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Permafrost and periglacial environment of Western Tibet

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Northwestern Tibet (=*Qiantang*) (78°–81°E; 33°–36°N), located between the Kunlun (7178 m a.s.l., West Kunlun Peak) and the Karakoram ranges, is the highest (mean elevation 5500 m a.s.l.), the coldest (MAT > 0°C) and the driest part (P >50 mm/y) of the Tibetan Plateau. This remote region, a mountainous desert with lacustrine depressions surrounded by patches of steppe, has rarely been visited so far. Except for a few early explorers, the first detailed records dealing with the glaciers and the periglacial environment prevailing on the plateau were provided in the early eighties by the scientific expeditions led by Chinese and Sino-Japonese teams. During summer 1989, the Sino-French Kunlun-Karakoram Geotraverse (Fig. 1a) carried out multidisciplinary research aimed at studying tectonics, Quaternary evolution and present environment of Qiangtang (Fort and Dollfus, 1992). We describe here the conditions and types of periglacial features observed and their controls (elevation, lithology, geomorphology). Evidence of fossil, periglacial features eventually suggest that periglacial environments prevailed here during most of the Upper Pleistocene.

Physical conditions favouring periglacial environment

Climatically, Qiantang is known as the driest part of the central Asiatic mountains (Fig. 1a). The annual amount of precipitation, which occurs mostly during summer as convective rain/snow falls (Flohn 1968, 1981), is very low. On the plateau, the mean annual precipitation is estimated to be only 20–50 mm (Chang, 1981), although it is probable that more precipitation occurs at higher altitudes (Flohn 1981). For instance, Ohata et al. (1989) have estimated the precipitation to be < 200 mm/yr at 5200 m a.s.l. (Aqsay Qin lacustrine plain) and < 350 mm at 6300 m a.s.l. (flank of West Kunlun Peak). At Tianshuihai (4860 m a.s.l.), our one-year record data (Aug. 1989 – Aug. 1990) (Fig. 1b and c) suggest that annual precipitation can be as low as 23 mm/yr, and show that the moisture content of air never exceeds 90%. At the same site, the total potential evaporation calculated for the same one-year period is 1607 mm (Dobremez, unpubl. data). This extreme aridity of Northwestern Tibet makes this area certainly the most severe, alpine desert on earth.

The mean annual temperature is negative (-2.1°C measured during our one-year record at Tianshuihai), yet this value is 8–9°C higher than what would be expected at these altitudes compared to adjacent areas of the same latitude, due to plateau effect (radiative budget in excess during summer). At Tianshuihai also, the contrasts recorded between the coldest (January) and warmest (July) months (mean annual amplitude: 20°C, for a maximal range of temperature of 45°C), and between the coldest and warmest hours of each day, show that there are many freeze-thaw cycles during a year (153 cycles during the period Aug. 1989 – Aug. 1990) (Fig. 1d). This number is certainly much higher if ground temperature, instead of air temperature, is considered, because of the heat concentrating on ground surface.

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In the adjacent Eastern Pamir, there are no fewer than 300 freeze-thaw cycles annually in soil at a depth of 2 cm (Gorbunov, 1983). From this we may also infer that the south-facing slopes can potentially undergo a freeze-thaw cycle every day of the year. On north facing slopes or in mountain shadow, the radiative budget is negative, promoting permafrost extension.

At these altitudes, the winds are strong and frequent. At the Tianshuihai site, the windy days (wind velocity > 4.5 m/s) exceed 80–100 days/year (Li et al. 1990). The wind may interfere subtedly on the development of permafrost, especially in flat areas: by lowering significantly the air temperatures thus increasing the ground-air thermic gradient, by increasing the dryness of the ground surface by exportation of fine particles, or/and by increasing its water retention by importation of salt particles. Occasionally, the wind may drift away the rare snow cover, which anyway is never thick enough to act as a thermal protection.

Geomorphologically, Western Tibet is not "simply" a plateau, a flat elevated terrane, but an alternation of mountain ranges (6200 m–6800/7000 m a.s.l.) and discrete, lower (5500–6200 m a.s.l.), flattened ridges, separated by 80–100 km^2 wide, endorheic

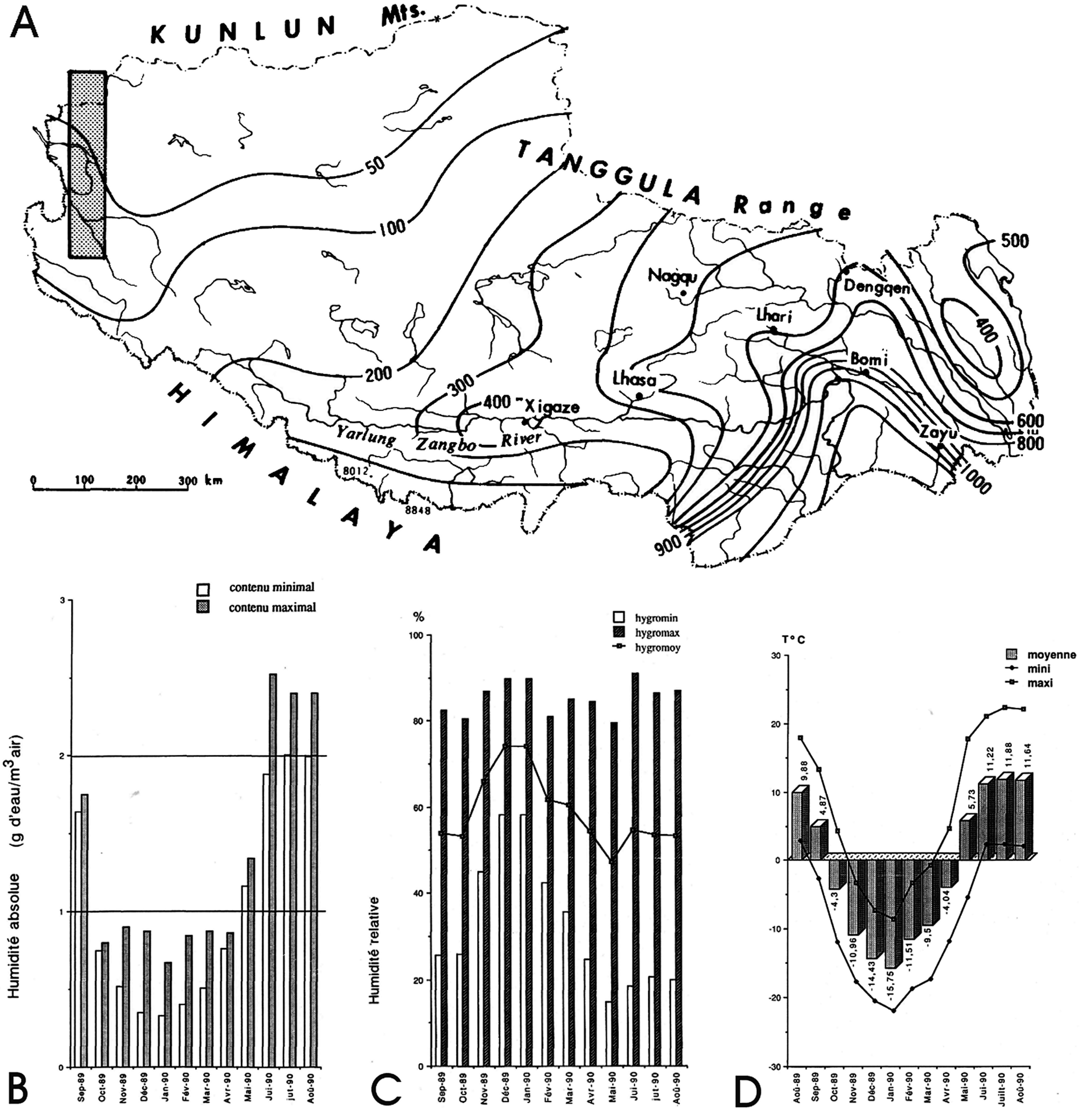

Fig. 1. Map (A) of mean annual precipitation distribution in Tibet (after Li, Zheng 1981) – the studied area corresponds to the gray rectangle (left); Hydrometric data (B, C) and thermal data (D) of Tianshuihai station (4860 m a.s.l.) annual cycle (Aug. 1989 – Aug. 1990), recorded by the Sino-French Kunlun-Karakoram Geotraverse (after Fort, Dollfus 1992)

plains (4400–5000 m a.s.l.), where fluvial, fanglomeratic and lacustrine sediments have accumulated during Pleistocene and Holocene (Fort and Dollfus, 1989; Gasse et al. 1991). The mountain ridges receive most of the precipitation, predominantly as snow. The modern glaciation is limited to ice-caps on summits >6400–6500 m. The snowline altitude varies from north to south between 5800–6200 m (north-facing slopes) and 6000–6400 m (south-facing slopes), thus reflecting a dryness gradient as a result of the general decrease of the mean elevation of valleys southwards.

The contrasts between slopes and nearly flat areas cause an unequal distribution of water in ground, which controls the occurrence of periglacial features. Zones of moisture concentration are mainly found along slopes high enough to get ice/snow meltwaters, at the foot of slopes or at the issue of gullies collecting melt/outspring waters, along the river floodplains and low terraces, and close to the lake shores and meadows developed on former lacustrine sediments. These latter are the source area of most salt particles blown away by wind and deposited on the surrounding slopes.

Under these climatic, altitudinal and topographic conditions, high-cold desertic and high-cold steppic landscapes prevail. In the northern part, the very short or non-existent growing season results in a very sparse vegetation with adapted species, like the cryophytic-xeric cussionlike Ceratoides compacta (>8% soil cover). Steppic communities are locally developed on the piedmont slopes (Carex moorcroftii, Stipa purpurea) and around the lake depressions (Stipa glareosa, Stipa subsessiliforma), whereas the only woody plants are found along some river beds (Myricaria hedini) (Chang 1981). In the southern part of Western Tibet, extensive Caragana versicolor and Juniperus communities are not rare in the lower (4300 m a.s.l.), warmer valleys, whereas the slopes are often covered by a Stipa purpurea steppe (Chang 1981).

From this rapid presentation of the Qiangtang environment, it appears that frost is acting everywhere. In the ground, the cryogenic activity, induced by the great number of freeze-thaw cycles, is directly controlled by moisture availability. Because of the extreme aridity of the climate, the edaphic conditions (controlled by slope and site) become a predominant factor in the distribution and type of periglacial features, which are also locally influenced by salt occurrences.

Present permafrost and associated cryogenic landforms and figures

Located quite above the 0°C isotherm (estimated to be about 3800 m a.s.l.; Li and He, 1989), Northwestern Tibet is potentially a zone of high altitudinal, continuous permafrost. Evidence for frost-shattering processes are everywhere in the landscapes. However, we found that the zone of detectable, continuous permafrost is not as widespread as formerly mapped (Li and He, 1989), because of limited moisture content in ground. Instead, we observed a rather extensive zone of discontinuous detectable permafrost, the patches of which are developed only on sites where water is available. Thus it can be questioned whether the absence of water in soil is a limiting factor to the development of features generally associated to permafrost. The summer dryness, by lowering the thermal conductivity, and increasing the albedo of the dry sediments and salt efflorescences, limits the heat transmissivity and the depth of the active layer.

Because the slopes represent dry, well drained areas, they are mostly shaped by frost shattering processes. Typical mountains slopes of Western Tibet are debris mantled, and/or are shaped as rectilinear, Richter slopes. Yet, additional forms of solifluxion also occur, limited in their extent by favourable factors: lithology, aspect, position in the hillslope profile, all related to the moisture content.

The rectilinear profiles correspond to unvegetated, rocky, denudation (or Richter) slopes, covered with a thin (few decimetre thick) sheet of debris, with a slope angle corresponding to the angle of stability (varying between 27–28° up to 34°) related with bedrock parameters such as jointing, bedding. The best examples of Richter slopes are encountered on monzonites (northwestern edge of the plateau), where they reach their final stage without any rocky spur but on their very top. Other examples are also found on shaly substrate.

In the composite slopes, the upper section may develop as a steep, rocky cliff, yet, most of the time, it exhibits an alternation of frost weathered pinnacles and frost gullies controlled by joints. The frost debris accumulates downwards as talus screes or cones (slope angle between 30–34°), built up by a combination of debris falls, avalanches and debris-flow. Solifluction features usually develop along the lower part of the slopes, resulting in a noticeable lowering of the slope angle (down to 20°).

Although frost shattering (and probably salt shattering as well) is the dominant process, solifluction –in fact seemingly mostly frost creep- plays an active part in the slope evolution. Typically, the talus or cone profiles are ondulated, and soli-gelifluction lobes occur in the lower part of slopes, where moisture may generally concentrate. Their size varies from 1–10 m in width, depending on rocky material. Their lower limit observed is on south facing slopes at about 4800 m, and may be as low as 4500 m a.s.l. on north-facing slopes. Even on Richter slopes, the thin sheet of debris displays a flat girdle pattern on surface, outlined by coarser material. This feature seems to be characteristic of arid alpine hillslopes, as also observed in the Kunlun Range (Iwata and Zheng, 1989) and in the Ladakh-Gandise range (Fort 1981), this being probably a result of dry slumping.

When the ground moisture content increases, the conditions are at best for the rock-glaciers to develop. This is particularly true when there is an upper, rocky slope that concentrates the snow or glacial meltwaters, or along avalanche tracks and/or small ravines. The lower altitudinal limit of active rock-glaciers varies between about 4800 m a.s.l. (south aspect) and 4600 m a.s.l. (north aspect). It can exceptionally descend lower, when rock-glaciers develop on a terminal moraine (Iwata and Zheng, 1989), hence probably revealing a MAT <-2°C, as noted in the Alps (Haeberli, 1985).

If patterned grounds are not absent from mountain slopes, their best yet limited occurrences are in the valleys or depressions, mostly at altitudes ranging between 4500 m a.s.l. and 5200 m a.s.l. They are good indicators of the existence of permafrost. Li and He (1989) have studied the most widespread continuous permafrost encountered in this region: the vicinity of the West Kunlun range, near and in the Tianshuihai lacustrine depression (4900–5000 m a.s.l.). There, the active layer is 1.0 to 1.5 m thick, the mean annual ground temperature is –3.2°C. The depth of no annual temperature amplitude is 13–15 m. From geothermal gradient and geophysical methods, Li and He (1989) estimated the permafrost thickness to be 117,9 m and 77,0 m respectively. They also indicate that this permafrost contains thick horizontal ice-rich layers and ice masses near the permafrost table. In association with it, masses of segregated ice, ice wedges and ice veins (>0.5 m high), thermokarst lakes, have also been reported by the same authors, together with ice-core mounds (pingos) about 1m high, with fissured summits and basal diameters of 3–5 m. Only one large pingo (basal diameter of 100 m), surrounded by slumped layers, has been observed (Li, 1987). This ice rich layer could be a relict of Holocene, more humid period, as suggested by the extension of lacustrine layers. In such arid and cold environment, the presence of shallow lakes seems to be a reinforcing factor for the surficial expression of permafrost.

In fact, observations made along our 500 km long transect led us to think that the Tianshuihai area cannot be considered as fully representative of the northwestern part of Tibet, because of the proximity of large and flat lacustrine water bodies susceptible to provide the moisture necessary for ground ice to develop. In other places, the nature and thickness of permafrost is unknown and, in fact, cryogenic features are more subtle and more spatially confined. Patterned ground, non sorted circles, cryogenic mounds (palsas; Fig. 2), upheaved stones, and icing along the river beds are the most typical landforms we encountered, with some characteristics that reflect the overall aridity of the environment, yet are not necessarily significant of the presence of permafrost (palsas excepted).

The best examples of patterned grounds are circles observed north of the Sumxi lake (5350 m a.s.l.). These figures developed at the base of a 5500 m a.s.l. high ridge underlain by Jurassic, north-dipping limestones, with dip slope flanks (24–28° slope angle) mantled by decimetric blocks dislodged by widely open, frost cracks. From the lower north-facing slope, we successively observed from top to foot solifluction lobes (17–7° slope angle), passing downward to non sorted, elongated stone circles developing on a colluvial piedmont (5350–5200 m a.s.l.), sloping (4–2°) in a northwest direction. The colluvial material includes frost-shattered, limestones clasts, calcareous, silty particles derived from frost shattering and dissolution, and from wind blown lacustrine silts (winnowed from the Holocene lacustrine deposits of lakes Sumxi and Longmu Co), and salt particles, also derived from the same lacustrine outcrops. On surface, fine particles are protected by a thin veneer of clasts (deflation pavement). The ground patterns observed are non sorted and very shallow, due to the low soil moisture content which favours an active layer without mid-portion desiccation (Van Vliet-Lanoe 1985). The ground temperatures measured (20/07/89, early afternoon) indicate that the active layer is 1.5 m thick at 5100 m a.s.l. (i.e. close to the limit of continuous permafrost), and only 0.4 m thick at 5350 m a.s.l. Yet, the excavations performed in the still frozen active layer (segregation ice) have shown that this layer varies in thickness.

Mineral palses (Fig. 2) are certainly the most striking periglacial features that typify this part of Tibet. These 5-to-10 m high mounds may extend laterally over tens of metres, and their surface is affected by desiccation cracks. Their development is related to segregation ice-lenses, very much dependant upon

Fig. 2. Cryogenic mound (mineral palse) associated to discontinuous permafrost affecting early-middle Holocene lacustrine sediments. East of Domar, Bangong lake watershed (photo M. Fort)

Fig. 3. Several generations of rock glaciers: inherited rock glaciers mantled with a thin veneer of sands and silts in the lower part; active rock glaciers (>4800 m a.s.l.) in the upper part. Chanthang valley, west of Rutog (photo M. Fort)

site-specific conditions. Indeed, these palses are only found in the vicinity of lacustrine bodies and/or in the valley bottoms, their growth being favoured by the presence of early-middle Holocene, laminated, lacustrine silts (Fort and Dollfus, 1992) and illimited supply of water.

Eventually, permafrost and periglacial features of Western Tibet appear as sensitive to and good indicators of climate change. On the one hand, inactive, silt-blown mantled rock-glaciers (Fig. 3) and rectilinear hillslope observed at lower (<4800 m a.s.l.) altitudes suggest that periglacial environment prevailed here during most of the Upper Pleistocene, hence refuting the idea of a generalized glaciation over Tibet. On the other hand, the warming trend in air temperature recently detected East of the Tibetan Plateau (Wang and French, 1994) might possibly cause progressive permafrost degradation, increasing dryness and potential risk of desertification in the near future.

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