LOWER CRETAUCEOUS STRATA IN THE LHASA TERRANE, TIBET, WITH IMPLICATIONS FOR UNDERSTANDING THE EARLY TECTONIC HISTORY OF THE TIBETAN PLATEAU

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ABSTRACT: Sedimentary strata in southern Tibet indicate that upper crustal deformation occurred throughout the region during Early Cretaceous time, suggesting that construction of the Tibetan plateau commenced tens of millions of years before the Late Cretaceous–early Tertiary Indo-Asian collision. Lower Cretaceous strata in the northern portion of the Lhasa terrane are characterized by lithic-rich conglomerate beds deposited in shallow marine and meandering-river fluvial environments. Sediments in these units were derived from two primary sources: volcanic rocks associated with Early Cretaceous intrusions, and sedimentary strata eroded from the northern Lhasa and southern Qiangtang terranes. The majority of detrital zircons from Lower Cretaceous fluvial conglomerate beds in northern Lhasa have U–Pb ages between 125 and 140 Ma and provide a maximum depositional age for these units of $125 \pm 2$ Ma. Lower Cretaceous strata in the southern portion of the Lhasa terrane consist of mudstone, quartzose sandstone, and subordinate quartzite-pebble conglomerate beds that were deposited in shallow marine and fluvial environments. Populations of detrital zircons in Lower Cretaceous conglomerate beds in southern Lhasa have U–Pb ages between 140 and 150 Ma, 500 and 600 Ma, and 850 and 950 Ma, and provide a maximum depositional age for these units of $143 \pm 2$ Ma. Both the modal composition and detrital-zircon U–Pb ages of the Lower Cretaceous conglomerate exposed in northern and southern Lhasa suggest different source areas, diachronous deposition, and possibly distinct genetic histories. Throughout most of the Lhasa terrane, the Lower Cretaceous clastic strata are overlain by a widespread limestone of Aptian–Albian age that was deposited in a shallow carbonate sea containing rudist patch reefs and muddy inter-reef zones. With respect to the tectono-sedimentary setting of the Lhasa terrane during Early Cretaceous time, the sedimentological and stratigraphic data are most consistent with a peripheral foreland basin model, which is interpreted to have resulted from the collision between the northern margin of the Lhasa terrane and the southern margin of Asia (the Qiangtang terrane). Several characteristics of the Aptian–Albian succession can be attributed to a peripheral foreland basin setting, although deposition within the region may have been influenced by a combination of mechanisms. Sedimentary characteristics of Lower Cretaceous rocks in the Lhasa terrane are consistent with recent ideas suggesting that portions of southern and central Tibet were deformed and above sea level before the Indo-Asian collision.

INTRODUCTION

In terms of its lithospheric-scale structure, the Tibetan plateau is not a single entity, but rather an amalgamation of individual terranes that accreted onto southern Asia in a series of collisions during Paleozoic and Mesozoic time (Figs. 1, 2; Allègre et al. 1984; Dewey et al. 1988; Sengör and Natal’in 1996; Yin and Harrison 2000). Today, the individual terranes of Tibet are delineated from one another by ~ E-W trending suture zones that are semicontinuous across the entire plateau (Liu 1988). Although recent investigations have suggested that the Paleozoic–Mesozoic amalgamation of the Tibetan plateau was accompanied by crustal deformation in the constituent terranes (Murphy et al. 1997), the nature of this deformation is poorly understood. Determining these pre-Cenozoic events is crucial because the style and extent of deformation that occurred prior to the Indo-Asian collision has direct implications for understanding the timing, location, and extent of deformation that occurred during the Indo-Asian collision (e.g., Kong et al. 1997). In other words, understanding what has happened since the Indo-Asian collision (ca. 55 Ma) is next to impossible without knowing the conditions of the Tibetan plateau before the collision.

The Lhasa terrane is the southernmost terrane of Tibet and extends for over 1000 km in an east to west direction and reaches 300 km from north to south at its widest point. It is bounded on the north by the Bangong suture and on the south by the Indus–Yarlung suture, which separates crust of Asian affinity from that of Greater India (Allègre et al. 1984). The Lhasa terrane rifted from the northern margin of Gondwanaland in Late Carboniferous time (Stampfl and Borel 2004), migrated northward, and eventually collided with the southern margin of Asia during latest Jurassic to Early Cretaceous time (Dewey et al. 1988; Stampfl and Borel 2004). Approximately 100 Myr after the Lhasa terrane accreted onto Asia, India collided with the southern margin of the Lhasa terrane, marking the initiation of the Indo-Asian collision (Yin and Harrison 2000). Before and during its accretion onto southern Asia, the Lhasa terrane was located between two subduction zones (Fig. 2A): one to its north, where it was part of the downgoing plate, and one to the south,
where it was part of the overriding plate (England and Searle 1986; Dewey et al. 1988; Yin and Harrison 2000). The nature of deformation that occurred in the Lhasa terrane during this time period is poorly constrained but important for reconstructing the history of deformation in the Tibetan plateau.

Despite widespread exposures of Lower Cretaceous strata in the Lhasa terrane, little is known of its Early Cretaceous tectono-sedimentary history. From what has been published, two very different hypotheses have been proposed to account for characteristics of the Early Cretaceous sedimentary record (Fig. 2), but because the strata are largely unstudied it has been difficult to evaluate their relative merit. The first hypothesis postulates that the accretion of the Lhasa terrane onto southern Asia resulted in crustal shortening, thickening, and surface uplift along the Bangong suture zone, which ultimately produced a peripheral foreland basin in the Lhasa terrane (Leeder et al. 1988; Murphy et al. 1997). The alternative hypothesis acknowledges that some deformation may have occurred during the accretion of the Lhasa terrane but suggests that it was back-arc extension associated with subduction of Neotethyan lithosphere along the southern margin of Lhasa that controlled the creation and infilling of accommodation during the Early Cretaceous (e.g., Zhang 2000; Zhang et al. 2004).

This paper presents new data on the composition, depositional facies, detrital zircon U–Pb ages, regional relationships, and provenance of Lower Cretaceous strata in the central portion of the Lhasa terrane. This new information allows the paleogeography and regional history of the area to be reconstructed in far greater detail than what was previously possible. The sedimentary and stratigraphic data indicate that Lower Cretaceous sedimentary rocks of the central Lhasa terrane were deposited primarily in marginal marine and coastal-plain environments. Petrographic and detrital-zircon data suggest that the Lower Cretaceous clastic strata in northern and southern Lhasa were derived from different source areas and possibly have different depositional ages. Throughout the study area, an Aptian–Albian shallow marine limestone overlies the Lower Cretaceous clastic strata, indicating widespread marine inundation during this time. With regard to the tectonic setting, the sedimentary and stratigraphic data are most consistent with a peripheral foreland basin.
model, wherein the Late Jurassic–Early Cretaceous suturing of the Lhasa terrane onto southern Asia caused flexural subsidence in the northern portion of the Lhasa terrane. The foreland basin is overprinted by arc volcanism that was associated not with subduction of Neotethyan oceanic lithosphere along the southern margin of the Lhasa terrane. Reconstructions of the region during Aptian–Albian time are more ambiguous, and although several basin models and tectonic settings can explain parts of the depositional record, no single hypothesis can account for all aspects of the strata.

**STUDY AREA**

The study area is located in the central portion of the Lhasa terrane (Kidd et al. 1988) and is broadly divided into northern and southern portions, with the lake Nam Co serving as a general border between the two regions (Fig. 1). Lower Cretaceous strata in both the north and south contain a basal clastic succession and an upper limestone unit (Fig. 3). The clastic sediments at the base of the Lower Cretaceous succession in the south overlie Jurassic limestone, shale, and local beds of volcanic material, whereas to the north, the underlying Jurassic units consist of marine shale and sandstone (Leeder et al. 1988; Yin et al. 1988). Simplifying the stratigraphic nomenclature, the Lower Cretaceous clastic deposits in the north are referred to as the Duba Formation and those in the south are called the Chumulung Formation (Yin et al. 1988). We divide the Duba Formation into informal lower and upper divisions. The clastic rocks of the Duba and Chumulung formations are generally considered to be Lower Cretaceous although some deposition may have taken place during the latest Jurassic (Yin et al. 1988).

Overlying the Duba Formation in the north are limestone beds of the Langshan Formation, and overlying the Chumulung Formation in the south are limestone and marl beds of the Penbo Member of the Takena Formation (Yin et al. 1988). Between northern and southern areas, the limestone at the top of the Lower Cretaceous succession is time transgressive (Fig. 3; Yin et al. 1988; this study). The Penbo Member in the south was deposited during Aptian–Albian time, and the Langshan Formation in the north was deposited from late Barremian to early Cenomanian time (Fig. 3; Smith and Xu 1988; Zhang et al. 2004; Leier 2005). The Penbo Member is roughly 300 m thick, whereas the thickness of the Langshan Formation is poorly constrained and varies between hundreds of meters to > 6 km (cf. Leeder et al. 1988; Zhang 2000). Based on Leeder et al. (1988) and our own observations, we use an ~ 1100 m thickness for the Langshan Formation in the northern half of the Lhasa terrane. The Lower Cretaceous limestone units are overlain by arkosic red beds of the Takena Formation in the southern portion of the study area. In the north, the contact between the limestone and the Upper Cretaceous strata is not exposed.

**LITHOFACIES**

Lithofacies in Lower Cretaceous rocks of the Lhasa terrane are typical of carbonate and coarse-grained clastic rocks, and are well understood in terms of depositional processes. Accordingly, the following section
focuses on the genetic associations of lithofacies that can be more broadly interpreted in terms of depositional systems.

Fine-Grained Heterolithic Lithofacies Association (Northern Study Area)

Description.—The fine-grained heterolithic lithofacies association comprises the lower Duba Formation (Figs. 4, 5) and consists of black laminated and massive mudstone with very thin to thick beds of gray tabular sandstone and minor conglomerate. This lithofacies association is present in the Duba region and in the Lunpola area (Fig. 1). The mudstone contains siltstone laminae and is commonly bioturbated with horizontal to subhorizontal burrows. Sandstone beds are typically 0.15 meters thick but vary from 1 cm to over 1 m, and commonly have sharp to erosional bases and sharp contacts with the overlying mudstone. Unidentifiable bivalve fragments are present in several of the sandstone beds. Thinner sandstone beds tend to be fine to very fine grained and contain oscillatory current ripples and rare unidirectional current ripples. Those beds greater than 5 cm thick are typically fine to medium grained and have plane-parallel laminae and oscillatory current ripples. Locally, thicker beds are structureless and contain granules and pebbles. Individual sandstone beds lack internal gradations in grain size but commonly have fine-grained caps. Vertical, subvertical, and subhorizontal unlined burrows are common in all sandstone beds. A few sandstone beds are moderately eroded by scour surfaces associated with overlying clast-supported pebble conglomerate beds. These conglomerate beds are well organized and contain rounded and well-rounded clasts, some with poorly developed imbrication.

Interpretation.—This lithofacies association is interpreted as deposits of a shallow marine shelf setting (e.g., Walker and Plint 1992; Orton and Reading 1993; Johnson and Baldwin 1996). The laminated mudstone is interpreted to have been deposited in a relatively quiet environment below fair-weather wave base, where fine-grained sediment was able to settle from suspension. Sand- and pebble-size sediments were introduced into the offshore area during high-energy events by storm-induced currents and/or hyperpycnal flows associated with terrestrial rivers (Duke 1990; Orton and Reading 1993; Nemec and Steel 1984). Sandstone beds with abundant oscillatory current ripples indicate that wave base was lowered contemporaneously with deposition of the coarser-grained material (e.g., Johnson and Baldwin 1996). Following the high-energy events, when low-energy conditions returned, mud-size particles were deposited from suspension and organisms burrowed into the deposits. The coarse grain size of some of the sediment suggests proximity to topographic relief (Orton and Reading 1993).

Red Sandstone–Conglomerate Lithofacies Association (Northern Study Area)

Description.—The red sandstone-conglomerate lithofacies association consists of upward-fining sandstone and conglomerate units interstratified with massive and laminated mudstone. This association is best exposed in the Duba area where it is at least 1300 m thick (Fig. 5). Sandstone and conglomerate units are generally between 6 and 10 m thick, have lenticular shapes, and overlie basal scour surfaces (Fig. 6). Laterally along the outcrop, these sequences commonly divide into...
Symbols used in measured sections

<table>
<thead>
<tr>
<th>Sandstone</th>
<th>Mudstone</th>
<th>Limestone</th>
<th>Poorly exposed (mudstone)</th>
</tr>
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<tbody>
<tr>
<td><strong>Cross-stratification</strong></td>
<td></td>
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<tr>
<td>Trough cross-strata</td>
<td>Planar cross-strata</td>
<td>Lateral-accretion sets</td>
<td>Planar bedding/planar lamination</td>
</tr>
<tr>
<td>Unidirectional current ripples</td>
<td>Oscillatory current ripples</td>
<td>Climbing ripples</td>
<td>Mud/silt-draped wave ripples</td>
</tr>
<tr>
<td>Mud-draped current ripples</td>
<td>Wavy bedding</td>
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<td></td>
</tr>
<tr>
<td>Hummocky cross-strata</td>
<td>Pebbles</td>
<td>Imbricated pebbles</td>
<td>Convolute pebbles</td>
</tr>
<tr>
<td>Mud rip-up</td>
<td>Flame/water escape</td>
<td>Bioturbation</td>
<td>Internal scour surface</td>
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<tr>
<td>Root traces</td>
<td>CaCO₃ nodules</td>
<td>Fossilized organic material</td>
<td>Bivalve</td>
</tr>
<tr>
<td>Orbitolinid foraminifera</td>
<td>Echinoid</td>
<td>Rudist</td>
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**Fig. 4.—Symbols used in the stratigraphic sections in Figures 5 and 7.**

Individual sandstone beds that are separated from one another by thin mudstone intervals (Fig. 6). The lower part of a typical sequence consists of a well-organized pebble-conglomerate bed (~2 m thick) with imbricated clasts, crude horizontal stratification, and weakly developed trough cross-stratification. The conglomerate beds occasionally fine upward into very coarse-grained pebbly sandstone with trough cross-stratification. The upper part of the sequence is composed of coarse- to medium-grained trough cross-stratified and horizontally laminated sandstone overlain by medium- to fine-grained sandstone with planeparallel laminae and unidirectional current ripples. In some instances, the cross-stratification is relatively planar and has thicknesses of roughly 1 meter. Internally, sandstone sequences locally contain large-scale cross-bedding (thicknesses > 2 m) consisting of sandstone and siltstone beds that dip orthogonally to the paleocurrent direction (as derived from trough cross-stratification; see below). The uppermost parts of the sandstone and conglomerate sequences are commonly bioturbated or massive and grade into red siltstone and claystone. The mudstone intervals are commonly mottled, and contain CaCO₃ nodules, root traces, vertical burrows, and thin tabular beds of fine-grained sandstone with unidirectional current ripples and climbing ripples (Fig. 6). In the uppermost 100 meters of this lithofacies association, just below the overlying limestone, the proportion of siltstone increases, conglomerate beds are absent, and the sandstone contains marine bivalve fragments (Fig. 5).

**Interpretation.—**This lithofacies association is interpreted as having been deposited by gravelly–sandy meandering rivers (e.g., Levey 1978; Nijman and Puigdefabregas 1978; Miall 1978, 1996). The sandstone and conglomerate sequences are interpreted as fluvial channel deposits, and the mudstone with CaCO₃ nodules and thin tabular sandstone beds are interpreted as sediments deposited in floodplains adjacent to the channels. Regular, repetitive, upward-finings sequences like those in this lithofacies association are most commonly produced by meandering rivers, as are the large-scale cross-beds, which are interpreted as bar-accretion sets (Allen 1964; Puigdefabregas and Van Vilet 1978; Smith, D. 1987; Smith, R., 1987; Miall 1996; Allen 2001). The fact that many of these accretion sets dip orthogonally to the paleocurrent direction provides evidence that the channels were migrating laterally. A few of the accretion sets consist of alternating beds of sandstone and siltstone, similar to inclined-heterolithic strata (IHS), which have been documented in both modern and ancient lower-coastal-plain fluvial deposits (Smith, D. 1987; Choi et al. 2004). Crudely stratified pebble conglomerate was deposited by low-relief bars along channel thalwegs (Hein and Walker 1977), and the overlying trough cross-stratified sandstone beds were deposited by migrating 3-D dunes as the paleochannels filled and migrated laterally. Intervals of massive mudstone that contain CaCO₃ nodules are interpreted as pelecypods that developed in a relatively well drained floodplain environment (Mack et al. 1993; Kraus 1999). Thin, tabular, rippled sandstone within the mudstone intervals are interpreted as crevasse-splay deposits.

**Massive Limestone Lithofacies Association (Northern Study Area)**

**Description.—**Limestone exposed in the northern portion of the Lhasa terrane is classified here as a single lithofacies association in order to interpret the depositional environment at a regional scale, although locally the lithofacies vary. The Langshan Formation in the Duba region (Figs. 1, 5) consists principally of laterally continuous, dark-gray to black orbitolinid wackestone and packstone (Fig. 5). The bulk of the bioclasts are fossils of Mesorbitolina aperta and Mesorbitolina subconcava, but in some beds there are also abundant gastropods (Tylostoma sp. and Acteonella sp.) and bivalve and echinoid fragments (Smith and Xu 1988; R.W. Scott, personal communication). North of Duba, in the Lunpola area (Fig. 1), they are thick-bedded, rudist-dominated, wackestone and packstone which also contain indeterminate bivalve and cnidaria fragments and the calcareous algae Ryncnoporiolum sp. and Cavenia sp. (R.W. Scott, personal communication). Locally, the rudist limestone is interbedded with packstone and grainstone beds composed of ooids,
Fig. 5.—Measured sections of the Lower Cretaceous Duba and Langshan formations in the northern part of the Lhasa terrane. Scale is in meters.
composite ooids, and oncoids. Massive peloidal and orbitolinid mudstone beds are the main lithofacies in the Nam Co area, although this mud-rich lithofacies is present to some extent at all of the locations.

**Interpretation.**—Limestone of this lithofacies association is interpreted as having been deposited within a shallow marine epeiric seaway that was dominated by low-energy lagoonal environments and localized patch reefs (e.g., Enos 1983), similar to the conclusions of Leeder et al. (1988). The common occurrence of peloidal and orbitolinid mudstone and wackestone indicate much of the region was occupied by muddy, low-energy, lagoonal environments (Leeder et al. 1988; Tucker and Wright 1990; Jones and Desrochers 1992). However, localized exposures of rudist-dominated limestone and ooidal packstone and grainstone suggest the former existence of patch reefs where energy levels were higher (Scott 1979; James and Bourque 1992; Wright and Burchette 1996).

**Bioturbated Mudstone–Sandstone Lithofacies Association (Southern Study Area)**

**Description.**—The bioturbated mudstone–sandstone lithofacies association occurs in the Lower Cretaceous Chumulong Formation in the southern half of the study area and is composed of brown, organic-rich claystone and siltstone with subordinate amounts of sandstone (Fig. 6). This lithofacies association is common in many parts of the Chumulong Formation, including the lower half of the succession and in the strata just below the Aptian–Albian limestone (Fig. 6). The mudstone is typically laminated and contains very fine-grained sandstone laminae with oscillatory current ripples; the laminae are often disturbed or destroyed by subhorizontal burrows and vertical to subvertical *Skolithos* burrows. Disarticulated fragments of oysters and unidentifiable bivalves are common in the mudstone intervals. Interbedded with the mudstone are thin- to thick-bedded, very fine to fine grained bioturbated sandstone with oscillatory and unidirectional current ripples, flaser bedding, oyster fragments, and small amounts of fossil wood and fossilized plant debris. Some intervals within this lithofacies association contain repetitive packages, 2–4 m thick, composed of mudstone in their lower parts and one or more ∼ 0.5-m-thick beds of fine-grained, bioturbated sandstone in their upper parts.

**Interpretation.**—Sediments of this lithofacies association are interpreted as having been deposited in a relatively low-energy lagoonal environment in a clastic marginal marine setting (e.g., Kirschbaum 1989). Low-diversity fossil assemblages that are dominated by oysters, small mudstone–sandstone packages, flaser bedding, and fossil plant and wood debris are all common characteristics of lagoonal deposits (Elliott 1974; Ward and Ashley 1989; Kirschbaum 1989).

**Upward-Coarsening Sandstone Lithofacies Association (Southern Study Area)**

**Description.**—The upward-coarsening sandstone lithofacies association is characterized by multiple upward-coarsening sequences of mudstone and sandstone 5–15 m thick (Fig. 6). The lowest part of a typical sequence contains mudstone and thinly bedded very fine-grained sandstone with oscillatory current ripples, occasional plane-parallel lamination, hummocky cross-stratification (HCS), and *Skolithos* burrows. Upward within individual sequences, these heterolithic deposits become progressively more sandstone-rich, eventually giving way to white to buff-colored upward-coarsening sandstone units that are 5–10 meters thick. The lower beds in these sandstone units are very fine- to fine-grained and contain plane-parallel laminae. Overlying these beds are fine- to medium-grained sandstone beds with abundant trough cross-stratification and occasional plane-parallel lamination. Subvertical to subhorizontal burrows are common in the lowermost sandstone but are rare in the upper, trough-cross-stratified beds. The upper surfaces of the sequences are sharp, commonly bioturbated, and overlain by interbedded mudstone, siltstone, and sandstone of the overlying upward-coarsening sequence.

**Interpretation.**—Strata of the upward-coarsening sandstone lithofacies association are interpreted as having been deposited in a wave-dominated shoreface environment that experienced repeated transgressions and regressions. The upward-coarsening sequences are interpreted as shallow marine parasequences that were deposited during shoreline progradation (Van Wagoner et al. 1988; Van Wagoner et al. 1990; Posamentier and Allen 1999). Mudstone in the lower part of the parasequence is interpreted to have been deposited in an offshore transition zone, the overlying mudstone and sandstone with HCS in a lower-shoreface environment, and the trough-cross-stratified sandstone in an upper-shoreface environment (Van Wagoner et al. 1990; Bhattacharya and Walker 1991; Walker and Plint 1992; Johnson and Baldwin 1996). The sharp, bioturbated upper surface of the sequences is interpreted as a transgressive surface that records a depositional hiatus as relative sea-level rose, the shoreline transgressed, and the depositional environment returned to deeper marine conditions (e.g., Van Wagoner et al. 1990; Posamentier and Allen 1999).

**Dark Brown Sandstone–Conglomerate Lithofacies Association (Southern Study Area)**

**Description.**—The dark-brown sandstone–conglomerate lithofacies association consists of interbedded siltstone, sandstone, and conglomerate (Figs. 6, 7). Siltstone intervals are brown and massive and often contain thin beds of very fine- and fine-grained sandstone with unidirectional current ripples and burrows. Organic-rich mudstone is present in the lowermost portion of the Lower Cretaceous succession, where coal layers also have been reported (Yin et al. 1988). Interstratified with the mudstone are thick (> 60 m) sequences of fine- to very coarse-grained sandstone and clast-supported pebble conglomerate (Fig. 7). These sandstone-conglomerate sequences overlie basal scour surfaces and are composed of multistory sandstone-conglomerate packages 2–8 m thick. Individual packages generally contain both conglomerate and sandstone beds, but those composed entirely of pebble conglomerate are common. Typical packages overlie a scour surface, contain lowermost beds of clast-supported, imbricated to crudely stratified, quartzite-pebble conglomerate, and are overlain by sandstone with trough cross-stratification and plane-parallel lamination. The sandstone fines upward within each package, and some contain relatively large (1.5 m) sets of planar, to slightly trough, cross-stratification. Siltstone and very fine-grained sandstone occasionally cap the upper parts of individual packages.

**Interpretation.**—The sediment, lithofacies, and architecture of this lithofacies association are most similar to those of low-sinuosity, sandy–gravely braided rivers (Miall 1978; Cant and Walker 1978; Willis 1993; Miall 1996). The imbricated, well-organized pebble-conglomerate beds are interpreted as deposits of gravely low-relief bars that migrated along channel thalwegs (e.g., Hein and Walker 1977). Trough cross-stratified sandstone was deposited by subaqueous three-dimensional dunes that migrated within the paleochannels. The sandstone with larger and more planar cross-stratification is interpreted as having been deposited by migrating two-dimensional dunes or transverse bars. The plane-parallel-laminated sandstone near the tops of individual packages are interpreted as having been deposited either in infilled channels or on bar tops where
the depth of flow is commonly shallow; local siltstone beds deposited atop the plane-parallel-laminated sandstone are interpreted as having been deposited during the waning stages of flow (e.g., Langford and Bracken 1987; Bristow 1993). The mudstone intervals interstratified among the sandstone sequences are interpreted to have been deposited in interfluvial floodplain environments (e.g., Cant and Walker 1978). The massive nature of the mudstone suggests that these may be paleosols, but no definitive evidence is present.

Cyclical Limestone Lithofacies Association (Southern Study Area)

Description.—In the southern half of the study area, Lower Cretaceous clastic strata of the bioturbated mudstone-sandstone lithofacies association are overlain by bioclast wackestone and packstone of the cyclical limestone lithofacies association (the Penbo Member of the Takena Formation; Fig. 6). The limestone contain orbitolinids (Mesorbitolina sp.), echinoids (Macraster sp., Selina sp.), and rare oysters (Ceratosreon (?) and ammonites (Kazanskyella sp.) (Smith and Xu 1988; R.W. Scott, personal communication). A succession of siltstone with minor sandstone overlies the wackestone, and is in turn overlain by a series of upward-coarsening limestone cycles 3–5 m thick (Figs. 6, 7). These cycles are composed, from bottom to top, of marly siltstone, orbitolinid wackestone (Mesorbitolina texana [Roemer]) and relatively coarse-grained and fossiliferous orbitolinid–oyster packstone, which also contain a subordinate amount of echinoderm debris and ostracodes. The packstone beds at the tops of the cycles contain numerous fossils, have sharp upper surfaces, and are overlain by marly siltstone of the overlying cycle. The limestone in the southern part of the study area eventually grade into siltstone and fine-grained sandstone with marine fossils (Leier 2005).

Interpretation.—Collectively, the cyclical limestone lithofacies association was deposited in a low energy, carbonate-dominated shallow-water marine environment. The carbonate cycles are interpreted as carbonate parasequences that record repeated shoaling and flooding of a shallow marine environment (e.g., Inden and Moore 1983; Jones and Desrochers 1992). The presence of siltstone and local sandstone in this lithofacies association suggests that although this location was dominated by carbonate sedimentation, it was proximal to limited clastic input, possibly associated with a nearby clastic shoreline.

PALEOCURRENT MEASUREMENTS

In order to reconstruct paleocurrent directions, the limbs of trough cross-stratification sets in fluvial sandstone were measured (following method I of DeCelles et al. 1983), as were the strike and dip of imbricated pebble and cobbles clasts in fluvial conglomerate beds.

Trough cross-strata of Lower Cretaceous fluvial sandstone in the northern half of the study area record southwest-directed sediment transport (Fig. 5). Near the exposed base of the Duba Formation, paleocurrents are generally south-southwest directed, whereas trough cross-stratification orientations near the top of the Duba Formation indicate a more west-directed flow (Fig. 5). Accretion sets in some of the fluvial sandstone sequences in the Duba area dip toward the northwest, orthogonal to the mean paleoflow direction, and suggest lateral channel migration. Imbricated clasts in a Lower Cretaceous marine conglomerate exposed in the Lunpolu area record south-southeastward sediment transport.

Paleocurrent data were more difficult to obtain in the southern half of the study area, owing to poorer exposures. Trough cross-stratification and imbricated clasts indicate southward-directed flow in three fluvial sequences, but northward-directed transport is indicated by trough cross-stratification in two fluvial units (Fig. 6). Paleocurrent data obtained from a fluvial sandstone interstratified with Aptian–Albian limestone indicate northwestward-directed sediment transport, which is similar to the paleocurrent data derived from the Upper Cretaceous fluvial sandstone beds that overlie the Lower Cretaceous strata (Leier 2005).
Fig. 8.—Sandstone composition. QmFLt (monocrystalline quartz, feldspar, total lithic grains), QtFL (total quartz, feldspar, lithic grains), and QpLvLaed (polycrystalline quartz, volcanic lithic grains, sedimentary lithic grains) diagrams of Lower Cretaceous sandstone in the Lhasa terrane. See Appendix for parameters and raw data. Circles represent Lower Cretaceous strata in the southern part of the Lhasa terrane, triangles represent sandstone from the northern part. Means of the samples are shown with open symbols and the standard deviations are shown with light gray (strata from northern Lhasa) and dark gray (strata from southern Lhasa). Fields are from Dickinson and Suczek (1979).

PETROGRAPHY

Petrographic thin sections were made from medium- and coarse-grained sandstone samples collected from measured stratigraphic sections. The thin sections were stained for potassium and calcium feldspar and point-counted (450 counts per slide) using a modified Gazzi-Dickinson method (Ingersoll et al. 1984); this modification involves the identification of monocrystalline quartz grains that are part of sedimentary lithic and plutonic fragments (Appendix, see Acknowledgments section for URL of JSR’s Data Archive). In addition, 7 conglomerate clast counts (100 clasts/site) were performed in the field. The petrographic counting parameters and raw data are available in the Appendix.

Northern Study Area

Lower Cretaceous sandstone (n = 13) consists of calcite-cemented litharenites and feldspathic litharenites with Qm:FLt modal compositions of 42:16:42 and Qt:FL of 57:16:27 (Fig. 8). Subangular to subrounded monocrystalline quartz grains are the dominant form of quartz. Feldspar grains constitute 10–20% of the modal composition, the bulk of which is plagioclase. Potassium feldspar is typically minor or absent, although several samples contain 2–5% of the total number of grains. In a few samples, up to 30% of the quartz and feldspar occur not as individual grains but as constituents of feldspatic plagioclase fragments (these are still counted as quartz or feldspar, following the Gazzi-Dickinson method). Lithic fragments are commonly the most abundant grain type in Lower Cretaceous sandstone. Most common are andesitic–dacitic volcanic grains containing microliths of plagioclase feldspar. Sedimentary and metamorphic lithic grains such as mudstone/shale, phyllite, schist, and limestone grains constitute an average of 20% of the modal composition. Some of the sandstone and siltstone lithic grains have minerals and characteristics (e.g., abundant plagioclase and chlorite matrix) that are similar to that of Jurassic sedimentary strata exposed 50 km to the north in the Lumphola area (Leier 2005). Clast counts are consistent with point-counting data in that the majority of the clasts consist of metasedimentary rocks, feldspar volcanic rocks, and granite. Zircon and tourmaline are the most common accessory minerals, but also present are pyroxene (omphacite), and minor amounts of chlorite and serpentine.

Southern Study Area

Unlike the feldspar-rich sandstone exposed in the northern portion of the Lhasa terrane, Lower Cretaceous sandstone (n = 13) in the south are almost entirely quartz arenites and sublitharenites (Qm:FLt 73:0:27 and Qt:FL 92:0:8; Fig. 8). Of the total quartz in the sandstone, the largest component is monocrystalline quartz, although in some samples polycrystalline quartz constitutes up to 15% of the total quartz. Consistent with the petrographic results, the clasts in pebble-conglomerate beds are almost entirely quartzite and vein quartz. No feldspar grains are present in the Lower Cretaceous sandstone in the south, and lithic fragments are rare. The lithic fragments that are present are generally fragments of phyllite and shale. Although sandstone units just below the Aptian–Albian limestone beds are similarly quartzose, they contain a small amount of volcanic material and a slightly higher percentage of sedimentary and metamorphic lithic fragments relative to sandstone lower in the Lower Cretaceous succession. Rare zircon and muscovite are present in a few sandstone samples, but accessory minerals are largely absent.

DETRITAL-ZIRCON GEOCHRONOLOGY

Uranium–lead age data of detrital zircons can provide valuable insight into the provenance and depositional history of sedimentary successions. We collected two samples of Lower Cretaceous sandstone, one from an exposure in the Penbo area in the south and the other from the Duba area in the north, to determine maximum depositional ages, constrain provenance sources, and better characterize the genetic relationship between the Lower Cretaceous strata in northern and southern Lhasa. Raw data from this analysis are included in the Appendix (see Acknowledgments section).

Methods

The two ~ 15 kg samples collected from the Penbo (sample CHMLN) and Duba areas (sample DUBA) were processed for detrital zircon analysis using standard procedures described in Gehrels (2000). Once separated, the detrital zircons were encased in epoxy within 1” ring mounts (1” equals 2.54 cm), which were then sanded and polished to produce a smooth flat surface that exposed the interiors of the zircon grains. One hundred individual zircon grains were analyzed from each sample. These were selected randomly from all sizes and shapes, although grains with obvious cracks or inclusions were avoided.

Uranium–lead ages of detrital zircons were obtained using a laser-ablation, multi-collector, inductively coupled plasma mass spectrometer (LA-MC-ICP-MS). The interiors of the zircon grains were ablated using a New Wave DUV193 Excimer laser operating at a wavelength of 193 nm
and using a spot diameter of 35–50 microns; laser ablation pits are ~ 20 microns deep. With the LA-MC-ICP-MS, the ablated material is carried via argon gas to the plasma source of a Micromass Isoprobe, which is configured in such a way that U and Pb can be measured simultaneously. Measurements are made in static mode using Faraday collectors for \(^{238}\)U, \(^{232}\)Th, \(^{208}\)Pb, \(^{206}\)Pb, and an ion-counting channel for \(^{204}\)Pb. Analyses consist of one 20-second integration with the peak centered but no laser firing (checking background levels), and twenty 1-second integrations with the laser firing on the zircon grain. At the end of each analysis a 30 second delay occurs, during which time the previous sample is purged from the system and peak signal intensity returns to background levels. The contribution of Hg to the \(^{204}\)Pb is accounted for by subtracting the background values. Common-lead corrections are made using the measured \(^{206}\)Pb of the sample and assuming initial Pb compositions from Stacey and Kramers (1975). A fragment of a zircon crystal of known age (564 ± 4 Ma, 2σ error; G.E. Gehrels, unpublished data) is analyzed after every fifth zircon analysis to correct for interelement and Pb isotope fractionation. The ages presented are \(^{206}\)Pb*/\(^{238}\)U ages for grains with ages less than ~ 1000 Ma and \(^{207}\)Pb*/\(^{206}\)Pb* ages for grains with ages greater than 1000 Ma. All uncertainties of individual grains are reported at the 1σ level and include only measurement errors; systematic errors would increase age uncertainties by 1–2%. Those analyses with greater than 10% uncertainty (\(^{206}\)Pb*/\(^{238}\)U ages) or more than 20% discordance or 5% reverse discordance are omitted from further consideration. The data from each sample are displayed on concordia diagrams and age-probability plots/histograms using the programs of Ludwig (2001). Age-probability plots depict each age and its uncertainty as a normal distribution, summing all ages from the analyzed zircons of a sample into one curve, which is then divided by the total number of analyzed zircons. Maximum depositional ages are calculated from the weighted mean of the youngest cluster with three or more overlapping ages; uncertainties reported with the maximum depositional ages include both the measurement and systematic errors.

**Results**

Sample DUBA, from the Lower Cretaceous Duba Formation, yielded 94 usable ages (Fig. 9). Many of the zircons are euhedral and have U/Th values indicative of a plutonic origin, consistent with the composition of the sandstone and conglomerate beds (see above). The youngest cluster of ages has a mean of 125 ± 2 Ma, which provides a maximum depositional age for the Duba Formation. Grains with ages between 120 and 150 Ma are the most numerous (peak at 141 Ma) and represent over 65% of the total population (Fig. 9). The remaining grains are in clusters between 250 and 340 Ma, 610 and 670 Ma, 700 and 900 Ma (peak at 850 Ma), 1000 and 1200 Ma (peak at 1040 Ma), and a few of Early Proterozoic age.

Sample CHMLN from the Lower Cretaceous Chumulon Formation from the southern half of the study area yielded 93 usable ages (Fig. 9). The zircons are typically subhedral to rounded. Unlike the DUBA sample, the CHMLN sample is composed chiefly of zircons of Paleozoic age and older (66 of the 93 grains are > 250 Ma). The maximum depositional age is 143 ± 2 Ma, corresponding to Early Cretaceous time. Zircons in this sample have age groupings of 140–160 Ma, 500–580 Ma (peak at 530 Ma), 620–710 Ma, 850–950 Ma (peak at 900 Ma), 1000–1300 Ma (peak at 1130 Ma), and near 2500 Ma (Fig. 9).

**Regional Interpretations**

The Early Cretaceous paleogeographic evolution of the Lhasa terrane is divided into three general stages (Fig. 10): (1) the Lhasa–Qiangtang collision to mid Neocomian (~ 145 to ~ 130 Ma); (2) mid Neocomian to early Aptian (~ 130 to ~ 120 Ma); and (3) Aptian–Albian (~ 120 to ~ 100 Ma).

**Lhasa–Qiangtang Collision (~ 145 Ma–130 Ma)**

**Northern Lhasa.**—The Early Cretaceous paleogeography of the northern portion of the Lhasa terrane is characterized by coarse-grained shallow marine and coastal environments that were located south of topographic relief (Fig. 10). Interbedded mudstone and sandstone beds with bivalve fragments and oscillatory current ripples suggest relatively shallow marine environments with water depths above wave base. Southward-directed paleocurrents, lithic-rich sandstone units with chlorite, pyroxene, and sedimentary-lithic grains, and Early Cretaceous erosional surfaces in the southern Qiangtang terrane (Kapp et al. 2005b), suggest that sediment composing the Lower Cretaceous strata was, at least in part, derived from the Bangong suture and the southern Qiangtang terrane. Abundant volcanic grains and plagioclase in the Early Cretaceous sandstone units indicate centers of volcanic activity, such as the Bangoin granite belt (Harris et al. 1988), also served as sediment sources. The paleoshoreline trend is inferred to have been approximately E-W to ESE–NNW, parallel to the east–west trending Bangong suture. This inference is derived from the distribution of facies, the lack of Lower Cretaceous marine rocks in the Qiangtang terrane (Liu 1988; Kapp et al. 2005b), and assuming that the shoreline was approximately perpendicular to the paleocurrent directions in the overlying fluvial strata.

**Southern Lhasa.**—During Early Cretaceous time the southern portion of the Lhasa terrane consisted of lagoonal, shoreface, and fluvial depositional environments (Fig. 10). The quartzose composition of the sandstone units and the textural maturity of the individual grains initially appear to suggest a stable tectonic setting; however, the beds of pebble conglomerate and sandstone with sedimentary lithic fragments are interpretive to indicate that much of the Lower Cretaceous sediment in the southern portion of the Lhasa terrane was recycled from quartzose sedimentary cover strata that were exposed in nearby uplifts (Fig. 10). Carboniferous strata of the Lhasa terrane were likely a primary sediment source for the Lower Cretaceous sandstone because: (1) strata of Carboniferous strata are thick and widespread throughout southern Tibet (Yin et al. 1988); (2) Carboniferous strata consist of quartzose sandstone, quartzite, and shale/phylite beds, making them a logical sediment source for the Lower Cretaceous sandstone and conglomerate; (3) detrital zircon age populations > 400 Ma from Lower Cretaceous strata are similar to those in Carboniferous rocks, suggesting sediment recycling (Leier 2005); and (4) at particular localities, Carboniferous rocks are in depositional contact with Carboniferous strata (Liu 1988), indicating that Carboniferous rocks were at the surface during this time.

**Mid Neocomian to Early Aptian (~ 130–120 Ma)**

**Northern Lhasa.**—Southwest-flowing, gravelly, meandering rivers occupied northern Lhasa during mid Neocomian to Aptian time (the upper Duba Formation; Fig. 10). Sandstone composition and conglomerate clasts indicate the sediment was derived from felsic volcanic and igneous rocks, as well as sedimentary and metasedimentary cover strata exposed near the Bangong suture. Numerous pebble and cobble conglomerate beds suggest topographic relief existed in the surrounding areas. The presence of inclined-heterolithic strata and the fact that the fluvial strata are stratigraphically located between marine units suggest a lower coastal plain setting (e.g., Smith, D. 1987).

**Southern Lhasa.**—As in the previous time period, sedimentary strata in the southern part of the Lhasa terrane indicate that the area was occupied by marginal marine, lagoonal, and lower coastal-plain environments during mid Neocomian to Aptian time (Fig. 10). Unlike the underlying
sedimentary units, conglomerate beds are absent within the strata, suggesting more subdued topography or a change in the source area.

**Relationship Between Lower Cretaceous Conglomerate Units—North and South.**—The sedimentary evidence indicates the Lower Cretaceous conglomerate beds of the Chumulong Formation in the south and those of the Duba Formation in the north may have had distinct sedimentary histories. It is difficult to reconcile the disparate compositions of the quartzose Chumulong Formation and the volcanic-rich Duba Formation with one shared provenance. Furthermore, removing Late Cretaceous and Cenozoic shortening of ~50% from the Lhasa terrane (Burg et al. 1983; Pan 1993), the distance between exposures of the pebble conglomerate units in the north and south is roughly 400 km, which is much greater than fluvial gravel fronts are typically thought to extend (e.g., Robinson and Slingerland 1998). Detrital-zircon age populations in conglomerates in northern and southern Lhasa also suggest different depositional ages. The youngest cluster of detrital zircon ages is ~143 Ma in the southern Chumulong Formation conglomerate beds in the south and ~125 Ma in the Duba Formation beds in the north (Fig. 9). Detrital-zircon ages can be used only to infer maximum depositional ages, but the 20 Myr disparity between the two units is significant, particularly because 140–100 Ma igneous rocks are present throughout the Lhasa terrane, where presumably they were acting as sediment sources (Kapp et al. 2005a). Thus, the conglomerate beds of the Chumulong Formation in the southern part of the Lhasa terrane may be millions of years older than the conglomerate beds of the Duba Formation in the northern half of the

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**Fig. 9.**—Detrital-zircon data from sandstone samples collected from the Duba Formation (DUBA) and the Chumulong Formation in the Penbo area (CHMLN). A) Concordia diagram. B) Relative probability plots of all of the detrital zircons. Insets include only the zircons of Mesozoic age. Histogram bins in the probability plots are 50 Ma; 5 Ma for the plots of Mesozoic zircons. See text for full discussion.
Lhasa terrane. Given the limited data set, however, this should be considered only a working hypothesis at this time, and it is quite possible the conglomerate beds in southern Lhasa are younger than the youngest ages of their detrital zircons. Moreover, a population of detrital zircons with ages ca. 140 Ma are present in conglomerate beds in both the northern and southern portion of the Lhasa terrane (Fig. 9), suggesting that some of the sediment in the two stratigraphic units may have been derived from a similar source. We emphasize that before any of this can be resolved more clearly and before the detrital-zircon evidence can be used more effectively, the zircon source areas in the Lhasa terrane will need to be better cataloged.

Aptian–Albian (~ 120–100 Ma)

Northern Lhasa.—The fossil assemblages and geographic distribution of carbonate facies indicate that the northern Lhasa terrane was covered by a shallow sea characterized by rudist patch reefs and muddy inter-reef areas (Fig. 10; e.g., Scott 1979; Leeder et al. 1988). Biostratigraphic
evidence indicates that deposition began in the northern part of the Lhasa terrane before it did in the south (Yin et al. 1988; Zhang 2000; Leier 2005). These environments persisted in the north through earliest Cenomanian time (Yin et al. 1988). Limestone in northern Lhasa is thicker than coeval strata exposed in the southern part of the Lhasa terrane (~ 1100 m in the north versus 300 m in the south), suggesting greater subsidence in northern Lhasa during this time period.

Southern Lhasa.—In Aptian time, shallow marine carbonate deposition replaced the marginal marine clastic environments in southern Lhasa. Although the region was dominated by carbonate deposition, it received an occasional influx of fine-grained clastic material derived from the south. An east–west trending shoreline is inferred to have existed to the south of the Penbo area, mimicking the southern margin of the Lhasa terrane and perpendicular to the north-directed palaeocurrents in interbedded sandstone. By the end of the Albian stage, the marine carbonate environments were replaced by a northward-prograding clastic shoreline and lower coastal plain (Leier et al. 2007).

**DISCUSSION**

The Early Cretaceous history of the Lhasa terrane can be divided into an initial stage from approximately earliest Cretaceous to Aptian time that was dominated by clastic deposition, and a latter stage spanning Aptian and Albian time that corresponds to widespread deposition of marine carbonate sediments. In the following paragraphs we discuss the tectonic setting and basin history of the Lhasa terrane during both of these stages, presenting the various basin models that have been proposed to explain deposition in the region and highlighting data from this and other studies that both support and contradict these hypotheses. Data from Lower Cretaceous strata support the hypothesis that during earliest Cretaceous time a peripheral foreland basin formed in the Lhasa terrane in response to the collision between the Lhasa and Qiangtang terranes. The data from Aptian–Albian strata are more ambiguous. Although several aspects of the Aptian–Albian succession can be attributed to a peripheral foreland basin setting, there are some aspects that cannot, suggesting that deposition in the region may have been influenced by a combination of mechanisms.

**Initial Stage—Earliest Cretaceous**

Structural and stratigraphic evidence indicates that the lowermost Cretaceous strata (earliest Cretaceous–Aptian age) in the Lhasa terrane were deposited in a peripheral foreland basin system. The Lhasa terrane collided with the southern margin of the Qiangtang terrane during Late Jurassic–Early Cretaceous time (Dewey et al. 1988), providing a tectonic setting conducive to the formation of a fold-thrust belt and a peripheral foreland basin (Leeder et al. 1988; Dickinson 1974). Structural data indicate that Early Cretaceous crustal thickening and rock uplift occurred in the northern margin of the Lhasa terrane as a south-verging fold-thrust belt developed in response to the Lhasa–Qiangtang collision (Murphy et al. 1997; Kapp et al. in press). Stratigraphic relationships indicate that the Qiangtang terrane was above sea level and being eroded by at least middle Cretaceous time (Fig. 10; Kapp et al. 2005b). The collision-related deformation is inferred to have provided a sediment source and created a crustal load on the northern part of the Lhasa terrane, which ultimately produced subsidence and created the peripheral foreland basin (Leeder et al. 1988; Murphy et al. 1997; Zhang et al. 2004). The sedimentary and stratigraphic data presented in this study and the derivative palaeogeographic reconstructions support the peripheral foreland basin model. For example, Lower Cretaceous sedimentary strata thicken to the north, suggesting that subsidence and/or sediment supply was greatest in this area (Fig. 10). Similar to the stratigraphic successions in many peripheral foreland basins, the depositional facies in the Upper Jurassic–Lower Cretaceous strata in northern Lhasa progress from fine-grained deepwater deposits at the base to coarse-grained nonmarine deposits near the top (Miall 1995). Paleocurrent data and sedimentary grains in Lower Cretaceous nonmarine strata indicate that sediment was derived from a northern source area near the Bangong suture and transported to the south-southwest, which is consistent with the hypothesis that a foreland basin formed in the Lhasa terrane in response to the collision between the Lhasa and Qiangtang terranes. The abundance of volcanic grains in the Lower Cretaceous clastic strata is atypical of collisional foreland basins but can be explained by arc activity associated with coeval subduction of oceanic crust beneath the southern margin of the Lhasa terrane (e.g., Coulon et al. 1986; Kapp et al. 2005b). The tectonic setting along the southern margin of the Lhasa terrane during this time period is less clear. Evidence indicates that subduction of Neotethyan oceanic crust had commenced by this time (Chu et al. 2006), and stratigraphic data (e.g., conglomerate beds) suggest that there may have been localized uplifts in the region. From latest Jurassic through the rest of Early Cretaceous time, volcanic activity migrated northward in response to shallowing of the subduction angle of the downgoing Neotethyan slab (Coulon et al. 1986; Kapp et al. 2005b).

**Second Stage—Aptian–Albian**

Several mechanisms can be invoked to explain the change from clastic nonmarine and shallow marine deposits associated with the earliest part of Cretaceous time to the extensive shallow marine carbonate strata of Aptian–Albian age (Fig. 10). A eustatic rise in sea level provides a simple way to explain widespread deposition of shallow marine carbonate within the Lhasa terrane; however, a rise in sea-level alone fails to account for the south-to-north increase in thickness of limestone strata in the Lhasa terrane, nor can it account for the thickness of these strata (assuming Airy isostasy, and accounting for > 1 km of carbonate strata). Northward subduction of Neotethyan oceanic lithosphere beneath the Lhasa terrane during this time could have resulted in dynamic effects in the overlying terrane, thereby providing accommodation for sediment accumulation (e.g., Gurnis 1992; Burgess and Moresi 1999). This model, however, predicts that the carbonate strata should increase in thickness from north-to-south instead of the south-to-north thickening trend observed. An additional possibility is that a crustal load developed along the southern margin of the Lhasa terrane as deformation in the Gangdese retroarc fold-thrust belt commenced (Leier et al. 2007). Although this may have influenced sedimentation and subsidence patterns in particular locations, the amount of Aptian–Albian subsidence in southern Lhasa was minor (strata are < 300 m thick in the south) and spatially removed from northern Lhasa (400–600 km), implying that the subsidence required for deposition of > 1 km of carbonate strata in northern Lhasa must have been derived from an alternative mechanism. Whereas evidence conclusively supporting any of the aforementioned processes is lacking, it remains possible that one or a combination of these processes influenced subsidence and sedimentation in the Lhasa terrane during Aptian–Albian time.

Normal faulting related to extensional forces is an appealing mechanism to explain the depositional patterns of Aptian–Albian strata (Zhang et al. 2004), and although this postulation is consistent with some of the stratigraphic data, there are many aspects of the stratigraphy that contradict this hypothesis. The vertical trend in depositional facies in the Lower Cretaceous succession, from coarse-grained fluvial strata (the Duba Formation) to shallow marine carbonate rocks (the Langshang Formation) is similar to that present in other extensional basins (e.g., Dickinson and Lawton 2001). However, this model is predicated on the supposition that the coarse-grained fluvial strata of the Duba Formation represent the base of a genetic succession. On the contrary, the
stratigraphic and sedimentary data presented in this and other studies (Leeder et al. 1988; Yin et al. 1988) indicate the coarse-grained fluvial deposits do not represent the base of a new succession but rather the uppermost part of a large-scale coarsening-and shallow-upward succession that begins with Upper Jurassic rocks (Figs. 3, 10). Thickness changes in age-equivalent Lower Cretaceous units have been used to argue for basin segmentation and normal faulting (Zhang et al. 2004), although such stratigraphic trends can also be explained by basin segmentation caused by thrust faults. Perhaps the most significant obstacle to the extensional basin model is the fact that structural relationships record regional contraction during Early Cretaceous time (Murphy et al. 1997; Kapp et al. in press). Small normal faults (< 1 m displacement) have been documented at one or two locations in strata of Aptian–Albian age (Zhang et al. 2004), but these occur on the scale of a single bed and distinguishing these features from localized tectonic synsedimentary deformation is required before they can be extrapolated to infer a regionally pervasive extensional stress field. It should be noted that the extensional basin model developed by Zhang et al. (2004) was derived from the study of Cretaceous strata exposed to the west of our study area, and it is plausible the Early Cretaceous tectonic settings in the two regions differed.

Whereas subsidence histories are typically helpful in identifying basin-forming mechanisms, the thicknesses and ages of the Upper Jurassic through Late Cretaceous strata in the Lhasa terrane are so poorly constrained that little substantive information is revealed from such analyses. Thickness estimates of Upper Jurassic strata in the northern portion of the Lhasa terrane vary from hundreds of meters to > 4 km, and thicknesses of Aptian–Albian limestone vary from hundreds of meters to > 6 km (cf. Leeder et al. 1988; Zang 2000). Given such a wide range of thicknesses, it is possible to derive subsidence histories that display both convex-upward and convex-downward profiles. Subsidence histories were reconstructed from the limited amount of data from this and other studies, but the results yielded a constant subsidence rate throughout the Cretaceous (see Appendix, URL in Acknowledgments section) and therefore cannot be used to support or refute any particular basin model.

Based on structural and stratigraphic data, we propose that the peripheral foreland basin hypothesized to have existed in the Lhasa terrane during earliest Cretaceous time (Leeder et al. 1988; Murphy et al. 1997; Zhang et al. 2004; this study) continued to influence deposition in the region during Aptian–Albian time. Folding and thrusting continued to occur in the northern margin of the Lhasa terrane during Aptian–Albian time (Kapp et al. in press); thus it is reasonable to assume the persistence of a crustal load in this region. This is supported by stratigraphic data showing a south-to-north thickening of strata of Aptian–Albian age. Although carbonate rocks are not typically associated with foreland basins, these deposits do occur in such settings and have been documented in several ancient foreland-basin sequences (e.g., Dorobek 1995; Allen and Allen 1990; Pigram et al. 1989). The presence of widespread carbonate deposits suggests that the relative influx of clastic material to the Lhasa terrane decreased during Aptian–Albian time, but the reasons for this decrease (e.g., climate change, decreased relief, etc.) are not known at this time.

Not every aspect of the Aptian–Albian depositional record can be explained by a peripheral foreland basin model alone. As mentioned above, the Early Cretaceous subsidence history in the area lacks the convex-upward pattern characteristic of foreland-basin systems (Angevine et al. 1990). Furthermore, marine limestone beds were deposited along the southern margin of the Lhasa terrane in locations 400–600 km distant from the hypothesized crustal load (once post-mid-Cretaceous shortening is removed), which is beyond the distances normally impacted by the flexural response of continental lithosphere (e.g., Allen and Allen 1990). Aptian–Albian deposition was likely influenced by a combination of several mechanisms, such as crustal loading along the southern margin of the terrane or dynamic topography, operating in conjunction with foreland basin subsidence. The specific factors and the relative role they may have played in influencing Aptian–Albian deposition are unclear, and more data are needed before the complete depositional and tectonic history of the region can be understood.

SUMMARY AND CONCLUSIONS

Lower Cretaceous sedimentary strata of the Lhasa terrane were deposited in marginal marine and coastal-plain environments. In the southern part of the Lhasa terrane, Lower Cretaceous rocks consist chiefly of shoreface and lagoonal strata with minor braided-stream deposits. Lower Cretaceous strata in the northern portion of the Lhasa terrane are characterized by lithic-rich conglomerate beds deposited in shallow marine and meandering-river fluvial environments. The maximum depositional age of conglomerate in southern Lhasa is 143 ± 2 Ma, whereas those in the north have a maximum age of 125 ± 2 Ma. All of the Lower Cretaceous clastic strata are overlain by a widespread Aptian–Albian limestone that was deposited in a shallow marine seaway that occupied the Lhasa terrane for ~ 20 Myr.

Sedimentary, stratigraphic, and structural data suggest that a latest Jurassic–Early Cretaceous peripheral foreland basin formed in the Lhasa terrane in response to the collision between the Lhasa and Qiangtang terranes. This peripheral foreland basin was the principal influence on sedimentation throughout most of Early Cretaceous time. Aspects of the Aptian–Albian carbonate deposits can be attributed to a peripheral foreland basin setting, although particular characteristics of these strata, such as their widespread spatial distribution, suggest that deposition in the region may have been influenced by a combination of mechanisms during this time. Lower Cretaceous deposits in the Lhasa terrane indicate that southern Tibet was tectonically active long before the Indo-Asian collision.

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