Palaeoclimatic interpretation of a topographic profile across middle Holocene regressive shorelines of Longmu Co (Western Tibet)

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Abstract

Most lakes and closed basins in Tibet are surrounded by abandoned shorelines attesting for high-water levels in the past. Two such lakes, Longmu Co and Sumxi Co (Western Tibet), were the focus of detailed palaeoclimatic work during the 1989 Sino-French expedition based on the study of lake sediments and analysis of a piston core. Here it is shown that additional information may be deduced from the abandoned shorelines around Longmu Co. A 1800 m long topographic profile was levelled from 75 m up to 230 m above the present lake elevation (5008 m), on which the shorelines form a flight of horizontal terraces separated by more or less degraded scarps. The elevations of the terraces were spaced regularly about 1.35 m, except for 3–5 m high lacunae recurring every 15–16 m. The potential annual evapo-transpiration was computed based on meteorological data collected at Tien Shui Hai from 13/08/89 to 11/09/90. Using a modified Penman formula a value of 1.60 ± 0.3 m/yr was obtained under close system conditions (no outlet) and a synthetic curve of lake regression was derived which appears to be consistent with the measured shoreline heights. It is concluded that the 1.35 m terraces represent annual regression of the lake level. By contrast, the 3–5 m high lacunae might reflect the periodic return, about every 9–12 yr, of particular climatic conditions responsible for a perturbation of the annual process of shoreline formation. All the shorelines of this profile have formed probably within one century, during a continuous and abrupt regression of the lake. Such evolution has also been identified in the sediments of a piston core collected at Sumxi Co, and dated at about 6–5.5 kyr B.P. The lake level must have been at its highest stand, shortly before that major regression. The mechanism responsible for this middle Holocene high stand and for the major sudden drop of the lake level remains uncertain.

1. Introduction

On satellite images (SPOT or Landsat) most Tibetan lakes, as well as some presently dry closed basins, appear to be surrounded by conspicuous regressive shoreline rings attesting for high-water levels in the past. There is evidence that at least some of these shorelines are of Holocene age (Fang, 1991). Although study of these shorelines might be important to understand late Quaternary climate changes in Tibet, little work was devoted to this common feature of Tibetan lakes. The 1989 Sino-French Kunlun–Karakorum geotraverse provided access to several lakes in western Tibet. Two of these lakes, Longmu Co (Co means lake) and Sumxi Co, lie in a closed pull-apart basin along
the N80°E striking left-lateral Gozha fault system (Fig. 1; Armijo et al., 1989; Liu et al., 1991). They have given rise to detailed palaeoclimatic and neotectonic work during the 1989 Sino-French expedition. A precise picture of the regional palaeo-environment over the last 13.0 kyr has been obtained from the study of lake deposits and analysis of a 10.5 m piston core (Fontes et al., 1994; Gasse et al., 1991; Van Campo and Gasse, 1993). All environmental variables show a stepwise establishment of warmer and wetter conditions than those of today, attributed to enhanced monsoonal circulation, with major pulses at ≈12.5, ≈10.0 and ≈7.5 kyr B.P. (Gasse et al., 1991). The highest Holocene lake stand is estimated at 7.5–6.0 kyr B.P., when the two lakes were connected in a large single lake. Water level rapidly dropped at ≈6.0–5.5 kyr B.P. leading to the disconnection of the two lakes. After a positive water level oscillation which did not reach the threshold, maximum in regional aridity and minimum residence time of the lake water are recorded around 4.2–3.8 kyr B.P. (Van Campo and Gasse, 1993; Fontes et al., 1994). At Sumxi, later on, the lakes experienced minor level fluctuations.

Hereafter, we show that the uppermost

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**Fig. 1.** (a) Location map of Sumxi Co and Longmu Co in western Tibet. (b) Interpretation of satellite images of Longmu Co and Sumxi Co basin. Modified from Gasse et al. (1991).
abandoned shorelines of Longmu Co provide additional informations about the onset and rate of the middle Holocene lake regression and the climatic conditions at that time.

2. Analysis of a topographic profile across the abandoned shorelines of Longmu Co

The highest shorelines, at an elevation of about 5240 m, lie about 230 m above the present lake level (5008 m) and 140 m above the topographic threshold that separates Longmu Co and Sunxi Co (5100 m; Fig. 1). These shorelines are wave cut benches that formed into coarse grained unconsolidated alluvium at elevations below 5180 m and into more indurated material above 5180 m. At the time of the high stand, the two lakes thus formed a single lake about 250 m deep. The highest outcropping sediments are sampled at elevations of 5105 m and 5098 m, \(^{14}\text{C}\) dated at \(\approx 7.3\) and \(7.6\) kyr B.P., respectively (Fig. 1; Gasse et al., 1991). The regressive shorelines situated between these elevations must thus have formed later than about 7 kyr B.P., probably during the middle Holocene regression phase identified in the piston-core and dated at about 6–5.5 kyr B.P.

The shorelines are particularly well preserved along the gently sloping shore bordering Longmu Co to the southeast. We levelled a 1800 m long topographic profile from 75 m to 230 m above the present lake stand, 5008 m (Figs. 2 and 3a). The profile consists of 263 points measured from a single station (digital theodolite Wild T2000 coupled with an infrared distance-meter Wild DI3000). The profile includes the highest shorelines from 5240 m down to 5080 m. Below this elevation, the relief of the shorelines becomes gradually smaller downwards so that we estimated that they might not have shown up on the profile. Besides, lithofacies, mineralogy and biological remains indicate that the regression from 5105 m to the present-day water level has not been linear. Lake Longmu experimented minor positive oscillations of late Holocene age (Van Campo and Gasse, 1993; Fontes et al., 1994). Slopes were computed taking the first derivative of the vertical coordinate as a function of the horizontal coordinate on a

120°E projection of the topographic profile. On the slope profile (Fig. 3b), we observe a flight of horizontal terraces (with slopes close to 0%) separated by more or less degraded scarps. Cliffs formed in indurated bedrock in the upper part of the profile (above 5180 m) have steep slopes, between 60% and 140%, whereas shorelines formed in unconsolidated alluvium in the lower part of the profile (below 5180 m) are more degraded with maximum slopes between 10% and 40% (Fig. 3b). When the slope profile is plotted as a function of elevation above the present lake level (Fig. 4a), the terraces appear to be rather regularly spaced in elevation except for “lacunae” that are uniformly sloping segments of the profile with no terraces and scarps (Fig. 4a,b). The elevations of the terraces can easily be extracted from the slope profile because they correspond to local minima in the slope profile. The difference in elevation between two successive terraces might be called “bench height”. It generally gives the height of a single step between two successive terraces. Fig. 4c
Fig. 3. N30°E projection of the profile (a) and of slope (b) across Longmu Co shorelines.

displays a histogram of "bench heights" obtained by this way. In some cases the "bench height" might correspond to the cumulative height of two successive steps if the terrace between them has not been identified because of a too sparse topographic sampling, or has been destroyed by erosion. The presence of the lacunae also results in some very high apparent benches, whose height is the delevelling of the segment of the profile with no flat terrace. Except for these few large values, most bench heights cluster around 1.35 m with a standard deviation of 0.5 m.

In order to investigate whether an overall trend in bench height distribution could be detected, bench heights were plotted as a function of elevation above lake level (Fig. 5). In spite of the lithologic transition at about 5180 m, the profile appears relatively uniform, suggesting that it has recorded a single continuous regression event. To check this inference, we investigated the possibility of discriminating shorelines of different ages on the basis of a morphological criterion, following the concept that the morphology of scarps such as the erosional benches we consider here, is a function of their age (Wallace, 1977).

The diffusion model of scarp degradation applies to scarp like landforms formed in unconsolidated materials (Hanks et al., 1984; Nash, 1980; Mayer, 1984; Pierce and Coleman, 1986). Models of scarp degradation assumes that, once the scarp is formed

Fig. 4. (a) Slope of the profile across Longmu Co shorelines plotted as function of elevation above the present lake level. The height of a shoreline is defined as the difference in elevation between two successive horizontal terraces. (b) Close up view of a segment of the profile. (c) Histogram of shoreline height.
and abandoned, it degrades first under the action of gravitational processes. This gravity-controlled phase is supposed to be almost instantaneous leading to a scarp slope at the angle of repose of the materials ($\approx 35^\circ$). Later on, the scarp degrades more gradually under various surface processes. The linear model of scarp degradation (Hanks et al., 1984; Nash, 1980) further assumes that the rate of downslope transfer of material is proportional to the slope. This model approximately accounts for the effect of surface processes that conserve mass. If we consider that the shorelines formed as steep erosional benches with slope $\alpha$ (Fig. 6a), separating horizontal terraces, their present maximum slope \( \tan \Phi \) (Figure 6b) could be related to their age through equation:

\[
\tan \Phi = \tan \alpha \times \text{erf}[\delta h \times \cot \alpha \times (\pi \tau)^{-1/2}]
\]  

(1)

where \( \alpha \) is the initial scarp-slope angle, \( \delta h \), the shoreline height (Fig. 6), and, \( \tau \), the degradation coefficient expressed in square meters:

\[
\tau = k t
\]  

(2)
(a) Initial state

\[ \alpha \]

\[ \delta h \]

\[ \text{Erosion} \]

(b) Present state

\[ \phi \]

\[ \delta h \]

Fig. 6. Surface processes acting on scarp formed in cohesionless materials result in smoothing of scarp profile. Initial steep scarp slope angle \( \alpha \) (a), is reduced to \( \phi \) in the present state (b).

with \( t \), the numerical age (kyr), and \( k \), the mass diffusivity constant (m² kyr⁻¹).

As a result, the degradation coefficient, which can be considered as a measurement of the degree of degradation of a scarp, can be estimated from Eq. (1) or by fitting synthetic scarp profiles with the profiles levelled in the field (e.g., Mayer, 1984; Avouac, 1993). The latter method could not be applied here because the available data are too limited for a fit adjustment with synthetic profiles.

Fig. 7 shows a plot of maximum scarp slope angle as a function of bench height (we considered only the shorelines formed in unconsolidated alluvium, i.e., at elevations below 175 m above lake level). The lines are the theoretical curves obtained from Eq. (1) for different degradation coefficients. The data appear to be much scattered partly because our sampling does not allow an accurate estimate of the maximum scarp-slope and partly because of natural source of errors due for example to gullying, small fan deposition at base of the scarp or trapped eolian sediments (Mayer, 1984; Pierce and Coleman, 1986; Hanks et al., 1984; Avouac, 1993).

There is however no evidence that the shorelines from the upper part of the profile might be more eroded (older) than in the lower part. The plot in Fig. 7 only allows a very rough estimate of the degradation coefficient between 0.5 m² and 8 m². Given that the shorelines are assumed to be 5.5 kyr old, a mass diffusivity constant between 0.2 and 1.4 m²/10³yr is deduced. This value is somewhat lower but comparable to the values obtained under similar arid environments for similar loose alluvium which generally lie in the range between 0.3 m²/10³yr and 5 m²/10³yr (Avouac, 1993). It is unlikely that the shorelines may be much older than 5.5 kyr B.P., as it would imply an even lower rate of degradation.

The absence of lacustrine sediments above 5105 m is however surprising if the Holocene lake extended at 5240 m. Furthermore, a significant proportion of littoral diatom species occur in a section (Gasse et al., 1991) situated at 5080 m and dated at 7.8–7.3 kyr B.P. Lacustrine sediments of this section are cut by deltaic deposits and sediments corresponding to the highest level may have been eroded. A possibility is that the highest stand level has been a transitory state during a short lived transgressions–regressions event.

3. Estimate of modern potential evaporation

The characteristic 1.35 m height might reflect annual regression of the lake level. We have thus computed the potential annual evaporation and tried to derive a theoretical regression rate for the
present climatic conditions. For areas where measured data on temperature, humidity and wind are available, the Penman method of predicting evaporation is likely to provide the most satisfactory results compared to other methods.

The original Penman method, established in 1948, consists of two terms: the energy (radiation) term and the aerodynamic (wind and humidity) term. In humid or temperate regions, where the formula has been elaborated, the prediction of evaporation is good. But under windy conditions and in the more arid regions the aerodynamic term becomes relatively more important. Doorenbos and Pruitt (1977) proposed a slightly modified Penman equation involving a revised wind function term:

\[ ET_0 = c[W \times R_n + (1 - W) \times f(u) \times (e_a - e_d)] \] (3)

with \( ET_0 \), free water evaporation in mm \( d^{-1} \),

radiation term:

\( W \), temperature-altitude-related weighting factor (for the effect of radiation on evaporation according to temperature and altitude),

\( R_n \), energy of net radiation in equivalent evaporation in mm \( d^{-1} \)

aerodynamic term:

\( 1 - W \), temperature-altitude-related weighting factor (for the effect of wind and humidity on evaporation according to temperature and altitude),

\[ f(u) = 0.27 \times (1 + U/100) \] where \( U \) is the 24 hr wind run in km \( d^{-1} \). This value, result of field experiences and adjustments, replaces the original Penman value \([f(u) = 0.26 \times (1 + U/100)]\) where \( U \) is in m \( d^{-1} \). The similarity between original and modified values is purely coincidental.

\( e_a - e_d \), vapor pressure deficit (difference between saturation vapor pressure at mean air temperature and the mean actual vapor pressure of the air, both in \( 10^5 \) Pa),

adjustment factor:

\( c \), to compensate differences between day-time wind and night-time wind (wind is considered in original formula to be double during day-time than during night-time).

On the basis of the meteorological data collected at Tien Shui Hai from 1/9/89 to 31/8/90 (Table 1; Dobremez, this issue) and after FAO (Food and Agriculture Organisation) drainage and irrigation paper n° 24 (Doorenbos and Pruitt, 1977), we obtained a potential evapotranspiration for the lake Longmu of \( E_{0,0} = 1.60 \pm 0.30 \) m yr. The 0.30 error bar, less than 20%, is due to uncertainties on data and on computation:

—Penman formula even modified has never been used in such drastic conditions;

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Data available on request from the authors</td>
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<tr>
<td>Data collected in Tien Shui Hai (4850 m asl, 35°40' N - 79°30' E) from 13/08/89 to 11/09/90</td>
</tr>
<tr>
<td>- date (day-month),</td>
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<tr>
<td>- minimum daily temperature (°C),</td>
</tr>
<tr>
<td>- maximum daily temperature (°C),</td>
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<tr>
<td>- average daily temperature (°C),</td>
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<tr>
<td>- daily temperature amplitude (°C),</td>
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<tr>
<td>- minimum daily Relative Humidity (%),</td>
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<tr>
<td>- maximum daily Relative Humidity (%),</td>
</tr>
<tr>
<td>- RH = average Relative Humidity (%),</td>
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<tr>
<td>- ( e_a ) = saturation vapour pressure (( 10^5 ) Pa),</td>
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<tr>
<td>- ( e_d ) = actual vapour pressure (( 10^5 ) Pa),</td>
</tr>
<tr>
<td>- ( e_a - e_d ) = vapour pressure deficit (( 10^5 ) Pa),</td>
</tr>
<tr>
<td>- ( U_2 ) = average wind speed at 2 m elevation in km d(^{-1}) (original data in km/week),</td>
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<tr>
<td>- ( f(u) = 0.27 \times (1 + U/100) ),</td>
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<tr>
<td>- cloudiness (in oktas) : personal estimation according to field observations,</td>
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<tr>
<td>- minimum RH records and Satellite images</td>
</tr>
<tr>
<td>- ( n/N ) ratio (actual to maximum sunshine hours) depending on cloudiness,</td>
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<tr>
<td>- c (day/night factor adjustment) depending on windspeed, maximum RH records and Solar Radiation.</td>
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<th>Table 2</th>
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<tr>
<td>Data after FAO (Food and Agriculture Organisation) drainage and irrigation paper n° 24 (Doorenbos and Pruitt, 1977)</td>
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<tr>
<td>- (1 - W) depending on temperature and altitude,</td>
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<tr>
<td>- W depending on temperature and altitude,</td>
</tr>
<tr>
<td>- ( R_3 ) (extra terrestrial radiation in mm d(^{-1}) equivalent evaporation) depending on month and latitude,</td>
</tr>
<tr>
<td>- N (duration of maximum possible sunshine in hours) according to month and latitude,</td>
</tr>
<tr>
<td>- ( R_4 ) (solar radiation in mm d(^{-1}) equivalent evaporation),</td>
</tr>
<tr>
<td>- ( R_{39} ) (net shortwave radiation in mm d(^{-1}) equivalent evaporation) = (1 - a).( R_4 ) with a = reflectivity = 0.06 for water (dimensionless),</td>
</tr>
<tr>
<td>- f (T) = effect of Temperature on longwave Radiation,</td>
</tr>
<tr>
<td>- f (ed) = 0.34 \times 0.044 \times e_d (effect of vapour pressure on longwave Radiation),</td>
</tr>
<tr>
<td>- f (n/N) = 0.1 + 0.9 n/N (effect of the ratio actual to maximum bright sunshine hours on longwave Radiation),</td>
</tr>
<tr>
<td>- ( R_{39} ) (net longwave radiation; constitute always a loss) (in mm d(^{-1}) equivalent evaporation),</td>
</tr>
<tr>
<td>- ( R_{39} ) (net radiation) (in mm d(^{-1}) equivalent evaporation) = ( R_{39} - R_{41} ) = net shortwave Radiation - net longwave Radiation.</td>
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—cloudiness has been estimated (in okta) according to relative humidity, to sequences of satellite pictures Spot and with 25 years of personal experience from high plateau climate. Simulating the effect of cloudiness on evaporation, we obtain a difference of evaporation less than 4% for an error of 1 okta (cloudiness).

—c (adjustment factor to compensate for the effect of day and night weather conditions, related to wind, temperature and relative humidity): as the air climate is well characterised even for wind (no wind during night, strong wind during afternoon), uncertainty on c value is low.

—duration of evaporation period: Penman formula can be used only if average daily temperature is above 0°C and evaporation occurs only on free watersurfaces; sublimation is always very limited.

In order to derive a precise figure of evapotranspiration, the exact dates of freezing and melting of the lakes should be known. They are only estimated after satellite images. For these periods, temperatures are very low, evaporation also: the error on total annual evapotranspiration is thus low.

—temperature: Longmu Co is 150 m above Tien Shui Hai where temperature data were collected. According to the local thermic gradient, average temperature is 0.75°C less in Longmu Co than in Tien Shui Hai. Simulation of temperature gives an increase or decrease of 1.5% of evapotranspiration per °C.

4. Comparison with a synthetic regression curve

Comparison with the 1.6 m/yr potential evaporation deduced from modern climatic conditions suggests that the 1.35m average shoreline height probably corresponds to the annual regression. We checked this inference using a model of lake regression inferred from a simple hydrological budget. If \( dh/dt \) is the average annual regression, we may write:

\[
dh/dt = -Ev(t) + F(t)/S(h)
\]  

where \( h \) is the elevation of lake level above present lake level at time \( t \); \( Ev(t) \), the potential evaporation at time \( t \); \( S(h) \), the lake area for a water level \( h \) above the present lake level; and \( F(t) \), the water input to the lake, due to ice melting and precipitation over the catchment area.

Assuming that the glaciers are in equilibrium, the water input at present is:

\[
F_o = S_{catch} r_o
\]  

where \( S_{catch} \) is the catchment area, and \( r_o \), the effective precipitation (fraction of precipitation which is not lost by evaporation or evapotranspiration before it reaches the lake). According to vegetation types (unpublished results of Sino-French 1989 Kunlun Karakoram scientific expedition), and to Domrös and Peng (1988), annual rainfall is estimated in the Sumxi-Longmu basin at 50 mm.

The shorelines considered here have recorded the regression of the single holocene Longmu Co–Sumxi Co. We thus consider the two lakes together. For \( S_{catch} = 3870 \text{ km}^2 \) (catchment area of Sumxi Co and Longmu Co; Gasse et al., 1991) and \( r_o = 50 \text{ mm/yr} \), we get a water input of \( 1.9 \times 10^8 \text{ m}^3/\text{yr} \). Given that the present lake area is \( S_o = 123 \text{ km}^2 \) (Sumxi Co+Longmu Co; Gasse et al., 1991), and that the evapotranspiration is 1.6 m/yr, we get an outflow \( S_o \times Ev_o \approx 1.9 \times 10^8 \text{ m}^3/\text{yr} = F_o \). Thus, Eq. (4) yields a zero regression rate. This means that the water budget of the present lake system is approximately in equilibrium.

If we now assume a potential evaporation at time \( t \) equal to the present one, Eq. (4) can be rewritten:

\[
dh/dt = Ev_o \times [(S_o/S(h)) - 1]
\]  

where \( Ev_o = Ev(0) = 1.6 \text{ m/yr} \).

The function \( S(h) \) could be determined from detailed topographic maps, if available. Here, we have simply measured on SPOT images the area of the highest-stand lake delimited by the highest shorelines (\( h = 230 \text{ m} \)), \( S_{230} \approx 1000 \text{ km}^2 \), and assumed a conical basin geometry (Fig. 8). We obtain:

\[
S(h) = S_o (1 + h/H)^2
\]  

where \( S_o = 123 \text{ km}^2 \), and \( H = 230/[(S_{230}/S_o)^{-aw} + 1/2 - 1] = 119 \text{ m} \).
produced a steeper slope and a sharper curvature near the origin, and even more uniform values between 75 m and 230 m. The close agreement between the measured bench heights (1.35 ± 0.5 m) and the theoretical annual regression estimated (1.25 m) from Eq. (8) lead us to conclude that the regression occurred at a time when the disequilibrium between potential evaporation and total incoming flow was close to the present day value.

Eq. (8) can be integrated yielding the time at which the lake level was at elevation h above the present lake level (assuming a single and continuous regression phase):

\[
t = t_{230} + \frac{1}{E_v} \times \left[ \frac{230 - h + H}{2} \times \ln \left( \frac{230}{h} \times \frac{H + h}{H + 230} \right) \right]
\]

(9)

where \( t_{230} \approx 5500 \) yr B.P. is the time at the beginning of the regression phase. It means that the water level has dropped abruptly. According to Eq. (9) it would have taken only 120 yr for the water level to drop, from its highest stand, over the 160 m corresponding to the profile.

A striking feature of Fig. 5 is the apparent regular distribution of the 3–5 m peaks, which correspond to the lacunae with no terraces and scarps. There is on average a difference in elevation of 15–16 m, with about 8–9 annual shorelines, between two successive peaks. The natural variability of the different factors which control potential evaporation and incoming flow would not allow variation of the annual regression rate by more than 50%. A 3–5 m drop in level cannot thus be interpreted as an annual regression, even under extreme climatic conditions. In addition, the frequent recurrence of these lacunae rules out that they have been related to tectonic events. We rather propose that the regularity of the process responsible for the formation of the benches has been disturbed by some recurring perturbations, probably forced by some seasonal atmospheric agitation, while the rate of regression of the lake would have been constant. Our 120 yr record would then show a 9–12 yr cycle with alternate “shoreline build up periods” and “lacunae periods”. During “shoreline build up periods”, the process of shoreline formation would have return

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**Fig. 8.** Longmu-Sumxi Co basin is assumed conical. The surface of the paleo lake that was standing at an elevation \( h \) above present lake level, \( S(h) \), is related to present lake surface, \( S(0) \), according to Eq. (6).

\[ H \] corresponds to the lake level variation, it can be compared to the 155 m observed.

Finally, Eq. (4) becomes:

\[
dh/dt = E_v \times [(1 + h/H)^{-2} - 1]
\]

(8)

The dashed line in Fig. 5 shows the corresponding curve. It implies a roughly constant annual regression between 75 and 230 m above the present lake level, of about 1.25 m. The hypothesis of a more realistic concave basin geometry would have only tend to a slightly different curve. It would have
regularly once a year, leading to shorelines regularly spaced in elevation. During "lacunae periods" the shorelines could not form or many would have formed within one single year so that they would have been so thin that they would have been readily eroded. The duration of the proposal cycle suggests that it could be related to the sun actvity.

5. Implications and conclusions

This study shows that levelling of topographic profiles across abandoned shorelines is a simple and powerful tool for the investigation of the process and timing of a palaeo-lake regression in addition to lake sediments analysis. The water level of Sumxi Co-Longmu Co paleolake reached a maximum, about 230 m above the present lake level, attributed to the highstand documented by the sediments study and dated at 7.7–6 kyr B.P.. The lake regressed suddenly by at least 160 m, within about 120 yr. This abrupt regression appears to have occurred at times of climatic conditions similar to the present ones, for which the present lake is at equilibrium. By contrast, at 7.7–6 kyr B.P., there has been enough water supplies by ice melting and precipitation to compensate for evaporation over the ten times larger paleolake (≈1000 km²).

The abrupt disruption of the lake balance could be related to different causes such as: (1) sudden decrease of the precipitation–evaporation balance, (2) total depletion of a finite water reservoir such as an ice sheet; (3) return to cold condition that would have inhibited ice melting; (4) sudden decrease of the catchment area due to a topographic threshold effect. The fact that many other lakes in Tibet are reported to have shown high levels in the middle Holocene and are also surrounded by abandoned shorelines supports the hypothesis of regional cause. Since there is no evidence for the existence of a large ice sheet in this part of Tibet, we favor the hypothesis of a sudden decrease of the precipitation–evaporation balance. Some lakes in eastern Africa have also experienced rapid middle Holocene regression (Van Campo and Gasse, 1993), it could reflect an important modification of the monsoonal circulation at that time.

It seems however unlikely that an abrupt climatic change alone could have induced such a rapid lake regression, unless some threshold effect is advocated. At time of the lake level higher stand (t230) incoming water to compensate evaporation should have been $16 \times 10^8$ m³/yr ($S_{230} \times Ev$, i.e. 8 times higher than present one ($S_0 \times Ev_0 = 1.9 \times 10^8$ m³/yr)). This simple calculation assumes a potential evaporation at $t_{230}$ equal to the present value, although it was probably less than that. In any case, even with a modification of monsoon, it seems unlikely that precipitations could have been high enough to provide such an amount of water. The effective drainage basin of Longmu-Sumxi lake at $t_{230}$ could have been significantly larger than at present if some of the neighbouring closed basins were occupied by lakes high enough to reach the topographic thresholds and feed Longmu-Sumxi Lake.

An unexpected result of this study is that a 9–12 yr climatic cycle seems to show up in the shoreline record which might be related to some climatic perturbation forced by the sun spot cycle. Levelling other profiles across abandoned shorelines of other Tibetan lakes ought to permit verification of the inference of such a periodic signal.

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References


