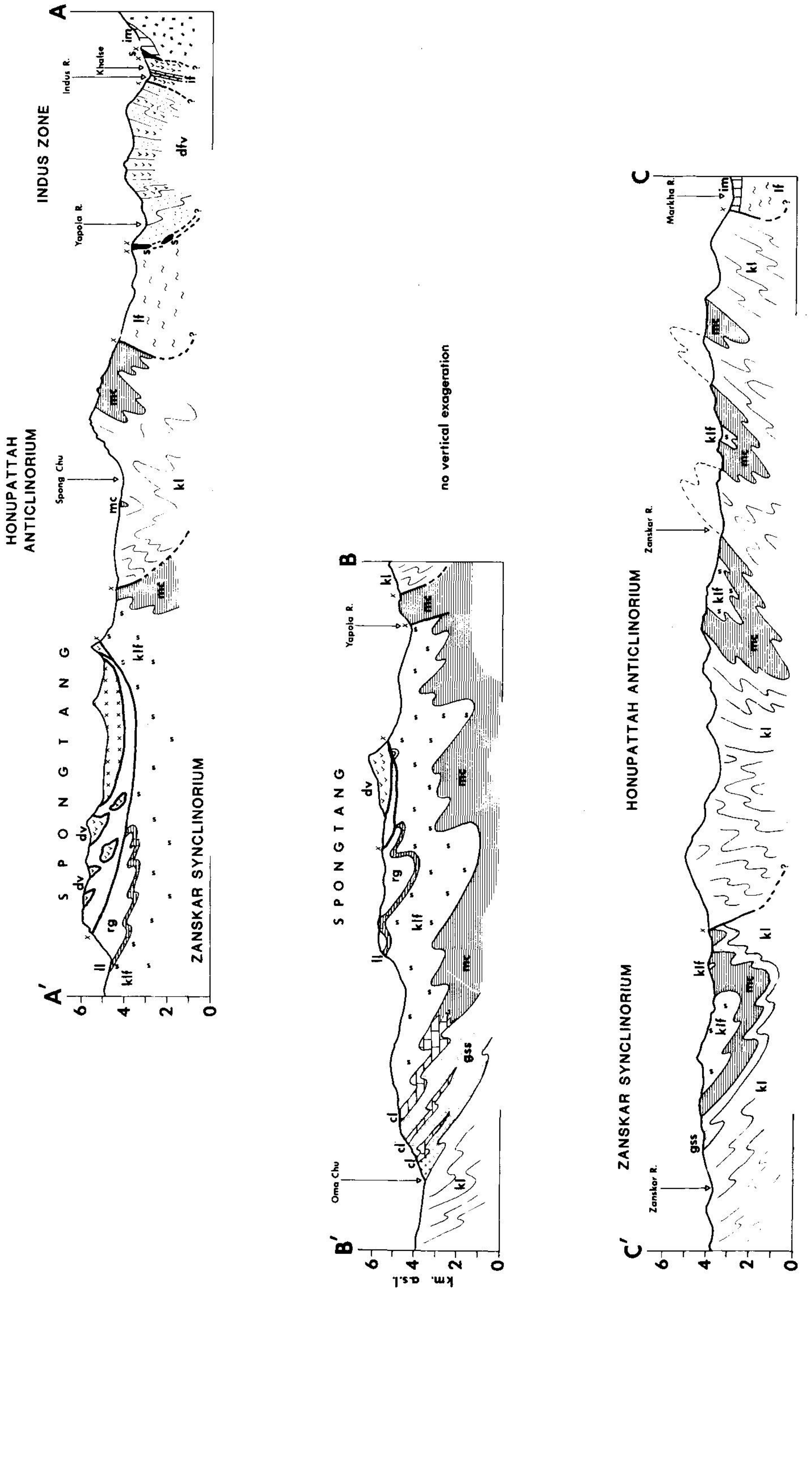

Fig. 2a Cross sections of the Zanskar Platform. See geologic map (Fig. 2) for explanation.

Baud et al. (1982) outlined six tectonic blocks separated by similar zones of NE to NNE underthrusting in the Zanskar Platform east of the Zanskar River.

The second phase of folding (F2) is represented by upright to slightly overturned open folds deforming the upper Kangi La Flysch, the Lingshed Limestone and the Red and Green Shales. This deformation did not greatly affect older Mesozoic rocks south of the Zanskar Synclinorium, although upright chevron folds in the Kioto Limestone south of the Oma Chu are probably due to this second phase of deformation. However, F2 is well developed in the Mesozoic rocks of the Honupattah Anticlinorium, where refolded isoclines were observed near Shilla, Honupattah, Sumdo and along the Zanskar River north of the Kangi-Naerung Fault. Axial plane cleavage and transposed bedding in the Multicolored Formation are folded about vertical and slightly NE verging axial planes. F2 folds developed in the Lower Eocene or slightly later. Pal et al. (1978) report Miocene members of the Indus Molasse thrown into broad, open folds. This second phase of deformation appears to have been caused by compression roughly normal to the NNW or NW regional strike of the Honupattah Anticlinorium. Reactivation, steepening and overturning of originally northeast dipping thrusts postulated by Andrieux et al. (1977) and Frank et al. (1977) probably accompanied this phase.

It is worthwhile to note that the Kangi-Naerung Fault dips steeply SW near Kangi, where the Honupattah Anticlinorium is narrow; whereas at Photoksar and Naerung, where the adjoining Anticlinorium is broader, the fault dips NE at moderate to shallow angles. Similarly, in the Kangi-Kangi La area, axial planes of open folds in the Lingshed Limestone vary from slightly SW dipping in the north, through the vertical, to slightly NE dipping in the south, probably in response to compression between the NE vergent Anticlinorium in the north and SW verging Mesozoic sediments to the south. Eastward along the Zanskar Synclinorium the Lingshed Limestone shows broader, more open folding. F2 folds, where they are overturned at all, are consistently SW verging. To the north, however, axial planes of F2 folds in the Kioto Limestone of the Honupattah Anticlinorium show a consistent dip change through the vertical, from SW dipping near the Zanskar Fault to NE dipping near the Kangi-Naerung fault. Baud et al. (1982) show a similar change in vergence in the northern half of their section from Markha to Zangla, east of the Zanskar River.

A third phase of deformation is exhibited in the Zanskar Synclinorium beneath the overthrust Spongtang Allochthon. Open F2 folds in the underlying Lingshed Limestone and Red and Green Shales are disrupted and overturned to the south. The basal thrust itself is regionally almost flat lying, dipping 15°-20° in the south and 5°-10° in the north toward the center of the Allochthon, forming a shallow structural basin. Both Fuchs (1977, 1979) and Frank et al. (1977) have associated the emplacement of the Spongtang Allochthon with a phase of southwest verging folding and imbricate thrusts (F1?), placing this composite event in Eocene or later time. While it seems probable that deformation in the greater Ladakh region was continuous from at least the Late Cretaceous through the Miocene, and while our Late Cretaceous (F1) and Lower Eocene or later (F2) phases of folding are dated on the basis of inexact field observation, it is apparent that the allochthon was emplaced very late in the deformational history of the region.

Metamorphism of rocks in the Zanskar Platform is generally very low grade. The sediments of the Zanskar Synclinorium are in sub-greenschist facies, while in the Honupattah Anticlinorium, the ubiquity of phyllites and low-grade chlorite schists suggests lower greenschist facies regional metamorphism. Along the Zanskar River a sudden increase in metamorphic grade occurs just south of the Zanskar Thrust, marked by extensive boudinage of marble lenses in strongly foliated calcareous schists. This occurrence may not be related to the fault zone per se. KUMAR (1977) and BAUD (1982) report a metamorphic (and structural?) culmination east of the Zanskar River, including kyanite schist, gneisses and granites. SHARMA and KUMAR (1978) show this metamorphic high as an anticlinorium, with a doubly plunging axis striking NNW, truncated in eastern Ladakh by the Zanskar Thrust. Our observations suggest that the "high-grade zone" may be extended westward across the Zanskar River. At its southern boundary, near the Khurma Chu drainage along the Zanskar River, metamorphosed rocks grade southward without sharp contacts into the sediments of the Zanskar Platform. Metamorphism apparently predates the last movement of the Zanskar Thrust.

Discussion

Stratigraphic results, including estimated thickness of each of the units described above, are summarized in Figure 3. The section tells a rather typical preorogenic story in which prograding platform deposits (Kioto Limestone and older carbonates) laid down over flyschoid rocks of the immature shelf and slope (Lamayuru Fm.), were succeeded by black shales (Spiti Shales), shallow marine carbonates deposited in a restricted, somewhat toxic environment (Chikkim Limestone), and intercalated shallow marine to deltaic sandstones (Giumal Sandstone). The unusual Multicolored Formation appears to be a more distal clastic facies derived from denudation of a subdued limestone terrain. Downwarping of the platform, accompanied by deposition of flysch (Kangi La Flysch) occurred in the Late Cretaceous. Quiet, shallow marine sedimentation resumed in Late Paleocene time, forming the Lingshed Limestone. Contemporaneous Alveolina limestones overlying the Dras Volcanics near Dras (MIDDLEMISS, 1919, cited by WADIA, 1937) may have been deposited in the same shallow basin as the Lingshed Limestone, suggesting that the Dras Volcanics were contiguous with the northern Indian Platform by this time. The overlying Red and Green Shales may have been continuous with the Indus Molasse prior to deformation and uplift, as suggested by FUCHS (1977).

The section beneath the Spongtang Allochthon is similar to that of the Tibetan Zone beneath the Kiogar exotic blocks in southern Tibet (HEIM and GANSSER, 1939). In both areas, an almost flat-lying basal thrust overlies 200–300 m of red and green shales and sandstones in open folds overturned to the south. A "brown sandstone" in the Kiogar region occupies the stratigraphic position of our narrow brown quartzite horizon. Below, in both areas, follow great thicknesses of Upper Cretaceous flysch (SHAH and SINHA, 1974), a multicolored calcarenite intercalated with marly limestone, the Giumal Sandstone with its deltaic lithology, the Spiti Shales, and finally the Kioto Limestone passing down into the Triassic. This stratigraphic correlation shows uniform sedimentation and a roughly simultaneous emplacement of exotic blocks in regions separated by about 400 km along the strike of the Indus-Tsangpo Suture Zone.

The Kiogar, Amlang La and Jungbwa exotics of southern Tibet themselves bear an intriguing resemblance to the Spongtang Allochthon; obvious, but perhaps surprising, is the fact that all these allochthons were overthrust to the south, although most workers postulate northward transport and subduction of oceanic lithosphere and mantle along the Indus-Tsangpo Suture Zone. FRANK et al. (1977) pointed out petrographic similarities between the Jungbwa and Spongtang peridotites. However, HEIM and GANSSER (1939) report only harzburgite and gabbronorite from the Jungbwa, while the Spongtang intrusive suite includes harzburgite, lherzolite, dunite, orthopyroxenite, gabbro, dolerite and hornblende diorite, as well as tonalite and rodingitized dikes intrusive into the peridotites. The inclusion of the island arc type Dras Volcanics in the Spongtang Allochthon suggests a complex tectonic history.

The Dras Volcanics and Flysch and the Indus Flysch of the Indus Zone near Khalse are bounded by fault zones including ophiolitic melange. Although we surmise (on the basis of scanty field evidence) that the Dras represents a volcanic and volcanoclastic equivalent to magmatism in the Ladakh Batholith, and members of the Batholith intrude the overlying Dras Volcanics west of our field area (WADIA, 1937), the structural position of the volcanics in the Indus Zone is problematical. SRIKANTIA and RAZDAN (1980) note "windows" in the Dras Volcanics between Dras and Kargil, suggesting that parts of the unit may be shallow thrust sheets. However, Late Paleocene to Lower Eocene Alveolina limestones overlie both the Dras Volcanics of the Indus Zone (WADIA, 1937) and the sediments of the Zanskar Platform (Lingshed Limestone, this paper). The Spongtang Allochthon, with its virtually flat-lying basal thrust, is emplaced over these limestones. Clearly, final movement of the Allochthon postdates deformation of the Dras Volcanics as well as folding of the Lingshed Limestone.

Fig. 3a

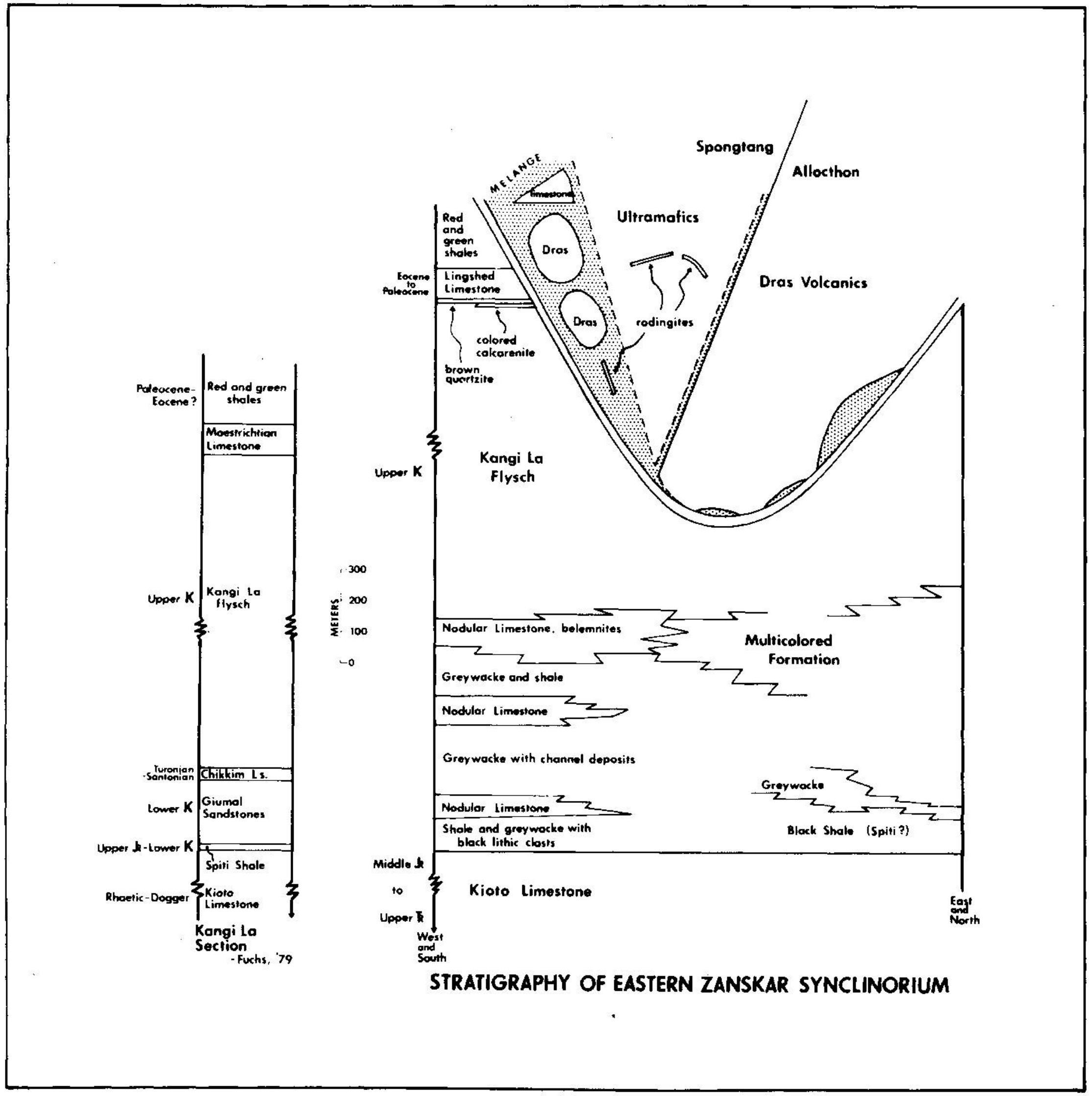

Fig. 3

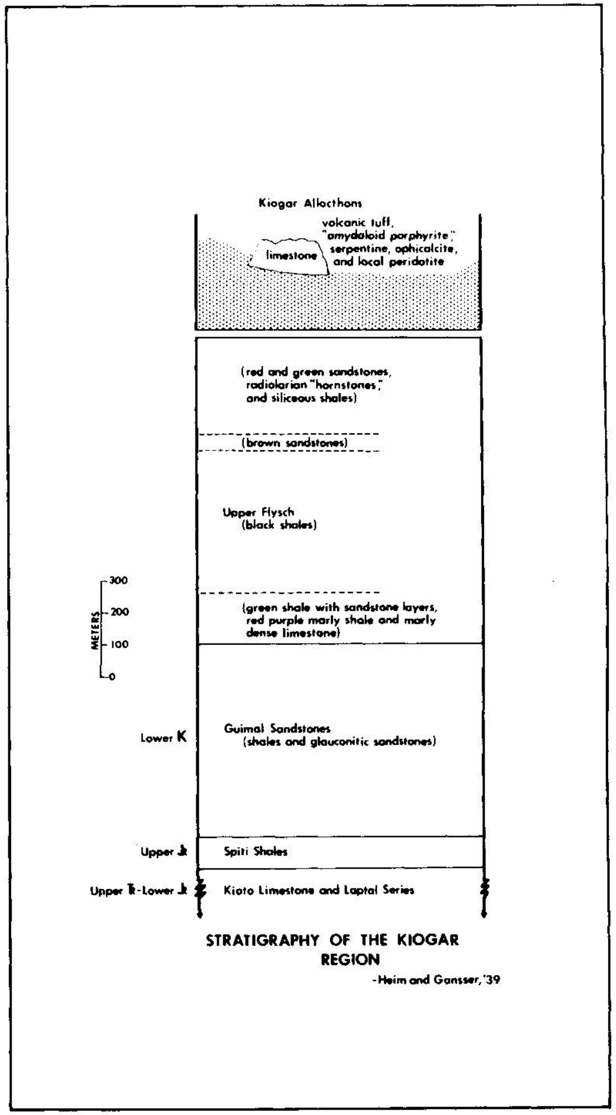

Fig. 3 and 3a Stratigraphic sections of the Zanskar Platform (District of Ladakh) and the Kiogar Region (Southern Tibet

The presence of ultramafic rocks in the Ladakh Batholith presents another intriguing problem. They have a different mineralogy and roughly isotropic fabric, unlike tectonised peridotites of the Spongtang Allochthon. Plagioclase-hornblende peridotite, hornblendite and ophitic gabbro from the batholith are, however, similar to plagioclase lherzolite, plagioclase wehrlite, hornblendite and ophitic gabbro from the Indus Zone (McMahon, 1901; Wadia, 1932, 1937). Wadia reports such rocks as "bosses" within the Dras Volcanics as well as along their periphery. The presence of plagioclase coexisting with spinel in aluminous peridotite from the Ladakh Batholith suggests that these rocks crystallized at pressures between 3 and 8 kb (Frost, 1976; Jenkins, 1981). An upper temperature limit of 950 to 1050 °C at these pressures is indicated by the presence of phlogopite and pargasitic amphibole (Modreski and Boettcher, 1973; Wendlandt and Eggler, 1980; Millhollen et al., 1974; Mysen and Boettcher, 1975; Cawthorn, 1976). The absence of talc, anthophyllite, tremolite and chlorite, on the other hand, provides a lower temperature limit of 700 to 800 °C (Evans, 1977; Jenkins, 1981). Although some of the ultramafic rocks in the Batholith could be magmatic cumulates, both McMahon (1901) and Wadia (1937) concluded on the basis of textural and field evidence that coarse grained hornblendites from the Indus Zone represented altered pyroxenite. Observed gradation between gabbro and granite from the batholith suggests chemical interaction between hot mafic rocks and superheated granitic liquids. Patchy zoning of amphibole and embayment of enclosed olivine in peridotite, relict olivine in hornblendite and gabbro, and replacement of pyroxene by amphibole in our samples suggest that many of the mafic rocks of the Ladakh Batholith may be hybrids, formed by chemical transfer across a compositional gradient between ultramafic rocks and felsic magmas.

The occurrence of ultramafic rocks in the Ladakh Batholith adds to the increasingly complex problem of reconstructing the tectonic history of the region. Ultramafic rocks have been intruded by felsic plutonic rocks in the Indus Zone (Wadia, 1937; Frank et al., 1977), the Ladakh Batholith, and even in the Spongtang Allochthon where tonalitic and gabbroic (?) dikes were observed. The ultramafic rocks are tectonically associated with volcanic rocks, the Shyok and Dras Volcanics, which are not members of the typical ophiolite suite. The proposed correlation of the Shyok Volcanics, the Dras Volcanics and broadly similar rocks from the Spongtang Allochthon into a single, volcanic arc extrusive suite invites a simple hypothesis to "connect the dots". Perhaps the Dras Volcanics, the Indus Zone ophiolitic melange, volcanic and ultramafic rocks near the margins and structural crest of the Ladakh Batholith, and the Shyok Volcanics are all expressions of the same subhorizontal "suture zone". The Ladakh Batholith and the volcanic rocks are members of a volcanic arc complex which was emplaced in oceanic lithosphere on the overthrust plate of a northward dipping subduction zone. Paleocene convergence of this volcanic arc with the northern Indian subcontinent caused cessation of active subduction. The "suture zone" was dismembered during rapid Eocene uplift of the Ladakh Batholith. Final movement of the Spongtang Allochthon, which clearly post-dates deformation associated with convergence, may be related to this Eocene unroofing event.

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Since his traverses with Arnold Heim in 1936, Professor Augusto Gansser has continued to establish the framework for study of Himalayan geology. Dr. Gerhard Fuchs, with his great knowledge of regional stratigraphy, opened the way for stratigraphic and structural study in the Zanskar Synclinorium. We are greatly in their debt.

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EXPLANATION

	rg	red and green shales
Paleocene Eocene	ll	Lingshed Limestone
Upper K	klf	Kangi La Flysch
Upper Jr-Mid K(?)	mc	Multicolored Formation
id K	clg	Chikkim Limestones and upper Guimal Sandstones
UpperJr-Lower K	gss	lower Guimal Sandstones and Spiti Shales
P(?)-Mid Jr	kl	Kioto Limestone and older platform sed's
Tr-Jr-K(?)	lf	Lamayuru Formation
Tertiary	im	Indus Molasse
Mid K	if	Indus Flysch
Mid-Upper K	dfv	Dras Flysch and Volcanics
	s	serpentinite

SPONGTANG ALLOCHTHON

		Ophiolitic Melange
	lcs	limestone and clastic sedimentary blocks
Mid-Upper K	dv	Dras (?) Volcanics
		ultramafics
	r	rodingites