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Chronostratigraphy of the upper Cenozoic Bunthang sequence and possible mechanisms controlling base level in Skardu intermontane basin, Karkakoram Himalaya, Pakistan

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ABSTRACT

A 1.3-km-thick section of basin-fill sediments within the Skardu intermontane basin of the Karakoram Himalaya, termed the Bunthang sequence, is predominantly reversely magnetized. Glacial deposits and landforms are closely associated with the Bunthang sequence. This implies that basin filling took place between glacial advances and prior to the present Brunhes normal chron, i.e., between 3.2 and 0.73 Ma.

Four major facies interinger within the Bunthang sequence: glacial facies; lacustrine facies, indicative of periods during which the Indus River was ponded within the basin; aggradational fluvial facies that represent periods during which the gradient of the Indus River was controlled by rising base level downstream; and alluvial fan conglomerates that prograde transversely from the basin margin into the basin at different stratigraphic levels. The last facies represents periods of decreased sedimentation by the Indus River relative to alluvial sedimentation from the basin margin.

Downstream from the Skardu Basin, the Indus River crosses the Nanga Parbat-Haramosh syntaxis; this is an area of rapid late Cenozoic uplift (as much as 1 cm/yr). Differential uplift of the Nanga Parbat-Haramosh syntaxis relative to its surrounding terrain led to local variations in Indus River gradient. Temporary ponding of the Indus River is inferred to have occurred when the uplift rate of the Nanga Parbat-Haramosh syntaxis exceeded the rate of downcutting by the Indus River. Temporary blockage of the Indus River Gorge through the Nanga Parbat-Haramosh syntaxis by glaciers or by major landslides may also have led to variations in base level. Temporal variations in the gradient and base level of the Indus River downstream from the Skardu Basin, are reflected in the different facies that interinger within the Bunthang sequence at Skardu.

INTRODUCTION

Extensive molasse sedimentation has occurred within intermontane basins and along the flanks of the Himalayan mountain range as a result of the convergence of Indian and Eurasian continental lithosphere since Eocene time (Fig. 1). Synorogenic sediments are included in the Rawalpindi and Siwalik Groups (Firman, 1910; Pilbeam and others, 1977), as well as in the Karewa Group of the Kashmir Basin (Godwin-Austen, 1859; Burbank, 1983; Burbank and Johnson, 1982, 1983). These strata are themselves locally deformed by the orogeny and have been succeeded by younger, nonmarine molasse sediments. The physical and magnetic polarity stratigraphy of the Siwalik and Karewa Groups has been investigated in detail throughout northern Pakistan and India by the cooperative efforts of workers from Peshawar University, Dartmouth College, the University of Southern California, Lamont-Doherty Geological Observatory, the Geological Survey of Pakistan, and the University of Arizona.

Few stratigraphic studies have been undertaken in the
Skardu Basin (Dainelli, 1922, 1934; Burgisser and others, 1982; Cronin, 1982; Johnson, 1986; Johnson and others, 1986). Many of the early explorers in the Indus River Valley noted the presence of sediments stranded as much as 1,000 m above the Indus River. Vigne (1841), Thompson (1849), Drew (1873), and de Filippi (1912) believed these sediments to be entirely fluvial and alluvial in nature, whereas Godwin-Austen (1864), Cunningham (1854), and Conway (1894) believed the deposits to be at least partly lacustrine. Oestreich (1906) first proposed that the Indus Valley above Skardu had initially been eroded to its bedrock floor, then filled with sediment to roughly 200 m above its present level, and then reexcavated by glaciers and the Indus. The pioneering work by Dainelli (1922, 1934) noted a thick exposure of sedimentary strata along the northern rim of the basin. These strata have been termed the Bunthang sequence (Cronin, 1982), after the local Balti name for the sequence’s largest outcrop (Figs. 2-4).

This chapter summarizes the current state of knowledge regarding the Bunthang sedimentary sequence of the Skardu Basin. The Bunthang sequence provides the most complete stratigraphic record of the late Cenozoic infilling of Skardu Basin, and is the most extensive example yet recognized of intermontane sedimentation within the Karakoram Himalaya north of the Main Mantle Thrust (MMT). This study of the stratigraphic rec-
ord preserved in the Bunthang sequence was undertaken to establish constraints for the timing of intermontane basin formation at Skardu through the use of magnetic-polarity stratigraphy (MPS). Such constraints permit the evaluation of possible mechanisms of basin evolution at Skardu and so further elucidate the late Cenozoic geologic history of the Karakoram Himalaya.

The general geographic, geologic, structural, and tectonic setting of the Skardu Basin has been considered elsewhere (Cronin, this volume). To summarize, Skardu Basin is located along the Indus River (Fig. 1), roughly 80 km southwest of Earth's second highest mountain peak (K2, 8,611 m) and upstream from the transverse massif containing Nanga Parbat (8,126 m) and Haramosh (7,397 m). The current base level of the Indus River through Skardu Basin is roughly 2,130 m, whereas the elevations of the peaks surrounding the basin commonly range from 4,500 m to 5,800 m. The Skardu Basin is in close proximity to the Karakoram glacial system, which is one of the greatest concentrations of glacial ice outside the polar regions. Evidence of recent glaciation is abundant in Skardu and Shigar Valleys.

The Indus-Tsangpo suture zone branches in the Kohistan-Ladakh region, and is marked by the Main Karakoram Thrust (MKT) to the north and the Main Mantle Thrust (MMT) to the south (Fig. 1; Gansser, 1977; Tahirzhelhi and others, 1979). Skardu Basin is located within the Kohistan-Ladakh terrane, which is interpreted to have originated as a magmatic arc that accreted onto Eurasian continental lithosphere prior to the final closure of the Tethys Ocean along the Indus-Tsangpo suture in the Late Cretaceous–early Tertiary (e.g., Tahirzhelhi and others, 1979; Bard and others, 1980; Andrews-Speed and Brookfield, 1982; Petterson and Windley, 1985; Searle and others, 1987). A single magmatic arc is postulated for the Kohistan area to the west of the Nanga Parbat–Haramosh massif; however, in the Skardu-Ladakh region to the east of the massif, a second arc sequence is inferred, which may have been the source for the flysch-like Katrzara Schist of Lower Cretaceous age (Petterson and Windley, 1985; Andrews-Speed and Brookfield, 1982; Casnelli and Ebbelin, 1977). The Skardu Basin rim is dominated by the Katrzara Schist (Zannettin, 1964; Casnelli and Ebbelin, 1977; Tahirzhelhi, 1982), which is locally intruded by tonalites−granodiorites of the Ladakh batholith.

The Kohistan-Ladakh terrane is inferred to be underthrust by Indian continental lithosphere (e.g., Powell and Conaghan, 1973; Seeber and Armbruster, 1981; Seeber and others, 1981; Ni and Barazangi, 1984; Coward and Butler, 1985), although the Skardu region has remarkably little recorded seismicity relative to the rest of the Karakoram Himalaya (Cronin, this volume). Lithologies ascribed to Indian continental lithosphere are exposed along the axis of the Nanga Parbat–Haramosh syntaxis (NP-H syntaxis): a pronounced salient in the surface trace of the MMT that reflects local, transverse uplift of a sliver of the underthrust Indian plate (Wadia, 1931). The NP-H syntaxis has undergone particularly rapid uplift relative to its surrounding terranes during the last 10 m.y. (Zeitler and others, 1982, 1986; Zeitler, 1985).
The Indus River flows to the northwest through the Skardu Basin, roughly parallel to the structural and lithologic grain of the surrounding Karakoram Mountains. The striking parallelism or colinearity of many of the major drainages to the east of the NP-H syntaxis, including the Indus, Shyok, and Shigar Rivers (Fig. 1), suggests that these drainages may have been localized along a system of northwest-trending fractures or faults (Casneci, 1976; Ebblin, 1976; Cronin, this volume). The drainage course of the Indus River maintains the same northwest trend as it passes through the NP-H syntaxis, a trend occupied by the Gilgit River drainage beyond the syntaxis. Hence, the structural trend along which these drainages have localized is inferred to predate the onset of differential uplift along the NP-H syntaxis.

**STRATIGRAPHY**

*Physical stratigraphy*

The terrigenous clastic sediments of the Skardu Basin reflect fluvial, alluvial, lacustrine, and glacial depositional environments. The principal source areas for this clastic detritus are the Deosai Mountains, the Deosai Plateau, the Masherbrum Range, and the Marshakala Group of the Haramosh Range, as well as the catchment areas of the upper Indus and Shyok Rivers, upstream from Skardu. The lithologies present in these source areas include a variety of sedimentary, metasedimentary, metavolcanic, and intrusive igneous rock types. Major factors involved in the degradation of the source areas include the following: high local relief, which is commonly in excess of 3,500 m; large diurnal temperature range, which enhances the effectiveness of frost wedging; and proximity to the glaciers of the Karakoram glacial system and the Deosai ice field (Godwin-Austin, 1864; Burgisser and others, 1982).

*Basal diamicite.* The oldest sediments exposed in the Skardu Basin are deposits of coarse boulder diamicite that are exposed on the Rock of Skardu (Karpochi) and in scattered localities at the base of the Bunthang outcrop (Fig. 3). The basal diamicite outcrops at Bunghang are dark brownish gray in color, and can be texturally described as very coarse, unstratified, matrix-supported, boulder diamicites, whose unsorted clasts range to several meters in diameter. A comparison between the clast population within the similar diamicites at the Rock of Skardu and Bunthang indicates that the same clast types are present at both localities. The diamicite nonconformably overlies the igneous/metamorphic basement of the basin wherever the basal contact is exposed. The diamicite is overlain by the lower Bunthang sequence at Bunghang and by the Karpochi sand atop the Rock of Skardu (Cronin, 1982).

The coarse diamicite at the Rock of Skardu has long been interpreted to be glacial in origin (Drew, 1873; Conway, 1894; Oestreich, 1906; De Filippi, 1912; Dainelli, 1922) and has been termed the Karpochi till (Cronin, 1982). Similarly, the diamicite at the base of Bunthang is informally termed the Bunthang till. Lydekker (1883) considered the Karpochi till to be evidence that a large glacier had extended from the Shigar Valley into Skardu. The Karpochi and Bunthang till outcrops seem to have been preserved as a result of their position on the lee side of isolated exposures of metamorphic bedrock. Although no independently datable material has been noted within them, the Bunthang and Karpochi tills are considered correlative due to their similar locations, elevations, stratigraphic positions, and states of consolidation.

*Bunthang sequence.* The sedimentary sequence that is stratigraphically positioned above the Bunthang till and beneath the oldest alluvial terrace deposits in Skardu Basin is termed the
Bunthang sequence (Cronin, 1982; Johnson, 1986). This sequence has been informally divided into lower, middle, and upper units, based on notable textural differences in the strata. The principal outcrop of the Bunthang sequence, located along the northeast wall of the Skardu Basin between the villages of Komara and Kuardu (Fig. 3), is approximately 5.3 km wide, 7.7 km long, and 1.3 km thick. Excellent exposures of the Bunthang sequence can be observed along Kuardu Canyon (Fig. 2) and in Ghothermal Canyon (Fig. 4). Other limited exposures occur east of Kuardu Canyon and between Chunda and Hoto. Some of the terrace deposits observable throughout the greater Skardu Basin may also be remnants of the Bunthang sequence. Isolated deposits that may be correlative with the Bunthang sequence have been noted elsewhere in both the Shigar and Indus River Valleys.

**Lower Bunthang sequence.** A locally deformed, conglomeratic sandstone overlies the Bunthang till on the north side of the mouth of Ghothermal Canyon. Strain in the sandstone appears to be greatest where it is closest to the erosional contact with the pervasively deformed Oro Canyon till (Cronin, 1982), and diminishes away from the till outcrop exposure. The observed deformation is tentatively ascribed to differential stress induced by glacier movement during the deposition and deformation of the Oro Canyon till, which postdates the deposition of the lower portion of the Bunthang sequence.

The basal sandstone lithosome is a planar- to cross-bedded, micaceous, lithic arkose that is locally conglomeratic. Small, climbing-ripple laminations are common, with current directions varying from southwest to northwest. The lateral continuity of the rippled beds is obscured by outcrop conditions; however, individual cosets do not appear to extend more than a few tens of meters. Included pebbles and granules are mostly angular to subrounded, micaceous, metamorphic detritus, which seem to reflect local bedrock lithologies. The basal sandstone is approximately 50 m thick as exposed near the base of Ghothermal Canyon, where it overlies the Bunthang till. A subtle color change from grayish orange at the base to light olive gray in the overlying mudstone suggests a gradual change in depositional environment or grain composition with the onset of mudstone deposition. The basal sandstone is interpreted to be fluvial, probably reflecting deposition in a braided-stream environment.

The basal sandstone of the lower Bunthang sequence grades upward into a massive, light olive gray, clayey siltstone to silty claystone. The massive mudstone is approximately 300 m thick, and becomes progressively less sandy upward throughout its lower 100 m. The mineralogic composition of the mudstone is dominated by quartz, feldspar, micas, and amphibole, suggesting that the muds were derived from mechanical processes rather than chemical weathering (Johnson, 1986). Calcite is a common cement, and joint surfaces often contain fibrous gypsum. Outcrops of the massive mudstone are often poorly exposed, covered
with a weathered layer from a few millimeters to 0.5 m thick. The mudstone is generally a slope-former, except where it is supported by more resistant beds.

A variety of small-scale structures are observable in the hand samples of the mudstone that were collected for paleomagnetic analysis. Wispy, fine sandstone or siltstone lenses are common within the seemingly structureless mudstone. Isolated granitic/metamorphic pebbles do not seem to be correlated with sandstone lenses or pebble stringers, suggesting that they may be glacial dropstones. A few isolated boulders that are interpreted to be dropstones were also observed in the lower Bunthang sequence mudstones. Two thin, subhorizontal, matrix-supported, boulder conglomerate lenses occur within the massive mudstone section, which are interpreted to be mudflow deposits. The tabular morphology of these beds suggests that the intervening mudstones may not have been subjected to postdepositional deformation.

The massive mudstone lithosome is interpreted to have been deposited in a glacio-lacustrine environment. The fine-grained particles contained in the mudstone probably originated as glacial flour, derived from local and regional glacier systems operating upstream. The onset of lacustrine sedimentation may have been gradual, punctuated by occasional fluvial interludes or by influxes of sand in a current-dominated proglacial lake. Eventually, fine-grained lacustrine sedimentation became dominant as the basin was fully ponded.

A distinctive sequence of thin (<5 m), laterally continuous, rhythmically bedded sandstones and mudstones extends for a thickness of approximately 100 m atop the massive-mudstone lithosome. These yellowish gray to light olive gray rhythmites form beautiful, banded cliffs beneath an erosional contact with the fanglomerates of the middle Bunthang sequence (Figure 4). A typical sedimentary cycle within this lithosome begins above a subhorizontal erosional base. A massive, pebbly to granular sandstone at the base of the coset grades into a horizontally laminated, very fine sandy siltstone within a few centimeters of the contact. The balance of a given coset is a massive mudstone. A set of small ripple laminae within these rhythms indicates a current direction to the northwest. As many as eight of these cosets are repeated vertically within 10 m.

The presence of possible varves, isolated dropstones, and mechanically produced fine-grained particles within these rhythms suggests that they were developed within a glacio-lacustrine environment. The rhythms are interpreted to be glacio-lacustrine turbidites. Turbidity flows can be generated in a glacio-lacustrine environment in a number of ways. Mass wasting from proglacial deltas within a glacial lake can be triggered by seismicity, ice pressure, or by landslides that rapidly load the unstable deltaic deposits. Significant pulses of water and sediment can result from the catastrophic failure of a glacier or landslide dam. The latter mechanism has often been witnessed in the Himalaya, and has been cited as the cause of catastrophic flooding along the Indus River (Vigne, 1841; Conway, 1893, De Filippi, 1912), as well as of rhythmic sedimentation in the Peshawar Basin (Bur-bank and Tahirkheli, 1985). Sudden pulses of water and sediment may originate in any of the glacial valleys that exist in abundance in the Shigar and upper Indus River Valleys, upstream of the Skardu Basin.

**Middle Bunthang sequence.** Exposures of the boulder conglomerate lithosome that typify the middle Bunthang sequence are generally along tall, vertical cliffs where access is poor; however, several outcrops have been examined at close range. As viewed from across Ghothamal Canyon (Fig. 4), the three principal conglomerate units within the middle Bunthang sequence commonly display sharp erosional bases and well-defined, locally channeled upper contacts with finer-grained strata. The lowest of these conglomeratic units is approximately 80 m thick, while the middle unit is ~65 m thick and the upper unit is ~45 m thick, as observed on the northern wall of Ghothamal Canyon. The thickness of the middle Bunthang sequence varies considerably across the Ghothamal Canyon outcrop, but averages approximately 300 m.

Clast sizes range up to several meters in diameter, although most of the coarse fractions are less than 0.25 m in diameter. The mean clast size increases toward the mountain front to the northeast. Most of the clasts are subrounded to angular Katara Schist, and the matrix consists primarily of dark, metamorphic lithics. Both the clasts and the matrix appear to be locally derived from lithologies that are present along the northeast margin of the basin.

The conglomerate units form wedge-shaped bodies that thicken toward the mountain front and thin basinward (Figs. 2, 5). Stratification within the conglomeratic units dips ~6° toward the basin. The finer-grained strata that separate the three conglomerate units are generally cross-bedded to planar-laminated sandstones that are locally conglomeratic. The lowermost of these finer-grained units is approximately 25 m thick; the upper sandy unit is ~85 m thick. Thinner bodies of mudstone also occur within the sandstone units. The mudstone is exposed in its greatest thickness below the uppermost conglomerate unit on the steep, southwest-facing wall of Bunthang, where its bluish gray color contrasts with the darker brown conglomerate and light yellowish tan sandstone. The sandstone/mudstone units thin toward the mountain front and thicken basinward, in counterpoint to the morphology of the conglomeratic units. The conglomerate lithosome is interpreted to be alluvial fanglomerate deposited along the basin margin, interfingerling with finer grained fluvial strata deposited in the interior of the basin. The included mudstone may reflect local or temporary ponding, or overbank deposition. Principal source areas for the fanglomerates are inferred to be along Oro Canyon above Komara, and in Kuardu Canyon.

**Upper Bunthang sequence.** Approximately 460 m of upper Bunthang sequence sediments onlap the uppermost fan surface that marks the top of the middle Bunthang sequence. The angular discordance between the flat-lying upper Bunthang strata and the top of the middle Bunthang fanglomerate reflects primary, undeformed bedding orientations characteristic of different depositional environments. The alluvial fan surface and the upper
terrace that was developed atop Bunthang during basin degradation both slope gently toward the basin, so outcrops of the upper Bunthang sequence exposed between these two surfaces are locally less than 70 m thick (Fig. 2). Strata of the upper Bunthang sequence can be grouped into three principal lithosomes: coarse sandstone, fine-grained sandstone/mudstone interbeds, and massive mudstone.

The sandstone lithosome is generally characterized by a light olive gray to light gray lithic arkose, which is medium- to coarse-grained and locally conglomeratic. Sandstone cosets commonly display channeled bases, indistinct bedding, or trough cross-lamination overlain by planar lamination or climbing-ripple lamination. Individual cosets have limited lateral extent, and tend to grade upward into finer-grained strata. The coarse sandstone lithosome is interpreted to be fluvial, accumulated primarily by lateral accretion in a relatively high-energy, braided stream system. A polymict, horizontally bedded, boulder conglomerate is observed locally; it contains clasts as much as 0.6 m in diameter, whose lithologies reflect source areas that are not restricted to the local Marshakala Mountain Group. These conglomerate stringers are interpreted to be channel lag deposits from the principal longitudinal stream system that occupied the basin at the time of deposition (Johnson, 1986).

The fine- to medium-grained sandstone/mudstone lithosome is commonly grayish orange to yellowish gray in color. The sandstone typically grades upward into horizontally laminated mudstone over a vertical interval of 1 to 2 m, and a given couplet is laterally extensive. The sandstone/mudstone lithosome is interpreted to reflect fluvial sedimentation in a relatively low-energy environment, in which aggradation is primarily by vertical accretion. This finer grained fluvial lithosome represents perhaps 80 percent of the 310 m of fluvial strata of the upper Bunthang sequence. Paleocurrent directions inferred from cross-laminations measured at many horizons throughout these fluvial strata generally indicate flow toward the northwest, similar to the flow direction of the present Indus River.

The massive mudstone lithosome is a lighter gray color than the mudstone encountered in the lower Bunthang sequence. Fine laminations are locally observed; however, the mudstone is more commonly massive. The mudstone forms laterally continuous beds, and is most prevalent in the uppermost 150 m of the Bunthang sequence. The mudstone lithosome also occurs in two places within the finer-grained fluvial strata, evident as bodies that are, respectively, 12.5 and 10 m thick. The massive mudstone is interpreted to be lacustrine.

**Geomorphology and preservation of the Bunthang outcrop.** The Bunthang outcrop would be impressive for its size alone, with its main upper terrace resting between 900 and 1,500 m above the Indus River and extending approximately 4 km outward from the mountain front. More remarkable, though, is its anomalously good state of preservation in an area that undoubtedly has one of the highest rates of erosion on Earth. Early in the process of basin degradation, a gently sloping alluvial surface was eroded onto the soft fluvial sands and lacustrine mudstone of the upper Bunthang sequence, and a few meters of alluvium were deposited locally on the surface. Roughly 1 km² of this uppermost geomorphic surface remains atop Bunthang. Although it represents a former base level for the combined Skardu-Shigar basin system, as well as for basins upstream, this geomorphic surface seems to have been preserved only at Bunthang. Small, isolated, flat-topped sedimentary deposits that may be correlative with the Bunthang sequence have also been observed, perched astride protected ridges in the Indus Gorge. Many additional terrace surfaces have been observed at lower levels on the Bunthang outcrop and elsewhere within the Skardu Basin.

Present-day Skardu has a remarkably arid alpine climate, and the sparse runoff that exists in the vicinity of Bunthang is effectively channeled to the side of the Bunthang outcrop into Oro, Ghothalam, or Kuardu Canyons. The original drainage area of the stream in Ghothalam Canyon may have been significantly reduced by stream capture in the course of cirque development near Taras (Fig. 4). The path of glaciers that extended from the hanging valley at Taras was controlled by the orientation of local fractures and foliation within the Katzara Schist (e.g., Cronin, this
volume; Zumberge, 1955), which deflected the glaciers southward toward Kuardu and away from the present Bunthang outcrop. The northern side of the Bunthang outcrop was eroded, in part, by glaciers that extended from Oro Canyon, northeast of Komara. Evidence of this glacial incursion is provided by the glacially deformed Oro Canyon till and by moraines along the Indus River between Komara and Kachura (Cronin, 1982). The large metamorphic exposure that forms most of the southwest face of Bunthang (Figs. 2, 3) has protected the Bunthang outcrop against erosion by the Indus River and by local glacial advances.

**Magnetic polarity stratigraphy**

The value of magnetic polarity stratigraphy (MPS) as a criterion for stratigraphic correlation and age determination in terrestrial clastic sequences has been amply demonstrated by earlier studies of the Pliocene- and Pleistocene-age Upper Siwalik and Kurewa Groups of northern Pakistan and India (e.g., Barndt and others, 1978; Johnson and others, 1979; Opdyke and others, 1979; Johnson and others, 1982; Burbank and Johnson, 1982, 1983; Burbank and Tahirkhel, 1985). Samples from 77 magnetic sites in the Bunthang sequence were analyzed in this study (Fig. 5): 37 sites within the lower Bunthang sequence (Cronin, 1982; Johnson, 1986) and 40 sites in the upper Bunthang sequence (Johnson, 1986). Four additional sites have recently been established within the middle Bunthang sequence; however, these data were not available for inclusion in this report. Three or more oriented samples of unweathered mudstone were collected at each site and analyzed in accordance with procedures described elsewhere (Johnson and others, 1975).

**Demagnetization.** Three types of magnetic behavior were observed during the stepwise thermal and alternating field (a.f.) demagnetization of samples collected from the Bunthang sequence. A representative set of results from stepwise demagnetization are displayed as Zijderveld projections in Figures 6 and 7. These diagrams reveal a simple, one-component remanence in some cases (Fig. 6; samples from the upper Bunthang sequence) or a two-component system in other cases (Fig. 7; samples from the lower Bunthang sequence). Heating to 400°C removed more than 90 percent of the natural remanent magnetic (NRM) moment of the samples from the lower Bunthang sequence, suggesting that magnetic remanence is carried by magnetite with very little hematite. Heating to 600°C removed only 50 percent of the NRM moment in samples collected near the base of the upper Bunthang sequence (not displayed), suggesting that hematite carries the magnetic remanence in these samples. For samples in the rest of the upper Bunthang sequence, heating to 600°C removed 80 percent of the NRM moment, and an additional 15 percent of the magnetic moment is removed after heating to 700°C. This indicates that magnetite and hematite are present, with the hematite component the less significant (Johnson, 1986).

In order to remove any postdepositional magnetic overprinting, the samples were partially demagnetized at 500°C, a blanket temperature chosen to remove approximately 50 percent of the

**NRM moment from each sample.** In similar fashion, a field strength of 35 milliTesla (mT) (350 Oersteds) was used for the partial a.f. demagnetization of fiable samples from the uppermost Bunthang sequence, based on the stepwise a.f. demagnetization of samples that had been randomly selected. All samples from the 40 upper Bunthang sequence sites displayed reversed polarity after demagnetization, yielding 37 class I sites and 3 class II sites.

**Figure 6.** Zijderveld projections for typical upper Bunthang samples from the same site, demagnetized using either (a) alternating fields or (b) thermal demagnetization methods. Untreated samples are reversely magnetized (negative upward inclination; southern declination). With progressive demagnetization, both samples remain reversely magnetized as magnetic moment (shown as distance from origin) decays. Plotted values are normalized to the magnetic moment for the corresponding untreated sample (M₀).
Class I sites are defined by an R value that is greater than 2.62 for 3 samples and 3.10 for 4 samples, while class II sites show good agreement between at least two out of three samples within the site but have an insufficient R value (Tarling, 1971).

The samples from the upper Bunthang sequence (Figs. 6, 8) are reversely magnetized (southerly declination, upward inclination) both before and after a.f. and thermal demagnetization. The upper Bunthang sequence is reversely magnetized throughout the 460-m-thick sample interval (Johnson, 1986). In contrast, samples from the lower Bunthang strata (Figs. 7, 9) are normally magnetized (northerly declination, downward inclination) both before and after a.f. demagnetization and also before thermal demagnetization. These early results agreed with those obtained by Cronin (1982), whose samples had been magnetically cleaned using a.f. demagnetization of 20 mT. Subsequent resampling of the sites within the lower Bunthang sequence that had displayed an apparent normal polarity, along with the thermal demagnetization of the existing samples, has shown that a.f. demagnetization was probably insufficient to reliably characterize the sites' primary remanent magnetization (Johnson, 1986). Of the 28 sites in the lower Bunthang sequence analyzed by Johnson (1986), 14 became reversely magnetized class I sites after thermal demagnetization, 7 became reversed class II sites, and 7 sites were unresolved class III sites (Fig. 9). All of the anomalous samples responsible for the ambiguities within the class II and class III sites show either declinations that shift toward the south or inclinations that shift in a reversed sense upon progressive thermal demagnetization. The details of the paleomagnetic data obtained in this study are given in Johnson (1986) and Cronin (1982).

The results of the blanket thermal demagnetization of both the upper and lower Bunthang samples at 500°C or higher are plotted on an equal-area stereonet in Figures 8 and 9. Samples from the upper Bunthang sequence are reversely magnetized both before and after thermal demagnetization (Fig. 8). The upper Bunthang sediments are inferred to have been deposited during a period of reversed magnetic polarity. In contrast to the reversed polarity in upper Bunthang samples, the lower Bunthang strata are normally magnetized prior to thermal blanket demagnetization, but become reversely magnetized after thermal demagnetization (Fig. 9). Lower Bunthang sediments thus contain two magnetic components of opposite polarity. Which polarity represents the Earth's magnetic field at the time of deposition?

The normal polarity component measured in samples from the lower Bunthang sequence (Fig. 9) is essentially that of the Earth's present magnetic field, indicating that this component is likely an overprint of the Brunhes normal chron upon a reversely magnetized primary remanence. Alternatively, the reversed polarity component could be an overprint imposed upon a normally magnetized primary remanence; however, it is more likely that the normally magnetized component is an unstable viscous normal overprint upon a stable, reversely magnetized primary remanence. The lower Bunthang sequence is interpreted to be reversely magnetized throughout the 405-m-thick sample interval (Johnson, 1986). Thus, both the upper and lower Bunthang sequences were deposited during a period of reversed magnetic polarity.

**Age of the Bunthang sequence. Temporal position.** The uniformity of magnetic polarity throughout the upper and lower Bunthang sequences precludes the possibility of correlation with the magnetic-polarity time scale by some method of pattern rec-
ognition. The existence of two thick bodies of reversely magnetized rock within the Bunthang sequence demonstrates that the onset of basin sedimentation predates the most recent major reversal: the Matuyama-Brunhes boundary event of 0.73 Ma (Mankinen and Dalrymple, 1979).

No fossils, pollen, volcanic ash, or other independently datable material has yet been found in the Bunthang sequence to permit a more precise chronometric fix between the observed MPS and the magnetic-polarity time scale (Mankinen and Dalrymple, 1979). The diamictite at Bunthang’s base is probably no older than 3.2 Ma, the date of the onset of late Cenozoic continental glaciation in Europe, Asia, and North America (Fillon and Williams, 1983; Berggren and Van Couvering, 1974). Hence, Skardu’s basin phase occurred sometime after the initial glaciation of the region (<3.2 Ma) and before the end of the Matuyama chron (>0.73 Ma). The Mammoth and Kaena subchrons of the Gauss normal chron may be too short (<0.1 Ma) to accommodate Bunthang sedimentation, so the Bunthang sequence was most probably deposited during the Matuyama reversed chron, between 2.48 and 0.73 Ma. Without an independent chronologic control, however, there can be no unique identification of which period(s) of reversed polarity between 3.2 and 0.73 Ma were responsible for the reversed remanence observed in the Bunthang strata. The inferred timing of Skardu’s basin phase indicates that the Bunthang sequence is at least partly correlative with the Karewa Group of the Kashmir Basin, 150 km southwest of the Skardu Basin (Burbank and Johnson, 1982, 1983), and with the Peshawar Basin sequence (Burbank and Tahir Kheli, 1985).

**Duration of deposition.** Both the upper and lower Bunthang sequences are more than 400 m thick, and are reversely magnetized throughout. The implication of the observed MPS is that the upper and lower Bunthang sequences were each deposited relatively quickly, during a time in which there were no significant magnetic reversals in the Earth’s magnetic field. The length of the respective periods of deposition of the upper and lower Bunthang sequence can be estimated by using a statistical model of geomagnetic reversals (Johnson and McGee, 1983). The Johnson and McGee model (1983) can be used to estimate the amount of time encompassed by the deposition of a particular sequence that contains a known number of magnetic reversals, given a magnetic reversal frequency that is characteristic of the period in which the deposition occurred. The model is based on the statistical properties of variations in the polarity of the Earth’s magnetic field and on the stochastic nature of the paleomagnetic sampling process.

If variable N is the number of sample sites, and R is the number of reversals contained or assumed within the sequence,
then the probability \( p \) that two adjacent sites show opposite polarity is given by:

\[
\frac{R}{(N - 1)}
\]

The mean reversal frequency \( \tau \) of the Earth's magnetic field during late Neogene time is 120,000 yr (Johnson and McGee, 1983). The duration of deposition \( \Delta t \) of a sequence is estimated to be

\[
\Delta t = \left( \frac{-1}{2} \ln(1 - 2p) \right) N \pm 2\sigma,
\]

where

\[
2\sigma = 2\sqrt{p(1 - p)} \left( \frac{\Delta t}{R} \right)
\]

(Johnson and McGee, 1983). Although the paleomagnetic sampling program described herein uncovered no magnetic reversals, it is assumed, in order to make a first-order estimate of the duration of deposition, that one does exist in the upper Bunthang sequence. The assumption of a single reversal yields an estimated deposition interval for the upper Bunthang sequence of \( \sim 126,000 \pm 249,000 \) yr (Table 1). This estimate provides a maximum value, because we have assumed the existence of the reversal. The Johnson and McGee model (1983) indicates that the upper Bunthang sequence was probably deposited in less than \( 376,000 \) yr (95 percent confidence level). The estimated depositional interval suggests that the 460-m thickness of the upper Bunthang sequence accumulated at a rate of at least 1.2 mm/yr. Similarly, the Johnson and McGee model (1983) yields a depositional interval for the lower Bunthang sequence of \( \sim 127,000 \pm 250,000 \) yr (Table 1), corresponding to a minimum rate of section accumulation of \( \sim 1.1 \) mm/yr.

### Table 1. Statistical Calculation of the Duration of Deposition (\( \Delta t \)) of the Bunthang Sequence

<table>
<thead>
<tr>
<th>Sequence Interval</th>
<th>( R )</th>
<th>( N )</th>
<th>( \Delta t ) (yr)</th>
<th>( \pm 2\sigma ) (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Bunthang</td>
<td>1</td>
<td>40</td>
<td>126,345</td>
<td>( \pm 249,429 )</td>
</tr>
<tr>
<td>Lower Bunthang</td>
<td>1</td>
<td>37</td>
<td>126,892</td>
<td>( \pm 250,234 )</td>
</tr>
<tr>
<td>Entire Bunthang</td>
<td>1</td>
<td>77</td>
<td>123,207</td>
<td>( \pm 244,788 )</td>
</tr>
</tbody>
</table>

The middle Bunthang sequence represents a gap of unknown duration within the MPS record of the Bunthang sequence. The fanglomerates and interbedded sandstone/mudstone beds may reflect rapid deposition within a glacially dominated environment; however, they may also reflect relatively slow deposition during an arid interglacial period, similar to the present environment in Skardu. (Note that the words “relatively slow” are used advisedly in discussing the rate of alluvial deposition along a margin of a Himalayan intermontane basin that has more than 3 km of vertical relief.) If it is assumed that the entire Bunthang sequence was deposited during a single reversed mag-

netozone, then the Johnson and McGee (1983) model would predict that the duration of Bunthang deposition was \( \sim 123,000 \pm 245,000 \) yr, yielding an average rate of section accumulation of at least 3.5 mm/yr.

### DISCUSSION: POSSIBLE MECHANISMS CONTROLLING BASE LEVEL

Why did the Indus River Valley at Skardu temporarily develop into a depositional basin in which approximately 1.3 km of sediment accumulated, later to be excavated by glacial and fluvial erosion? The base level of the Indus River had to rise downstream relative to Skardu as a result of some mechanism that was unable to sustain the elevation differential for more than, at most, about 2 Ma. The deposition of at least the upper and lower Bunthang sequences seems to have been rapid, based on the foregoing statistical analysis. This change in the base level of the Indus River at Skardu could be accomplished by depressing the Skardu area relative to a regional mean topographic surface, or by differentially uplifting the course of the Indus River downstream from Skardu.

Evidence of intermontane basin development by a pull-apart mechanism has been suggested for the upper Sutlej River Basin, approximately 400 km southeast of Skardu (Ni and Barazangi, 1985), and is a speculative mechanism whereby the gap through which the Shigar River flows to meet the Indus may have developed (Cronin, this volume). The delicate interplay of fluvial, alluvial, and lacustrine strata in the Bunthang sequence resembles the stratigraphy described in basins along strike-slip faults (e.g., Hempton and others, 1983; Crowell, 1974; Link and Osborne, 1978; Steel and Gloppen, 1980; Heward and Reading, 1980). The Bunthang outcrop displays no direct evidence of normal or strike-slip faulting that may be related to extensional basin development, however, and the seismicity that evinces the origin of the upper Sutlej River Basin appears to be absent in the Skardu region based on the current, sparse seismic record.

The abundant evidence of extensive glaciation at Skardu, together with the presence of glacial till at the base of the basin-fill sequence, suggests the possibility that a depositional basin could have been developed at Skardu as a result of the glacial erosion of a closed depression. The depression would subsequently fill with sediment, which would later be exhumed as glacial and fluvial erosion incise the drainage course downstream. An analogy for this model is provided by Yosemite Valley in the Sierra Nevada Mountains of California. Pleistocene glaciation excavated a depression that is as much as 600 m deeper than the bedrock sill that controls the current base level of the Merced River through the Yosemite Valley (Matthes, 1930; Gutenberg and others, 1956). This closed depression was filled with a cyclic succession of coarse glacial and alluvial detritus and fine lacustrine sediment (Scharff, 1977). Future erosion of the bedrock sill by fluvial erosion will lead to the progressive exposure of Yosemite Valley’s basin-fill sequence. Although glaciation has certainly been significant in the enlargement of the river valley at Skardu,
the presence of sandstone interpreted to be fluvial near the base of Bunthang, between the basal till and the lacustrine mudstone in the lower Bunthang sequence, would seem to preclude further consideration of the "glaciated depression" model as a dominant mechanism for basin formation.

Fission-track analysis of a plutonic bedrock sample collected 2 km west of the base of the Bunthang outcrop at Komara yielded an apatite annealing age of 8.2 ± 1.7 Ma and a zircon annealing age of 15.4 ± 1.3 Ma (Zeitler, 1985). These data indicate that the depositional basement of the Bunthang sequence is undergoing an increase in elevation comparable to that of the surrounding region, rather than a local decrease in relative elevation. It can be inferred that the mechanism(s) responsible for variations in base level at Skardu must involve uplift downstream that has proceeded at a more rapid rate than uplift in the Skardu region.

The map pattern of the MMT indicates that an axis of local uplift exists along the NP-H syntaxis, transverse to the course of the Indus River downstream of the Skardu Valley (Fig. 10). Uplift rates inferred from fission-track cooling data show that the interior of the NP-H syntaxis has undergone rapid uplift during the last 10 m.y. as much as 1 cm/yr (Zeitler, 1985; Zeitler and others, 1982, 1986). The Raikot fault displaces Quaternary glacio-alluvial strata, and has a recent record of seismic activity along the western edge of the NP-H syntaxis (Madin, 1986; Khurshid and others, 1984; Yielding and others, 1984). This north-trending, east-dipping, oblique-slip fault displays both right-lateral and reverse components of displacement (Madin, 1986; Casnadi, 1976).

The Raikot fault also correlates with local changes in the gradient of the Indus River (Seeber and Gornitz, 1983). The Indus River has an anomalously steep gradient throughout the Karakoram Himalaya (Seeber and Gornitz, 1983). The onset of steepening spatially correlates with the edge of a zone of relatively little seismic activity, termed the Skardu quiet zone (Cronin, this volume). The mean gradient of the Indus River from the Indo-Pakistan border, upriver from Kharmang, to Rondon (i.e., to locality B, Fig. 4) is approximately 3.3 m/km, as determined from Operational Navigation Chart G-7. The gradient steepens to a mean of 10.8 m/km through the NP-H syntaxis (between localities B and C), with most of the steepening apparently concentrated along the western edge of the uplift, and then decreases to 5.1 m/km (between localities C and D). The gradient anomaly continues downstream to where the river is impounded at the Tarbela Dam (Seeber and Gornitz, 1983). Clearly, the late Tertiary-Quaternary uplift of the NP-H syntaxis has had a significant effect on the gradient and base level of the Indus River during the inferred time interval of Bunthang sequence deposition.

Significant changes in base level also could have been affected by other mechanisms, such as local variations in lithology or fracture density that would lead to different resistance to erosion, strike-slip displacement transverse to the river course, and ephemeral blockages provided by material that was rapidly deposited in the Indus River Valley by glaciers or landslides.

Landslides and glaciers are both known to have affected the course of the Indus River during recent centuries; however, dams produced by these mechanisms are typically short lived. Landslide dams tend to fail catastrophically, because water is generally able to pipe rapidly through the poorly compacted landslide mass. Mechanical erosion by flow both over and through a saturated landslide mass, followed by instability and rapid structural failure, tend to make landslides ineffective for impounding water for extended periods of time. De Filippi (1912) described a famous instance in which the Indus River was dammed by a landslide:

In 1841, a landslide in the deep gorge of the Indus to the west of Nanga Parbat almost entirely dammed up the course of the river, forming a lake about 40 miles long. Six months later the dam gave way, and the huge reservoir was emptied in a single day, obliterating every trace of life for 800 miles of valley. At Attock, where the valley opens onto the Punjab plain, Gulab Singh's Sikh army was encamped. The fearful flood swept it away, destroying 500 men.

Fluvial systems can also be temporarily dammed by glaciers and glacial deposits. Vigne (1841) reported the failure of a glacially dammed river as follows:

The Nubra Tsuch is, as well as I could collect, a head water, formed by a vast barrier of ice, that has dammed up a valley formed between two spurs of the Kurukurum. Various and most conflicting were the accounts given of its extent, but all agreed that it was very large. . . Not many
years ago, the protecting glacier gave way, and the mighty flood, no longer confined, rushed down the valley of the Shy-Yok, destroying every village that came within its reach; and descending in one day, from Nebra to Skardu [Skardu], a distance, with all its windings, of not less than 125 miles, where the proofs of its fury and its volume are still to be seen.

Burbank and Tahirkheli (1985) described a section of more than 20 m, composed of thin rhythmites at Piran in the Peshawar Basin, which they interpreted to be catastrophic flood deposits. Catastrophic inundation of the Indus Valley is inferred to be a frequent event, occurring at least four times in the 19th century due to the failure of either a glacial or a landslide dam. Although these mechanisms are certainly capable of impounding a significant amount of water and sediment, the current database is insufficient to demonstrate that the Buntang sequence was deposited in the sort of very short time interval during which a sufficiently large glacier or landslide could have dammed the Indus River. It is possible that the landslide and/or glacier damming mechanisms may have been responsible for at least some of the smaller-scale ponding events that are thought to have occurred during the deposition of the Buntang sequence.

CONCLUSIONS

The structurally localized Indus River Valley at Skardu was a depositional basin within which sediments accumulated to a thickness of more than 1.3 km during late Cenozoic time. The Buntang sequence is the most complete remnant of that early basin phase. The initiation of basin sedimentation at Skardu occurred after the onset of glaciation in the region ≤ 3.2 m.y. ago, based on the occurrence of a till deposit at the base of the lower Buntang sequence. The uppermost mudstones of the upper Buntang sequence were deposited no later than 0.73 Ma, as evinced by the reversed polarity of all 40 paleomagnetic sites that have been established in the upper Buntang sequence. It is perhaps most likely that the thick sequences of reversely magnetized mudstone in both the upper and lower Buntang sequence were deposited during the Matuyama reversed chron, between 2.48 and 0.73 Ma, rather than during the brief reversed subchrons of the Gauss normal chron. The absence of any recorded magnetic reversals within the sampled sections, combined with the lack of any independently datable material found within the strata prevents a more accurate determination of the timing of Buntang sequence deposition at this time. The upper and lower Buntang sequence were each deposited in a short period of time, very likely less than 400,000 yr. The amount of time during which the coarse strata of the middle Buntang sequence were deposited is unknown.

Skardu Basin developed within the preexisting Indus River Valley in response to changes in the base level of the Indus River. The general temporal correlation of rapid uplift along the NP-H syntaxis, transverse to the Indus River downstream from Skardu, and basinal sedimentation in Skardu suggests that the Indus River may have been ponded by the syntaxial uplift. The spatial correlation of knickpoints along the present course of the Indus River with the NP-H syntaxis suggests that the uplift of this transverse massif is able to affect gradient and base level along the Indus. Large glaciers and landslides may have also played a role in altering the gradient and base level of the Indus River, affecting basin sedimentation upstream in Skardu Basin.

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