Geochemical Evaluation of Fenghuoshan Group Lacustrine Carbonates, North-Central Tibet: Implications for the Paleoaltimetry of the Eocene Tibetan Plateau

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ABSTRACT

A sedimentologic, petrologic, and geochemical evaluation of lacustrine carbonates from the Eocene-Oligocene Fenghuoshan Group of north-central Tibet provides insight into the paleoenvironmental and paleolimnological setting of the Hoh Xil basin during the mid-Tertiary. Fenghuoshan lacustrine rocks consist primarily of carbonate mudstones and wackestones. These carbonates are generally less than 3 m in thickness and are intercalated with siliciclastic lacustrine and fluvial/alluvial plain deposits. Individual limestone beds coarsen and contain increasing amounts of siliciclastic material upward. Fenghuoshan carbonates also contain abundant ostracode, bivalve, and charaphyte fossils. Sedimentologic evidence suggests that carbonate deposition occurred in shallow, relatively short-lived lacustrine systems that were subsequently filled by alluvial deposits of coeval fluvial systems. Stable C and O isotopic analysis of Fenghuoshan carbonates show $\delta^{18}O$ values ranging from −11.7‰ to −10.3‰ (Vienna Pee Dee Belemnite [VPDB]) and $\delta^{13}C$ values between −7.1‰ and −2.2‰ (VPDB). The lack of correlation between the two isotopic systems supports the sedimentological interpretation of a shallow, hydrologically open lacustrine setting during the time of carbonate deposition. This interpretation is reinforced by the mineralogy and Mg/Ca molar ratios from Fenghuoshan lacustrine carbonates that indicate fresh water conditions. In addition, petrographic analysis and the $\delta^{18}O$ composition of samples suggest that Fenghuoshan lacustrine rocks have not undergone significant diagenetic alteration. Collectively, these data indicate that the isotopic composition of Fenghuoshan Group carbonates may be used to infer the oxygen isotopic composition of meteoric water feeding these lacustrine basins at the time of deposition, from which we derive estimates of the paleoaltimetry of north-central Tibet during Middle Eocene time. Model results using the isotopic data from Fenghuoshan carbonates indicate that the hypsometric mean elevation of the drainage basins feeding Hoh Xil lakes was ≲2 km. Together with estimates of the Eocene paleoaltimetry from the Lunpola basin to the south, these results provide the first direct evidence for the differential uplift of the northern margin of the Tibetan Plateau.

Introduction

Determining the paleoaltimetry of regions of high topography is a growing area of research (e.g., Drummond et al. 1993*b*; Sahagian and Maus 1994; Chamberlain et al. 1999; Chamberlain and Poage 2000; Dettman and Lohmann 2000; Garzione et al. 2000*b*; Rowley et al. 2001; Fricke 2003). Paleoaltimetric studies can aid in deciphering dynamic Earth problems such as the timing, relief, and uplift rates of mountain belts (Dettman and Lohmann 2000; Garzione et al. 2000*a*; Rowley et al. 2001), mantle dynamics (England and Houseman 1986), and global atmospheric circulation and precipitation patterns (Rind et al. 1997). Methods to determine paleoaltitude include the use of fossil leaf physiognomy (Forest et al. 1999; Spicer et al. 2003), vesicle size and distribution in basalt flows (e.g., Sahagian and Maus 1994), and the oxygen isotopic composition of authigenic minerals. The use of oxygen isotopes from lacustrine carbonates, in particular, has been applied to paleoaltimetric problems by putting quantitative bounds on the timing of development of orography in the Himalaya and the Tibetan Plateau (Garzione et al. 2000*a*; Rowley et al. 2001; Currie et al. 2005).

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Lacustrine carbonates have been used in isotope-based paleoelevation models because of their potential to record the stable isotopic composition of the waters from which they precipitate (e.g., Oana and Deevey 1960; Stuvier 1970; Rothe et al. 1974; Anadón and Utrilla 1993; Drummond et al. 1995). While numerous empirical studies have determined that authigenic lacustrine carbonates precipitate in isotopic equilibrium with lake water (Turner et al. 1983; McKenzie 1985; Fritz et al. 1987; Gasse and Fontes 1987; Talbot 1990; Drummond et al. 1996), there can be dramatic shifts of the isotopic composition of lake water relative to the precipitation feeding a given lacustrine system. The oxygen isotopic composition of lake water with respect to regional meteoric water is primarily controlled by the hydrology of a particular lacustrine system (Kelts and Talbot 1989). Factors such as ground- and surface-water flux, precipitation-evaporation balance, and water residence time can all cause the oxygen isotopic composition of lake water to diverge from regional meteoric water values. This divergence is commonly manifested as an increase in lake water $\delta^{18}O$ values relative to original meteoric compositions (Kelts and Talbot 1989; Talbot 1990; Talbot and Kelts 1990). Therefore, paleoaltimetric models using water compositions derived from the isotopic composition of lacustrine carbonates will generally predict elevations that are less than or equal to the mean elevation of a given drainage basin (Rowley et al. 2001). Diagenetic alteration of carbonate can also result in changes in oxygen isotope composition. Both low- and high-temperature diagenesis of primary calcite to dolomite can result in changes from original $\delta^{18}O$ values (Matthews and Katz 1977; Drummond et al. 1993*a*; Garzione et al. 2004) that could potentially cause errors in paleoelevation estimates.

Based on past studies of the hydrology and carbonate mineralogy of both modern and ancient lake systems, it is possible to assess the relative effects of evaporative enrichment on the isotopic composition of ancient lacustrine carbonate as well as the degree and type of diagenetic alteration through mineralogic, petrographic, and geochemical analyses (Rothe et al. 1974; Kelts and Hsu 1978; Bein 1986; Suchecki et al. 1988; Kelts and Talbot 1989; Talbot and Kelts 1990; Mason and Surdam 1992; Talbot 1994; Fontes et al. 1996; Utrilla et al. 1998; Anadón et al. 2000; Dutkiewicz et al. 2000; Reinhardt and Ricken 2000; Poulson and John 2003). From these types of analyses, more accurate estimates of ancient meteoric water composition can be made that can then be used in stable isotope-based models of paleoaltimetry.

This article presents a geochemical evaluation of lacustrine carbonates from the Fenghuoshan Group of southern Qinghai Province, China, in order to determine their potential use as a proxy for the isotopic composition of Eocene meteoric water in north-central Tibet. Based on the mineralogy, O and C isotopic composition, and Mg/Ca molar ratios of Fenghuoshan lacustrine deposits, estimates of the oxygen isotopic composition of paleometeoric water will be used as input in the model of Rowley et al. (2001) to calculate the Eocene paleoaltimetry of the northern Tibetan Plateau. These rocks are important in that their depositional age (~39–36 Ma) corresponds with the early stages of India-Asia collision (beginning at ~50 Ma; Garzanti et al. 1996; Zhu et al. 2005). Therefore, model calculations of regional paleoelevation based on Fenghuoshan carbonate oxygen isotopic compositions can provide an estimate of the elevation of the northern Tibetan Plateau during the onset of Himalayan orogenesis.

Geological Setting

The lacustrine rocks analyzed in this study were sampled from outcrops of the Fenghuoshan Group located near the village of Erdaogou in southwestern Qinghai Province, China (fig. 1). The study area is currently situated in the north-central part of the Tibetan Plateau at elevations ranging from 4700 to 5300 m. The Fenghuoshan Group was deposited in the Hoh Xil basin during Paleocene-Oligocene time in response to flexural subsidence (Liu and Wang 2001; Liu et al. 2001) associated with northward-propagating thrust systems. To the south, the initial collision of India and Asia resulted in the closure of the eastern Neotethyan Sea, while farther west, branches of the Neotethys occupied parts of the present-day Tarim, Fergana, and Caspian depressions (Vinogradov 1967; Wang 1985). Discrepancies between global and local estimates of paleolatitude during Fenghuoshan Group deposition make it difficult to determine the paleolatitude of the Hoh Xil basin except to indicate that there is consensus that it was situated at <35°N latitude (Liu et al. 2003).

In the study area, the Fenghuoshan Group is >4 km thick and consists of both fluvial and lacustrine lithologies (Leeder et al. 1988; Liu and Wang 2001) exposed in an imbricate thrust sequence (Coward et al. 1988). The focus of our investigation is Unit 3 of the Fenghuoshan Group (as defined by Liu and Wang [2001]), which consists of ~1400 m of interbedded mudstone, sandstone, conglomerate, and

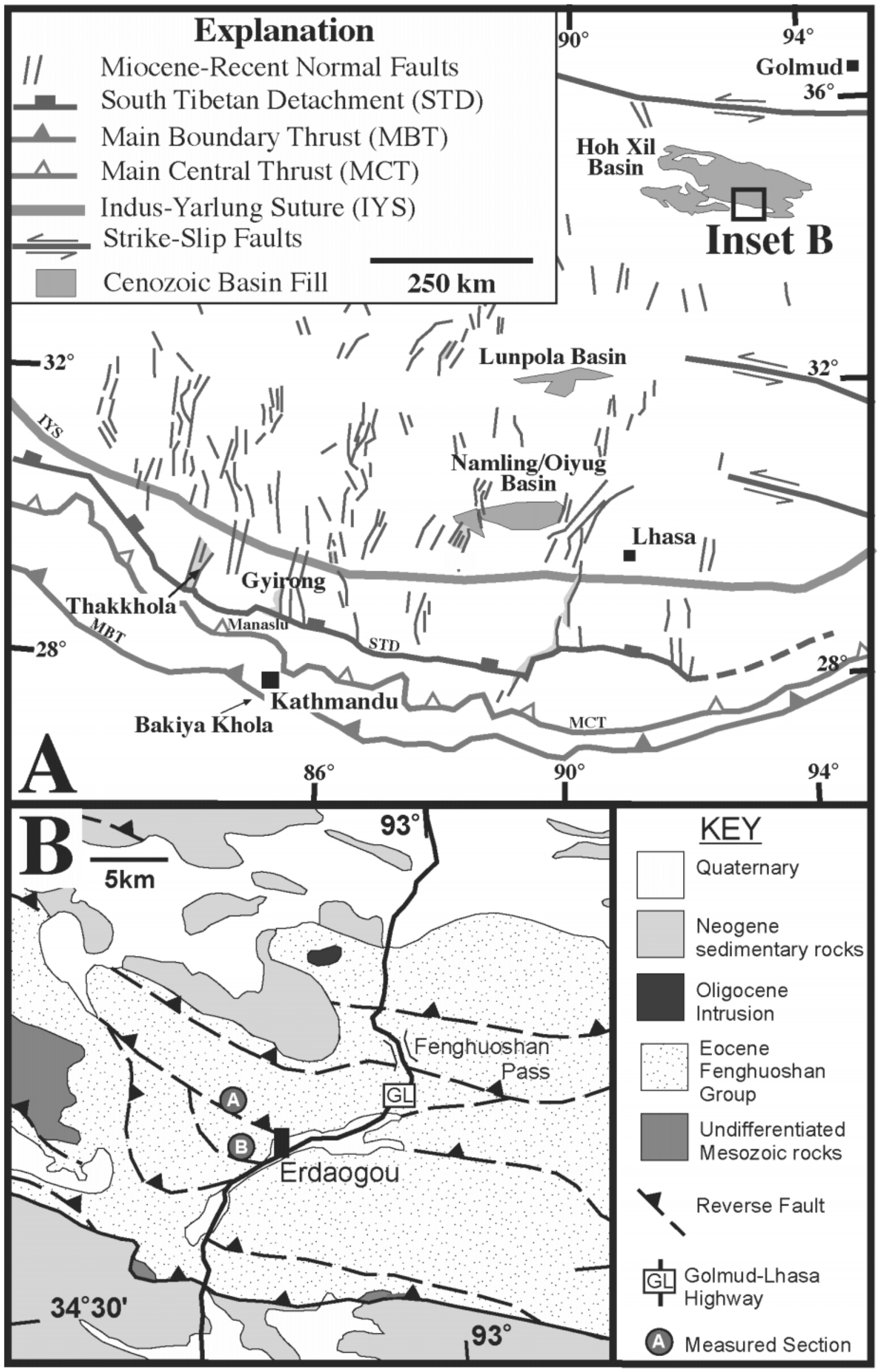

Figure 1. *A*, Generalized tectonic map of central Tibet and the eastern Himalaya. Map also shows location of Cenozoic basins and localities referred to in text, including the Hoh Xil basin. Modified from Dewey et al. (1988). *B*, Simplified geologic map of the study area near the village of Erdagou, showing location of measured stratigraphic sections displayed in figure 2. Modified from Kidd et al. (1988).

limestone. Magnetostratigraphic correlations, together with fossil charaphytes and ostracodes, indicate that Unit 3 was deposited during Middle–Late Eocene time (chrons 18–16; Liu et al. 2001, 2003). This corresponds to the time interval of ~40–35 Ma using the timescale of Gradstein et al. (1995). The depositional age is further constrained by Oligocene-aged (28.6 ± 0.3 Ma) syenitic igneous rocks that intrude Fenghuoshan Group strata ~15 km north of Erdaogou (D. B. Rowley, unpub. data).

Sedimentology

Description. As part of our study, two stratigraphic sections were measured through the limestone-bearing interval in the middle part of Fenghuoshan Group Unit 3 (fig. 2). Both sections consist of an overall upward-fining sequence of siliciclastic mudstones, sandstones, and limestones. In general, the thickness of the stratigraphic interval containing limestones, as well as the thickness of individual limestone beds, increases from north to south. The middle part of Unit 3 is dominated by reddish-brown to gray, structureless, sandy mudstone. Individual mudstone beds range in thickness from 10 cm to >2 m. In the measured sections, some mudstone horizons contain abundant root traces, zones of illuviated clay, and rare nodular carbonate horizons.

Associated with the red and gray mudstones in the upper part of the unit are gray limestone beds.

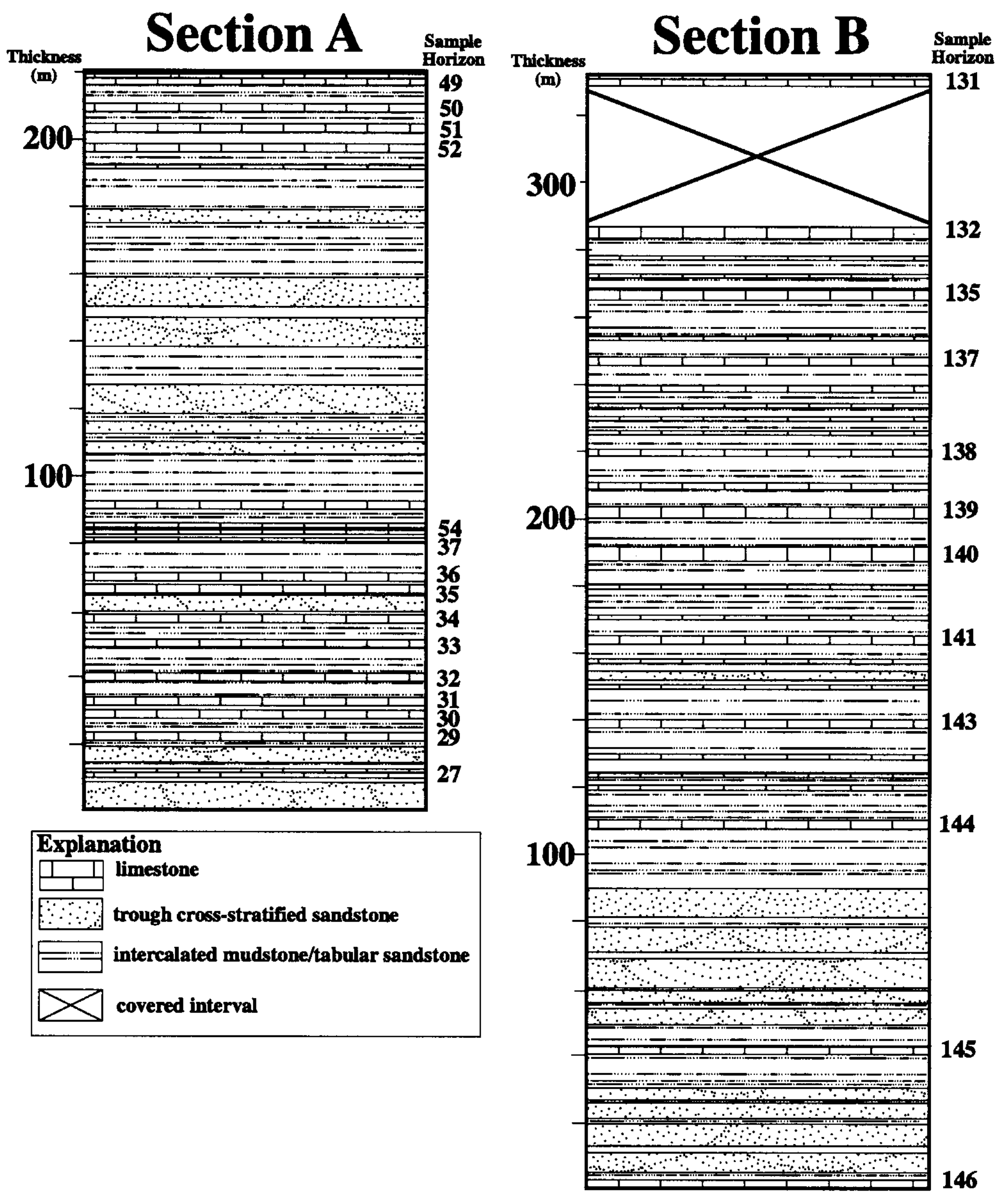

Figure 2. Generalized logs of measured stratigraphic sections of Fenghuoshan Group Unit 3 near the village of Erdaogou. Individual carbonate beds sampled for this study are listed to the right of each column. See figure 1 for section locations.

Unit 3 limestones exist as thin, isolated beds <20 cm thick or upward-coarsening packages up to 2 m in thickness. Thin, isolated beds consist of brecciated to nodular lime mudstone and wackestone that commonly contains root traces. These limestones are interbedded with red/gray siliciclastic mudstone, siltstone, and fine-grained sandstone that also contain root traces.

Thicker limestones commonly consist of overall upward-coarsening packages <2.0 m thick. Internally, these beds consist of basal nodular and brecciated mudstones and wackestones that are overlain by weakly laminated to structureless mudstones and wackestones and capped by sandy to silty, structureless to plane-parallel and ripple cross-laminated sandy grainstones comprised of intraclasts and shell fragments. In most cases, the upward-coarsening carbonate lithologies are accompanied by an upsection increase in detrital silt and sand and are overlain by nodular to brecciated wackestones containing millimeter- to centimeter-scale root traces. Tabular beds of structureless to rooted sandstone, siltstone, and mudstone, however, overlie most limestone intervals.

Petrographic analyses show that Fenghuoshan Group limestones are dominantly mudstones and wackestones (Cyr 2004). Allochems found throughout the suite include *Chara* gyrogonites and stem fragments, ostracode valves, and both gastropod and bivalve shells (fig. 3). Most ostracode valves display sweeping extinction under cross-polarized light. Although most limestones contain some microcrystalline recrystallization of original micritic material, the observed alteration is not pervasive throughout any given sample (fig. 3*B*). Some thin sections also display sparry-calcite infilling of shell interstices, primary-pore space, and microfractures. The total spar content of any given sample, however, is <5% (Cyr 2004).

Abundant tabular, upward-fining, medium- to fine-grained sandstone beds <30 cm thick are also interbedded with mudstones in the studied stratigraphic interval. These sandstones have erosive bases and commonly contain plane-parallel and ripple cross laminations, root traces, and both vertical and horizontal burrows. Bedding plane surfaces commonly contain symmetrical or asymmetrical ripples and primary-current lineations.

The middle part of Unit 3 also contains several upward-fining, sheetlike sandstone bodies up to 8 m in thickness. Internally, these bodies consist of coalesced, broadly lenticular beds of coarse- to fine-grained sandstone 0.5–2 m thick. Individual lenses have erosive bases and internally contain trough

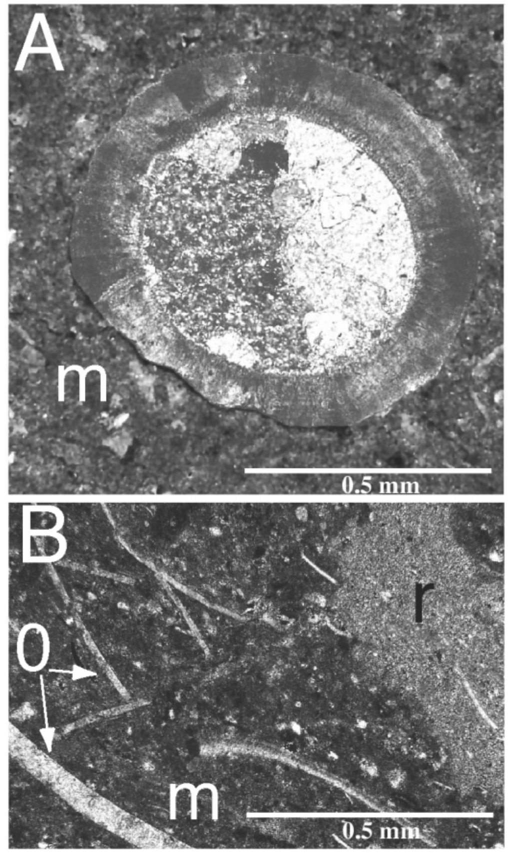

Figure 3. Photomicrographs of Fenghuoshan Group carbonates. *A*, Spar-filled charaphyte gyrogonite displaying radial and concentric microstructures produced during cellular calcification (cf. Leitch 1990). Microstructure preservation argues against pervasive microrecrystallization of carbonate sample. Sample 141, cross-polarized light. *B*, Ostracode valve fragments (*O*) and both primary (*m*) and recrystallized (*r*) micrite. Sample 032, cross-polarized light.

cross stratification and ripple cross lamination that indicate sediment transport to the northeast.

Interpretation. The studied Fenghuoshan Group stratigraphic intervals are interpreted as fluvial channel, alluvial plain, palustrine, and lacustrine deposits. Sheetlike sandstone bodies are interpreted as the deposits of low-sinuosity, braided fluvial channels (e.g., Friend et al. 1979). Mudstones with root traces are interpreted as floodplain or lacustrine mudflat deposits (Stollhofen et al. 2000), while those containing zones of illuviated clay and carbonate nodules are interpreted as calcic paleosols (Mack et al. 1993). Tabular, upward-fining, cross-laminated sandstones containing root traces and burrows are interpreted as having been deposited during unconfined overbank sedimentation on floodplains (i.e., crevasse splays) or during sheet flood events in marginal lacustrine settings. Symmetrically rippled tops to some of these beds suggest deposition in standing water (Bohacs et al. 2000).

Limestone beds in the middle part of Unit 3 are interpreted as shallow lacustrine and palustrine deposits. Thin, brecciated/nodular limestone beds with root traces are interpreted as being deposited in palustrine environments along the margins of larger lacustrine systems or in shallow floodplain ponds (Platt and Wright 1991; Cavinato and Miccadei 2000). Upward-coarsening limestones were deposited during fluctuations in lake level. Thin, basal, nodular to brecciated mudstones represent lake margin carbonates deposited during initial stages of lake level rise (Tucker and Wright 1990). Overlying horizontally laminated to structureless limestones are interpreted as having been deposited below the influence of surface waves. Plane-parallel and ripple cross-laminated beds were deposited in littoral environments. Nodular to brecciated limestone capping the shallowing upward sequence represents a return to marginal lacustrine environments (Tucker and Wright 1990). Interbedded fluvial and alluvial deposits suggest progradational or lateral infilling of lacustrine basins.

The interpreted depositional environments suggest deposition in an integrated fluvial-lacustrine system. Lakes were generally shallow and probably of small areal extent but large enough to generate surface waves capable of producing the laminated grainstones. Open lacustrine environments were surrounded by palustrine or mudflat depositional systems, suggesting potential fluctuations in lake level. The lacustrine lithofacies assemblages indicate deposition in a low-energy ramp-type setting (Platt and Wright 1991). The predominance of bioclastic and bioturbated micrite suggests oxygenated bottom waters. Abundant macrofaunal remains, as well as the lack of oolitic grains and evaporite minerals or remnant evaporite features, imply that lake waters had relatively low salinities (Kelts and Hsu 1978). The presence of abundant *Chara* fragments in most samples indicates that micrite precipitation may have been driven by aquatic macrophyte photosynthesis or extracellular calcification (Dean 1981; McConnaughey 1991). Petrographic evidence suggests that Fenghuoshan carbonates have undergone little diagenetic alteration, as there is no evidence for pervasive shell or micrite recrystallization (fig. 3).

Mineralogy and Geochemistry

In order to evaluate the potential use of the Fenghuoshan Group lacustrine carbonates as proxies for the isotopic composition of paleometeoric waters, mineralogical and geochemical evaluations were conducted on primary micrite, allochems, and sparry calcite from 39 carbonate mudstone/wackestone samples from the study area. Powder X-ray diffraction (XRD) analysis was used to determine carbonate mineralogy and magnesium content of bulk carbonate. Evaluation of carbonate $\delta^{18}O$ and $\delta^{13}C$ compositions allowed assessment of the lacustrine basin hydrology and precipitation-evaporation balance during the time of deposition. Ca and Mg concentrations calculated from XRD results were compared to Ca and Mg concentrations as determined from direct-current plasma emission spectrometry (DCP) in order to provide an independent evaluation of XRD observations as well as to allow further examination of the possible effects of diagenesis on carbonate $\delta^{18}O$ compositions.

Analytical Methods. *Mineralogy*. The mineralogic composition of Fenghuoshan Group limestones was determined by XRD, using Cu$K\alpha$ radiation, on a Sintag powder diffractometer at Miami University. Samples for XRD analysis were obtained from thin-section billets or from polished slabs using a small chisel and powdered using a mortar and pestle. Molar % Mg was determined by measuring the relative positions of the [104] and [101] peak reflections of carbonate species and quartz, respectively; the latter being taken as a standard (Goldsmith et al. 1955). Relative percentage of carbonate species was calculated by the ratio of the integrated peak intensity of the calcite and dolomite [104] peaks.

Stable Isotope Geochemistry. Samples for isotopic analysis were obtained using a microdrill (100-μm-diameter bit) on thin-section billets to directly determine sampled material. Isotopic data from powdered samples were collected on a gas source mass spectrometer at Harvard University. Approximately 2 mg of bulk sample was loaded into a stainless steel vial and dried in an oven at 50°C for 48 h. Samples were dissolved on line in a common acid bath of orthophosphoric acid at 90°C. Precision (1σ) averages were 0.07‰ for oxygen and 0.05‰ for carbon.

Major-Element Geochemistry. Samples for geochemical analysis were obtained using methods similar to those described above for X-ray powder diffraction. Then 200 mg of each sample powder was dissolved for 48 h in 100 mg of 5% HNO_3. These sample solutions were first diluted and then analyzed for Ca^{2+} and Mg^{2+} on a Beckman Spectra Span V plasma source and direct current argon plasma atomic emission spectrometer (DCP-AES) at Miami University.

Results and Interpretations. *Carbonate Mineralogy.* The XRD analyses indicate that the dominant carbonate mineral in the samples is calcite, with minor amounts of dolomite (<6%; table 1). In terms of calcite composition, all but one of the samples is composed of low-magnesium calcite (<5% Mg). While minor amounts of dolomite are present in some Fenghuoshan samples, it most likely precipitated during early diagenesis of primary calcite (see below).

Stable Isotopes. Carbon and oxygen isotopic results for Fenghuoshan carbonates are presented in table 1. Isotopic values are given in conventional per mill (‰) notation relative to VPDB (Vienna Pee Dee Belemnite). The $\delta^{18}O$ of Fenghuoshan samples displays relatively little variation, with values ranging between −11.7‰ and −10.3‰, while $\delta^{13}C$ values have a slightly broader range, from −7.1‰ to −2.2‰ (table 1). Fenghuoshan O and C stable isotopic compositions do not display covariance, possessing an R^2 value of 0.02 (fig. 3). As mentioned above, the stable isotopic composition of authigenic lacustrine deposits has the ability to record paleoenvironmental factors such as the average composition of precipitation across a given drainage basin, the evaporative evolution and residence time of lakes, and biologic productivity at the time of $CaCO_3$ precipitation (McKenzie 1982, 1985; Kelts and Talbot 1989; Talbot 1990). Although the isotopic signature of a given lake is unique to that particular system, patterns have been determined

Table 1. Fenghuoshan Group Carbonate % Mg Calcite, $\delta^{13}C$, $\delta^{18}O$, and Mg/[Mg + Ca] Compositions

Sample	Mol % Mg[a]	% Dol	$\delta^{13}C$ (VPDB; ‰)	$\delta^{18}O$ (VPDB; ‰)	$\delta^{18}O$ (VSMOW; ‰)	Ca (ppm)	Mg (ppm)	Mg/[Mg+Ca]
027	2.1	2.1	−3.1	−11.6	18.9	233,401	6336	.026
029	2.4	.0	−3.6	−11.2	19.3	236,535	7795	.032
030A	1.7	6.3	−4.6	−10.7	19.8			
030B	1.8	4.5	−4.4	−10.5	20.0			
030C	3.3	5.7	−4.6	−10.7	19.8	176,985	8306	.045
031	.4	5.6	−5.6	−11.3	19.2			
031A	2.2	5.9	−4.4	−10.5	20.0	154,703	5486	.034
032A	2.3	.0	−3.5	−11.2	19.3			
032B	2.6	.0	−4.2	−11.2	19.3			
032C	2.4	.0	−3.4	−11.7	18.8	221,668	3960	.018
033A	2.5	.0	−3.1	−11.0	19.6			
033B	.0	.0	−2.9	−11.0	19.5	262,362	4667	.017
033C	2.0	3.9	−4.5	−10.9	19.6			
034	2.2	.0	−2.6	−11.1	19.5	238,875	4150	.017
035	1.1	3.7	−3.5	−10.8	19.7			
036	2.4	.0	−3.3	−11.1	19.4	207,854	4869	.023
037	2.6	.0	−2.3	−11.0	19.5	265,584	8171	.030
049A	2.2	.0	−6.2	−10.3	20.3	161,286	6622	.039
049B	1.8	5.7	−5.8	−10.7	19.9	138,073	4692	.033
049D	2.5	.0	−4.7	−11.3	19.2	303,745	6452	.021
050A	3.0	.0	−3.4	−11.5	19.0	224,024	5030	.022
050C	2.3	.0	−4.0	−11.7	18.8	175,378	2999	.017
052B	1.5	.0	−5.4	−11.3	19.3	128,481	3670	.028
054	2.4	.0	−2.2	−11.1	19.4	207,541	3497	.017
131A	1.9	.0	−5.7	−10.7	19.8	107,279	1892	.017
135A	1.9	.0	−5.9	−11.1	19.5			
135B	3.4	.0	−5.8	−11.0	19.5	356,312	5225	.014
137	2.3	.0	−5.3	−11.2	19.3	246,608	10,193	.040
138	3.8	.0	−5.3	−11.0	19.6	385,262	6256	.016
139	1.8	.0	−6.4	−11.0	19.5	330,242	6066	.018
140	1.9	.0	−6.2	−11.1	19.4			
140A	2.6	.0	−6.6	−11.2	19.4	284,896	5821	.020
141	1.9	.0	−7.1	−11.2	19.3	216,049	6159	.028
143	2.4	.0	−5.9	−11.3	19.2	236,142	5738	.024
143A	2.5	.0	−6.2	−11.3	19.2			
143B	2.4	.0	−6.0	−11.4	19.1			
144	2.5	.0	−5.0	−11.6	18.9	244,830	5854	.023
145	3.3	.0	−3.7	−11.7	18.8	351,876	3771	.011
146	2.8	.0	−4.3	−11.4	19.1	355,432	5820	.016

Note. All samples are micrite. VPDB = Vienna Pee Dee Belemnite. VSMOW = Vienna standard mean ocean water.
[a] Calculated from X-ray diffraction analyses.

for various groups of systems with respect to carbonate stable isotopic composition (Talbot 1990; Talbot and Kelts 1990).

The $\delta^{18}O$ and $\delta^{13}C$ isotopic patterns derived from Fenghuoshan Group carbonates are similar to those in other studies that have interpreted their data as indicative of low-residence time, open-system lacustrine dynamics (fig. 4). The narrow range of $\delta^{18}O$ in our samples is characteristic of hydrologically open lake basins and suggests relatively uniform lake water composition throughout the history of carbonate deposition in the studied stratigraphic interval (Talbot 1990; Talbot and Kelts 1990). Studies of Holocene Tibetan lacustrine systems have determined that uncorrelated $\delta^{18}O$ and $\delta^{13}C$ stable isotopic patterns, similar to those displayed by Fenghuoshan carbonates, are suggestive of short residence times and hydrologically open conditions with high precipitation-evaporation ratios (Fontes et al. 1996).

Variations in $\delta^{13}C$ are most intimately associated with biological processes operating in the basin (McKenzie 1985; Kelts and Talbot 1989; Talbot 1990; Talbot and Kelts 1990). The $\delta^{13}C$ composition of Fenghuoshan lacustrine carbonates occupies a fairly narrow range in comparison to the stable isotopic variation observed in other studies of lacustrine deposits (fig. 4). This suggests that, similar to the $\delta^{18}O$ signature, the $\delta^{13}C$ pattern observed is the result of carbonate deposition in hydrologically open, relatively short residence time lacustrine systems with a positive inflow-evaporation balance.

Major-Element Geochemistry. The major-element chemistry of Fenghuoshan lacustrine carbonates is highly variable (table 1). Ca^{2+} concentrations of whole-rock carbonate samples range from near-stoichiometric calcite at 385,262 ppm to 107,279 ppm, with Mg^{2+} concentrations varying between 10,193 and ~1890 ppm (table 1).

Similar to stable isotopic composition, major-element (Ca^{2+}, Mg^{2+}) concentrations in lacustrine carbonates can be useful in the interpretation of factors such as the influence of evaporation on lake water chemistry (Eugster and Hardie 1978), the relative salinity of paleowaters (Eugster and Hardie 1978; Valero-Garces et al. 1999; Dutkiewicz et al. 2000), and the degree of high-temperature diagenetic alteration (Matthews and Katz 1977). A negative precipitation-evaporation balance is manifested by an increase in Mg/Ca ratios as progressive evaporation of lake waters leads to more saline conditions (e.g., Eugster and Hardie 1978; Mayayo et al. 1996; Valero-Garces et al. 1999; Dutkiewicz et al. 2000). Mg/[Mg + Ca] values of carbonate from closed lacustrine systems are commonly >0.1 (Mayayo et al. 1996; Dutkiewicz et al. 2000). Mg/[Mg + Ca] values from Fenghuoshan samples are <0.05 (table 1), suggesting formation in open lacustrine systems with a positive precipitation-evaporation balance.

Possible Diagenetic Effects. Diagenetic alteration has the potential to significantly affect the oxygen isotopic composition of authigenic carbonate and to skew calculations of paleometeoric water isotopic composition (Matthews and Katz 1977; Campos and Hallam 1979; Dickson and Coleman 1980; Drummond et al. 1993*a*). The effects of diagenesis can be estimated by petrographic examination of the degree of recrystallization of micrite and shell material, comparing the $\delta^{18}O$ composition of micrite to spar and shell material, or comparing major-element ratios to $\delta^{18}O$ (e.g., Matthews and Katz 1977).

Petrographic analyses reveal that sampled Fenghuoshan carbonates are dominantly carbonate mudstones and wackestones (Cyr 2004). Dickson and Coleman (1980) and Poulson and John (2003) reported that fine-grained carbonates are less susceptible to remineralization by diagenetic fluids because of their extremely low permeability. In fact, the small percentage of secondary sparry calcite observed in Fenghuoshan samples is most likely of an early diagenetic origin and unlikely to be significantly different from the original $\delta^{18}O$ composition of micritic material (Cyr 2004). This is evidenced by analysis of primary micrite and sparry calcite (sampled from the interior of an ostracodes test) from sample 035, which yielded similar $\delta^{18}O$ values (−11.24‰ and −10.39‰, respectively). This indicates that the calcite spar most likely precipitated from pore fluids similar in composition to lacustrine waters in which the primary micritic calcite formed.

Comparing the $\delta^{18}O$ composition of micrite to that of shell material is another way to test for alteration of bulk carbonate material. Dickson and Coleman (1980) reported that the isotopic reequilibration of lime mud with diagenetic fluids rendered those mudstones lighter in $\delta^{18}O$ than any skeletal remains. The $\delta^{18}O$ compositions of micrite and calcite ostracode tests from two Fenghuoshan samples (031 and 032B) are similar (−11.32‰ [ostracode] vs. −10.54‰ [micrite] and −11.26‰ [micrite] vs. −11.14‰ [calcite], respectively), suggesting little diagenetic alteration.

Dolomitization of calcite is another type of diagenetic alteration that could enrich Fenghuoshan carbonates away from oxygen isotopic compositions in equilibrium with meteoric water (Drummond et al. 1993*a*). Calculation of the relative

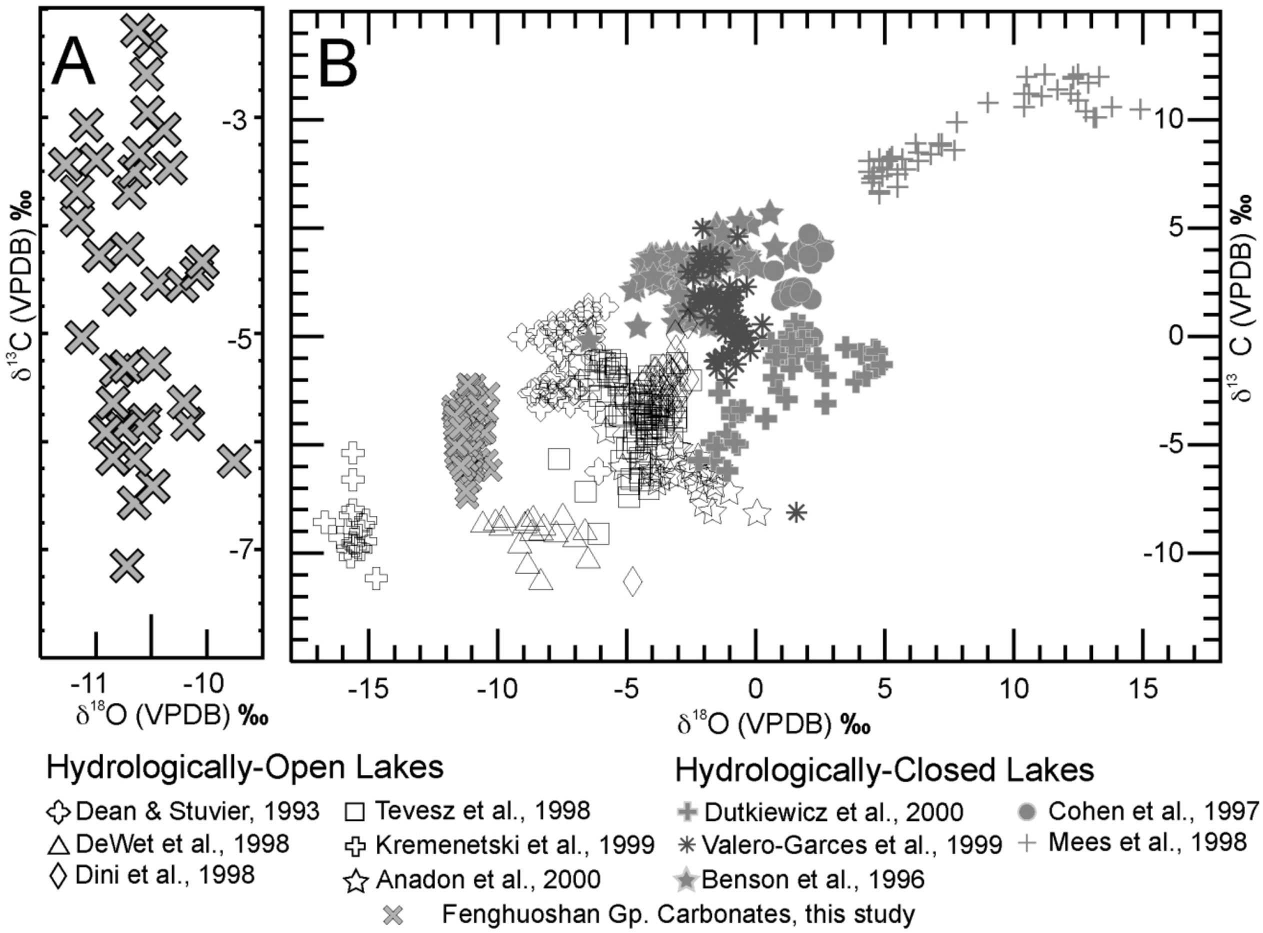

Figure 4. *A*, Plot of $\delta^{13}C$ versus $\delta^{18}O$ for Fenghuoshan Group carbonates. Low R^2 (0.02) suggests a lack of covariance between the isotopic systems. $N = 39$. Data are listed in table 1. *B*, Comparison of Fenghuoshan lacustrine carbonate C and O isotopic compositions with data from both open and closed lacustrine systems.

abundances of calcite and dolomite in Fenghuoshan carbonates shows that calcite is the dominant phase, but small percentages of dolomite (<6%) are present in ~25% of the samples (table 1). While it is possible that dolomitization may have altered the oxygen isotopic composition of the samples, it has probably not done so to a significant degree. When compared to Fenghuoshan samples that are 100% calcite (fig. 5), the samples containing dolomite do not fall outside of the range of calcite $\delta^{18}O$ compositions. The close correlation of the isotopic values suggests that dolomite in the samples may have precipitated during early-diagenetic alteration of original calcite and that $\delta^{18}O$ may have experienced some enrichment as a result. However, given the relatively low percentages of dolomite in the samples and the overlapping $\delta^{18}O$ values, paleoelevation estimates will not differ significantly from calculations based on $\delta^{18}O$ from samples that are 100% calcite.

It should be noted that the narrow range of $\delta^{18}O$ values of Fenghuoshan Group carbonates might be indicative of pervasive carbonate diagenesis. The lack of recrystallized shell material or extensive microrecrystallization textures within sampled micrites (e.g., Garzione et al. 2004), however, indicates that recorded values are representative of original carbonate isotopic compositions. In addition, in the Qaidam basin north of the study area (fig. 1), $\delta^{18}O$ values of Eocene lacustrine carbonates and early diagenetic calcite cements from sandstones also have narrow compositional ranges (<3‰; Rieser et al. 2003; Graham et al. 2005), suggesting that the factors controlling the observed values were regional in extent.

Summary. The $\delta^{18}O/\delta^{13}C$ and Mg/Ca composi-

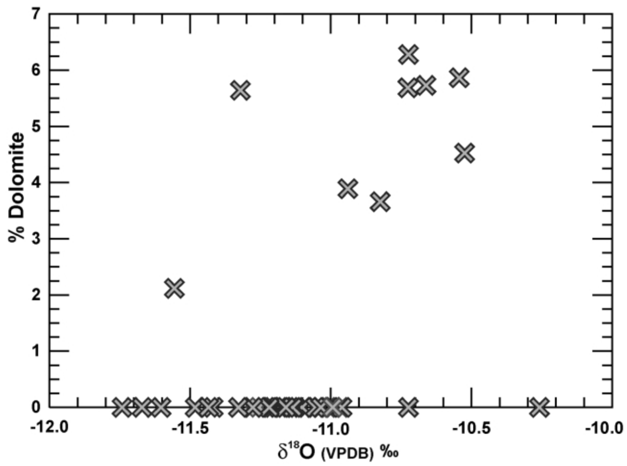

Figure 5. Relative percent dolomite versus $\delta^{18}O$ (VPDB). The range of $\delta^{18}O$ of Fenghuoshan carbonate samples containing dolomite is within the range of $\delta^{18}O$ in samples where dolomite is absent. This suggests that dolomite is primary and preserves the oxygen isotopic composition of meteoric water or that secondary dolomitization has not greatly effected the oxygen isotopic composition of the original calcite.

tion of Fenghuoshan Group carbonates indicates precipitation in open lacustrine systems with positive precipitation-evaporation ratios. Comparisons between micrite, sparry calcite, and shell material show that they are compositionally similar with respect to $\delta^{18}O$. Early diagenetic processes, such as dolomitization, probably did not significantly effect the original $\delta^{18}O$ of samples. In addition, petrographic examination of Fenghuoshan carbonates shows that there is little recrystallization of micritic or shell material. Collectively, these interpretations indicate that Fenghuoshan carbonates have an oxygen isotopic composition that can be used to estimate the $\delta^{18}O$ composition of paleometeoric water (table 2).

Paleoaltitude of the Tibetan Plateau

The geochemical evidence presented above suggests that lacustrine carbonates of the Fenghuoshan Group were deposited in shallow, short-lived, hydrologically open lacustrine systems with a positive precipitation-evaporation balance and that they have not been significantly altered from their original oxygen isotopic chemistry by diagenesis. Rowley et al. (2001), in testing their model, found good agreement between the elevation of modern lakes in the Himalaya and across the southern Tibetan Plateau and model results based on the $\delta^{18}O$ composition of lake water. This agreement suggests that Fenghuoshan carbonates may be used to estimate the $\delta^{18}O$ composition of the average basin-wide precipitation at the time of their deposition. These values can be used in the paleoaltimetric model of Rowley et al. (2001) to calculate the average elevation of Fenghuoshan lakes and the surrounding drainage basin at the time of carbonate deposition. Even if calculated meteoric water oxygen isotopic compositions are slightly enriched relative to actual basin-wide precipitation, the paleoaltimetric estimations presented here will still constrain a minimum elevation for the north-central Tibetan Plateau during Middle Eocene time.

Calculation of Meteoric Water Isotopic Composition. Lacustrine carbonate precipitates in isotopic equilibrium with the lake waters in which it forms (Kelts and Talbot 1989; Talbot and Kelts 1990). Because of the temperature dependence of calcite-water fractionation, in order to determine the isotopic composition of the water from which ancient lacustrine carbonates precipitated, it is necessary to estimate paleolake water temperature. While there is no direct way to calculate the temperature of a given paleolake at the time of carbonate precipitation, a general range of temperature estimates can be made by evaluating the modern temperature range of lakes where shallow-water carbonates, similar to those from the Fenghuoshan Group, are produced. In both temperate, open-system lacustrine environments and closed evaporative lakes, most carbonate precipitates at water temperatures ranging between 15° and 30°C (Talbot 1990; Drummond et al. 1995; Rosen et al. 1995; Teranes et al. 1999). Given this temperature range and the average $\delta^{18}O$ of Fenghuoshan carbonates of −11.1‰ (VPDB), calculations of the $\delta^{18}O_{VSMOW}$ (Vienna standard mean ocean water) of Fenghuoshan paleolake waters using the calcite-water fractionation factor of Friedman and O'Neil (1977) yield an average composition of -9.7 ± 2.8‰ (table 2).

The Model. The Rowley et al. (2001) model is based on equilibrium fractionation of ^{18}O relative to ^{16}O between precipitation and water vapor as a function of the phases involved (water vapor, liquid water, and water ice) and the temperature at which fractionation takes place. Through Rayleigh-type distillation as the result of orographic ascent of a vapor mass, precipitation becomes progressively more depleted with respect to ^{18}O. The model calculates changes in isotopic composition of successive precipitation events with respect to increasing elevation. When compared with model results, the difference between the $\delta^{18}O$ of a low-elevation site and the paleometeoric water composition at ele-

Table 2. Predicted Lake Water Isotopic Composition and Paleoelevations of Eocene Fenghuoshan Lacustrine Drainage Basins Using Lake Water Temperatures of 15°–30°C

	δ^{18}Oc (VSMOW; ‰)	δ^{18}Ow (VSMOW; ‰)[a]				Average δ^{18}Ow (‰)	Δ δ^{18}Op (‰)	Predicted elevation (m)	1σ uncertainty (m)		2σ uncertainty (m)	
Sample		15°C	20°C	25°C	30°C				Plus	Minus	Plus	Minus
027	18.9	−11.8	−10.6	−9.6	−8.6	−10.1	−4.1	2243	578	657	1085	1402
029	19.3	−11.4	−10.3	−9.2	−8.2	−9.8	−3.8	2075	598	680	1124	1451
030A	19.8	−10.9	−9.8	−8.7	−7.7	−9.3	−3.3	1856	625	710	1174	1514
030B	20.0	−10.7	−9.6	−8.5	−7.5	−9.1	−3.1	1758	637	723	1197	1542
030C	19.8	−10.9	−9.8	−8.7	−7.7	−9.3	−3.3	1857	625	710	1174	1514
031	19.2	−11.5	−10.4	−9.3	−8.3	−9.9	−3.9	2137	591	671	1109	1433
031A	20.0	−10.7	−9.6	−8.6	−7.5	−9.1	−3.1	1767	636	722	1194	1540
032A	19.3	−11.4	−10.2	−9.2	−8.2	−9.7	−3.7	2067	599	681	1126	1453
032B	19.3	−11.4	−10.3	−9.2	−8.2	−9.8	−3.8	2083	597	679	1122	1449
032C	18.8	−11.9	−10.8	−9.8	−8.7	−10.3	−4.3	2326	568	645	1066	1378
033A	19.6	−11.2	−10.0	−9.0	−8.0	−9.5	−3.5	1972	611	694	1147	1481
033B	19.5	−11.2	−10.1	−9.0	−8.0	−9.6	−3.6	2003	607	690	1140	1472
033C	19.6	−11.1	−10.0	−8.9	−7.9	−9.5	−3.5	1959	612	696	1150	1484
034	19.5	−11.2	−10.1	−9.1	−8.0	−9.6	−3.6	2011	606	689	1138	1469
035	19.7	−11.0	−9.9	−8.8	−7.8	−9.4	−3.4	1904	619	703	1163	1500
036	19.4	−11.3	−10.2	−9.1	−8.1	−9.7	−3.7	2035	603	685	1133	1462
037	19.5	−11.2	−10.1	−9.0	−8.0	−9.6	−3.6	1985	609	692	1144	1477
049A	20.3	−10.5	−9.3	−8.3	−7.3	−8.8	−2.8	1625	653	741	1227	1580
049B	19.9	−10.9	−9.7	−8.7	−7.7	−9.2	−3.2	1825	629	714	1181	1523
049D	19.2	−11.5	−10.4	−9.3	−8.3	−9.8	−3.8	2117	593	674	1114	1439
050A	19.0	−11.7	−10.6	−9.5	−8.5	−10.1	−4.1	2210	582	661	1093	1412
050C	18.8	−11.9	−10.7	−9.7	−8.7	−10.2	−4.2	2294	571	650	1073	1387
052B	19.3	−11.5	−10.3	−9.3	−8.3	−9.8	−3.8	2107	594	676	1116	1442
054	19.4	−11.3	−10.2	−9.1	−8.1	−9.7	−3.7	2047	602	684	1130	1459
131A	19.8	−10.9	−9.8	−8.7	−7.7	−9.3	−3.3	1856	625	710	1174	1514
135A	19.5	−11.3	−10.1	−9.1	−8.1	−9.6	−3.6	2013	606	688	1138	1469
135B	19.5	−11.2	−10.1	−9.0	−8.0	−9.6	−3.6	2004	607	690	1140	1471
137	19.3	−11.4	−10.3	−9.2	−8.2	−9.8	−3.8	2087	597	678	1121	1447
138	19.6	−11.2	−10.0	−9.0	−8.0	−9.5	−3.5	1969	611	694	1148	1482
139	19.5	−11.2	−10.1	−9.0	−8.0	−9.6	−3.6	1984	609	692	1145	1477
140	19.4	−11.3	−10.2	−9.1	−8.1	−9.7	−3.7	2051	601	683	1129	1458
140A	19.4	−11.4	−10.2	−9.2	−8.2	−9.7	−3.7	2063	600	682	1127	1455
141	19.3	−11.4	−10.3	−9.2	−8.2	−9.8	−3.8	2090	596	678	1120	1447
143	19.2	−11.5	−10.4	−9.3	−8.3	−9.8	−3.8	2117	593	674	1114	1439
143A	19.2	−11.5	−10.4	−9.3	−8.3	−9.9	−3.9	2140	590	671	1109	1432
143B	19.1	−11.6	−10.5	−9.4	−8.4	−10.0	−4.0	2181	585	665	1099	1420
144	18.9	−11.8	−10.7	−9.6	−8.6	−10.2	−4.2	2264	575	654	1080	1396
145	18.8	−11.9	−10.7	−9.7	−8.7	−10.2	−4.2	2294	571	650	1073	1387
146	19.1	−11.6	−10.5	−9.4	−8.4	−10.0	−4.0	2188	584	664	1097	1418
Average						−9.7	−3.7	2040	602	685	1132	1461

Note. δ^{18}Oc is the measured oxygen isotopic composition of calcite. δ^{18}Ow is the calculated paleolake water composition; the 2σ error for δ^{18}Ow is 2.8‰ for all samples. $\Delta\delta^{18}$Op is the estimated difference between low- and high-altitude precipitation.
[a] Calculated using calcite-water fractionation factor of Friedman and O'Neil (1977).

vation (as estimated from the Fenghuoshan carbonates) symbolized by $\Delta(\delta^{18}O)$ provides an estimate of regional paleoelevation. This model has successfully been demonstrated to provide reasonable matches of modern elevations and hypsometry of the Alps, Tibet, and the Himalaya, as well as for southern Tibet and Himalaya in the Late Miocene (Rowley et al. 2001), southern Tibet in the mid-Miocene (Currie et al. 2005), and the Eocene-Miocene Lunpola basin in central Tibet (Currie and Rowley 2004).

During the Eocene, the Hoh Xil basin was situated south of ~35°N latitude (Liu et al. 2003). Given the reconstructed paleogeographic setting, moisture-carrying air masses were most likely derived from Neotethyan sources to the west during summer-month monsoonal conditions. This is consistent with results from global general circulation models for the Eocene indicating that moist air masses entering Tibet were derived primarily from the west-southwest (Sewall et al. 2000). Since it is the difference in δ^{18}O between a potentially high-elevation location and a near–sea level site that provides the basis for the estimate of paleoaltitude, the δ^{18}O of the low-elevation site plays an important role in the model. Unfortunately, at present there are no reported low-elevation Middle Eocene paleometeoric water data west-southwest of the Tibetan Plateau to compare with our Fenghuoshan carbonate data. Following Rowley et al. (2001) and Currie et al. (2005), we adopt a low-elevation value of $\delta^{18}O$ of −6‰. This value is more depleted than virtually all low-elevation (<100 m), low-latitude (<35°) stations in the modern-day International Atomic Energy Agency Global Network of Isotopes in Precipitation data set (Rozanski et al. 1993), which, given the model, results in a lower estimated paleoelevation. The calculated model elevation is evaluated within the 2σ variation of the temperature-dependent meteoric water isotopic compositions described above, as well as the observed 2σ variability in the initial air mass temperature and relative humidity data sets (Rowley et al. 2001).

Model Results. Based on the average $\delta^{18}O_{(VSMOW)}$ meteoric water compositions calculated for Middle Eocene Fenghuoshan lakes, the average $\Delta(\delta^{18}O)$ is −3.7‰ (table 2). This corresponds with an average paleoelevation of Hoh Xil basin watersheds of ~2.0 km (2040^{+1460}_{-1130} m; table 2; fig. 6). Given the associated siliciclastic sedimentology and paleocurrent indications of derivation from sources to the south, it is likely that the paleoelevation of Fenghuoshan lakes was below the mean elevation of the drainages in the Middle Eocene. Hence, 2.0 km represents an upper bound on the average elevation of the Hoh Xil basin at that time.

These calculations suggest that the northern part of the Tibetan Plateau had not obtained elevations in excess of 2.0 km until after the Middle Eocene. Existing interpretations of the uplift history of the Tibetan Plateau range from conclusions that Tibet did not achieve significant altitudes until the Pliocene (Xu 1981) to suggestions that northern Tibet may have been raised to elevations of ~3–4 km during the Late Mesozoic (Murphy et al. 1997). For the Neogene, several different studies have made paleoaltimetric estimates for the Himalaya and Tibet (fig. 7). Garzione et al. (2000*a*, 2000*b*) and Rowley et al. (2001) used oxygen isotopes to infer that the Himalaya in the vicinities of the Thakkhola and Gyirong basins were at high elevations by ~10 Ma. France-Lanord et al. (1988) derived a paleoelevation estimate in excess of 6 km based on the calculated isotopic composition the meteoric waters associated with hydrothermal alteration around the Manaslu pluton at ~20 Ma. Spicer et al. (2003), using fossil leaf physiognomy, calculated an elevation of the southern Tibetan Plateau of ~4.6 km at ~15 Ma. The floral-based estimate of Spicer et al. (2003)

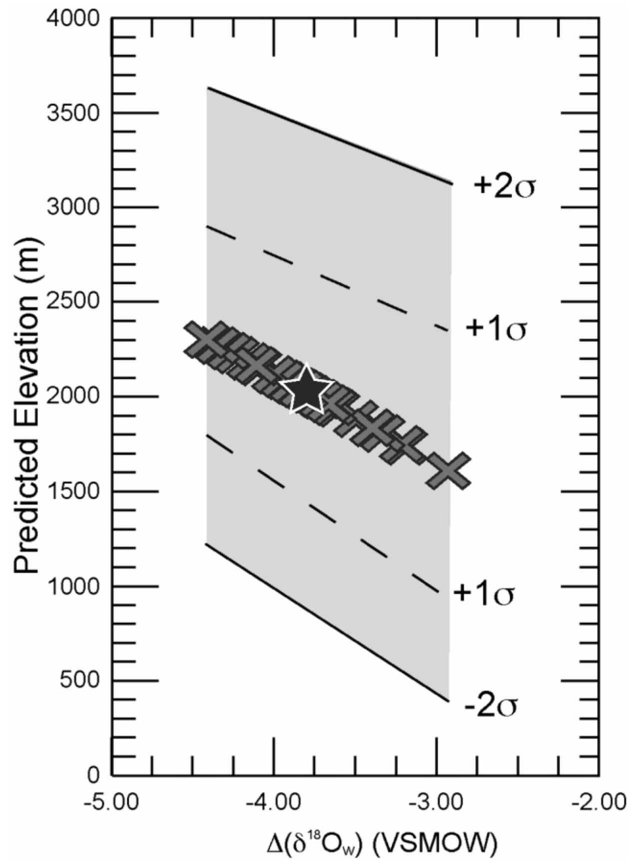

Figure 6. Plot of $\Delta(\delta^{18}O_w$; ‰) versus elevation (m) as predicted from Fenghuoshan lacustrine calcite, assuming a temperature range from 15° to 30°C. Large star indicates the average elevation as predicted from paleometeoric water calculations. The solid and dashed lines represent calculated 2σ and 1σ error ranges, respectively, for the model elevation predictions.

is entirely consistent with results based on oxygen isotopes of soil carbonates from the same section (Currie et al. 2005). Currie and Rowley (2004), using the isotopic composition of lacustrine and soil carbonates from the Tertiary strata of the Lunpola basin, determined that central Tibet has been at elevations of ~4.6 km since Late Eocene–Early Oligocene time (~34 Ma).

Collectively, these studies indicate that at least the Himalaya and southern and central Tibetan Plateau reached elevations similar to those that currently exist by ≥15 Ma and that the Lunpola region of central Tibet did so at >34 Ma (fig. 7). To date, the isotopic data from the Fenghuoshan Group are the only indications of relatively lower elevations (<2 km) for any part of the present-day Tibetan Plateau since the Middle Eocene, although $\delta^{18}O$ values

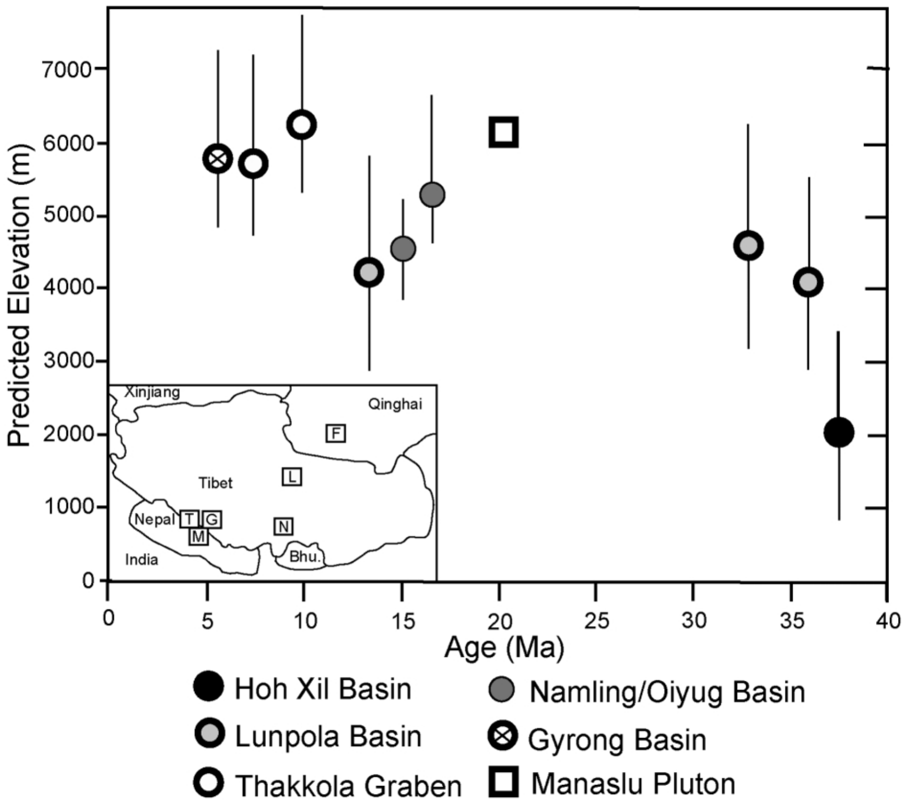

Figure 7. Predicted elevations of different regions of the Tibetan Plateau since the Eocene. Median ages are approximated based on the reported age range of the sampled stratigraphic interval. Inset map shows the locations of each area. F = Fenghuoshan (Hoh Xil basin), G = Gyirong, L = Lunpola, M = Manaslu, N = Namling/Oiyug, Q = Qaidam, and T = Thakkhola. Vertical error bars are based on reported model errors. Thakkhola and Gyirong data are from Rowley et al. (2001); Namling data are from Spicer et al. (2003) and Currie et al. (2005); Lunpola data are from Currie and Rowley (2004); Manaslu data are from France-Lanord et al. (1988).

of early-diagenetic calcite cements from Eocene sandstones from the Qaidam basin north of the study area (Graham et al. 2005) indicate similarly low elevations. Given that it is unlikely that plateau uplift occurred instantaneously between Middle and Late Eocene time, the boundary between high and low topography during Fenghuoshan Group deposition existed somewhere between the Hoh Xil and Lunpola basins. An ~2-km mean elevation of the fluvial drainages flowing into the Hoh Xil basin from the south is consistent with results reported by Currie and Rowley (2004) that indicate that central Tibet was raised to an ~4.5-km mean elevation by the Late Eocene. This suggests that uplift of the Tibetan Plateau has progressed northward through time and that roughly the northern third of the plateau has experienced uplift in excess of 2.7 km since ~36 Ma. Exactly when uplift of the northern Tibet occurred, however, has yet to be resolved.

Conclusions

Sedimentologic evidence from carbonates of the Fenghuoshan Group of north-central Tibet show that they were deposited in shallow lacustrine systems with positive inflow-evaporation balances. The results of mineralogic, stable isotopic, and major-element analyses of Fenghuoshan Group carbonates suggest that Hoh Xil basin lacustrine systems were not evaporatively enriched and that sample isotopic compositions have not been significantly modified by diagenetic alteration. These interpretations allow Fenghuoshan Group carbonates to be used to infer the oxygen isotopic composition of regional meteoric water for the purpose of estimating the elevation of the Tibetan Plateau at the time of carbonate deposition. Model results indicate a regional elevation for Hoh Xil drainage basins of ~2.0 km. This implies surface uplift of this region of >2.7 km since the Middle

Eocene. Current data from paleoaltimetry, however, cannot resolve when this uplift occurred.

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