Late Quaternary Glacial History of Northeast Tibet
Frank Lehmkühl, Lewis A. Owen and Edward Derbyshire

Abstract

The nature and extent of past and present glaciation on the Tibetan Plateau is reviewed. Geomorphological and sedimentological data are presented from key areas in northeastern Tibet that include: the source lakes of the Huang He and its surroundings; Yeniugou; the Nianbaruyeze Shan and its hinterland, including the Aba Basin; the Zoige Basin; and the marginal ranges of southeast Tibet. These data show a strong regional control on snowline elevations both today and during former glaciations. Present snowlines rise by about 100 m for each degree of longitude westward, from 4,800 m in the southeastern part of the plateau to more than 5,300 m in the northwest margin of the plateau. During the Last Glacial the snowlines ranged from 4,000 m to 4,700 m between the southeast and northwest of Tibet. The Pleistocene snowline depression, therefore, ranged from 600 m to 800 m. These results, together with other field evidence, show that no ice sheet existed during the Last Glacial Maximum across the northeastern margin of the plateau. Rather, glaciers and ice caps extended outwards from the main mountain ranges.

KEYWORDS: Tibet; glaciation; permafrost; ice contact fans; equilibrium line altitudes.

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Introduction

The nature and extent of Pleistocene glaciation across the Tibetan Plateau has been a contentious topic since the beginning of this century. Early Western explorers brought back conflicting evidence. Hedin (1925) considered the plateau too dry to sustain large ice sheets, while Tafel (1914), Trinkler (1930) and Ward (1922, 1930 and 1936) argued for extensive ice sheet coverage in some areas. Some foreign scholars, notably Sinizen (1958), maintained the belief that the whole of the Tibetan Plateau was covered with ice during glacial times. Similarly, Wang and Chung (1965) used evidence based on the former extent of lakes, U-shaped valleys, moraines and erratics down to 4,200 m to argue for a fairly continuous ice cover on the Tibetan Plateau during Late Quaternary times. Cui (1964), however, argued that glaciation was restricted to small glaciated areas. By 1980, the consensus in China was firmly in support of limited glaciation (Zheng, 1989). Opinion favouring only limited glacial cover of the Tibetan Plateau strengthened following the intensified geological exploration of the plateau by units of the Chinese Academy of Sciences between 1950–1980.

The opening up of China to foreign travellers and scientists in the 1980s, however, has served to renew the debate. With the increased attention given to all aspects of global change, the presence or absence of an extensive sheet ice over Tibet has become a key issue. This is because of the influence of the Tibetan Plateau on the general circulation of the atmosphere (Bolling, 1950) and, in particular, its role in causing variations in the Asiatic monsoon (Ruddiman & Kutzbach, 1989, Prell & Kutzbach, 1992). At present, two main contrasting views exist. The most extreme is that of Kuhle (1985, 1987), who postulated that an extensive Pleistocene ice sheet on the Tibetan Plateau covered 2–2.4 million km² and reached up to 2.5 km in thickness. In contrast, Li et al. (1991), Shi et al. (1992) and Derbyshire et al. (1991) expounded the view that ice cover was less extensive, with an ice cap covering only about 297,000 km². In addition, Hövermann and Lehmkühl (1994), Lehmkühl (1995) and Lehmkühl and Liu (1994) provided evidence that glaciation of the eastern margin of the Tibetan Plateau occurred by expanded ice caps rather than an extensive inland ice sheet. An even more limited ice cover was suggested by von Wissmann (1959).

The extent of the Last Glacial Maximum (LGM) and older glaciations, on and around the Tibetan Plateau has now been extensively mapped by Chinese scientists. Although there are differences in detail between one worker and another (for example, Zheng and Jiao (1991), Shi (1992), Shi et al. (1992) and Li et al. (1991)), they all broadly agree that glaciation on the Tibetan Plateau was of limited extent and of mountain and plateau type. The most extensive map of glacial reconstructions for the whole of Tibet was published in 1991 at a scale of 1:3,000,000, with selected regions enlarged (Li et al., 1991; Shi et al., 1992; Fig. 1E). This map was based on field investigations, aerial photogrammetric work, satellite imagery and 1:100,000 scale aerial survey topographic maps of the entire plateau. The map shows ice-scultped landforms, prominent moraines, glacialfluvial plains and fans, and paleolakes and shorelines. However, this map also highlights a number of questions worthy of detailed investigation. It shows, for example, a small ice sheet (morainic platform) of the penultimate glaciation in Northeast
Figure 1. Various reconstructions for the last glaciation maximum on the Tibetan Plateau. The numbers in part A show the mountain areas at the northern and eastern margins of the Plateau where remnants of older glaciation are described (see text for details).
Figure 1. (Cont.) Various reconstructions for the last glacial maximum on the Tibetan Plateau.
Tibet in the source area of the Huang He. Shi et al. (1992) suggested that this ice sheet may have been larger than the reconstruction shows. Lehmkuhl and Liu (1994) pointed out a need for detailed field observations to test the validity of both the map and the glacial reconstructions of Li et al. (1991) and Shi et al. (1992).

One of the main reasons for the differing opinions on the extent and distribution of Pleistocene glaciation in and around the Tibetan Plateau is the lack of a uniform stratigraphic nomenclature for ice-marginal and glacial landforms and stratigraphy throughout the region. In many cases, the Chinese Pleistocene stratigraphy has followed the classic model of Penck and Brückner (1901–1908) for the glaciation of the Alps. Following Penck and Brückner’s four-glaciation stratigraphy, Chinese workers have sought to divide their glacial sequences into three to four Pleistocene glaciations with similar time frames. In the Tanggula Shan (Shan is chinese for Mountains) at the centre of the Tibetan Plateau, for example, Zheng and Jiao (1991) have assigned moraines that were more or less directly in front of the recent glaciers to the Last Glacial (Würmian of Penck and Brückner), and the terminal moraines situated outside them were correlated with older glaciations. As Hövermann and Lehmkuhl (1994 a and b) and Lehmkuhl (1995) clearly highlighted, the “older” moraines are very fresh and have thin layers of solifluction debris on them and little or no loess cover. In fact, these “older” forms are of Late Glacial age, while the younger moraines probably date from the Holocene. Such observations illustrate the problems within much of the Chinese work, arising from attempts to assign ages to glacial landforms based on the outdated glacial framework of Penck and Brückner.

Despite the preconditioning of opinions arising from the dominance of Penck and Brückner’s glacial stratigraphy, even in China, unequivocal evidence for at least two to three Pleistocene glaciations has been found in the mountain ranges on the margins of the Tibetan Plateau. These can be distinguished on the basis of weathering criteria, the nature of loess and solifluction deposits that overlie the moraines, and the associated terrace sequences. For example, two glaciations are recognized on the northern slope of the West Kunlun Shan (Fig. 1A: location 1) Hövermann & Hövermann, 1991, three glaciations on the northeastern border of the Plateau, in the Dalija Shan (Fig. 1A: location 2; Li & Pan, 1989), three glaciations on the northern slope of Nianbaoyeze (Fig. 1A: location 3; Lehmkuhl, 1995) and two glaciations on the Yulongxue Shan (Ives & Zhang, 1993) (Fig. 1A: location 4).

Nevertheless, debate continues on the question of ice margins on the northern and eastern edges of the Tibetan Plateau. As Trinkler (1930) recognized long ago, U-shaped valleys are common in the Kunlun Shan and, on this basis, he argued for extensive ice in western Tibet. Zheng et al. (1990) and Li and Shi (1992) found evidence of only limited glaciation in the Kunlun Shan while Hövermann and Hövermann (1991) found moraines of the last glaciation as low as 2,000 m in this region and inferred an ELA (Equilibrium Line Altitude) of about 4,000 m. The same type of arguments have driven research on the eastern margin of the Plateau (see Lehmkuhl & Liu, 1994; Lehmkuhl, 1995). On the eastern slopes of Mt. Gongga, the Mozixian accumulation (29°37′N/102°05′E) of coarse boulders and gravels, up to 4 x 4 x 4 m in size at 1,750 m, have been regarded as remnants of a former glacier (Heim, 1933; von Wissmann, 1959) with an ELA of about 1,450 m. The modern glacier terminated at about 2,900 m and the ELA-depression can be calculated of about 1,000 m, which is in accordance with cirque altitudes at 4,100 m in the surrounding area. Other authors (e.g. Berkner, 1991) have argued that the Mozixian accumulation was deposited by an extreme flood event and have rejected the idea of glacial ice as low as 2,900 m. The same debate surrounds the Zaguan diamicton (see below).

In view of the above controversy, it is useful to consider the different concepts and arguments underlying the various interpretations of the field evidence, particularly the data on sediments and landforms. The area of study is particularly large, yet the interpretation of the Quaternary glaciations is based only on a few small isolated sites. The regional field relationships, as well as the interpretation of landforms, are often controversial.

Models of Tibetan Plateau Glaciation

The six maps in Figure 1 show the various reconstructions of the Last Glaciation Maximum (LGM) on the Tibetan Plateau. These are discussed in detail by Hövermann and Lehmkuhl (1993). The first map (Fig. 1A) is from Klute’s (1930) and shows the distribution of glacial ice in High Asia during the Last Glacial. He believed that ice was more extensive in the western part of the Plateau as well as in the mountain ranges towards the east which extend to longitude 90°E in the area of the Three River Gorges. Klute’s (1930) view, however, was based on the poor knowledge of the relief of Tibet common at that time. Klute’s (1930) model of climatic change during the last glaciation was based on a temperature depression of 4°C, with a shift of the climatic zones towards the south and an intensification of the atmospheric circulation such that precipitation increased towards the dry areas of central Asia. This, and the weakening of the monsoon circulation because of the cooler climate, was believed to have caused a more extensive glaciation in the western part of the Tibetan Plateau compared to the eastern part. Klute’s (1930) map was in agreement with the field observations published at the time.

Frenzel (1960) showed a very restricted LGM ice extent on his map of the Tibetan Plateau (Fig. 1B). This was based on the detailed work of von Wissmann (1959), who evaluated the observations of the earliest explorers. This early work was essentially based on ice margins landforms and moraines, and included calculations of the modern and Last Glacial ELA and the ELA depressions. The evaluation by von Wissmann was based on two main principles: 1) more confidence could be attached to those ice margins identified by different researchers; and 2) the ice margins were of Last Glacial age. This method took into account the higher ice margins only and, in some areas, discounted the lower ones which were attributed either to an earlier glaciation or to non-glacial depositional processes. Some of these lower moraines may also be Last Glacial in age. If this is so, then von Wissmann’s map is valid only as an estimate of the minimum extent of former glaciers during the LGM. However, in some areas parts of the margins may be Late Glacial rather than of LGM age. This model contrasts with Klute’s because it invokes a diminution of climatic change during the LGM towards the arid regions and towards the higher altitudes in central and High Asia. In addition, the ELA-depression is less at higher altitudes and in the more arid areas. Therefore, the extent of the glaciation is greater on the eastern margins of the Tibetan Plateau than on the western side.

An alternative view of late Quaternary glaciation on the Tibetan Plateau is provided by Russian Scientists and published in Academia Nauk CCCR (1964: Fig. 1C). The Russian Atlas shows extensive Pleistocene glaciation in Central Asia. All the mountain ranges at the margins of the Tibetan Plateau are shown as having been glaciated as far as their forelands. The basins of Qinghai Hu (Hu is chinese for lake) and Qaidam, as well as of the interior of the Tibetan Plateau, were mapped as ice-free,
although the lakes were thought to have been much more extensive. The view of the extent of ice in the southeastern sector of the Tibetan Plateau towards 26°N is interesting, because it includes the extensive lake section around Dali.

Von Wissmann (1937) suggested that the name Dali be assigned to the youngest glaciation in China, corresponding to the Alpine Würm, particularly because the name Dali refers to the youngest Quaternary unit at the southernmost edge of visible glaciation, which is based on cirques that are at altitudes of about 3,700 m, described at that time in China. This name is still used in Chinese Quaternary stratigraphy. There may have been some misinterpretation of evidence, especially by Russian workers who interpreted the lakes at about 2,000 m as glacially-dammed. This model shows a greater contrast between the marginal ranges and the interior of the Plateau.

The model of Kuhle (1985) shows a similar ice extent in the marginal ranges to the previous model, but in contrast to the Russians, he shows an ice sheet covering the whole of the Tibetan Plateau (Fig. 1D). This view is based on field observations along the northeastern, western and southern margins of the Tibetan Plateau. Kuhle makes an almost linear connection between the Pleistocene elevations of the ELA on the northeastern and southern margins of the Tibetan Plateau. In this way, it is inferred that the whole Tibetan Plateau lay above the ELA during the LGM. However, this line of argument fails to take into account a rise of more than 400 m in the ELA towards the interior of the Plateau because of a decline in precipitation and an increase in temperature (the so-called Massenerhebungseffekt of Troll, 1955).

The case for such a large ice sheet in the central parts of the Tibetan Plateau is mainly based on morphological forms such as roches moutonnées or flat-floored U-shaped valleys, glacially polished rock surfaces and remnants of moraines, all of which provide convergent evidence. Han (1991) argued on the same basis for an older (middle Early Pleistocene) ice sheet covering the entire Tibetan Plateau. He estimated that the altitude of the Tibetan Plateau was about 2,000 m at that time and calculated a snowline of 1,800 m for southern Tibet and 1,600 m for the Kunlun Shan on the northern margins. Arguing that such a 1.7 km thick ice sheet would have caused isotatic uplift after melting, he estimated that the ELA lay at 700 to 1,300 m a.s.l. (the current ELA being about 4,400 to 6,000 m). The claim that snowlines were of such low elevation in subtropical latitudes calls to mind the well known controversy on the supposed glaciation of the Lushan in southeastern China (Derbyshire, 1983).

The glacial reconstruction map used by Shi (1992) is based on a detailed 1:3,000,000 scale map produced by Li et al. (1991: Fig. 1E). This reconstruction shows that glaciation was restricted to the higher mountain ranges, dated by lacustrine sediments within moraines (in western Tibet 47 to 35 ka and 21 to 15 ka) as Last Glacial Maximum, and here interpreted as about 18 to 16 ka. The map is based on morphological investigations and mapping of the glacial erosional features such as cirques and U-shaped valleys as well as terminal and lateral moraines. In the marginal mountains, diamictics often interpreted in the older literature as moraines are here interpreted as mudflows and debris flows. As a result, the extent of glaciation is more restricted in those areas. These two maps (Shi et al., 1992; Li et al., 1991) differ from each other in some areas, illustrating the different opinions that have arisen about the age of some moraines. A new departure is the view that an ice sheet of some 50,000 km² in area occupied the source region of the Huang He between 33° and 35°N and 96° and 99°E, during the penultimate
glaciation. The great uncertainty about the extent of ice on the Tibetan Plateau during the LGM can be seen in the Atlas of Paleoclimates and Paleoenvironments of the Northern Hemisphere, edited by Frenzel et al. (1992). In the maps showing the conditions 20 to 18 ka ago, the glaciated area is restricted to the highest mountain peaks in a similar manner to the map of Frenzel (1960, see Fig. 1B). In the map by Conchon et al. (in Frenzel et al. 1992, p.49, Fig. 1F) the glaciation is fairly continuous in the western parts of the Plateau, much more so than in the east, and an almost complete ice cover is shown over the mountains. This map thus seems similar to that of Klute (Fig. 1A), although the detail is better due to the advances in factual knowledge of the Plateau since Klute's time.

Using new and previously published data, this paper will examine the evidence for the extent and style of Pleistocene glaciation in eastern Tibet. This paper is based on a series of studies along a 600 km long NNE—SSW traverse between Xining (upper Huang He (the Chinese River)) and Yushu (upper Yangtze drainage system), on the northeastern edge of the Tibetan Plateau. Sites of principal interest include the source lakes of the Huang He and the northeastern margins of the Tibetan Plateau. The latter includes Yenigou, the Nianbaoeye Shan, the Aba Basin and the Zoige Basin on the eastern fringes of the Plateau (Fig. 2).

The North-Eastern Tibetan Plateau

The North-Eastern Tibetan Plateau comprises a series of NW–SE trending mountain ranges (e.g. the Anyêmaqên Shan and the Bayan Har Shan) separated by basins, many of which contain lakes (e.g. Chaling Hu & Ngoring Hu (Hu is Chinese for lake)). The heights of the basins average between 4,200 and 4,500 m, with surrounding peaks rising to more than 6,000 m a.s.l. (Fig. 2).

The area considered in detail in this paper may be divided into four distinct terrains (Fig. 2): the northeastern edge of the Tibetan Plateau; the mountains of the Anyêmaqên; the high Plateau surface containing the source lakes of the Huang He, i.e., Ngoring Hu and Chaling Hu; and the mountains in the upper reaches of the Yangtze River. Geologically, the region comprises Permian and Triassic siliciclastic rocks and limestones which have undergone low grade metamorphism, and acid to intermediate intrusive. The main geological structures trend NW–SE, consisting mainly of reverse faults that bound many of the small mountain ranges and delimit the Tertiary and Quaternary intermontane basins.

The climate is semi-arid with mean annual temperatures between 1 and -4°C. The winters are cold with mean January temperatures between -12 and -16°C, with minima reaching as low as -24°C in the coldest years for altitudes up to 4,200 m. Mean annual air temperatures are 0.5°C at Zoige (3,447 m a.s.l.) and -4.1°C at Maduo (4,272 m a.s.l.). Altitudinal and geographical control is quite strong. Temperatures are controlled by altitude, decreasing northwards at a rate of 0.5°C/100 m. The precipitation is also controlled by local factors such as relief and windward-leeward situations. For example, in the Anyêmaqên Shan precipitation exceeds 800 mm a¹ at the snowline (approximately 4,950–5,000 m) and 1200 mm a¹ on the mountain summits. In contrast, at lower elevations within the basins, precipitation may be as low as 300–500 mm a¹ (Wang & Derbyshire, 1987), although it increases towards the east. The precipitation is derived largely from the East Asian summer monsoon, with precipitation falling mainly during May to August along the Plateau’s eastern margins. In general, precipitation decreases towards the northwest and also towards the centre of the Plateau.

In the south (e.g. along the southern slopes of Nianbaoeye and the Bayan Har Shan), late summer (August to September) climate is also influenced by the South Asian monsoon. In the Zoige Plateau, at the eastern end of the study area, precipitation totals 649 mm a¹, but is only 360mm a¹ at Maduo in the northeast (Dornos & Peng, 1988).

The intermontane basins within the field area are elongated in a northwest-southeast direction. These basins are delimited by steep mountain ranges and are fringed by extensive, gently-sloping pediment fans (e.g. fans east of Huashixia). The fans are made up of thick gravels, capped with a thin cover of loess. However, some fans consist mainly of gently dipping bedrock capped with thin gravels (see discussion on ‘ice marginal ramps’, below). Lakes occupy many of these basins, including those of tectonic origin (e.g. Qinghai Hu-Lake). Other lakes are the result of drainage dammed by the spread of large sand dunes as around Maduo (e.g. Mianhaling, 34°45’N/98°8’E). Around Maduo, at altitudes above 4,200 m, small thermokarst lakes are common within the basins or on the floodplain of the Huang He.

Northeastern Tibet is drained by two great river systems, the Huang He to the east and the Yangtze River to the southeast. These rivers and their tributaries cut deep gorges along the edge of the Tibetan Plateau (e.g. at Tiannalbel). Elsewhere, thick valley fills are present. Today, glaciers exist only in the Anyêmaqên Shan and are of valley, cirque and hanging types. The Anyêmaqên Shan also have one small ice cap with a total area of 120 km². The valley glaciers descend to altitudes of between 4,500 to 4,550 m a.s.l., with the ablation zone extending through a depth of 450 m. Glaciers have developed mainly on the western and southern slopes of the Anyêmaqên Shan, beneath peaks greater than 6,000 m.

Evidence for Quaternary Glaciation:

a regional review

There is considerable contention over the criteria used to distinguish glaciated from non-glaciated landscapes in Tibet. Evidence is based on three main criteria: valley form; ice marginal ramps; and sedimentology.

The most problematical approach adopted in the past has been to use valley form to reconstruct past glaciations. Throughout the region most of the valleys are broad and U-shaped. Their form may be attributed to either glacial erosion or periglacial mass wastage, or both. Particularly impressive is the extensive mass wasting on many of the high peaks (e.g. the peaks of the Dongjunichang Shan, 34°31’N/ 99°16’E). These summits are unlikely to have been covered with ice during the Last Glacial.

At other locations, the valleys have impressive terraces and any evidence of glacial landforms may have been destroyed or buried. At Wenquan village, for example, the valley shows little evidence of glaciation, but has impressive terraces rising to 20–30 m above the present river level. These terraces are dissected fans. Where sections are available, these fans can be seen to consist of phyllite overlain by moderately rounded, imbricated polytomic gravels with a crude down-valley stratification. These units are overlain by pebbly gravels with intercalations of silts. The section is capped by aeolian silts 0.5 to 1 m thick.

Kuhle (e.g. 1984; 1987a; 1988; 1990; 1991a) has used landforms that he calls “ice-contact ramps” to support the view that extensive ice sheets and glaciers covered most of the Tibetan Plateau during the Last Glacial Maximum. The landforms in question have the appearance of extensive fans which slope at several degrees away from supposed former ice margins and have steep (reversed) scarp slopes at their highest points interpreted
as an ice-contact face marking the former ice margin. However, very similar landforms may be produced by the erosion of both pediment fans and bedrock (cf. Derbyshire et al., 1991; Lehmkühl, 1995).

Sedimentological evidence provides the best means of reconstructing former glaciations. Thin veneers of till are present at numerous locations along the Xining-Yushu traverse. Typically, they comprise massive matrix-supported diamictons, with edge-rounded and bullet-shaped clasts, from pebble to boulder size, in a clayey-silt matrix. In the majority of locations, intensive cryogenic heaving has destroyed any evidence of sedimentary structures. Such intense cryoturbation may also lead to the misinterpretation of sediment types, as is the case at Duogerongtan, where cryoturbated marlstones and clays have been misinterpreted as lodgement tills in some preliminary work by Lanzhou University.

At some locations, tills are easily indentifiable. Along the highway south of Yematan (34°36'N/98°E), metre deep excavations reveal massive matrix-supported diamictons, containing edge rounded, bullet shaped striated cobbles of psammites, phyllites and granites, set in a clayey-silt matrix. Large granite erratics on the surface of the landscape have a strong long axis orientation trending between 320° and 030°, indicating an ice flow direction from the Bayan Har Shan approximately 60 km to the SW.

The detailed glacial geomorphology and Quaternary successions in each part of the study region are outlined below.

**Source lakes of the Huang He**

This area is characterized by small W-E-trending basins, at altitudes of between 4,170 to 4,300 m a.s.l. The source lakes of the Huang He, the Ngoring Hu (Oring Tso) in the west and the Chaling Hu (Tsaring Tso) in the east, are present within these basins (Fig. 3). The basins are approximately 30 km wide and stretch for several tens of kilometres. Hummocky mounds are present throughout these basins on old penepelain surfaces, with altitudes up to 4,500 m (Lehmkühl & Spöhnemann 1994). In the north, the source area of the Huang He is limited in extent because of the Buqin Shan. These mountains comprise Palaeozoic rocks and reach an altitude of more than 5,100 m. They lie parallel to the main crest of the Burfan Bualai Shan, 30 to 40 km further north. The Buqin Shan is the watershed between the Huang He to the south and the internally drained Qaidam Basin.
to the north. To the south, the basins are limited by the NW-SE trending Bayan Har Shan, the main water divide north of the Yangtze riversystem. The mountains are covered with decimetre-thick soliflucted colluvium and aeolian (sand and sandy loess) Quaternary sediments. Colluvium is present on slopes and hills covered by alpine meadows to an altitude of 4,500 m in the north and 4,800–5,000 m in the south. Widespread peat bogs (the naka-moore described by Tafel, 1914), with permafrost are present within the basins. Occasionally, active and fossil sand dunes are also found, especially in the Huang He valley and in the surrounding small lakes south of the upper Huang He; the so-called finger lakes. In the area of the upper Huang He, north of the Chaling Hu, seven different landscape units can be recognised (Fig. 3). From North to South they include:

1. The mountain range of the Buqin Shan (4,700 to 5,153 m), comprising Palaeozoic rocks;
2. The sub-montane region of the Buqin Shan (4,600 to 5,028 m), comprising Triassic and Jurassic rocks;
3. The Tertiary basin in the foreland of the Buqin Shan (4,400 to 4,600 m);
4. Uplifted older fan deposits (equivalent to Kuhle's “ice-contact-fans”) (4,340 to 4,590 m);
5. Alluvial fans (4,250 to 4,400 m);
6. The floodplain of the Huang He (4,276 to 4,240 m); and
7. The fault scarp and pediment remnants at altitudes of between 4,350 and 4,500 m, consisting mainly of Palaeozoic rocks.

The most dramatic and contentious landforms in this region are those classified as “ice-contact fans” by Kuhle (1990). These landforms (Fig. 4) slope SSW towards the Chaling Hu and Ngoring Hu and are best examined near the gold diggers' camp sites at 35°14'N/97°44'E (black arrow in Fig. 3). The “ice-contact fans” are triangular in plan and slope away from the mountain front at angles of between 1.3 and 1.9° greater than those of the surrounding valley floors, which slope 0.6–0.8° (Figs 5 and 6). The highest point on these fans is between 100 and 140 m higher than the surrounding Tertiary basin. The tops of the “ice-contact” fans are shown by the dots in Figure 3. The surface slope of the fans is 2° southwestwards from an altitude of approximately 4,660 m to approximately 4,250 m at Chaling Hu. Kuhle (1991) reported that these fan-like forms slope at between 7 and 10°, but our measurements all fall within the range 1 to 2°. The northern margins of the ‘fans’ are bounded by steep, reverse (N facing) scarp slopes that are at right angles to the sloping surface of the ‘fan’. These scarps descend more than 50 m to a terraced landscape drained by SE flowing streams, running parallel to the scarp slope. The southern slopes of the Buqin Shan are surmounted by fans of similar geometry, but they are less extensive. Exposures within the “ice contact fans” at the gold diggers’ camps show that they consist of Tertiary red marlsstones with an occasional decimetre-thick bed of cross-stratified sandstone. These red marllstones can be traced in exposures northwards. Eroded remnants of marlstone are also exposed over several hundred metres on the lower slopes of the Buqin Shan. It is within these sediments that the miners are recovering gold. The Tertiary rocks are capped by a 2 – 3 m thick layer of unconsolidated gravels.
They consist of green meta-sandstones and phyllites, with occasional granite clasts. The pebbles are well rounded with a moderately high sphericity and most are frost-shattered. These gravels are extensive and can be traced towards the Buqin Shan, the southernmost range of the Burhan Budal Shan. They maintain their thickness right up to the apex of the fan-like landforms. These gravels are capped by a 50 cm thick sediment. A soil sample taken at an altitude of 4,520 m from a depth of 40 cm consists of reddish-yellow (Munsell 5.5YR7/6) clayey silt (37.7% clay, 45.6% silt and 16.7% sand). Such clay-rich sediments are not found as a surface mantle elsewhere in eastern Tibet. However, similar lithologies are present within Tertiary strata (Lehmkuhl, 1995).

Figure 6 shows a schematic section through these landforms
from the Buqin Shan towards the Erling Hu. The fan surfaces contain small periglacial dry valleys. Clearly, these fan-like landforms are not constructional features of ice-contact origin as suggested by Kuhle (e.g. 1984; 1991a). Rather, they are the result of deposition of intermontane basin sediments during Tertiary times. These were then faulted to produce impressive cuestas, the backslips of which dip south-westwards. They are probably bounded by faults to the north of the scarp slope. The impressive terraces to the north of the scarp may be the consequence of faulting or erosion as streams were redirected to the east after scarp formation. The gravels capping the fans are probably of pediment type, deposited by streams draining from the Buqin Shan prior to a period of extension and faulting. These gravels are interpreted as Tertiary or early Quaternary fluvial deposits, later uplifted within the basin and incised by fluvial erosion. At present, none of the streams on the main fans is large enough to carry such gravels. In addition, there is no facies change towards the apex of the fans as would be expected if these were of ice-contact origin. On the contrary, the high degree of frost-shattering suggests that these gravels may be residual deposits weathered from the upper layers of the Tertiary conglomerates after faulting. Some other authors have also interpreted such sediments as of Early Quaternary/Late Tertiary age (e.g. Derbyshire et al., 1991).

There are no indications of ice contact on these fans, the surface gravels being well rounded and overlain by a reddish soil. However, at the base of the 140 m high fan, where it abuts the scarp slope of the older fan (on the right side of the transverse valley close to the southern edge of the Tertiary basin: arrow in Fig. 3), there is an accumulation of a diamicton some 8 to 10 m thick. Clearly, this is quite distinct from the main fan. It shows both edge-rounded and sharp gravels and pebbles, as well as some boulders up to 50 cm in diameter at the base. There are some cryptoburial structures within this deposit. It is overlain by 50 to 60 cm of massive silt with a well developed palaeosol (remarkably better developed than the Holocene soil, and so perhaps dating from the Last Interglacial: Fig. 7). The palaeosol is overlain, in turn, by a 160 cm-thick cryptoturbated diamicton. The sediments at the base, underlying the well developed soil, may be of fluvial or glacioluvial origin. The upper diamicton is a solifluction layer that formed during the Last Glacial and was overlain by loess during Late Glacial times.

There is some evidence of late Quaternary glaciation in the region. Around a pass at 35°05′N/98°42′E in the Buqin Shan range (to the south of the small settlement of Huashixia), somewhat degraded cirques lie at altitudes of between 4400 to 4500 m. In addition, there may be older remnants of end moraines near Huashixia, at altitudes around 4200 m.

Satellite images and aerial photographs show moraines and glacial erosional landforms, attributed here to late Quaternary glaciers (LGM), that extended more than 40 km beyond the main range of the Bayan Har Shan. These include terminal moraines enclosing a lake basin 30 km towards the north of Chaling Hu, at 4,412 m (34°30′N/97°43′E; marked by three stars in Figure 3). Figure 6 also shows north-south aligned lateral moraines that link U-shaped valleys in the south. These well-developed glacial landforms have a thin (1 to 3 cm thick) cover of aeolian silts and
sands, probably representing only a brief period of deposition. On this basis the moraines are attributed to the Last Glacial Maximum.

The old fan remnants north of the Chaling Hu fit well into the west-east-trending tectonic lineaments. In all probability, there is a west-east trending fault line along the northern edge of the fan, paralleling the other tectonic structures (see Fig. 3). The surficial sediments here are unusually reddish in the upper half meter (Munsell colour 5.5YR 7/6) and contain 37.7% clay-grade, matching closely the characteristics of Tertiary sediments from the surrounding region and contrasting sharply with the Quaternary silts and sands. In contrast, Kuhle (1984, 1987a and 1991a) interpreted them as glacial forms produced by an ice-sheet during Late Glacial times. In view of their sedimentological characteristic, however, they cannot be used to infer the former extent or existence of an extensive glaciation.

The smooth and undulating relief in this area (Fig. 5) contrasts sharply with the mountain crests northeast of Madoi and in the upper Huang He region. These smooth landforms led Li et al. (1991) and Shi et al. (1992) to postulate the existence of a large regional ice sheet (50,000 km²) during the penultimate glaciation, confined within the area between 33 and 35°N and 96 to 99°E (Fig. 2). No glacial sediments are found in this area. The only unequivocal glacial sediments are those south of Madoi and in the area of the finger lakes on the northern slopes of the Bayan Har Shan. The most distant erratic boulders of granite, derived from the central Bayan Har Shan, are found 67 km north of the Bayan Har Shan pass, near the settlement of Yemutan (34°32'N/98°E) at an altitude of 4,260 m (one star in Fig. 3). However, there are no moraine ridges hereabouts, the boulders being associated with sandy silts only decimetres thick. Their obvious provenance from glaciers flowing out of the Bayan Har Shan supports the early work of Tafel (1914). However, the age of these deposits

**Figure 7.** Exposure in a fan north of Chaling Hu containing a diamicton at the base overlain by 50 to 60 cm thick massive silt with a well developed palaeosol. On top of this is a 160 cm thick diamicton that is interpreted as a solifluction deposit.

**Figure 8.** Exposures in the hills surrounding Xinxin Hu, south of Madoi. Different solifluction, aeolian and lacustrine deposits indicate various climatic stages. At least two higher lake levels, 5 and 17 m above the recent lake level are present.
remains unknown. Morphological studies using satellite images support the possibility that a small ice sheet of relatively greater age was present on the Bayan Har Shan and that it extended as far as the Chaling Hu and the finger lakes. The diamict on the steeper side of the uplifted older fan mentioned above was probably deposited during this glaciation.

On the basis of the terminal moraines surrounding a small tongue basin at an altitude of about 4,400 m a.s.l., the ELA of the last glaciation has been calculated by Lehmkuhl (1995) at between 4,750 to 4,830 m. Near Yematran, erratices are present at an altitude of about 4,300 m. These were probably deposited during the penultimate glaciation, when the ELA was between 4,550 and 4,580 m. Since there are no modern glaciers in the Bayan Har Shan, the current snowline is clearly higher than 5,300 m. Thus, the ELA-depression is probably about 700 m. To the north of the Chaling Hu, the snowline of the Last Glacial Maximum was about 4,800 m, while further to the east it lay at 4,500 m. These data show clearly that snowlines rise towards the interior of the Tibetan Plateau.

An older glaciation probably reached the northern margin of the Chaling Hu from the Bayan Har Shan. The map in Li et al. (1991) shows an extensive ice body on this part of the Tibetan Plateau during the penultimate glaciation, although the evidence for such a glaciation of this age has yet to be confirmed.

In the source area of the Huang He, south of the settlement of Madoi near the pass to the Xinxin finger lake (34°52'N/98°08'E), an exposure at 4,290 m reveals ice-wedge casts at the top of a small hill (Fig. 8A). These ice-wedge casts are filled up to 2 m deep with reddish fine sand (from the north) and are overlain by a thin layer (5 cm) of solifluction debris and a 50 cm thick deposit of yellowish aeolian silt, in which the Holocene humic layer is clearly seen (Lehmkuhl 1995, Hövermann & Lehmkuhl 1994a). The ice wedge casts can be dated to the LGM (cf. Derbyshire et al., 1991). The map of Li et al. (1991) indicates ages between 12 and 24 ka for ice wedges and an age of 45.2 ka for a higher lake level of the Chaling Hu. After the degradation of the frozen ground, the wedge became filled with reddish sand, indicating warmer climatic conditions, perhaps coinciding with the evidence for a drier (and possibly warmer) period at about 13 to 12 ka that is shown by the lacustrine records at Qinghai Hu (Kelts et al., 1989). The thin solifluction layer indicates cooler conditions, perhaps during the Younger Dryas. The development of black steppe soil horizons, and the various aeolian phases indicated by the loess and sand accumulations, may date from the Holocene. The sand wedge casts and solifluction layers support the view that the climatic conditions during the LGM were cold and arid. Karte (1990) showed that sand-filled wedge casts indicate rapid temperature reduction in cold-arid environments with mean annual air temperatures below -12 to -20°C and an annual precipitation of less than 100 mm a. Given that the present mean temperature is around -4°C, a temperature depression of -8°C is suggested for the LGM.

On a sloping site at about 4,248 m and >30 m above the modern lake level, two layers of solifluction debris overlies schist and lacustrine sediments (Fig. 8B). In some places the upper solifluction debris can be seen filling former ice wedge casts. Further downslope, at about 4,237 m (32 m above the recent lake level), the solifluction debris overlies a gytja. In addition, there are two higher lake levels, 5 and 17 m above the present water levels. At c. 23 m above the lake level (4238 m) some 2 m of aeolian silt layers are exposed. They contain more than 16% CaCO3 and are distinctly more sandy towards the top (at the top: 18.8% clay, 50.2% silt, and 31% sand; at the Bottom: 17.3% clay, 60.1% silt, and 16.7% sand). The higher content of sand and the presence of some small, rather angular pebbles towards the top of the profile (colluvium) indicate more solifluction and aeolian activity, perhaps of late Holocene (Neoglacial) age. Two TL dates were obtained from this profile at depths of 48 to 55 cm and 197 to 202 cm. The results (12 ± 1.0 ka and 18 ± 1.5 ka) indicate a Late Glacial age (for details see Lehmkuhl, 1995). Unlike the upper slope exposures, there is no solifluction debris underneath the loess-like sediments in this section, a fact that might be explained by a higher lake level at that time, in all probability that are Late Glacial and Early Holocene in age.

The sedimentary sequence at both Xinxin Hu and Chaling Hu, their palaeoclimatic interpretation and the record of landscape evolution are summarized in Table 1.

The northeastern margin of the Tibetan Plateau: Yeniuguu, Nianbaoyeze Shan, Aba Basin and Zoige Basin

The landscape between the Sichuan Basin in the east and the northeastern region of the Tibetan Plateau may be divided into two broad areas, and these further divided into subregions (Hövermann & Lehmkuhl, 1994a), as follows:

1. The catchment area of the Yangtze river system in the mountains west of the Sichuan Basin characterised by narrow valleys. This area includes the valley of the Minjiang He and the high mountain chains (e.g. the Minshan, highest point Xuebaoding at an altitude of 5,588 m a.s.l.) and the
upper Dadu He catchment. Deep fluvial incision has generated a landscape of steep slopes and narrow V-shaped valleys, with a relative relief of up to 3,000 m. Natural disasters are common and include rockfalls, landslides, debris flows associated with earthquakes and high river flood events following heavy summer rainfalls (Lehmkuhl & Pörtge, 1991; Tang et al., 1994). The gradients of the Yangtze tributaries are typically steeper than those of the Huang He catchment. The longitudinal gradients lie in the range 1–5% and waterfalls are common in the tributaries.

2. The upper Huang He catchment includes many old planation surface remnants, some higher mountain massifs (e.g. the granite massifs of Nianbaoyeze and Yanggongshan as well as the Anyêmaqên Shan) and some intermontane basins (e.g. the Zoige and Aba basins). The landscape is smooth with slope and stream gradients more gentle than those found in the Yangtze drainage system. In the tectonic basins, such as the Zoige or Aba Basins, the relative relief is only about 200–400 m. Meandering rivers with low gradients have developed on the flat valley floors

Yeniuguo

At Yeniuguo, approximately 7–8 km south of Yemantan, an 8–10 m high cliff section is exposed in a gently dipping fan-like surface at an elevation of approximately 4,175 m (34°32′N/98°E), on the southern edge of an extensive plain (Fig. 9). This section comprises decimetre-thick beds of clast-supported well sorted and rounded pebbles of brown green sandstones and grey phyllite. Centimetre-thick beds of sands and silts are interbedded within the gravels. Small channel fills consisting of silty sand, approximately a metre wide and tens of centimetres-thick are present throughout the section. Half way up the section, there is a 50–60 cm thick, laterally-continuous and well consolidated red sandy-silty diamicton containing small pebbles. This unit does not deform any of the underlying sediments. Towards the top of the section, the gravels are involuted and ice wedge casts are present.

Pebble imbrication within the gravels indicates that the palaeoflow direction was towards the NNE. The fan also slopes in a northerly direction and has prograded across an undulating surface made up of diamicton containing a mixture of edge-rounded and striated granite clasts. The fan rises some 10 m above the undulating surface. About 100 m north of this fan section, however, small degraded ridges containing granite erratics can be seen trending 075° to 080°. An extensive floodplain stretches into the distance to the south of the steep cliffs of the fan: it has no obvious landforms such as moraine ridges.

The above features suggest that streams flowed northwards to build the fan, which prograded on to an extensive sheet of till. Sediment sources for the fan may have been either fluvial aggradation during a period of high sediment loads or high sediment loads and discharges during deglaciation. The absence of any debris flow facies, other than the diamicton in mid-section, and the abundance of fluvial bedforms dominated by well rounded and well sorting clasts, suggests that fluvial deposition was the most likely process of formation. Since fan formation, incision has played a part in producing the extensive floodplain to the south and destroying any evidence of glaciation. Clearly, fan-like landforms cannot be used to delimit former ice margins if their internal composition and structure are not examined. Re-examination of these fan-like landforms, including an evaluation of the sedimentology of the constituent deposits strongly supports the view that glaciation was less extensive than proposed by Kühle (1990).
Figure 10. Distribution of Pleistocene glaciation in the Nianbaoyeze.

The Nianbaoyeze Shan

The Nianbaoyeze Shan lie in the transition zone between the marginal mountain ranges and the interior of the Tibetan Plateau. This is a critical region for the investigation of Pleistocene glacial extents in eastern Tibet because it is a transitional zone between the moist margins of the Tibetan Plateau influenced by the summer monsoon, and the dry Plateau interior.
The granite massif of Nianbaoze (33° 33'30"N/101° 10'2"E; Fig. 10) is situated on the main Huang He -Yangtze watershed, south-west of the “great bend” (first loop) of the Huang He. With a summit of 5,369 m, it rises about 800 m above the surrounding peneplain (the “main surface” of Lehmkuhl and Spöhnemann (1994) at about 4,400–4,200 m) and lies above the modern snowline. The peneplain is underlain by Triassic crystalline schists. The present glacial cover around the highest mountain peak of Nianbaoze has an area of about 5.1 km²; the present generalised snowline having been calculated at an average altitude of 5,100 m a.s.l. Pleistocene glacial landforms such as moraines, cirques and transient valleys are well developed and moraines and erratics composed of big granite boulders resting on a surface of crystalline schists clearly indicate the extent of former glaciers. Pleistocene glaciation was mainly restricted to the higher parts of the Nianbaoze massif and its environs. The restricted nature of the glaciation is indicated by moraines and erratic granite boulders on the slopes and valley floors. Such boulders are entirely lacking in the surrounding lower mountains, providing a clear picture of the maximum ice extent. This type of glaciation, with ice distributed on isolated mountain group, and individual massifs lying above the general Plateau elevation, was noted at several places in the eastern and central Tibetan Plateau (cf. Hövermann et al., 1993; Hövermann & Lehmkuhl, 1994b; Lehmkuhl, 1995).

In addition to several younger ice margins, different Pleistocene terminal moraines can be distinguished on the northern slopes of the Nianbaoze massif, using geomorphological criteria (Lehmkuhl, 1995: Fig. 10). Three main Pleistocene glaciations can be differentiated on the basis of relative weathering criteria of the overlying deposits (either aeolian sandy silt or solifluction debris) and palaeosols (cf. Lehmkuhl, 1995). Three main sets of moraines represent each of these glaciations, as follows:

1) The Ximencuo Moraine is well developed and comprises large granite boulders up to 4 m in length and with a thin (10 to 20 cm) sandy silt aeolian deposits that thickens to 40–60 cm on associated terraces. Several tongue basins in the central mountain areas, often with finger lakes, are characteristic of this glacial stage. The terminal moraine complexes comprise two to three ridges of large granite rocks, the first being approximately 20–40 m above the downstream valley floors. These terminal moraines are connected to a narrow, 6–8 m high terrace (terrace 1) in the northern and western parts of the Nianbaoze Shan (Fig. 11). Such moraines, consisting of large erratic boulders (the so-called “Big-Boulder-Moraine”), have also been found in other parts of the Tibetan Plateau (Hövermann & Lehmkuhl, 1994b; Hövermann et al., 1993; Lehmkuhl, 1995; Lehmkuhl & Liu, 1994).

2) The Jukuee Moraine, observed along the valley floor (Fig. 12), contains only a few granite boulders and is represented by lateral moraines at several places. It is also connected to a terrace (terrace 2), mapped on the basis of a series of remnants. These moraines are covered by a 50–70 cm thick layer of sandy loess. At some places, especially on the second terrace, the loess is also covered by layers of solifluction debris more than 1 m thick, e.g. adjacent to the Huang He. On the basis of the presence of the loess cover and the degree of weathering and erosion, this moraine is attributed to the penultimate glaciation. The basal layers of the sandy loess on the second terrace of the Huang He (just above the junction between the Jukuee He and the Ha'a river north-east of the Nianbaoze) confirms this correlation and have TL dates in excess of 200 ka (cf. Lehmkuhl, 1995).
Figure 12. Remnants of granitic erratics mark the ice margin of the Juhehe moraines in the Nianbaoyeze Shan.

Figure 13. Pleistocene terraces in the Aba Basin.
Basin of Zoige, Hei He (3420m a.s.l.)

Figure 14. Exposure in a bank of the Hei He (He = River) in the Zoige Basin.

3) The Ha'a Moraine is inferred from accumulations of a few erratic granite boulders (up to more than 8 m³). Such evidence has been found along the north-eastern and south-eastern margins of the Nianbaoyeze massif on the slopes and valley floors, several km in front of the Jiuxuehe moraine. As yet, there has been no clear evidence found to indicate the age of the glaciation responsible for this moraine.

In addition to these three main phases of Pleistocene glaciation, several younger stages have been recognised in the main valleys of the Nianbaoyeze Shan. These include a Neoglacial or younger Late Glacial complex and a historical complex. The latter probably represents the Little Ice Age. A soil buried beneath a lateral moraine gave a radiocarbon age of 1,385 ± 70 BP (see Lehmkulh 1997 for details) provides a minimum age for these moraine. Neither of the moraine systems have any aeolian cover. Other Lateglacial terminal moraine complexes occur downstream. These extend up to the Xinjucuo moraine, within most of the valleys in the northern part of Nianbaoyeze massif.

Radiocarbon dated organic material, mainly from peat bogs overlying the moraines, has yielded Holocene ages. This applies to the material obtained from in front of the terminal moraines of the LGM (cf. Lehmkulh, 1995). Radiocarbon ages of basal organic material provides only a minimum age for the terminal moraines, because the lag time between glacier retreat and the development of organic material can be in the order of several thousand years. Lehmkulh (1995, 1997) has interpreted the development of peat formation as coincident with the onset of humid conditions during the Holocene. The oldest humic layer within the Xinjucuo stage was dated at 9,185 ± 145 ¹⁴C years BP (cf. Lehmkulh, 1995; 1997). This provides a minimum age for the terminal moraines.

On the basis of TL dating of the loess cover on the first terrace associated with the Xinjucuo Moraine, the LGM is constrained to between 36 ka for the western Nianbaoyeze and 54/56 ka for the northern Nianbaoyeze (cf. Lehmkulh, 1995). This suggests that the maximum glacial extent during the Last Glacial in the Nianbaoyeze region occurred in the early stages of the last glaciation before 54 ka, in oxygen isotopic stage 4.

On the basis of geomorphological studies, the "Big Boulder Moraines" (Hövermann et al., 1993) of the last glaciation may be divided into a penultimate sequence and an older glaciation. Uncertainty surrounds the dating of these terminal moraines, which was carried out using TL-dating of the loess overlying the associated glaciofluvial terraces. Different results have been obtained from the laboratories in Guangzhou and Heidelberg (Lehmkulh, 1995). Whilst both sets of results indicate a last

Figure 15. Profile from the Sichuan Basin across, the Nianbaoyeze to the Bayan Har Shan. Reconstruction of the expansion of the glaciers, and ELAs during the last glaciation (section lined, lower line) and the present glaciation (black, upper line). The snowlines rise by about 100 m for each degree of longitude westward, from 4,800 m to more than 5,300 m (recent snowline) and from 4,000 m to 4,700 m (snowline of the last glaciation). The Pleistocene snowline depression is calculated to have been between 600 and 1000 m.
glaciation age, the Guanzhou dates suggest an early Last Glacial age for the Xinemencuo-moraine, equivalent to oxygen isotopic stage 4.

Evidence indicating at least two extensive Pleistocene glaciations militates against the idea that a young (since 250 ka BP) and rapid tectonic uplift event occurred in this area. If such an uplift had occurred, the penultimate and older glaciations would have been of smaller extent compared to the youngest glaciation because summit altitudes would have been lower.

The Hinterland of the Nianbaoyeze Shan, including the Aba basin

As indicated above, river gradients are less on the northern slopes of the Nianbaoyeze Shan (the Huang He catchment) than they are on the southern side (upper Yangtze catchment). The main rivers on the northern slopes are, in part, braided and are accumulating gravels. These rivers occupy box-shaped and V-shaped valleys with longitudinal gradients of 0.1 – 0.3°. The next basin, Zoige, provides a local base level with its gentler gradients in which sand and gravel accumulate. It is situated about 80 to 90 km downstream of the Nianbaoyeze massif at an altitude of 3,400 – 3,440 m. The steeper gradients on the south side (averaging between 0.3° and 1.1°, but reaching 3.3°) have resulted in deeply incised meandering rivers with turbulent discharges. The tectonic basin further to the south-east of the Nianbaoyeze, the Aba Basin, is only 30 to 40 km downstream of the Zoige Basin and 3,300 – 3,400 m in altitude.

Several Pleistocene terraces within the Aba basin are covered by thick loess (Fig. 13). The Last Glacial terrace is about 40 m above the river bed, with older Pleistocene terraces up to 300 m higher. TL dating of the basal part of the loess on the 40 m terrace confirms a Last Glacial age for this terrace, even given differences in the results from the two TL laboratories referred to above. The dates from Guangzhou indicate that loess began to accumulate in the first cold period of the last ice age (oxygen isotopic stage 4), while the Heidelberg results indicate the process took place during the last cold period of the last glaciation (oxygen isotopic stage 2: see Lehmkhul 1995 for detailed discussion).

Zoige basin

The Zoige Basin (Fig. 2) is at 33° – 34°10’N/102° – 103°10’E, within the ‘great bend’ of the Huang He. Here, the Huang He changes course from W-E to SE-NW. Some 100 km further on, near Marqü, the Huang He enters a small graben-like basin. A further 75 km downstream, the Huang He cuts through the Xiqing Shan. The Zoige Basin ranges in altitude from 3,400 m to 3,800 m above sea level. The surrounding mountains rise to more than 4,300 m. To the north, the basin is surrounded by high mountains made up of interbedded limestones and sandstones.

The basin fill comprises rocks and sediments of Triassic to Recent age. These have been eroded to produce an undulating landscape with a relative relief of about 300 m. Recent drilling has shown that the basin fill has a maximum thickness of about 300 m (Liu Shijian, pers. comm.). The uppermost deposits comprise peat, fluvioglacial sands and gravels, and aeolian silts and sands. These have formed as a result of the progressive migration of the Huang He during the Pleistocene and Holocene. The total area of peat bogs in the depressions is estimated to be 4,000 km². At present, the Huang He and its tributaries meander with a gradient of 0.4% and recently abandoned river courses are confined within a belt approximately 1–2 km wide. This acts as the local base-level, at altitudes of between 3,400 and 3,440 m above sea level. The river is known to flood to heights of about 3 m.

The wide floodplain of the Huang He and its main lower terrace are extensively covered by aeolian deposits (mainly sandy loess and sand dunes) that overlie lacustrine deposits, particularly at the heads of the tributary valleys. These lacustrine sediments may have been laid down in a large palaeolake created by damming of the Huang He or prior to the development of the Huang He drainage. Alternatively, they may have been deposited in smaller lakes in the tributary valley heads, formed by a west-east dislocation of the Huang He. These hypotheses require testing.

In the Zoige Basin, the youngest (last glaciation) terrace is 8 – 12 m high and up to 21 km wide. This terrace forms the Holocene valley floor. In some places an older terrace can be seen at 28 – 41 m above the present day floodplain. According to Chinese geologists (Liu Shijian pers. comm.) this terrace may have formed in the older Middle Pleistocene. The bedrock is covered by solifluction debris of the last glaciation and a thin layer of sandy loess. In some parts, the Pleistocene sand dunes have been reactivated by overgrazing (Lehmkul, 1993; Zheng, 1994). At the confluence with the Hei He, a main tributary of the Huang He in the northern part of the Zoige Basin (3,420 m a.s.l., 33°57’N/102°17’E), an exposure in an oxbow channel revealed a horizon with relict involutions. There is also a soil wedge filled with sandy loess, interpreted as an ice-wedge pseudomorph indicative of former permafrost. This horizon is covered by a 140 cm thick layer of homogeneous sandy silt (Fig. 14). The basal layers of this silt have been TL dated to 21 ± 2 ka. In addition, numerous mammalian bones have been found by Chinese scientists in last glaciation deposits about 2 to 3 m below the surface. One yak bone (Bos primigenius bojanus) gave a radiocarbon date of 26,620 ± 600 BP.

Discussion

The main results of extensive research being undertaken in north-eastern Tibet, including the mountain ranges from the Minshan to the Bajian Har Shan, are outlined in Hövermann and Lehmkul (1994b), Lehmkul (1995) and Lehmkul and Liu (1994) and are summarised in the profile shown in Figure 15.

In the Minshan, the marginal ranges in the upper catchment of the Minjiang He close to the Sichuan Basin, it may be inferred on the basis of clearly developed moraines, cirques and troughs that the last glacial ELA lay at an altitude of 4,000 m. The calculated results correspond to altitudes of the glacial isochrones discussed many years ago by v. Wissmann (1959) and Frenzel (1960), as well as with those reported in recent Chinese investigations (e.g. Tang et al., 1994) and with the work of Hövermann and Lehmkul (1994b) and Lehmkul and Rost (1993) on the Pleistocene glaciation in this region.

Near Lixian (31°26’N/103°11’E), in the catchment area of the Zagunao He, bouldery diamictic flows occur within the terraces. Chinese scientists have classified these as moraines of 3–5 glacial stages, correlated with several glaciations. The last stage is represented by the lowest moraine, between 1,950 m and 2,060 m (the “Zagunao Glaciation”, regarded as a correlative of the Würmian of the European Alps; see English summary in Tang and Shang 1991). A U-shaped valley lying above these deposits has been incised to produce deep, box-shaped gorges. Even so, these deposits cannot be explained as rockfall masses as suggested by Frenzel (1994), because a significant number of boulders have been well rounded by glacial action and the deposits are interstratified with silt. Furthermore, there is no obvious source for such a large rockfall accumulation. As the catchment area
rises to altitudes of over 5,900 m, a palaeosnowline of approximately 3,900 m has been calculated, a result in accordance with those for the Minshan region and consistent with the calculations of v. Wissmann (1959).

Further to the west, on the eastern slope of the Yanggongshan in the catchment of the Heishui He, the lowest terminal moraines lie at about 2,840 m. The valleys were occupied by an extensive glacier network with an ELA of about 4,050 m. It is possible that morainic deposits at even lower altitudes have been removed or covered by landslides, debris-flows, rockfall and slides on the steep slopes within these narrow valleys, especially on the eastern slopes of the Yanggongshan. Rather low cirque altitudes of 3,900 m - 4,000 m point to this possibility (cf. Lehmkühl & Liu, 1994).

The profile in Figure 15 shows that, in general, the mountains west of the Yanggongshan as far as the Aba Basin and the Nianbaoze massif, are lower than 4,200 m. The lack of evidence for Pleistocene glaciations suggests that these mountains were not sufficiently high to support glaciers. Cirque altitudes indicate that the Pleistocene ELAs were between 4,200 and 4,300 m north of the Aba Basin.

In the Zoige Basin at altitudes between 3,400 and 3,500 m a.s.l. and about 100 km north-east of Aba, involutions (cryoturbation) and ice-wedge casts provide evidence of permafrost conditions with a maximum mean annual air temperature of -6°C for the LGM (cf. Lehmkühl, 1995; Lehmkühl and Liu, 1994). On the basis of the present mean annual temperature (0.7°C) in the Zoige Basin and depression of the lower limit of permafrost from c. 4,300 m at present to at least 3,300 m in the LGM, a temperature depression of at least 6°C is inferred. Such a temperature, taken together with the evidence of sand wedges, suggests greater aridity, and supports the view that the ELA depression during the LGM was between 600 to 800 m in this region. In the Nianbaoze Shan, to the west of the Zoige Basin, a small ice cap developed in the LGM, centred on a small but high granite dome. The terminal moraine altitudes indicate that the ELA during the LGM was about 4,350 m to 4,400 m.

In the Anyêmaqên Shan, a network of valley glaciers existed during the Pleistocene (Tafel, 1914; Rock, 1956; v. Wissmann, 1959; Kuhle, 1987a). The ELAs during the last glaciation rose in elevation towards the interior of the Plateau. This is testified by the higher elevation of terminal moraines on western slopes compared to those on the east. Hövermann and Lehmkühl (1994b) showed that, on the western slopes of the Anyêmaqên, the terminal moraines of LGM age lie at 4,140 m (e.g. at a point on the road 25 km north of Ichikai: 34°32'N/99°10'E).

At the western end of the profile (Fig. 15), in the central Bayan Har Shan, less weathered granite boulders and relatively fresh glacial landforms (mainly U-shaped valleys) are present. These strongly suggest that a small ice cap was present during the LGM. On the basis of terminal moraine altitudes, the ELA on the northern slopes of Bayan Har Shan lay at an altitude of about 4,750 m. Traces of an older glaciation (the penultimate) can be found at about 67 km north of the Bayan Har Shan pass, verifying an ELA at about 4,600 m. Sand wedges and two layers of solifluction debris on top of limnic and aeolian sediments on the eastern slope of Ximinx Hu indicate higher aridity during the LGM. According to Derbyshire et al. (1991:500), these sand wedges date from the LGM approximately 18 ka ago. The basal layers of loess at an altitude of 4,338 m a.s.l. on top of the solifluction layers have been dated by thermoluminescence to 18 ± 1.5 ka (cf. Lehmkühl, 1995). This is evidence of a change from dominantly debris transportation and deposition on the slopes to aeolian deposition. No evidence has been found in this area suggesting a more extensive plateau glaciation of greater age. For example, a morainic platform of the penultimate glaciation (cf. Shi et al., 1992; Li et al., 1991). Furthermore, there are no deposits of younger Pleistocene glaciations within the basins and valleys of the Yangtze River system, (e.g. south of the Bayan Har Shan, Yushu), the Aba Basin east of the Nianbaoze massif at 3,300-3,400 m and other tributary valleys of the Dadu. Several terraces exist, but the higher ones are covered by decimetres of loess. The loess series on some of the higher terraces have interbedded palaeosols, presumably of interstadial and interglacial age. They are partly covered with soliflucted debris of the last glaciation.

In summary, the ELA during the LGM in this part of the Tibetan Plateau varied from 3,800 m to 4,000 m in the marginal ranges of the Sichuan Basin (e.g. the Minshan). This represents an ELA depression of 800 - 1,000 m, at about 4,200 m north of Aba, 4,300 m (against a present day snowline of 5,000 m) in the Nianbaoze massif, and at about 4,700 m (present snowline above 5,300 m) in the Bayan Har Shan further west. This accords with the trends determined by v. Wissmann (1959), although his ELAs were generally between 200 m - 400 m higher. Present ELA values as well as other altitudinal limits such as the lower limit of periglacial activity and the treeline, all rise in a similar fashion towards the interior of the Plateau (cf. Lehmkühl, 1995). This effect can be explained by the so-called "Massenerhebungseffekt" (Troll, 1955) of the older literature. It results from the high radiation values and lower precipitation totals characteristic of the central parts of mountains. This effect can be observed even in small mountains such as the European Alps and is likely to be much greater in higher mountains and plateaux in sub tropical latitudes (cf. Wissmann, 1959). The ELA depressions in Figure 15 are 800-1,000 m in the east and 500 m in the west. Similarly, both the modern and LGM ELAs rise towards the centre of the Tibetan Plateau in northern and north-eastern Tibet. For example, present day ELAs rise from 3,300 m in the Qining Shan (34°15'N/100°10'E) to 4,150 m in the Laji Shan (36°55'/N/101°E) (Lehmkühl & Rost, 1993). This general rise in the altitude of the ELAs corresponds with a decrease in precipitation from east to west, a trend that was more pronounced during glacial times than it is today (cf. Lehmkühl, 1995).

An assessment of former ice extents based on evaluation of landforms and sediments, as discussed above, clearly shows that the distribution of glacier ice in eastern Tibet was considerably less extensive than that proposed by Kuhle (1985). The glacial limits defined by Shi Yafeng et al. (1992) are similar to those described here, although they vary in fine detail on the basis of some of our re-interpreted sections.

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