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Lacustrine Sedimentation in a Semiarid Alpine Setting: An Example from Ladakh, Northwestern Himalaya

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The Lamayuru lacustrine strata in Ladakh typify many of the carbonate-rich Pleistocene alpine lakes found in the semiarid environment of the northern Himalaya. Created by a 200-m-thick landslide, the lake was in existence by at least 35,000 yr ago, and may have persisted until 500–1000 yr ago. Represented in the center by thin turbidites and laminated muds, the lacustrine sedimentation along the lake margins and low-relief deltas characteristically displays a marked contrast between (1) clastic lenses representing rapid, sporadic, matrix-poor debris flows and periglacial inputs from the alpine slopes and (2) abundant, diverse, shallow-water, biologically dominated carbonate strata, among which organism-rich, chalky beds and oncolithic and encrusted stem-rich strata predominate. Resemblances of the Lamayuru lacustrine strata and their setting to those of former lakes throughout areas north of the Greater Himalayan crest suggest that the alpine, semiarid environment would favor diversified, spacially restricted carbonate sedimentation punctuated by occasional clastic influxes. Such a depositional regime contrasts strongly with that found immediately south of the Himalayan crest where more humid conditions promote a more continuous clastic influx into intramontane lakes.

INTRODUCTION

In the arid and semiarid valleys lying north of the main crest of the Himalaya, Quaternary sedimentation is typically clastic, coarse-grained, discontinuous, and biologically sterile. The tills, outwash, fanglomerates, and colluvium that have aggraded in most valleys certainly reflect past climatic changes, but the detailed record of the timing and magnitude of Pleistocene climatic changes is poorly known. Scattered sparsely across this dry region, however, are remnants of lacustrine sediments that potentially provide a rather continuous, sensitive, and datable record of former climatic and depositional conditions. The stratigraphy and petrography of these lacustrine remnants reveal both the processes and the external climatic controls that regulated depositional conditions in the past.

We report here an investigation of the late Pleistocene lacustrine deposits of the Lamayuru valley, a tributary of the upper Indus River valley in Ladakh, northwestern Himalaya. The depositional record of this 200-m-thick succession reveals a complex interplay between biologically and chemically dominated sedimentation within the lake and pulses of coarse clastic detritus

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that punctuate the fine-grained sequences along the margins of the former lake. These successions are interpreted as representing a predominantly dry late Pleistocene climate in which occasional intense storms flushed colluvial debris into the former lake.

HISTORICAL BACKGROUND

For more than a century, travelers following the ancient caravan trail joining Srinagar to Leh and Kashgar have remarked on the spectacular lacustrine deposits of Lamayuru. In 1848, A. Cunningham recognized the sediments as the undoubted evidence for a huge lake that existed at a "relatively recent epoch." According to the legend reported by Cunningham (1854), the lake was drained by the lama Naropa when he founded the first Buddhist monastery of Lamayuru, one of the oldest of Ladakh. Drew (1875) was the first to point out the abundance of alluvium interfingered with lacustrine silts. More recently, Dainelli (1922) suggested the lake was formed during a "fairly old glacial period" at a time when a glacier tongue, descending the adjacent Yapola valley (Fig. 1), dammed the small Lamayuru tributary before converging with the Indus glacier. In his archeologic reconstruction, Pandey (1975) mentioned again the legend, specifying that the former mystic lake of Lamayuru had clear waters which were rapidly drained. Bür-

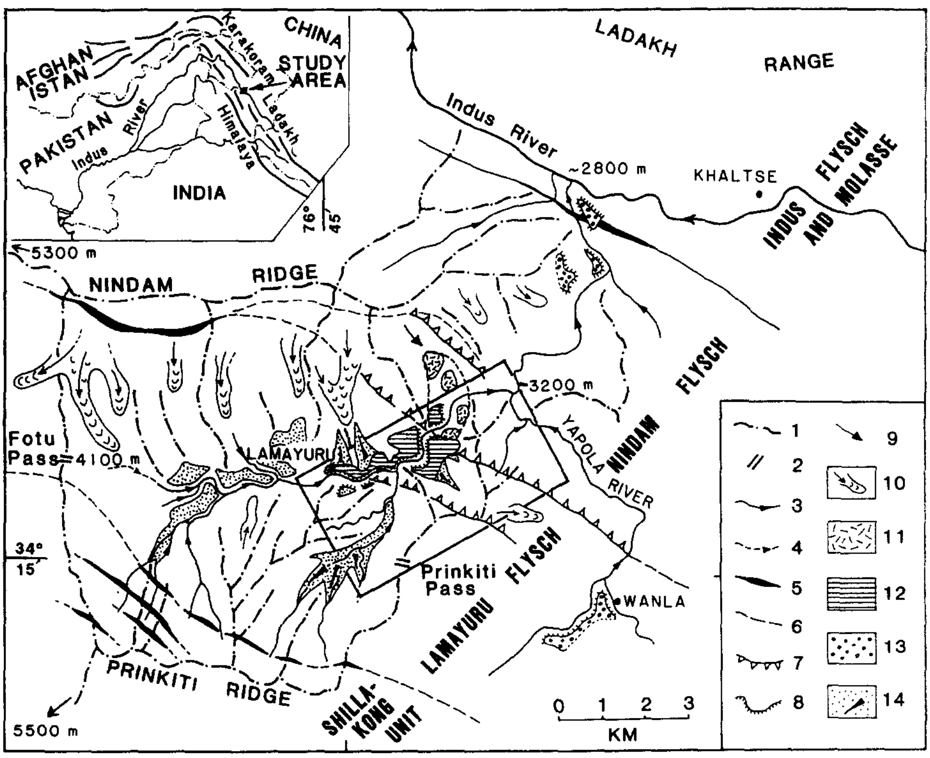

FIG. 1. Geomorphological and geological setting of the Pleistocene Lamayuru lake. Most slopes are covered by frost-shattered debris. The strike of the geologic outcrops is controlled by the Indus Suture Zone. Box, area covered by Figure 3. Inset, location of the study area. 1, Ridge; 2, pass; 3, perennial stream; 4, intermittent stream; 5, serpentinite lense; 6, geologic contact; 7, monoclinal (hogback) scarp; 8, alluvial/lacustrine scarp; 9, direction of the debris tongue which dammed the Lamayuru catchment; 10, solifluction tongues (occurrence favored by the presence of serpentine lenses); 11, brecciated landslide material; 12, lacustrine silts; 13, prelacustrine alluvial gravels; 14, late lacustrine fanglomerates, grading to the top of the lake.

gisser *et al.* (1982) speculated that this sudden draining probably caused catastrophic events downstream and that the erosion of the lacustrine sediments "must have happened after the last glaciation."

Prior to the present study, however, little was known about the Lamayuru lake's age, origin, or depositional history. These unresolved questions are addressed in this paper, and the results are cast in the broader context of the control exerted by Pleistocene climatic changes on sedimentation in high-relief alpine environments.

STUDY AREA

Present Environment

The Lamayuru site extends along a small, easterly flowing tributary of the Yapola River, this latter carrying glacial meltwater draining from the Spongtang Range toward the Indus River, a few kilometers downstream of Khaltse (Fig. 1). Covering approximately 75 km^2, the Lamayuru watershed extends over a steep alpine terrain, from 3200 m near the Yapola confluence to more than 5500 m along the Prinkiti and Nindam ridges. The area is characterized by a semiarid continental climate (Table 1), as also indicated by barren mountainsides devoid of all but the most hardy vegetation: dwarfed, stunted, prickly xerophytic shrubs (e.g., *Artemisia, Caragana*) are typical, except along the streams where small trees (*Alnus, Betula*) may develop. There is a strong contrast between north- and south-facing slopes. Whereas snow frequently covers the former for several months each winter, snow melts rapidly from the south slopes following each storm. There are no permanent snowfields in the catchment; the upper slopes lie entirely below the modern equilibrium-line altitude (presently at $\approx$5500 m, see Burbank and Fort, 1985) and are subject to intense frost shattering.

Geomorphic Setting

The geomorphic setting of the valley is primarily controlled by contrasting lithologic units. At a regional scale, the juxtaposition of three east–west-trending belts of limestones, pelites, and sandstones modulates the morphology of the valley. The sandstone bands of the Nindam volcaniclastic flysch (Bassoullet *et al.*, 1980) make up the northern ridge of Nindam and control the location of gorges downstream along the valley, where the dam lay that created the lake. The argillaceous and calcareous flysch units of Lamayuru crop out over most of the watershed and are responsible both for smooth, subdued landforms and for the widening of the valley in its central part, where most of the lacustrine basin extends (Fig. 1). To the south, the Tethyan Shillakong carbonates abruptly limit the catchment. Elongated serpentinite lenses, occasionally bounding internal and external thrust contacts between these three units, become important at a local scale.

Most of the rocks of the watershed are very susceptible to frost-shattering. This property, added to the prevailing alpine

TABLE 1. MAIN CLIMATIC DATA FOR THE STATIONS OF LEH (3514 m) AND DRAS (3066 m), LADAKH HIMALAYA

		J	F	M	A	M	J	J	A	S	O	N	D	YEAR
LEH	T	−7.4	−5.7	+0.3	6.0	10.2	14.4	17.4	17.0	13.2	7.0	0.9	−4.5	5.7
	P	10	8	7	6	6	5	12	15	7	3	1	5	83
DRAS	T	−15.7	−14.5	−10.6	−0.5	7.9	13.6	17.0	17.1	13.1	5.6	−2.7	−11.0	1.8
	P	97	97	138	104	62	17	16	14	18	20	12	54	649

Note. The present climate of Lamayuru is intermediate between these two stations. T, mean temperatures in °C; P, mean precipitation in millimeters. Data from Flohn, 1958.

conditions, explains the development of an extensive periglacial morphology, as expressed by extensive taluses that blanket the slopes. The high clay content of some rocks, particularly the flysch, favors mass-wasting processes, including slumps, debris slides, and rockslides. Serpentinites localize the development of spectacular lobate debris flows or tongues converging toward the valley bottoms (Fort, 1983). Large quantities of frost-shattered debris are transported downslope by snowmelt runoff and slush-flow avalanches. Along the lower slopes, this periglacial debris grades progressively into fanglomeratic and alluvial benches of the Lamayuru fluvial system.

Geometry of Lacustrine Sediments

The whitish lacustrine silts contrast strikingly with the adjacent dark-gray flysch outcrops. The silts aggraded within a paleovalley whose topography reveals at least two stages of development (Figs. 2 and 3). The higher altitude, older stage is represented by a wide valley topography with gentle slopes graded to fluvial conglomerates along the valley axis. The lower slopes are mantled with periglacial debris; no till is evident but the possibility of influence from glaciation up-valley cannot be excluded. Subsequently, approximately 100 m of dissection created steep inner slopes and a narrow valley bottom, above which are perched consolidated remnants of fluvial gravels of the first stage.

The original extent of the lake was about 2 km^2 and is well delineated by rather continuous horizontal shorelines lying up to 200 m above the present thalweg (Fig. 2). Subsequent dissection and slumping, affecting both the bedrock (shales) and the lacustrine sediments, have preserved only a

FIG. 2a. View east toward the main Lamayuru lacustrine basin. Clastic, poorly sorted strata in the foreground are characteristic of the final stage of deposition and have built up the aggradational transport slopes that are converging toward the center of the former lake. In the background, the former lake shore level is prominently delineated by the sharp contrast of clear lacustrine beds and the surrounding grey Lamayuru flysch outcrops (MF.LAD.75.02.33).

limited part of the original fill, mostly along the former sides of the basin (Fig. 3). Whereas upstream discrete lenses of lacustrine silts are interbedded with coarse-grained fluvial and colluvial strata, lacustrine sequences more than 50 m thick are continuously exposed farther downstream.

ORIGIN OF THE LAKE

In most alpine areas, lakes commonly result from either filling of glacially eroded depressions or damming by landslide masses, glaciers, or glacial deposits. Practically, these causes are not always easy to separate in the field. Moreover, as shown in several places in the Himalaya, they are often combined: e.g., Skardu (Cronin, 1982), Sarat-Muhammadabad (Goudie *et al.*, 1984, Fig. 16), and Gilgit (Owen, 1988) in Pakistan, Marpha in central Nepal (Fort, 1980), and near Garbang, west of Nepal (Heim and Gansser, 1939).

In the downstream gorge of the Lamayuru drainage, the steep walls of the prelacustrine valley are blanketed with a 200-m-thick greenish-purple, nonstratified, poorly consolidated breccia (Fig. 4). The breccia lies unconformably on the steeply dipping Nindam sandstones, the Lamayuru siltstones, and the serpentinites along their tectonic contact. It locally covers remnants of indurated gravelly conglomerates related to the former valley floor. The brecciated material has a local origin; centimeter- to decimeter-size clasts and a few blocks (up to 4 m) of purple/green sandstones and tuffs, grey siltstones, and green serpentinites are embedded within an abundant greenish-grey, silty-clay matrix. The mixture of local lithologies and lack of pyroxenite clasts from the Yapola valley effec-

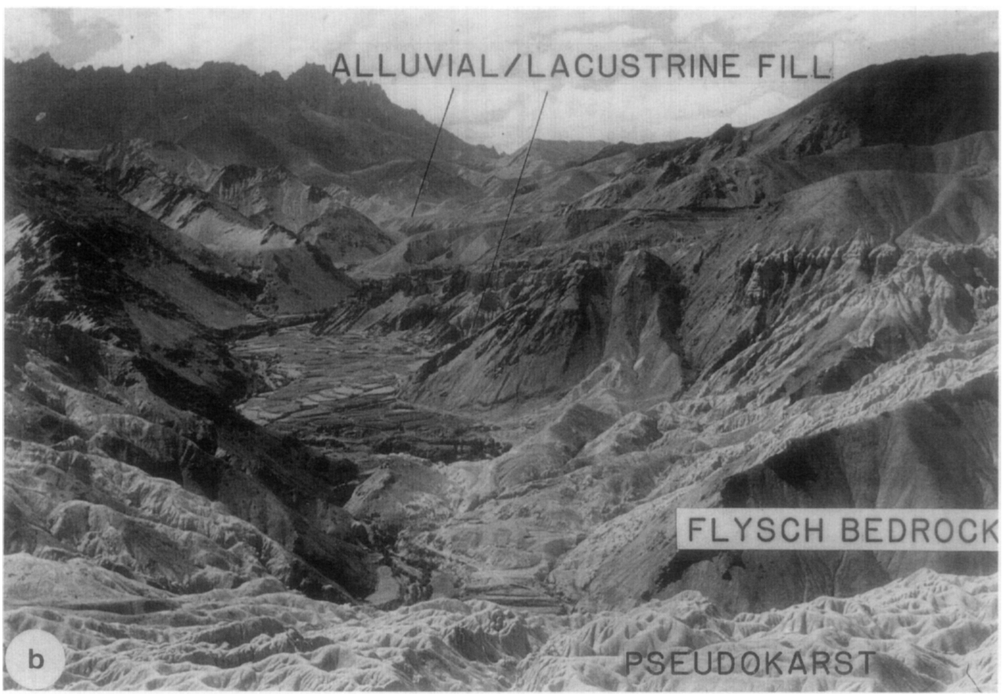

FIG. 2b. View west along the upper Lamayuru valley. In the foreground are slumped, pseudokarstified lake beds in which hollows caused by piping and sapping are noticeable. Upvalley the readily traceable former lake shore connects gradually upstream with the alluvial layers that prograded downstream along the Lamayuru main fluvial system (MF.LAD.77.12.21).

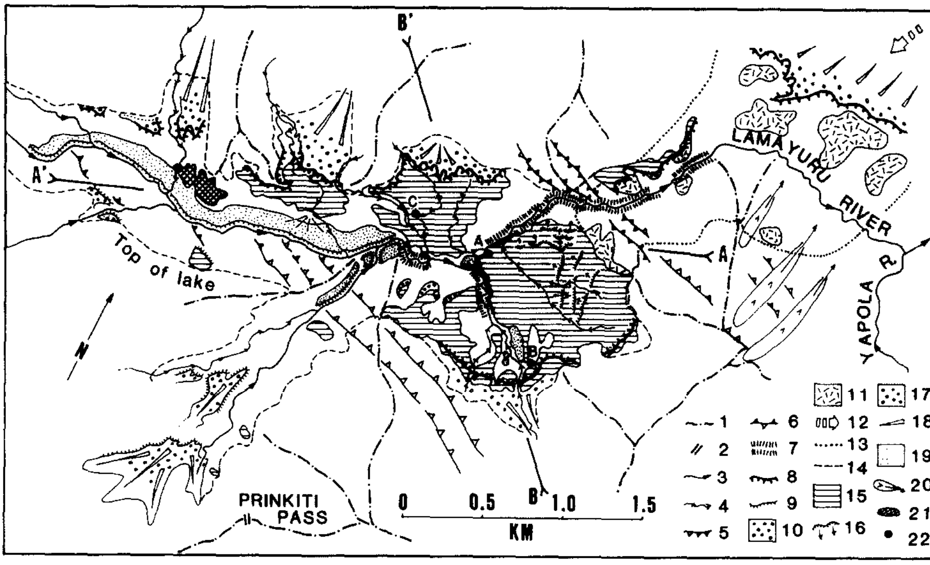

FIG. 3. Map of the Lamayuru lacustrine deposits based on mapping and aerial photoanalysis. 1, Ridge; 2, pass; 3, perennial stream; 4, intermittent stream; 5, monoclinal (hogback) scarp; 6, vertical scarp; 7, gorge; 8, scarp outlining the topmost level of lacustrine silts; 9, postlacustrine terrace scarp; 10, prelacustrine alluvial conglomerates; 11, brecciated material that dammed the Lamayuru valley and caused the creation of the lake; 12, direction of travel of the breccia; 13, probable extension of slide material; 14, reconstructed highest lake level; 15, lacustrine silts; 16, postlacustrine slumps in lacustrine silts; 17, late lacustrine fanglomeratic aggradation; 18, late lacustrine fan; 19, postlacustrine alluvium; 20, current active badlands; 21, Lamayuru village; 22, location of sections in Figures 6, 8, and 9; AA' and BB = sections given in Figure 12.

tively eliminates the glacial damming hypothesis proposed by Dainelli (1922). Features such as shearing and overconsolidation of the matrix, or clasts with crushed edges and corners usually considered as typical of till (Derbyshire *et al.*, 1987; Fort and Derbyshire, 1988), have not been observed. Moreover, examination of the

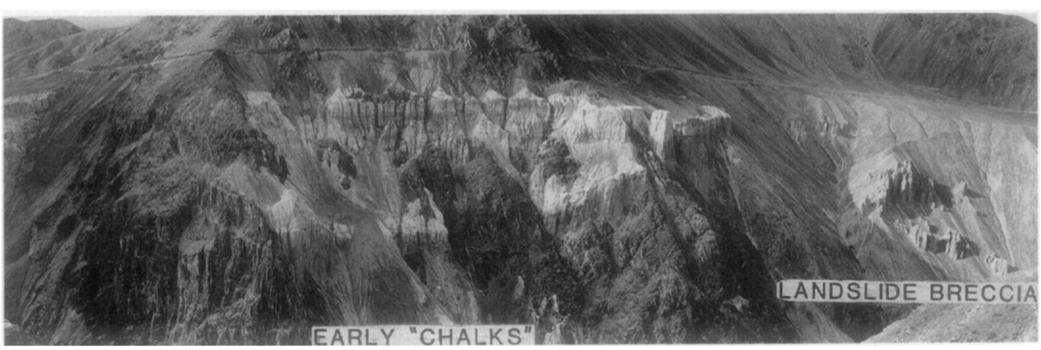

FIG. 4. View north of the landslide that caused the damming of the lake. The material visible on the extreme right of the photo is a poorly consolidated breccia which represents the remnants of a huge landslide derived from the southern flank of the Nindam ridge (visible on the right background). The breccia lies unconformably on the steeply dipping Nindam sandstone, serpentinites, and Lamayuru siltstones (from right to left), which crop out along the gorges terminating the lacustrine basin downstream. The breccia is covered by the whitish lacustrine silts that pass upward into coarser clastic colluvium. The upper lake level corresponds to the landslide height. Outcrops of the earliest "chalk" deposits directly mantle the bedrock upstream (left) of the landslide (MF.LAD.81.11.19/20).

Yapola valley reveals no evidence to suggest that its lower reaches have ever been glaciated since its incision. Hence, the breccia is inferred to represent the dissected remnants of a landslide (approximate volume of 300,000 m^3) whose source was the southern flank of Nindam ridge (Figs. 1 and 3). This landslide was certainly facilitated by the local geomorphic setting in which shales and serpentinites, fractured and loosened by periglacial processes, readily absorb water and become very susceptible to failure.

LACUSTRINE SEDIMENTATION

The sharp contact between the breccia and the overlying lacustrine silts indicates the dam was massive and resistant enough to cause an immediate flooding of the valley upstream and to initiate lacustrine sedimentation. The present analysis is based upon *in situ* outcrops which, except for those rare exposures in the very bottom of the lake basin, are mostly preserved close to the upper slopes of the paleovalley. Although sedimentation was continuous, three stages of sedimentation can be discerned within a 200-m-thick stratigraphic succession. An early stage, during which the newly formed basin was flooded, was followed by an interval characterized by striking contrasts in deposition between the margins and the center of the lake and by extensive biological activity associated with small deltaic platforms. The final stage was marked by the abrupt passage from lacustrine to alluvial and colluvial sedimentation, which clearly indicates the basin was entirely filled with sediments before the dissection started.

Initial Phase of Deposition

Following damming of the drainage, the flooding of the newly created basin commenced. The present average discharge of the river is very low (a few liters per second) but increases greatly during the snow melting season. During the Lamayuru event, the discharge might have been higher, with more humid periglacial conditions, but this cannot be quantified. Depending on assumptions made concerning the paleohydrology, the lake is very likely to have filled in a few years to a few tens of years. The basal deposits are represented by discontinuous, white, chalky beds that crop out strikingly along the valley walls (Fig. 4). These beds are prominently stratified and are very rich in organic debris (Fig. 5). Their thickness varies from a few centimeters to 2–3 m, and they directly drape the bedrock or its occasional colluvial cover. Their layering is generally parallel to the dip of the basin slope, but can occasionally exhibit cross-beds that prefigure the deltaic facies better developed in the overlying units.

The porous consistency of these chalky beds is attributable to their high organic content, represented mostly by pellets (Figs. 5c and 5e), and to the absence of early diagenesis. In addition, these beds contain a great abundance of organisms, including Gastropods, Charophytes with their gyrogonites (Fig. 5b) (Freytet and Plaziat, 1982; Dean and Fouch, 1983) and fibroradial algal concretions of various shapes, either isolated or hemispheric (oncoliths) or as a complete coating on other organic debris (stems, leaves) (Fig. 5d). All these components have developed in the areas of shallow-water sedimentation or in areas adjacent to the shore (in the case of oncoliths; Freytet and Plaziat, 1982; Dean and Eggleston, 1982; Casanova, 1987). Moreover, the occurrence of gypsum crystals (some as rosettes) along some stratification planes (Fig. 5f) indicates synsedimentary deposition under semiarid conditions and shallow-water environment. In many cases, the gypsum crystals have been replaced by calcite during early diagenesis. In these basal layers, diagenesis never went beyond an incipient stage of compaction, which was responsible for crushing most of the Gastropods and gyrogonites included in the sediments. Many of the components of this basal unit have a distinct paleobathymetric significance, inasmuch as they are

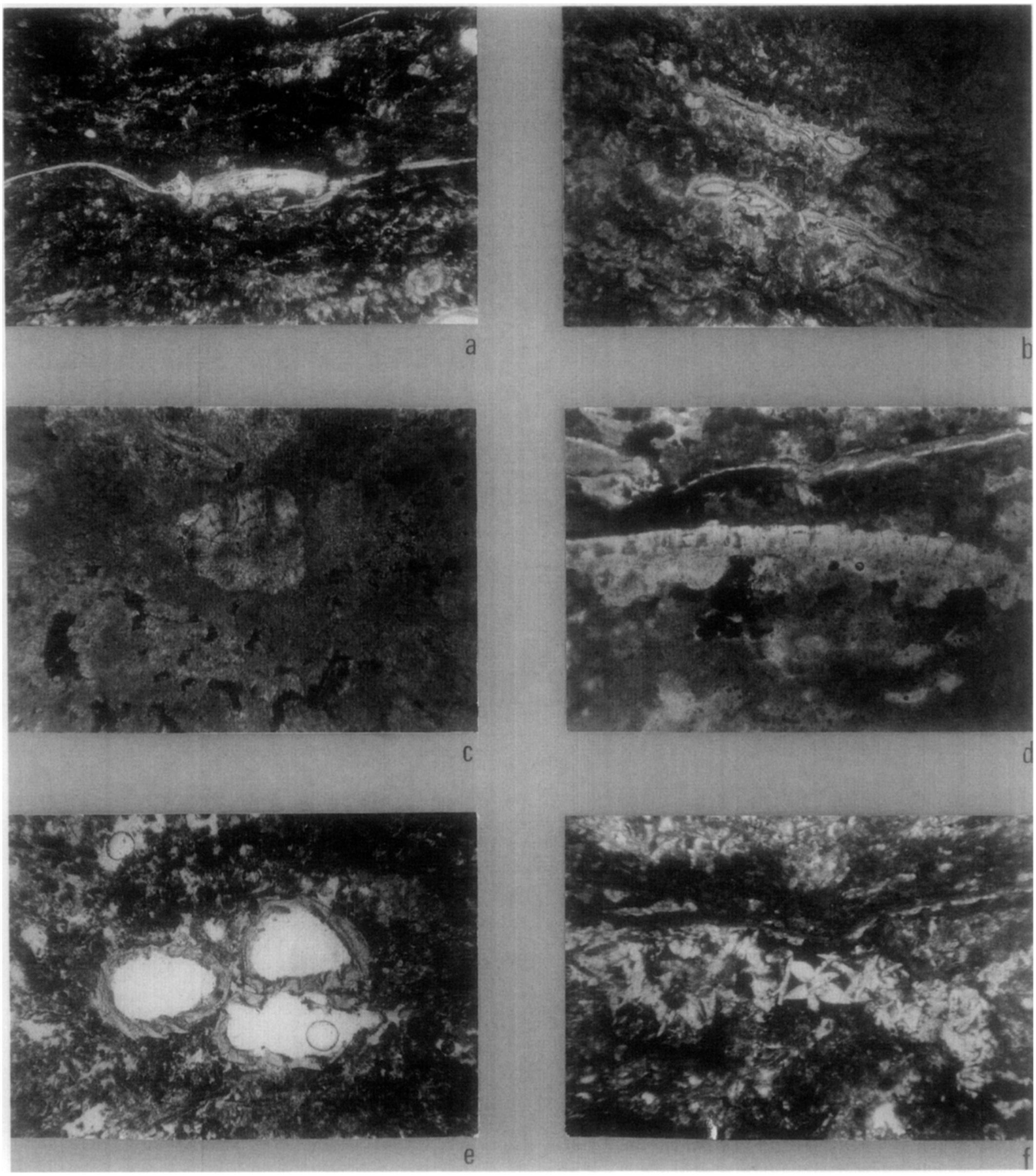

FIG. 5. Microfacies of the chalky beds. (a) Poorly bedded sediment: organic debris-rich, wackestone beds alternating with organic debris-poor, wacke-mudstone beds. Among the organisms are crushed Gastropods (arrow) and barely identifiable Charophyte debris (stems and leaves) (natural light). Length, 1.6 mm. (b) Poorly bedded sediment, displaying a packstone/wackestone texture and a dark, micritic matrix. Flattened, crushed, still not yet dissociated gyrogonites (oogoniums of Charophytes) are found together with isolated, matrix supported, monocrystalline debris of gyrogonites (natural light). Length, 1.6 mm. (c) Micritic, oncolithic limestone, with a clotted texture which may correspond to fecal pellets. The oncolith in the center is made of two subspherical elements with a characteristic fibroradial fabric (cross nichols). Length, 0.85 mm. (d) Micritic limestone with algal encrustations, probably developed from and around a leaf. Note the contrast between the upper face, where small juxtaposed prisms are the result of successive, curved laminations, and the lower face, encrusted only by some hemispherical concretions made of fibroradial, internal fabric (cross nichols). Length, 0.85 mm. (e) Micritic limestone with pellets and gyrogonites. In the central part can be seen the section of three gyrogonites not yet deformed or in their incipient stage of dissociation. The matrix is made of small pellets (dark grains) within a microsparitic cement (natural light). Length, 1.6 mm; (f) Biodetritic sediment, containing poorly recognizable elements. Note the beds of gypsum crystals, grouped into rosettes. These crystals have been epigenetically replaced by calcsparite. Length, 1.6 mm.

unlikely to have been deposited in water more than 10 m deep. On the other hand, these chalky, basal deposits crop out over a broad altitudinal range (>120 m). This apparent contradiction suggests that these beds represent a time-transgressive, rapidly accumulating lithofacies that was deposited at successively higher elevation along the valley walls as waters of the lake gradually rose toward the top of the dam.

Main Phase of Deposition

The main phase of sedimentation was marked by the development of subenvironments characterized by distinctive depositional patterns, in part reflecting an increasing influence of the adjacent slopes and shores of the lacustrine basin. Along the valley sides and at the outlet of small rivulets, coarse detrital material accumulated in deltas, changing the originally steep slope of the paleovalley into localized shelves of shallow water where intense biologic activity could take place and intermingle with more clastic sedimentation. The mixed biochemical and clastic regime is schematically expressed by the succession of three basic units: (a) deep-water deposits, where clastic laminae and turbidites prevail and where the direct biologic influence is reduced; (b) deltaic deposits, where foresets of clastic beds alternate with biochemical and biodetrital beds (low-Mg calcite); (c) shallow-water marginal-shore deposits, where horizontal biochemical and biodetrital beds interfinger with discrete fanglomeratic lenses.

Deep-water deposition. Deposits representing conditions in the central part of the lake are rarely preserved. This is because of both the extensive erosion of lacustrine deposits from the valley axis, and the extensive failure, consisting of a series of back-tilted slump blocks from the valley walls, which occurred after the end of lake filling. These deeper water units are characterized by massive and broadly laminated silty beds with fine, 2- to 3-cm-thick sandy beds and occasional 2- to 5-cm-thick pebbly lenses (Fig. 6). Horizontal stratification is weakly expressed by internally graded 5- to 7-mm-thick turbidite beds, which grade in places to more regular, parallel, horizontal, millimetric, silty carbonate-rich laminae. In this succession, lack of foreset structures and of coarse colluvial layers is noticeable.

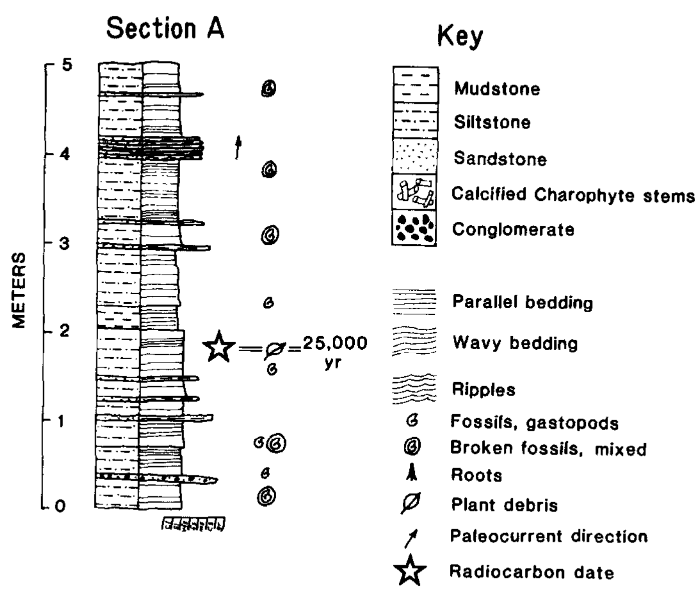

FIG. 6. Deep-water facies of the lacustrine deposits at location A, Figure 3.

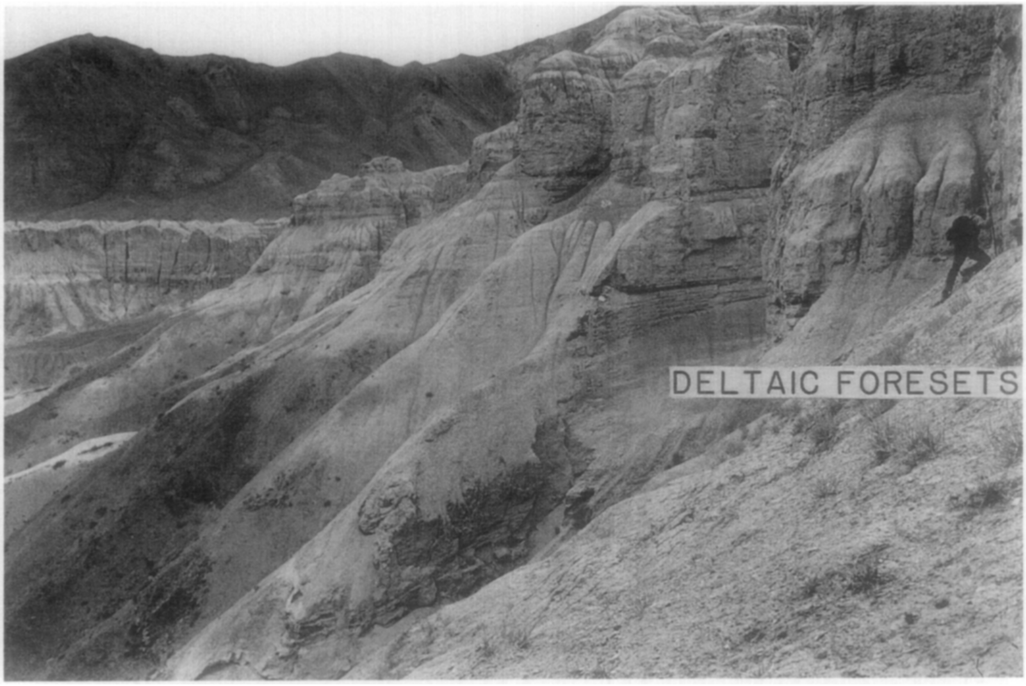

FIG. 7. Deltaic facies of the lacustrine deposits. A 20-m-thick deltaic complex (lower half of the photo) passes gradually upward to a marginal, shallow water complex (upper half). The foreground and the dark slope in the middle ground correspond to the flysch bedrock through which the prelacustrine valley was cut. Foreset beds, dipping at 15°–20°, pass upward to the nearly horizontal topset beds (MF.LAD.81.11.04).

Organic components are not rare; carbonized wood is occasionally preserved in the turbidites and scattered shell debris is rather regularly interbedded every 10 to 30 cm in the silts (mostly Gastropods, including a few Planorbs).

These observations suggest deposition in a progressively deeper water body. The rapid submersion of the lower, narrow Lamayuru paleovalley was accompanied by a longitudinal expansion upstream along the axis of the valley and its affluents. This resulted in an immediate and rather abundant filling by density flows that were fed by the clastic debris delivered by the main Lamayuru channel and its tributaries. Subsequently, however, the sedimentary inputs could not keep pace with the rising elevation of the water surface and turbidites graded rapidly into fine regular laminae that typify deeper water sedimentation that is well removed from fluctuating conditions along the shoreline. This style of deposition appears to have persisted throughout the lake filling, whereas the marginal type of

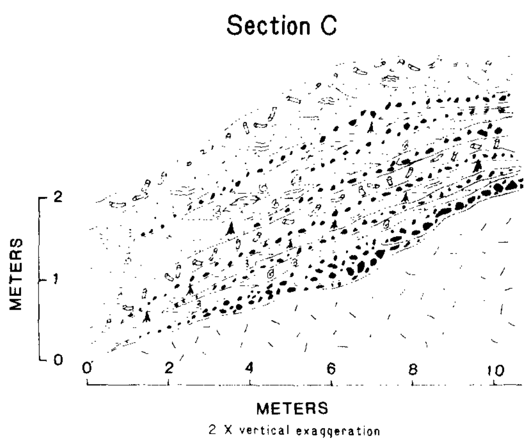

FIG. 8. Section of deltaic facies at location C, Figure 3. Legend: same as Figure 6.

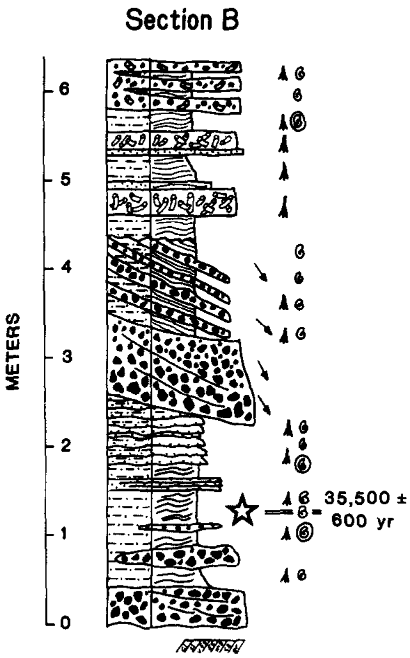

FIG. 9. Section of deltaic facies at location B, Figure 3. Legend: same as Figure 6.

sedimentation evolved imperceptibly toward increasingly shallow environments until shallow-water facies encroached on the center of the lake basin.

Deltaic complexes. Deltaic complexes of various shapes and extension developed locally along the steep slopes of the paleovalley at the mouth of some rivulets (Fig. 7). These complexes generally include foreset beds, grading rapidly to deeper water silty bottomset laminae, and topset layers which either grade to silty laminae (Fig. 8) or pass gradually to marginal shallow-water complexes (Fig. 9). Deltas range from 1 to 20 m in thickness, with the thickest complexes located more typically in the lower, steeper parts of the basin. Delta complexes practically disappear in the upper 20 m of the basin fill.

The foreset beds, dipping at 12°–20°, are composed predominantly of thick clastic beds that alternate with thin, white, chalky, shell-bearing beds (Figs. 9 and 10) or, more rarely, with beds of encrusted stem debris. Internally, the clastic (colluvial) layers are weakly parallel bedded. They generally contain 1- to 3-cm-long clasts with rare angular blocks up to 20 cm. All this clastic material is derived from the adjacent slopes. Their upward fining frequently gives way to thin, 1- to 3-cm-thick, chalky shell-bearing beds, very similar in content to previously described deep-water units that pass laterally to fine, gray, bottomset muds. In some deltas, encrusted stem-bearing beds, 2 to 10 cm thick, occur in the upper part of the foresets, interbedded with the clastic layers or with the chalky shell-bearing beds (Fig. 11). Charophyte stems, encrusted when the Charophytes were still alive along the lake shore, were fractured, transported short distances, and accumulated within the foresets with other detrital material.

These deltas were built intermittently, depending upon the volume of clastic inputs brought from the adjacent slopes and upon the rate of rise of the water surface. Whereas the abundance of colluvial material indicates that slope processes were very active, occurrences of interbedded biochemical layers indicate periods of relative quiescence and/or relative stability in sedimentation in the marginal shallow-water environment; such a condition is favorable to organic activity.

Lake shore complexes. The sediments of the lake-shore facies correspond to a complex, rapidly evolving alternation of laminated lacustrine beds with detrital, shore-controlled layers that were deposited on the gentler slopes of the upper paleovalley (Fig. 12). Both structures and components of these beds indicate a shallow lacustrine environment. "Lake shore" sedimentation predominated through the upper 50 m of the lake filling, but such sediments also occasionally are observed on the top of the formerly described deltaic complexes as discrete 1-m-thick beds (Fig. 9).

Fine-grained beds, composed of massive to slightly laminated, rootlet-bearing, silty muds (locally more than 1 m thick), alternate with thin (a few centimeters thick)

FIG. 10. Lake marginal facies. Deltaic progradation consisting of layers of chalky, biogenic strata, fine siltstones, and angular, colluvial detritus. Location: base of the site C, Figure 3 (MF.LAD.81.10.31).

sandy beds and/or chalky silts (similar to previously described deep-water units) (Fig. 13). These muds and silts are very rich in organic components: Ostracods, Charophytes, and algal concretions (oncoliths), but they also display stems or leaf imprints preserved along the strata, and *in situ* rootlets fossilized in the muds. These beds clearly represent the marginal shoreline conditions which were shallow enough (a few meters) to allow plants to flourish and where typically periods of emersion and submersion alternate.

Other evidence for extensive shallow shelves and proximity of the lake shore is provided by occurrences of gravelly to fine sandy, fining upward, clastic lenses of colluvial material, that pinch out within a few tens of meters toward the lake center, or that accumulated within local small deltas, exhibiting foresets less than 2 m thick. Furthermore, accumulation of detrital, encrusted stem-bearing beds indicates that the plants which lived on the shallow lake bottom were sometimes subject to storm-induced waves, capable of breaking them up. In such a small lake in a steep-sided valley, storm-generated waves could only affect shallow depths.

In brief, there is good evidence that the upper stage of the lake filling was rather regular and continuous, with a more widespread extension of the lake marginal conditions toward the center of the lake. Characteristic of it were intense organic activity, shallow-water waves and dynamics, and common pulses of colluvial debris from the adjacent slopes. This sedimentation developed at the expense of the deeper water turbidites and laminated muds, and it indicates a progressive shrinkage of the lake.

Final Stage

The last stage of deposition is marked by an abrupt passage from lacustrine sedimentation to colluvial and alluvial sedimentation, in which coarser material becomes ubiquitous. This type of sedimentation makes up the thickest part of the filling along the upstream section of the water-

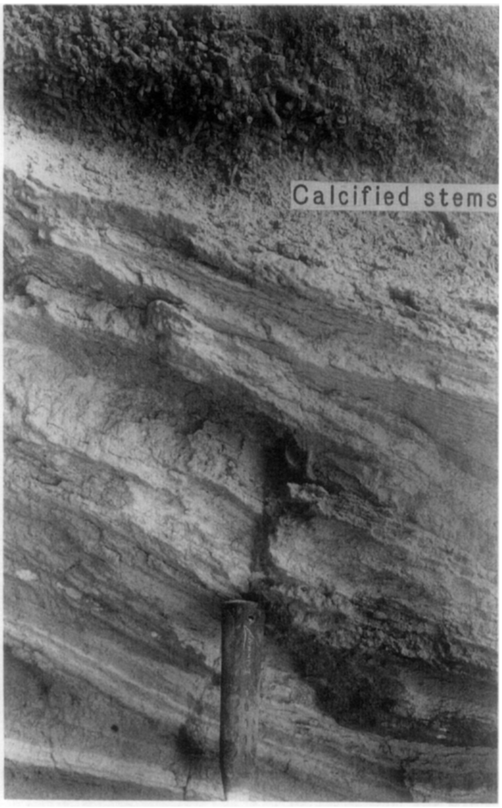

FIG. 11. Detail of the deltaic complex. The lower part displays thin, chalky shell-bearing beds. They are abruptly overlain by encrusted stem-bearing beds (top of the photo), mobilized by irregular storm waves, and transported along shallow shelves before being aggraded as topset beds. Location: site C, Figure 3 (MF.LAD.77.12.18).

shed (10 to several tens of meters), whereas it contributes to a very limited, superficial part of the basin downstream (a few meters to 10 m). One of the best examples of this sedimentation is displayed along the cliffs below the Lamayuru Monastery (Fig. 14).

Coarse material is predominant throughout these strata, but variations in silt percentage create a coarse layering of the sediments. Centimetric to decimetric silt-rich beds alternate with coarse debris lenses, often several meters thick. The constituent debris is derived both from the Lamayuru fluvial system and the surrounding slopes, made up of frost-susceptible rocks. The coarse deposits are typically poorly sorted and are partially clast-supported. These appear to represent matrix-poor debris flows (Bull, 1977) or grain flows (Blissenbach, 1954; Hooke, 1967). This facies predominates in the colluvial beds, whereas it alternates with elongated lenses of better-sorted, subrounded fragments in the alluvial beds.

Along the slopes, the colluvial layers prograded toward the center of the lake and built up aggradational transport slopes (Fig. 2) which connect with the alluvial accumulation along the axis of the main valley. These alluvial layers prograded downstream until they eventually adjusted their longitudinal profile to the lowest part of the basin, i.e., the local base level, as determined by the height of the landslide which dammed the valley (Fig. 12). The extensive lateral remnants of these colluvial transport surfaces and alluvial benches clearly indicate that the former lake had been entirely filled up and was superceded by a considerable interval of subaerial deposition prior to the breaching of the landslide dam and the initiation of the dissection.

AGE OF DEPOSITION

Athough Dainelli (1922) speculated that the Lamayuru lake resulted from glacial damming during an ancient glaciation, our data indicate that deposition was probably entirely late Pleistocene in age. The normal magnetic polarity of the sediments suggests a Brunhes age, and all of the identified species of Ostracods are extant today. Two radiocarbon dates were obtained for organic material collected from separate stratigraphic levels and depositional facies. From the shoreline complex at 3560 m altitude (about 170 m above the valley floor), Gastropod shells were sieved out of a shell-rich siltstone. These shells yielded an age of 35,500 ± 600 ^{14}C yr (age according to M. Stuiver, UW QL 1648). Because of the presence of abundant carbonates (Mesozoic rocks) within the catchment and the probable high levels of dissolved carbonate in the Lamayuru lake, it is likely that this

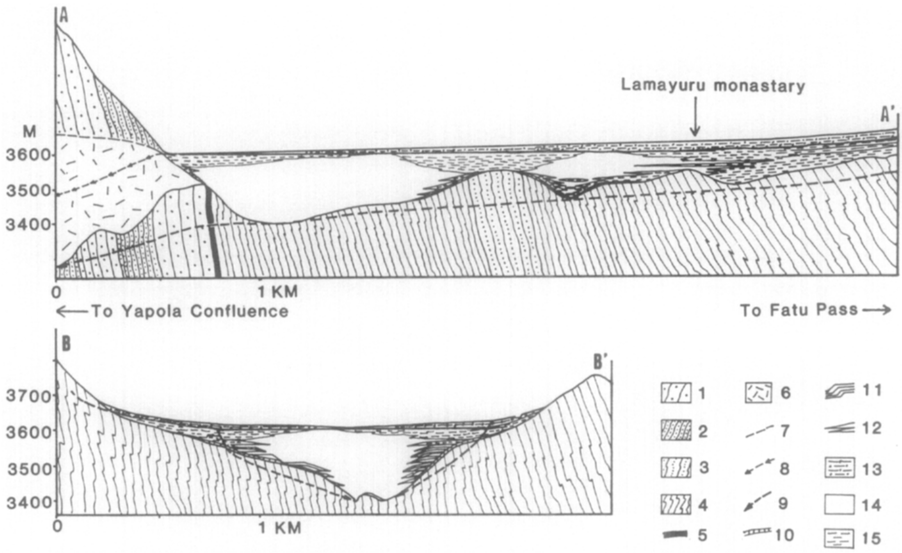

FIG. 12. Reconstructed longitudinal (A) and transverse (B) sections of the Pleistocene lake of Lamayuru, displaying the variations of facies within the sedimentary sequence. 1, Massive sandstone facies in the Nindam flysch; 2, shale facies in the Nindam flysch; 3, sandstone facies in the Lamayuru flysch; 4, shale facies in the Lamayuru flysch; 5, serpentine along the contact Nindam/Lamayuru flyschs; 6, breccia (landslide material that dammed the Lamayuru valley); 7, assumed upper limit of breccia; 8, probable position of the lake outlet before the dissection; 9, approximate present level of Lamayuru brook (in A) and small ravines (in B) entrenched across the lacustrine silts or bedrock; 10, basal chalky layer; 11, deltaic foreset facies; 12, topset facies; 13, colluvial and alluvial material associated with topset and foreset layers; 14, lacustrine silts; 15, subaerial colluviual and alluvial fans. Horizontal plane represents the top of the lake before final grading by the Lamayuru brook and tributaries.

date may be somewhat older (but probably less than 1000 yr) than the true age of deposition, due to the carbonate disequilibrium between the lake and the atmosphere. The second date was derived from scattered wood fragments found along partings in the deep-water facies at an elevation of 3390 m, 5 m above the valley bottom. These beds are likely to have been slumped from a higher stratigraphic position in the lacustrine sequence. Their age is >25,500 ^{14}C yr (UW QL 1647). Consequently, although portions of the middle to upper lake filling were clearly being deposited about 35,000 yr ago, the duration of sedimentation can be estimated only as a function of the average rate of lacustrine deposition (Sadler, 1981). Given the apparent high rate of production of periglacial debris on adjacent slopes, the lake may have filled with sediments in as little as 1000 yr. Alternatively, filling may have taken considerably more than 10,000 yr.

DISCUSSION

Although the Lamayuru lake clearly resulted from a landslide, the precise cause of the landslide is unknown. Given an age of the lacustrine sediments of early to middle last glaciation in this region, possibly enhanced levels of groundwater and/or seasonal frozen ground resulting from glacial and periglacial climatic conditions triggered the landslide. Given the absence of reliable dates on the inception of glacial advances during the last glaciation in the northwestern Himalaya, it is not possible to correlate directly the lacustrine and glacial records. Both seismically induced and aseismic slope failures are common in this mountain-

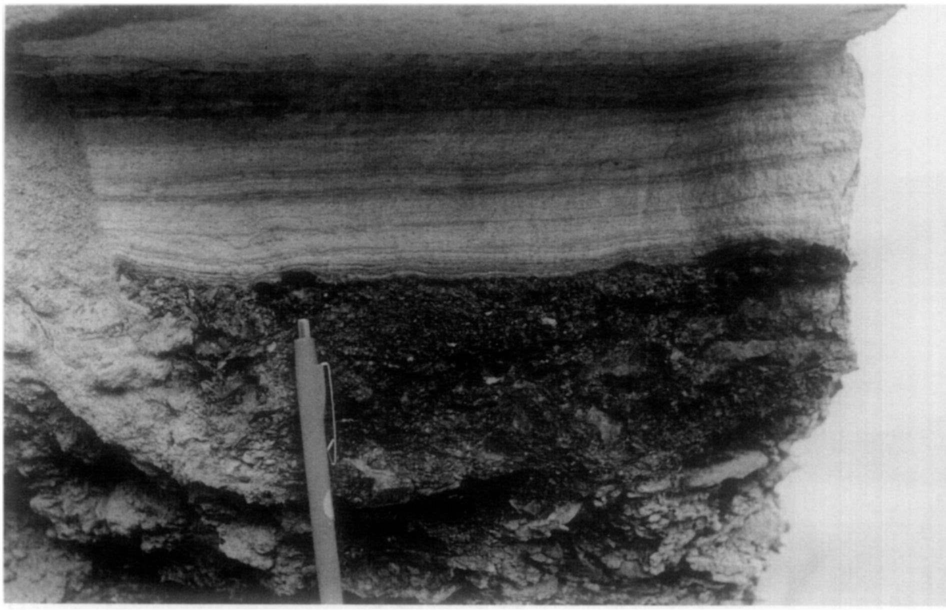

FIG. 13. Shore platform facies. Finely laminated Charophyte- and pellet-rich beds overlying lense of angular colluvium. Location: platform adjacent to site B, Figure 3 (MF.LAD.81.11.11).

ous region where high rates of Quaternary uplift (Zeitler, 1985; Burbank and Johnson, 1983) and fluvial incision (Seeber and Gornitz, 1983; Goudie *et al.*, 1984) prevail. The Indus River itself has been completely dammed by massive landslides (most recently in 1841, cf. Abbott, 1849; Becher, 1859), and the record of multiple catastrophic floods within the Peshawar basin due to breaching of landslide dams (Burbank, 1983) suggests that such events have not been geologically uncommon. At Lamayuru, accelerated incision (as indicated by the narrow, prelacustrine inner gorge) may have oversteepened the adjacent slopes and precipitated the landslide.

The deltaic and shore-margin deposits of the Lamayuru lake display an interplay between high-energy clastic sedimentation and carbonate deposition resulting from intense biological activity. The abrupt contacts between these angular, poorly sorted, nonstratified, clastic units and the enclosing lacustrine carbonates indicate that the clastic inputs represent very discrete and episodic pulses of sediment mobilization along the subaerial valley slopes and gullies. These short-lived but rapidly aggrading coarse influxes essentially overwhelmed the continuous, but much slower, biogenic inputs. The lack of observable rythmicity within the marginal deltaic units suggests that clastic influxes (other than along the axial drainage) were not seasonal or annual in nature, but rather resulted from irregularly spaced storm or snowmelt events of sufficient magnitude to mobilize the nearby and readily available periglacial debris.

The abundant and relatively diverse carbonate-rich deposits that are found through the entire interval of lacustrine deposition attest to extensive biological activity along the lake margins. The purity of many of the chalky, pellet-, and Charophyte-rich deposits suggests long intervals of quiescence within protected bays and indicates that the organisms that have produced the pellets were living along the shores and not in burrows. In more exposed areas, extensive beds of fractured, carbonate-encrusted stems indicate breakage and concentration

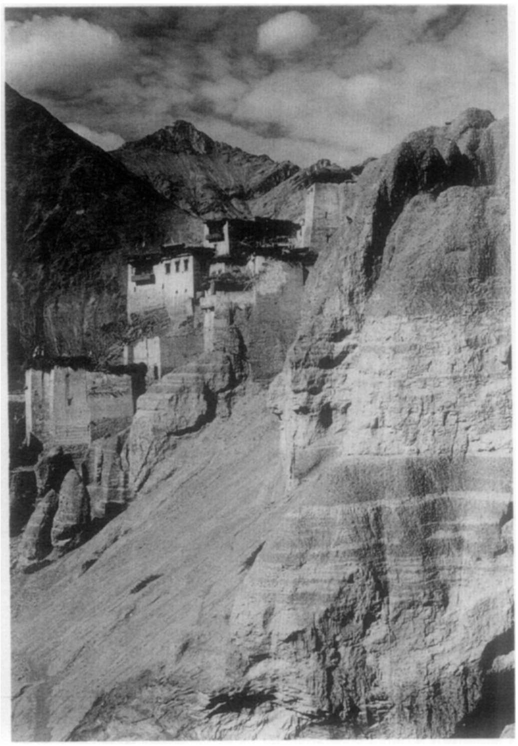

FIG. 14. Colluvial and alluvial sedimentation that characterizes the final stage of the lake filling, well displayed along the cliffs on which the Lamayuru monastery (white buildings in the upper half) was built. The coarse layering of the sediments is created by variations in silt percentage. Nevertheless, all beds contain predominately coarse, clastic debris, which were derived from the Lamayuru fluvial system and from the frost-susceptible surrounding rocky slopes (MF.LAD.77.13.09).

of debris by storm waves operating along shallow shoreline platforms. Whereas the "pure" chalky carbonates occur throughout the sedimentary filling of the lake, the higher energy, wave-induced concentrations appear confined to the later intervals of deposition, when increasing restriction of the lake resulted from the development of large shoreline platforms.

Because of the progressive incision of the Indus River valley and the resultant lowering of local base level, the aggradation and preservation of the Lamayuru lacustrine and succeeding clastic deposits was completely dependent upon the existence and structural integrity of the landslide dam. As soon as the dam had been breached, incision of the weakly consolidated Lamayuru valley fill would have proceeded rapidly. Although the time of breaching of the dam is unknown, both the legend of the draining of the lake by the founding Lama Naropa at Lamayuru (Naropa was living in the time of Rin-chen bzang-po, i.e., 956–1055 A.D., according to Snellgrove and Shorupski, 1977, p. 21) and paintings at the monastery of Alchi (the oldest of Ladakh) of boats on a lake (quoted by Bürgisser *et al.*, 1982) suggest that the incision commenced only within the past 1000 yr. If the estimate for the breaching of the dam is correct, then the dissection of 200 m of lacustrine fill has proceeded rapidly since then. Although this would represent a locally rather high rate of erosion, such rates would be consistent with the rates determined for similar valley fills in other regions of the Himalaya (Fort, 1987). At Lamayuru, rapid rotational slides and earthflows are likely to have been important components of the dissection process of the lacustrine sediments. Today, slumped blocks and an extensive area of normal faults and pseudo-karst developed in the lake beds and characterized by both piping and sapping attest to the continuing erosional removal of the valley fill (Fig. 2b). The present Lamayuru stream is incising through the flysch bedrock, a few meters below the bottom of the lake, i.e., the former prelacustrine talweg of the stream.

The palaeoclimatic conditions under which deposition probably occurred can be inferred from the character of the lacustrine deposits. The prevailing climate today in this region is semiarid to arid. The lack of evidence for perennial fluvial activity in the shoreline and marginal delta deposits, the sporadic nature of clastic deposition, and the apparent debris-flow origin of the clastic lenses all suggest a scarcity of water during deposition of the lake beds. The presence of interstratal gypsum crystals (Fig.

5f) appears to indicate at least intermittent evaporitic deposition. Yet, there is no evidence to show that the lake evolved as a closed lake, such as those found in Afghanistan or in Tibet (Müller *et al.*, 1972; Forstner, 1973; Hutchinson, 1937).

Further paleoclimatic evidence can be inferred from the Ostracods that are common constituents of the carbonate sediments. The predominant species of Ostracod (G. Carbonnel, written communication, 1984) is *Candona albicans* Brady or cf. *albicans*, with lesser abundance of *Parastenocypris delormei* Singh and occasional occurrences of *Darwinula stevensoni* Brady and Robertson. The relatively low diversity of Ostracod fauna suggests a limited range of aquatic conditions characterized by coolwater tributaries (Singh, 1974; G. Carbonnel, written communication, 1984). The low abundance of *Darwinula delormei*, despite lacustrine conditions that should have provided a generally favorable habitat for it (Singh, 1977), may be attributable to relatively high concentrations of total dissolved solids (>175 ppm, Delorme, 1964). In sum, although the palaeoclimatic indicators are not definitive, the early to middle last glacial environmental conditions appear to have been cool and semiarid with coldwater streams, perhaps glacially fed and containing high dissolved loads, feeding into the rapidly filling lake.

Comparison of the lacustrine strata at Lamayuru with other lake deposits in the northwestern Himalaya indicates both strong similarities and differences that appear to be primarily a function of climate. For example, when compared with the Karewa lacustrine strata of nearby Kashmir (Bhatt, 1976; Burbank and Johnson, 1983; Singh, 1982), the Gastropod and Ostracod faunas that predominate at Lamayuru are also found in high abundances in the Kashmiri deposits. However, in contrast to the typically oxidized, carbonaterich sediments of Lamayuru, the Karewas are dominated by clastic, blue-gray muds and extensive peat deposits. The Karewa lakes appear to have been fed by vigorous, perennial rivers that carried large detrital loads: they typify the semihumid to humid climate prevailing on this southwestern side of the Himalaya. Although evidence for rich faunal activity is ubiquitous within the Karewas, it was never of sufficient magnitude to overwhelm the large, and apparently persistent, influx of detrital material, except in peat-rich swamps that were effectively isolated from river inputs.

When the Lamayuru strata are compared with other lacustrine deposits found to the north of the main Himalayan crest, many more similarities are seen. Lake beds at Tar, Khaltse and Leh (Bürgisser *et al.*, 1983), and Skardu (Cronin 1982, Bürgisser *et al.*, 1983) in the upper Indus drainage, at the Shyok-Indus confluence (Owen, 1988), and in the Ghunjerab valley in the Karakorum, and at Marpha in the Nepal Himalaya (Fort, 1980) all contain substantial quantities of oxidized, carbonate-rich strata that strongly resemble those at Lamayuru. The relative abundance of clastic sediment in these other localities appears to be a function of their proximity either to glaciers or large rivers. All of these lacustrine strata north of the Himalayan crest exist in a semiarid to arid alpine environment. Such an environment is commonly characterized by "flashy" flows in its rivers and sporadic, high-intensity depositional events. In the quiescent intervals between such events, biologically dominated carbonate deposition is likely to prevail in lakes found in this environment, provided small delta platforms are formed, thus creating adequate biotopes. In a different sedimentological context, such biotopes may also be found associated with travertine-dammed lakes (cf. Band-e-Amir lakes of Afghanistan, Lang and Lucas, 1970).

In sum, the contrasts seen in the sedimentology of Quaternary lakes in adjacent regions of the northwestern Himalaya appear to be modulated largely by strong climatic differences on opposite sides of the range crest.

CONCLUSION

The lacustrine strata at Lamayuru provide an example of late Quaternary sedimentation within a small lake in an arid to semiarid alpine setting. The lake at Lamayuru was created by a large landslide. The lake was certainly in existence by 35,000 yr ago and may have persisted until as recently as 500–1000 yr ago. Further research would help to relate these lake deposits to the late glacial history of the region. The most striking feature of the lacustrine strata is the stark contrast between clastic and biologically dominated strata. Clastic influxes are rapid, brief, and sporadic, and, at Lamayuru, they often appear to represent matrix-poor debris flows of granule- to pebble-sized, periglacial detritus from the steep adjacent slopes. In the frequently extensive intervals between clastic influxes, a diverse, biologically modulated deposition predominates along the margins of the lake. Abundant Charophytes, Gastropods, pellets, and Ostracods produced rather pure, chalky beds. High levels of dissolved carbonate led to the growth of oncoliths and extensive encrustation of the stems of shallow-water plants. The resulting carbonate-rich strata are found throughout the margins of the former lake.

The lacustrine strata found at Lamayuru bear strong resemblances to remnants of former lakes throughout much of the upper Indus drainage and other areas north of the main Himalayan crest where carbonate rocks are abundant. The semiarid to arid climate in the alpine environment appears to favor diverse shallow-water carbonate deposition punctuated by occasional clastic influxes. Such a depositional regime contrasts strongly with that found immediately south of the Himalayan crest where more humid conditions promote a much more continuous clastic influx into intramontane lakes.

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