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The Tibetan Ice Sheet, Its Impact on the Palaeomonsoon and Relation to the Earth's Orbital Variations

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Summary: Evidence for an ice sheet covering Tibet during the Last Glacial Maximum means a radical rethinking about glaciation in the Northern Hemisphere. The ice sheet's subtropical latitude, vast size (2.4 million km²) and high elevation (~6000 m asl) caused a substantial, albedo-induced cooling of the Earth's atmosphere and the disruption of summer monsoon circulation. The uplift of Tibet and the reaching of specific threshold values of plateau elevation being synchronous with the onset of the ice ages at ~2.8 Ma B.P. and their intensification from ~1 Ma B.P. onwards, a causal link between these factors seems likely.

Zusammenfassung: Der Nachweis einer hocheiszeitlichen Inlandvereisung Tibets bedeutet eine grundlegende Veränderung unserer Vorstellungen über die nordhemisphärische Vereisung. Aufgrund ihrer subtropischen Lage, bei großer Fläche (2.4 Mio km²) und Höhe (~6000 m ü.M.) hat diese Vereisung sowohl einen großen albedobedingten Wärmeverlust der Erdatmosphäre als auch den Zusammenbruch der Sommermonsunzirkulation verursacht. Da die Hebung Tibets und das Erreichen von spezifischen Schwellenwerten der Plateauhöhe zeitlich korreliert ist mit dem Beginn der Eiszeiten bei ~2.8 Ma B.P. und ihrer Intensivierung ab ~1 Ma B.P., wird ein ursächlicher Zusammenhang wahrscheinlich.

INTRODUCTION

Tibet is the Earth's largest high plateau, with an area of 2.6 million km² and an average elevation of 4600 m. Owing to its subtropical latitude (27-39 °N) extreme insolation values ranging between 800 to more than 1300 W/m² have been recorded in the summer months (KUHLE & JACOBSEN 1988). Heating of the plateau's debris surfaces causes about 80 % of this insolation to be converted into heat radiation, generating a pronounced low-pressure system over the plateau (FLOHN 1981). The cooler, moister air masses of the summer monsoon drawn in from the Indian Ocean are deflected from east to west by the Himalayas and so do not reach the interior of the Tibetan plateau. Hence the Himalayas act as a climatic divide with convective precipitation of >6000 mm/a on their southern, and <300 mm/a on their northern slopes. Precipitation is low over the entire plateau: between 700 mm/a in the east to <50 mm/a in the west. Evaporation rates being high (ranging from 2500 mm/a in NW Tibet, VAN CAMPO & GASSE 1993) to 3200 mm/a in the Qaidam Basin (CHEN KEZAO & BOWLER 1986), the climate is semiarid to hyperarid, as indicated by the numerous saltwater lakes on the plateau. This aridity was the decisive factor in assessing glacier size during the Last Glacial Maximum (LGM). Although in the first half of this century various authors reported evidence of significant Pleistocene glaciers (HUNTINGTON 1906, TAFEL 1914, TRINKLER 1930, NORIN 1932, DE TERRA 1932, ODELL 1925) it was generally assumed that glaciation was not extensive, with maximum ice margins only a few kilometres beyond the modern ones (WISSMANN 1959, SHI et al 1992). In recent years, however, results have shown that the late Pleistocene climate was substantially more humid than today's, with large freshwater lakes in the Qaidam basin (59,000 km²; CHEN CEZAO & BOWLER1986) and in the Tengger, Gobi (PACHUR & WÜNNEMANN 1995, WÜNNEMANN & PACHUR1988) and Zunggar (RHODES et al. 1996) deserts bordering Tibet in the north. At the same time, the argument that aridity is, in principle, a limiting factor for glaciation has proved to be obsolete. Spitsbergen with <300 mm/a of precipitation and Ellesmere Island with <30 mm/a were long considered to have had little ice cover during the ice ages. However, it has since been shown that during the LGM Spitsbergen was an integral part of the 2000-3000 m thick Barents Ice Sheet (MANGERUD et al. 1998, LANDVIK et al. 1998), and Ellesmere Island was covered by the ≥1000 m thick Innuitian Ice Sheet (DENTON & HUGHES 1981, DYKE 1979, ENGLAND 1999). Evidently, the decisive control of the extent of glaciation is not precipitation but an increase in the area available for terrestrial glaciation owing to the lowering of the ELA (Equilibrium Line Altitude). The present mean ELA in Tibet is 5600 m asl, i.e. still in the steep relief of the peak region. Here, ELA variations of ±100 m induce differences in area of ~10,000 km². Below 5600 m asl, however, the plateau region begins, with exponential rates of area increase of 120,000 to 150,000 km² per 100 m of ELA depression. Even an ELA anomaly of -300 m means that ~25 % of the total area of Tibet would be ice-covered, -600 m would mean an ice cover of about 55 % (today: 6 %). Sensitivity experiments with simulation models, which evaluate separately the effects of ice sheets, CO_2 and orbital insolation on the climate development, suggest that the growth of an ice sheet covering the entire Tibetan plateau is much more probable and starts earlier than in the high latitudes of the Laurentide and Fennoscandian ice sheets (VERBITSKY & OGLESBY 1992, MARSIAT 1994)

GEOLOGICAL EVIDENCE FOR A TIBETAN ICE SHEET

However, evidence for a Tibetan ice sheet during the LGM is not based on its theoretical plausibility but on geological and geomorphological indicators. The difficulty was to select the regions for fieldwork in such a way that the N-S and E-W traverses would give the greatest possible cover of the various climatic and orographic settings of the 2.6 mio. km² area, so that individual results could be linked to yield a supraregional picture. A relatively complete net of coordinates has now been built up (Fig. 1), starting with the Dhaulagiri and Annapurna Himalayas in 1976 (KUHLE 1982) and ending with the extremely arid Aksai Shin (NW Tibet) in 1996 (KUHLE 1999). Evidence of LGM end moraines was found in all the major val-

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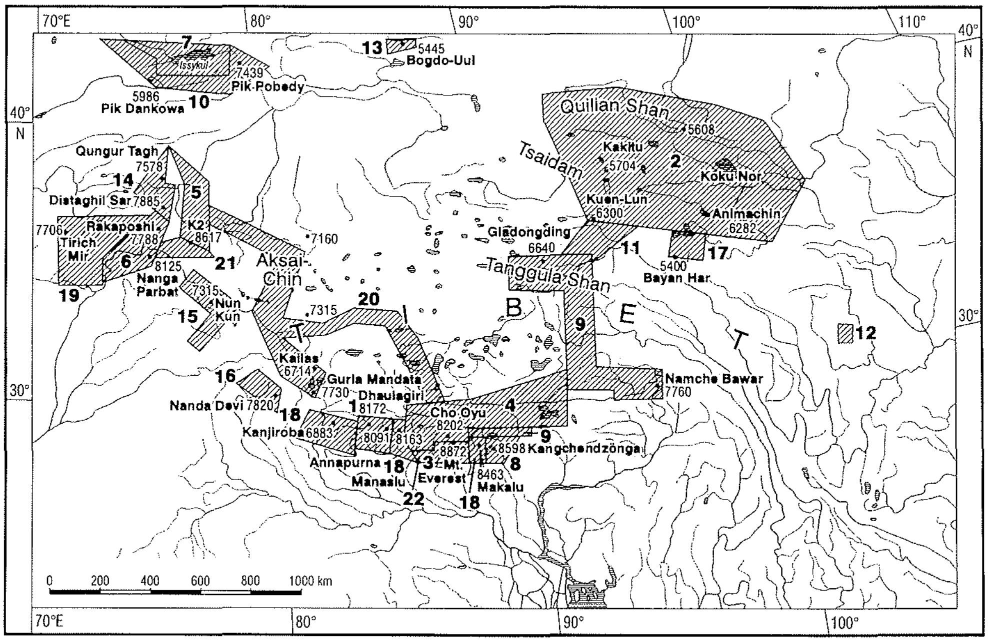

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Fig. 1: The areas in Tibet and High Asia investigated by the author since 1976 (KUHLE 1982-1999).

Abb. 1: Arbeitsgebiete des Autors in Tibet und Hochasien seit 1976 (KUHLE 1982-1999).

leys draining the southern flanks of the 14 peaks rising above 8000 m in the Himalayas and Karakoram. These moraines reach down to 980 m in the Indus valley (KUHLE 1997), 1100 m in the Alaknanda valley (KUHLE 1997), 1100 m in the Kali Gandaki (KUHLE 1982), 650 m in the Madi Khola (KUHLE 1997), 460 m in the Marsyandi Khola (KUHLE 1997), <1000 m in the Bote Chu (KUHLE 1999), ~600 m in the Arun valley (KUHLE 1997), and 890 m in the Tamur valley (KUHLE 1990), i.e. down to the foothills. Further upvalley, these ice margins were confirmed by corresponding finds of moraines and erratics on the valley flanks (Figs. 2, 3) and by glacial striations (Fig. 4). Especially the erratics - often deposited on a different type of bedrock more than 1000 to 1300 m above the valley floors - are valuable indicators: since convergent evolution produces no forms in any way similar, the only explanation is that the boulders were removed and deposited at their present elevations by glaciers. On the northern edge of the Tibetan plateau, the Karakoram and Kuen Lun northern slopes, end moraines – sometimes as much as several hundred metres thick – were deposited as far down as 2000 m asl in the Tarim Basin.

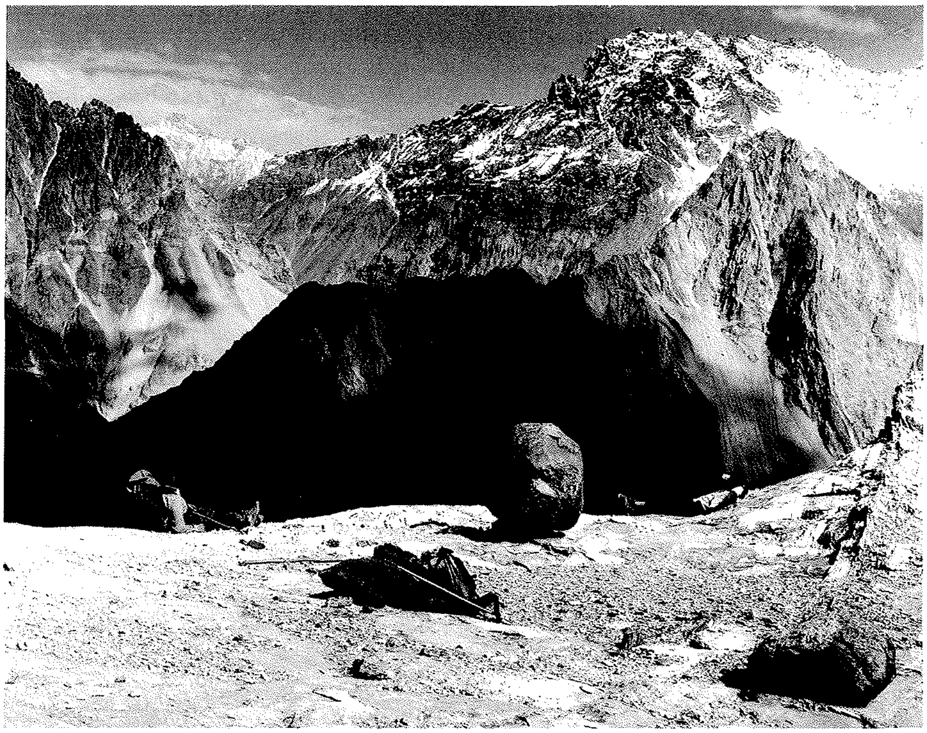


Fig. 2: Erratics, including granite boulders (between the two people), 900 m above the Hunza Valley floor, on the outcropping beds of evaporite bedrocks (36°28'30"N, 74°00'50"E, 3370 m asl). These erratics and even higher-lying ground moraine remains indicate that a >1000 m thick ice-stream system once filled the valleys visible in the background. Photo by M. KUHLE, 1992.

Abb. 2: Erratische Blöcke, darunter Granitblöcke (zwischen den beiden Personen), 900 m über dem Hunza-Talboden, auf den Schichtköpfen von anstehenden Evaporiten (36°28'30"N, 74°00'50"E, 3370 m ü.M.). Diese Erratika und noch höher liegende Grundmoränenreste beweisen eine über 1000 m mächtige Eisstromnetzverfüllung der im Hintergrund sichtbaren Täler. Foto M. KUHLE, 1992.

Fig. 3: Granite erratic (with person) on limestone bedrock in the rain shadow of the >7000 m high main Karakoram crest (to the S, background) above the floor of the Shimshal Valley (middle of photo) (36°28'N, 75°26'E, 4350 m asl). The boulder testifies that a glacier once filled the arid Shimshal Valley up to a depth of at least 1150 m. Photo by M. KUHLE, 1992.

Abb. 3: Ferntransportierter erratischer Granitblock (mit Person) auf anstehenden Kalkfelsen im Niederschlagsschatten des über 7000 m hohen Karakorum-Hauptkammes (im S im Hintergrund) über dem Boden des Shimshal-Tales (Mittelgrund) (36°28'N, 75°26'E, 4350 m ü.M.). Der Block beweist, dass das aride Shimshal-Tal in einer Mächtigkeit von mind. 1150 m mit Gletschereis ausgefüllt war. Foto M. KUHLE, 1992.

Fig. 4: Glacial striations on quartzite bedrock with iron manganese surface crust in the arid (~50 mm/a) Surukwat Valley, Aghil Mts, NW Tibet (36°20'N, 76°36'E, 3700 m asl). Photo by M. KUHLE, 1986.

Abb. 4: Gletscherschrammen auf anstehendem Quarzit mit Eisenmangankrustenoberfläche im ariden (~50 mm/a) Surukwat-Tal, Aghil-Gebirge, Nordwest-Tibet (36°20'N, 76°36'E, 3700 m ü.M.). Foto M. KUHLE, 1986.

TL dating of the moraines yielded ages of 32 ky and 22 ky B.P, thus dating this ice margin to the LGM (KUHLE 1994). Further upvalley, evidence was found of ice up to 2000 m thick. Whereas the heavily channelled ice-streams in the mountains bounding the plateau were able to transport great quantities of material and to create large depositional landforms owing to their superglacial moraine deposits and strong erosive capacity, the relatively flat plateau region of Tibet is covered by monotonous ground moraine. The plateau is largely built up of more or less metamorphic sedimentary rocks, with only local occurrence of massive crystalline rocks such as granite. Thus it is often possible to identify as erratics the granite boulders scattered on passes and hills (Figs. 5, 6), or incorporated in the ground moraine (Figs. 7, 8, 9). The extremely low relief of High Tibet with its hill-and-basin landscape precludes alternative explanations such as spontaneous mass movements or fluvial transport. Mapping of morainic deposits, erratics (100 and more kilometres away from their source area) and glacial stria-

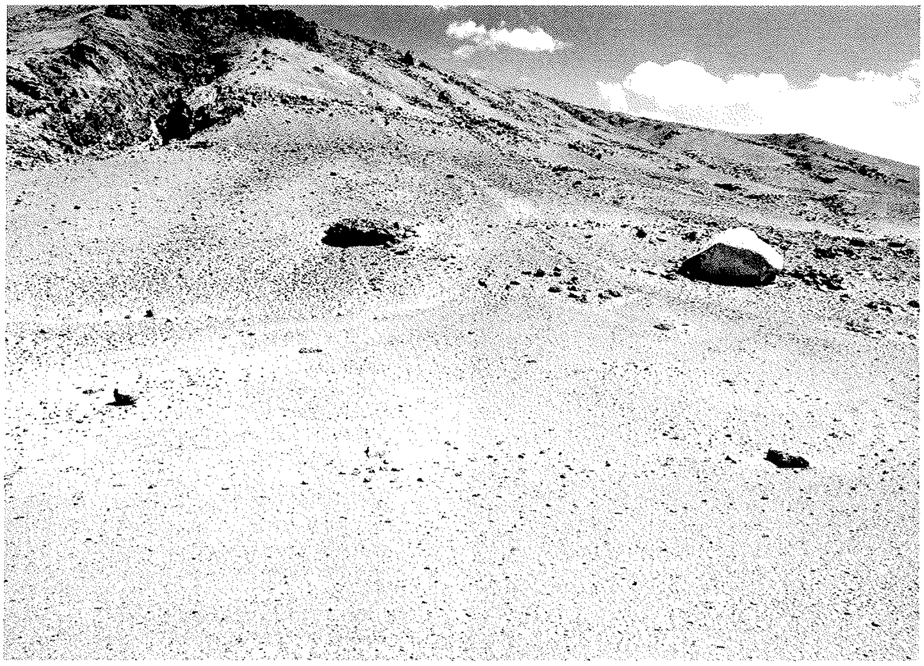


Fig. 5: Hut-sized granite erratic in the lowest-lying and most arid (~100 mm/a) part of central western Tibet, immediately E of Nako Tso (lake) (33°33'N, 79°57'E, 4225 m asl). The slope is covered up to the top by ground moraine containing more erratics. The bedrock consists of sedimentary rocks. Photo by M. KUHLE, 1996.

Abb. 5: Hütten-großer, erratischer Granitblock im am tiefsten gelegenen und aridesten (~100 mm/a) Gebiet Zentral-West-Tibets, unmittelbar E-lich des Nako Tso (lake) (33°33'N, 79°57'E; 4225 m ü.M.). Der Hang ist bis zur Kulmination hinauf mit Grundmoräne bedeckt, die weitere erratische Granitblöcke enthält. Der im Untergrund anstehende Fels besteht aus Sedimentgesteinen. Foto M. KUHLE, 1996.

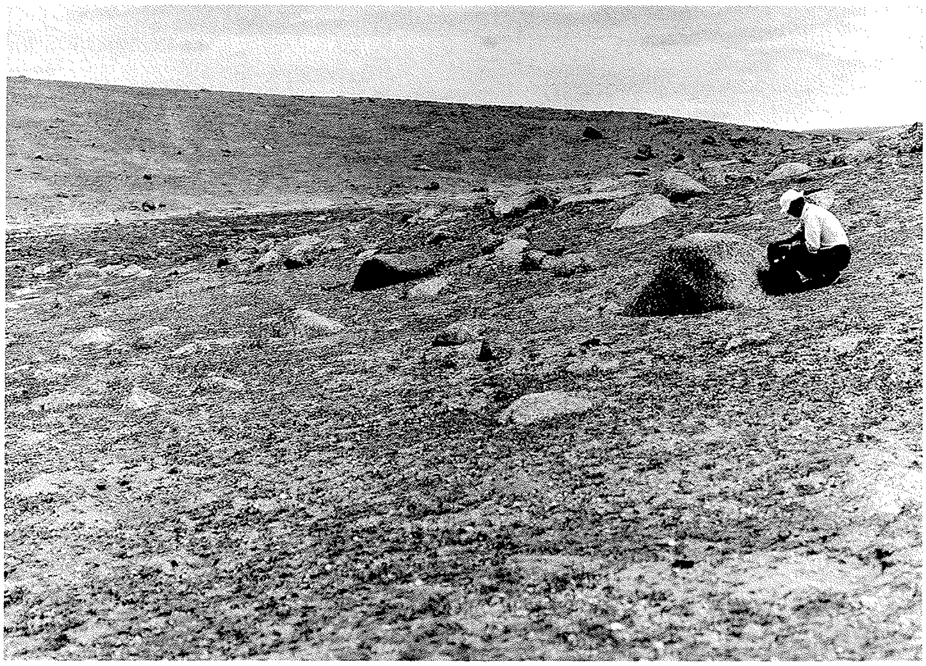


Fig. 6: Polymictic, different-coloured erratics, comprising six varieties of granite, in N Tibet, S of Kakitu (38°01'N, 96°24'E, 4500 m asl). They are located in an extensive, gently undulated ground moraine landscape. Photo by M. KUHLE, 1981.

Abb. 6: Polymikte, verschiedenfarbige, aus sechs Varietäten bestehende erratische Granitblöcke in Nord-Tibet, südlich des Kakitu (38°01'N, 96°24'E, 4500 m ü.M.). Sie liegen in einer flächendeckenden, leicht welligen Grundmoränenlandschaft. Foto M. KUHLE, 1981).

tions can be used to reconstruct the presence of a continuous ice sheet as thick as ≥1200 m in Tibet during the LGM (KUHLE 1988, 1991, 1997, 1999; Fig. 10). Via transfluence passes, the ice sheets joined up with the ice streams of the mountains bordering the plateau, and so did not create independent ice margins. [Evidence for these transfluences is supplied by large-scale ice-scour limits and erratics. In 1925 already, ODELL (1925) discovered erratics on Phusi La (5411 m asl), leading him to surmise that ice must have flowed to the southern slopes of the Himalayas from the interior of Tibet.] The presently available TL and ^{14}C dates of ice margins in the main valleys and foothills confirm that they date to the LGM (KUHLE 1994, 1997, 1998). As yet, there are no absolute dates of moraine material from the plateau itself, except for a sequence of tree trunks in a moraine-dammed lake in the middle of the Tsangpo valley (29° 18'N / 94° 21'E) which were ^{14}C-dated by the author to ages ranging between primarily LGM and Lateglacial age (48,580 to 9820 a B.P.) (KUHLE 1997, 1998). However, lake sediments and lake terraces in western and central Tibet provide proxy dates. The chronologies of Bangong Co (GASSE et al. 1996), Longmu Co (AVOUAC et al. 1996), Sumxi Co (VAN CAMPO & GASSE 1993) and Siling Co (KASSHIWAYA et al. 1991) record a major environmental change at ≈10 ky, when the abrupt onset of the summer monsoon led to the opening of the lake systems. Maximum lake levels were dated to 7.6 ky B.P. at Longmu Co (AVOUAC et al. 1996). By contrast, lakes in the previously unglaciated areas of the Qaidam basin, Gobi, Tengger and Zunggar deserts

Fig. 7: Granite erratics „floating" in ground moraine in central Tibet near Nyingzhong (30°24'N, 90°57'E, 4190 m asl). The bedrock consists of metamorphic sedimentary rocks. Photo by M. KUHLE, 1991.

Abb. 7: In Grundmoräne "schwimmende" erratische Granitblöcke im mittleren Zentral-Tibet bei Nyingzhong (30°24'N, 90°57'E, 4190 m ü.M.). Im Untergrund stehen metamorphe Sedimentgesteine an. Foto M. KUHLE, 1991.

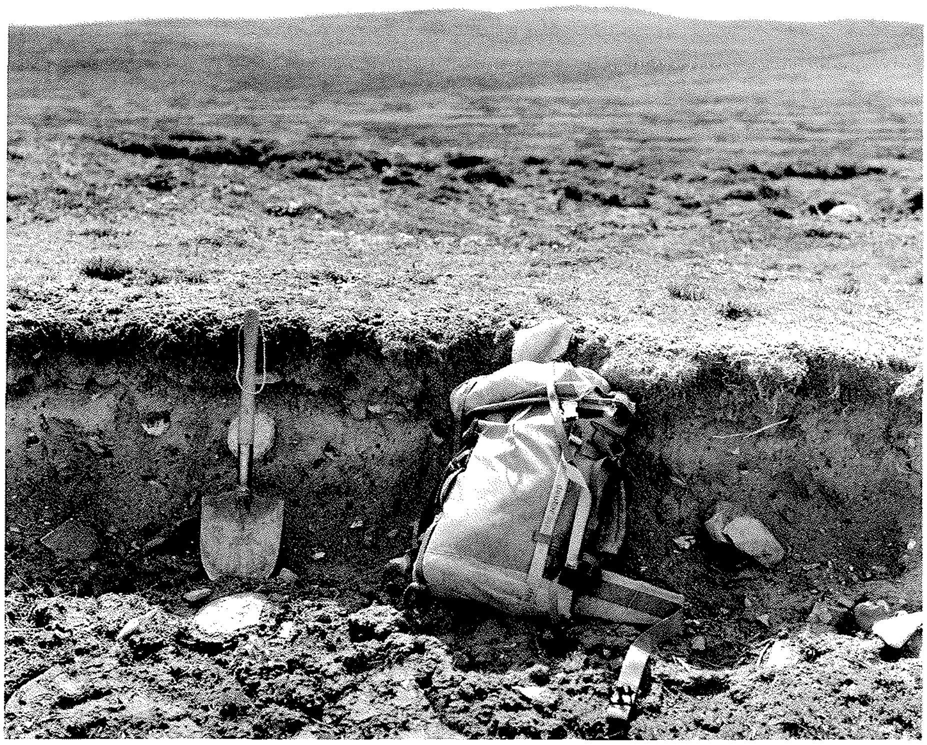


Fig. 8: Excavated ground moraine cover with erratic granite and quartzite boulders in NE Tibet in the Yen Yougo basin (34°39'49"N, 98°04'E, 4110 m asl). The ground moraine is up to 1 m thick and blankets a gentle hilly landscape of sedimentary rocks. On top of the backpack a striated clast from the ground moraine (see Fig. 9). Photo by M. KUHLE, 1994.

Abb. 8: Aufgegrabene Grundmoränendecke mit erratischen Granit- und Quarzitblöcken in Nordost-Tibet im Becken von Yen Yougo (34°39'49"N, 98°04'E, 4110 m ü.M.). Die bis zu meter-mächtige Grundmoränendecke überkleidet eine flache Hügellandschaft aus Sedimentgesteinen. Auf dem Rucksack liegt ein gekritztes Geschiebe, das der Grundmoräne entnommen wurde (s. Abb. 9). Foto M. KUHLE, 1994.

all have continuous lacustrine sediment records of up to ~40 ky B.P. (CHEN CEZAO & BOWLER 1986, PACHUR & WÜNNEMANN 1995, WÜNNEMANN & PACHUR 1998, RHODES et al. 1996). The young, Holocene age of the central Tibetan lakes points to the Pleistocene ice cover of the plateau with extensive lake formation in the now hyperarid northern forelands.

Available data suggest that the ELA fell by an average of 1200 m down to 4400 m during the LGM. Hence the ELA was below the elevation of the plateau, and glaciers covered ~95 % of the total area, leaving only parts of the Tsangpo depression, the Qaidam basin and the area of Lake Qinghai ice-free (KUHLE 1998, Figs. 10, 11).

ECOLOGICAL EFFECTS OF A SUBTROPICAL ICE SHEET

The ecological effects of a subtropical ice sheet covering some 2.4 million km² are substantial. The albedo of snow-covered ice surfaces ranges between 75 and 95 %, i.e. this proportion of solar radiation is reflected back and does not form part of the heat balance of the Earth's atmosphere. Whereas the Tibetan plateau is now one of the Earth's major heating surfaces,

Fig. 9: Glacially striated quartzite clast. Sample location see Fig. 8. Lab photo.

Abb. 9: Glazigen-gekritztes Quarzit-Geschiebe. Entnahmelokalität s. Abb. 8. Laboraufnahme.

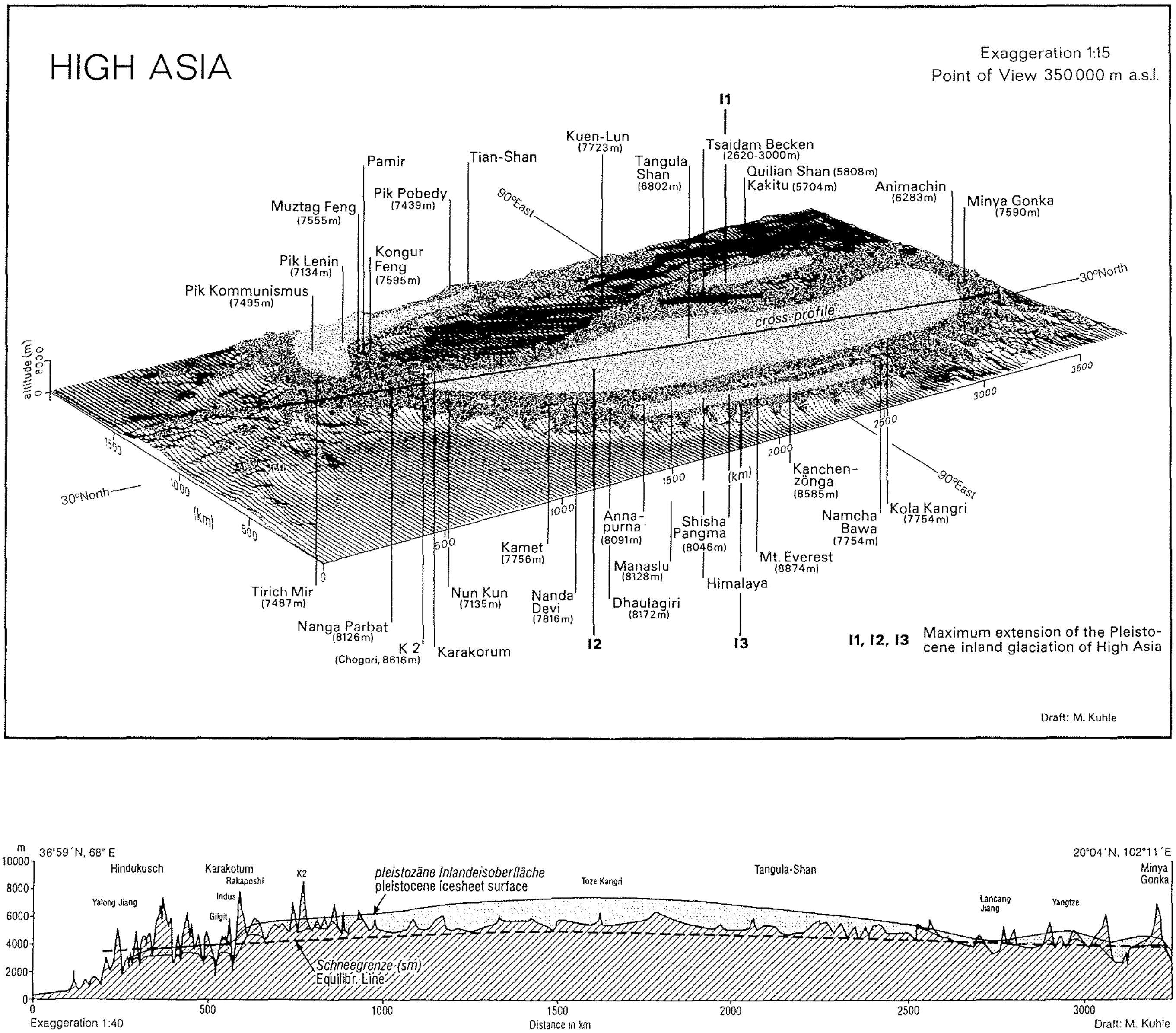


Fig. 10: (top) The reconstructed 2.4 million km² ice sheet, or ice stream network, covering the Tibetan plateau, with the three centres I1, I2, I3. Only peaks higher than 6000 m rise above the ice surface. (bottom) Cross profile of the central ice sheet from Hindu Kush in the west to Minya Gonka in the east.

Abb. 10: (oben) Das 2.4 Mio km² große tibetische Inlandeis, resp. Eisstromnetz mit seinen Zentren I1, I2, I3. Nur Gipfel mit mehr als ca. 6000 m ü. M. ragten über die Eisoberfläche. (unten) Querprofil des zentralen Inlandeises vom Hindukush im Westen bis zum Minya Gonka im Osten.

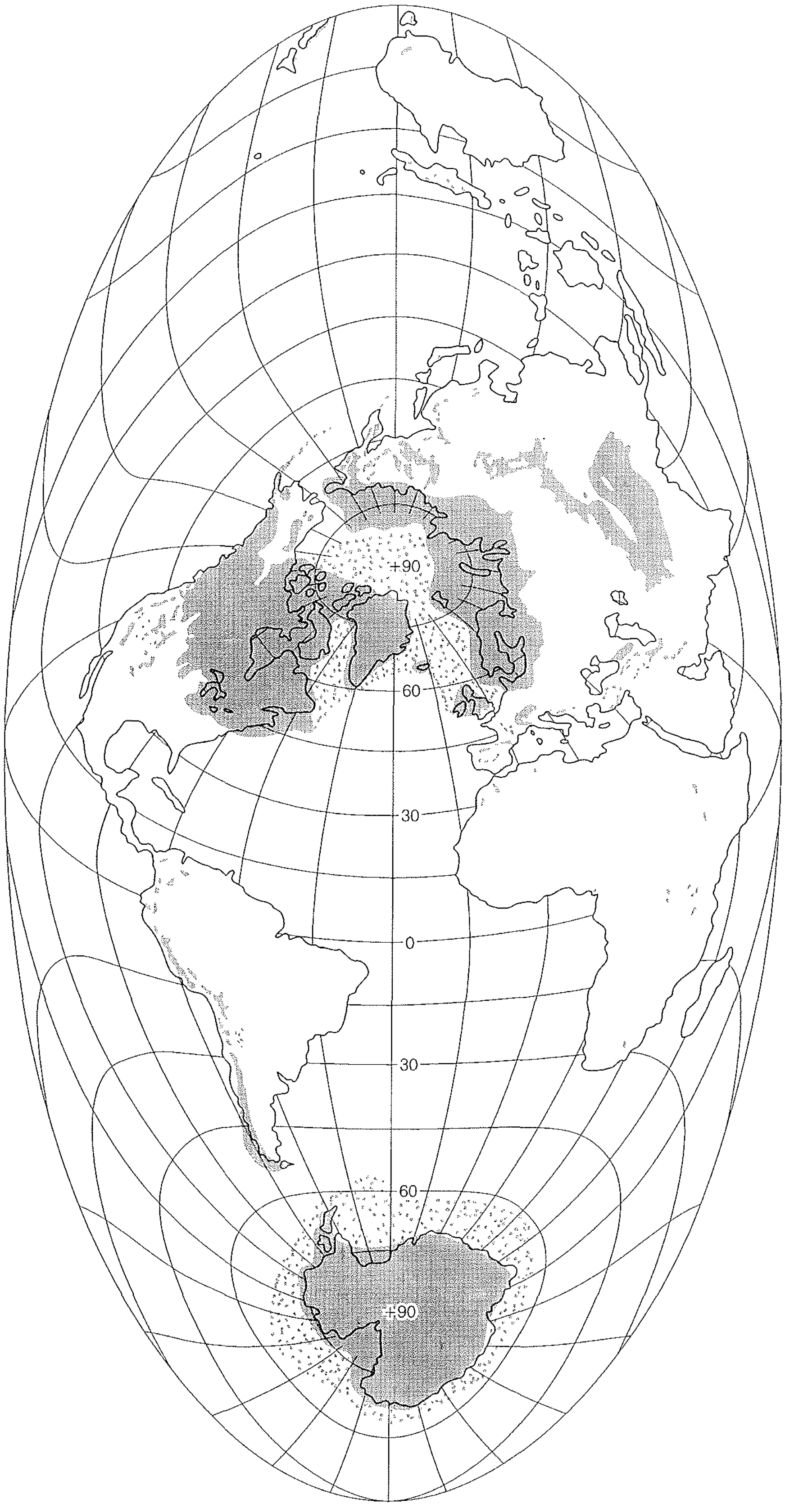


Fig. 11: Maximum extent of glaciated areas during the LGM, based on an equal-area projection. Continental ice is indicated by a dense, marine ice by a sparse signature. In comparison with the near-pole, lowland ice sheets, the 2.4 million km² Tibetan ice sheet is remarkable for its unique, extremely insolation-favoured, subtropical location with an average elevation of 6000 m asl. Based on BROECKER & DENTON (1990), modified after KUHLE (1982-1999).

Abb. 11: Ausdehnung der Gletscher während des LGM (flächentreue Projektion). Landeis wird durch eine dichte, Meereis durch eine dünne Signatur angezeigt. Im Vergleich zu den polnahen Flachlandeisen liegt das etwa 2.4 Mio km² große tibetische Inlandeis mit einer durchschnittlichen Höhe von ca. 6000 m ü.M. in subtropischer Breite und damit in einem Bereich mit extrem hohen Einstrahlungswerten. Kartengrundlage nach BROECKER & DENTON (1990) abgeändert nach KUHLE (1982-1999).

this energy was lost when the plateau was ice-covered. Energy balance calculations suggest that during the LGM 70.5 % of the albedo-induced energy loss was caused by the Nordic lowland glaciers, and 20.5 % was solely due to the ice on the Tibetan plateau (BIELEFELD 1997). Sensitivity experiments with a general circulation model (FELZER et al. 1998) suggest that the Nordic lowland glaciers caused –2.8 °C of the –6.5 °C ice age decrease in GMT (Global Mean Temperature). Accordingly, the Tibetan ice sheet would have caused a GMT drop of -0.8 °C (this is a minimum value; the energy loss due to the Tibetan glaciation amounts to even 32 %, when the changed infrared emission is taken into account, cf. BIELEFELD 1997).

A further effect of the Tibetan ice sheet was the weakening or interruption of the summer monsoon since a low-pressure cell was unable to form over the ice [The interruption of the summer monsoon during the glacials was already visible in the reconstruction of the LGM glaciers in the Dhaulagiri and Annapurna Himalayas (KUHLE 1982). Whereas today the unfavourable insolation conditions on southern aspects are more than offset by high monsoon rainfall, leading to lower ELAs on southern slopes, the ELA of the northern slopes was lower during the LGM that is, the dependence of glacier formation on slope aspect was not distorted by precipitation on windward slopes.] Deep-sea cores from the Arabian Sea point to changes in the upwelling system off Arabia which are caused by intensity fluctuations of the SW Indian summer monsoon circulation. They show that the summer monsoon was substantially less vigorous during glacial phases (EMEIS et al. 1995). Loess-palaeosol sequences in China enable the intensity fluctuations of the East Asian summer monsoon to be reconstructed and also confirm that during glacial times the summer monsoon had been dramatically weakened (RUTTER & DING 1993). At the same time, however, there is evidence of a strengthened Asian winter monsoon during the ice ages. Like a mirror image of the summer monsoon, the winter monsoon arises as a result of a temperature difference, in this case between cold continental air masses and relatively warm air over the Pacific and Indian oceans. The resulting cold/dry anticyclonic winds blow loess out of Inner Asia and deposit it on the loess plateau of China. Particle-size measurements of loess-palaeosol sequences serve as indicators of the differing strength of the winter monsoon and document its increased intensity during glacial stages (XIAO et al. 1995, DING et al. 1995). Sensitivity experiments have shown that the Nordic lowland ice sheets have only little effect on monsoon circulation, whose intensity is primarily controlled by direct insolation at low latitudes (FELZER et al. 1998). Ice-age weakening of the summer monsoon and strengthening of the winter monsoon is hence a clear pointer to glaciation at a subtropical latitude, i.e. on the Tibetan plateau (ANDERSON & PRELL 1993, EMEIS et al. 1995). The Tibetan ice sheet thus influenced the Earth's atmospheric circulation and heat balance at a crucial point. The climate-ecological signal may have been strong enough to exert a decisive influence on the global tendency towards glaciation: Tibet may have been the trigger for the ice ages (KUHLE 1987, 1998). Tibet's key role is confirmed by computer models showing that the Tibetan ice sheet is not only the first to form at the onset of a glacial cycle, but that when the build-up of Tibetan ice is artificially delayed the Nordic lowland ice sheets develop much more slowly. The global ice volume then measures only half of the ice volume during the LGM (MARSIAT 1994).

SYNCHRONISM OF TIBETAN UPLIFT AND THE ICE AGES

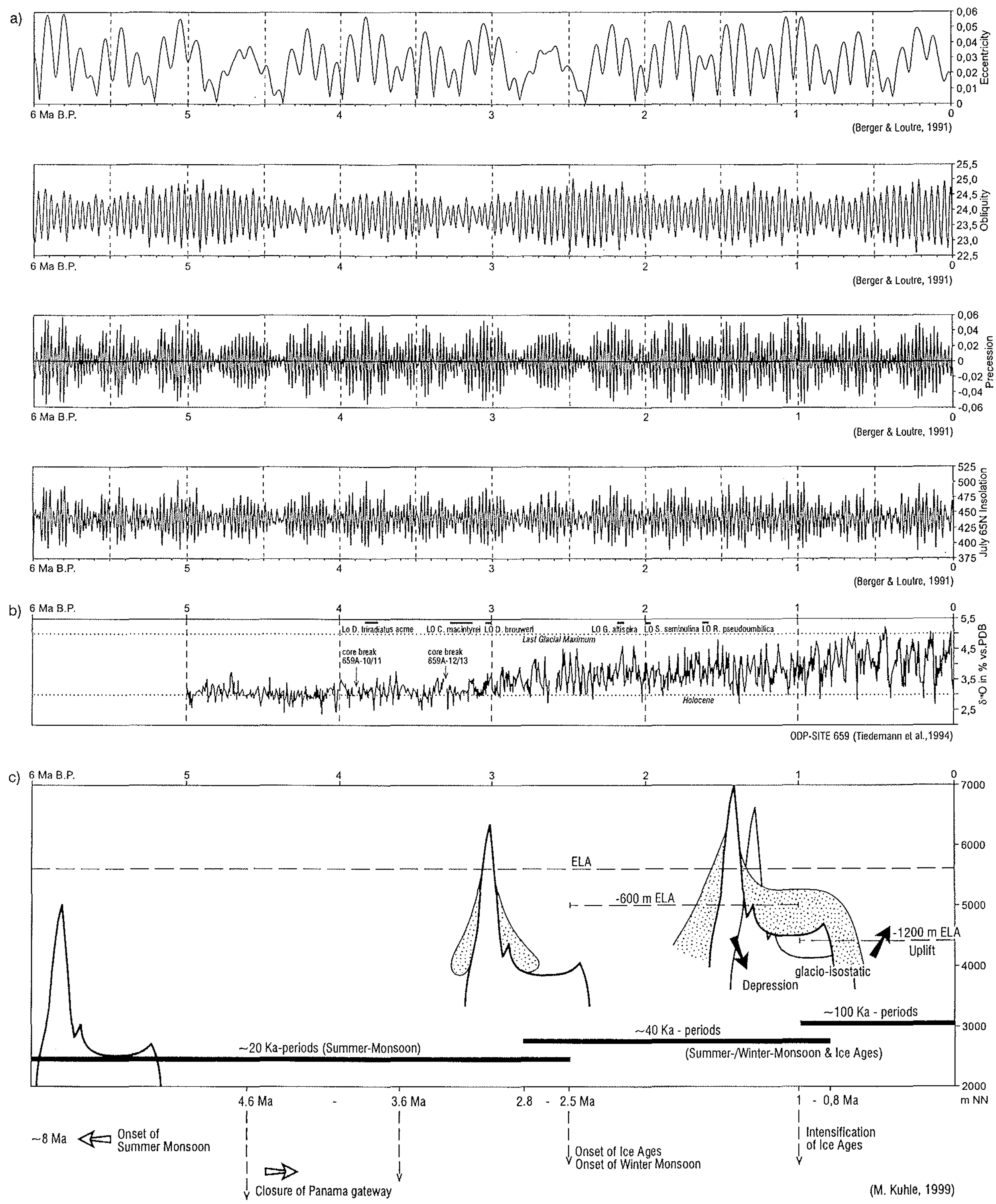
For the role of the Tibetan ice sheet as trigger of the ice ages to be plausible, it must be shown that the uplift record was synchronous with that of Quaternary climate changes. From a different perspective, the uplift of Tibet has already been linked with the onset of the ice ages (RUDDIMAN & KUTZBACH 1991, RUDDIMAN et al. 1997). On the one hand, uplift is presumed to have changed the large-scale circulation of the atmosphere leading to a greater climate-geographical differentiation of the Northern Hemisphere. At the same time, the onset of summer monsoon rainfalls is assumed to have increased the chemical weathering rate of silicate rocks and thus reduced the CO_2 content of the atmosphere. In accordance with the uplift chronology of Tibet and the Himalaya, this effect is presumed to have caused a general cooling of the Northern Hemisphere by 7-9 °C between 20 and 15 Ma B.P. However, the ice ages began only relatively abruptly between 2.8 and 2.5 Ma B.P. and intensified considerably from 1-0.8 Ma B.P. onwards (MORLEY & DWORETZKY 1991, TIEDEMANN et al. 1994, MASLIN et al. 1996, MASLIN et al. 1998; Fig. 12b). Neither the time markers nor the abrupt nature of the onset and development of the ice ages are consistent with the theories of a long-term geological cause (MASLIN et al. 1998). Furthermore, the Vostok ice core records show an inverse relation between greenhouse gases and temperature change during the ice ages: the CO_2 content of the atmosphere changes in the wake of the glacial/interglacial transitions and is by no means their promoter (FISCHER et al. 1999). In our view, it is Tibet's ice sheet that accounts for the plateau's global climatic relevance. Uplift of the Tibetan plateau remains irrelevant for the absolute heat balance of the Earth's atmosphere until the level of ELA is reached. Owing to the special orographic situation of the plateau as described above, the difference between an ice sheet covering only 2-4 % of the area (~48,000 to 120,000 km^2) and an 80 % ice cover (~2 million km^2) corresponds to an average uplift of ~1000 m. In geological terms, however, the time required for such an uplift is only short - a few hundred ky - [ZHONG & DING (1996) reconstruct uplift rates of 1.0-2.0 mm/a for the period around 3 Ma B.P., and 2.0-7.0 mm/a for 2 Ma B.P.; for the period around 1.3 Ma B.P. DING et al. (1995), give an uplift rate of 2.3 mm/a.] – and thus fits in with the abrupt onset of the ice age.

Hence it is necessary to establish when the Tibetan plateau reached the climatically relevant altitude zone between ~4000 m asl (2-4 % glaciation and seasonal winter snow cover) and ~4600-5000 m asl (80-95 % ice sheet). A first intensive uplift phase between 20 and 8 Ma B.P. has been confirmed (HARRISON et al. 1992, COPELAND 1997), although the absolute elevation that the plateau reached at this time (8 Ma B.P.) cannot be definitely established from the geological setting. From a climate-ecological point of view, however, evidence seems to support the onset of the summer monsoon at 8 Ma B.P. (QUADE et al. 1989, PRELL & KUTZBACH 1992, TIEDEMANN et al. 1994, DE MENOCAL 1995). Simulations with a general circulation model have shown that the Indian summer monsoon only occurs with an intensity similar to today's when the Tibetan plateau has reached at least half of its present elevation, i.e. 2000-2500 m asl (MANABE & BROCCOLI 1985, PRELL & KUTZBACH 1992). At the same time, finds of a Hipparion fauna and associated vegetation in Middle Pliocene sediments of S Tibet indicate a warm-tropical steppe climate with lengthy dry periods (CHEN 1981, JI et al. 1981), so the plateau cannot have reached the ELA level, and even an only seasonal snow cover can be excluded. Hence the plateau attained an elevation of between 2000 and, at most, 3000 m asl during the Miocene/Pliocene. There is geological evidence of a further phase of intensive uplift in the late Pliocene/early Pleistocene (CHEN KEZAO & BOWLER 1986, CHEN ZHILIANG 1999, JIN XIAOCHI 1999). This phase is linked in climate-ecological terms with the start of the Asian winter monsoon (DING et al. 1992, JIN XIAOCHI 1999), which has been established by dating the loess palaeosol sequences of central China to 2.5 Ma B.P. (KUKLA & AN 1989, AN et al. 1990, DING et al. 1992). The intensity of the winter monsoon basically depends on the development of a cold anticyclone over High Asia, this being primarily controlled by the high albedo of a winter snow cover (FLOHN 1981, DING et al. 1992, DING et al. 1995, XIAO et al. 1995). The onset of the Asian winter monsoon thus indicates a plateau elevation of at least ~4000 m asl, which is necessary for a seasonal snow cover. With this, Tibet's albedo effectivity influences the global heat balance for the first time, starting at 2.5 Ma B.P. at the latest. At first this involves a general cooling of the Northern Hemisphere; at the same time, however, phases of decreased insolation resulting from earth orbital variations are enhanced by subtropical ice/snow cover. According to the $\delta^{18}O$ records of benthic foraminifera, between 2.5 and 1 Ma B.P. global ice volumes totalled only half to two-thirds of those during the late Pleistocene (SHACKLETON et al. 1988, MORLEY & DWORETZKY 1991, TIEDEMANN et al. 1994), i.e. for the Tibetan Plateau an ELA depression of 600-900 m must be considered. Given a plateau height averaging 4000 m, such a depression of the ELA would generate a 25 % glaciation at most, i.e. Tibet's cooling effect remained low and, accordingly, growth of the Nordic ice sheets remained incomplete and did not survive phases of enhanced insolation (MARSIAT 1994). Since high-latitude insolation is primarily controlled by the 41 ky cycle of obliquity (MANGERUD al. 1998, FELZER et al., 1998), glacial/interglacial pulses at this time follow a 40 ky periodicity (SHACKLETON et al. 1988, MORLEY & DWORETZKY 1991, TIEDEMANN et al. 1994). The reaching of the plateau's present average elevation of 4600 m (or possibly even up to ~5000 m) is, in our opinion, reflected by the intensification of global glaciation between 1 Ma and 0.8 Ma B.P. and the change to a dominant 100 ky periodicity (SHACKLETON et al. 1988, MORLEY & DWORETZKY 1991, TIEDEMANN et al. 1994). Geological indicators confirm that uplift occurred during this interval (CHEN KEZAO & BOWLER 1986, CHEN ZHILIANG 1999, JIN XIAOCHI 1999). The growth of a Tibetan ice sheet resulted in the maximum cooling effect (-0.8 °C GMT anomaly) and thus the complete development of the Nordic lowland ice sheets (KUHLE 1987, 1998). Ice thus continued to build up during phases of enhanced insolation as long as the cooling effect of the Tibetan ice was maintained. However, maximum ice thicknesses of up to 2000 m would have resulted in a glacioisostasy-induced reduction of plateau height by 600-700 m, i.e. down to ~4300 m asl (KUHLE 1995). Increased insolation now caused the Tibetan ice sheet to melt, whereby the change from a cold-based ice sheet to a more temperate, more viscous flow with extremely rapid ice disintegration is to be expected, as HUGHES (1998) postulated for the Nordic lowland ice sheets. Thus a world-wide warm interglacial phase would prevail until postglacial uplift caused the plateau to re-enter the critical ELA elevation zone, which occurred after about 15-20 ky [That the Tibetan plateau was lower during Postglacial time than it is today, can be proved by morainic deposits on the northern Shisha Pangma slopes. These extensive pedestal moraines were left by the ice during the Late Glacial. Since then small, local plateau glaciers have formed on the moraine surfaces, which can only be explained by strong glacio-isostatic uplift in the meantime, thus raising the plateau closer to the local ELA (KUHLE 1988). To attain its present elevation of about 4600 m asl within 20 ky, the plateau must have undergone uplift at a rate of about 15 mm/a. In view of modern evidence of an uplift rate of 12 mm/a for the Tibetan plateau (HSU et al. 1998), this value seems appropriate.].

This chronology of Tibetan uplift and glaciation history coincides with the chronology of the intensity fluctuations of the summer and winter monsoon. Under modern orographic conditions the intensity of monsoon circulation is primarily controlled by insolation in low latitudes (PRELL & KUTZBACH 1997, FELZER et al. 1998) and thus should follow the 21 ky cycles of precession. However, there is only evidence for dominant 20 ky monsoon cycles prior to 2.8 Ma B.P. (DE MENOCAL 1995). Starting at 2.8 and 2.5 Ma B.P., respectively, the summer and the incipient winter monsoon follow the 41 ky cycles and from ~1 Ma B.P. onwards the 100 ky glacial cycles, whereby glacials have a weak summer and strong winter monsoon, and interglacials *vice versa* (RUTTER & DING 1993, TIEDEMANN et al. 1994, DE MENOCAL 1995, EMEIS et al. 1995, XIAO et al. 1995, DING et al. 1995). As described above, such an aberrant pattern of monsoon circulation can be explained by the existence of a Tibetan ice sheet during glacial times (Fig. 12c).

THE TIBETAN ICE SHEET AS THE TRIGGER OF THE ICE AGES

From the start, the theory that ice ages were caused by insolation fluctuations due to earth orbital variations (CROLL 1875) involved contradictions, orbital parameters being old and constant and the ice ages young and exceptional in terms of Earth history (Figs. 12a+b). The first modern correlation analyses of the ice ages up to 250 ky B.P. by HAYS et al. (1976) yielded a paradoxical result: insolation fluctuations are primarily due to precession (~21 ky periodicity) and obliquity (~41 ky periodicity) – however, they can only explain 10 and 25 %, respectively, of the variation of global ice volume. By contrast, 50 % of the variance features a 100 ky cycle. Eccentricity, which fluctuates in ~91 ky cycles, varied by only 0.1 % in the past 500 ky and is therefore considered to be too weak to cause these climatic fluctuations. In addition, the latest numerical and analytical comparisons have confirmed that neither the onset of the ice ages at ~2.5 Ma B.P., nor its intensification, nor the 100 ky periodicity since ~1 Ma B.P. can be explained primarily by earth orbital variations (BERGER & LOUTRE 1991, MASLIN et al. 1998, BERGER et al. 1999; Fig. 12). Therefore, ocean circulation and atmospheric CO_2 content have been proposed as terrestrial feedback processes. The formation of the Isthmus of Panama between 4.6 and 3.6 Ma B.P. (HAUG & TIEDEMANN 1998) led to deep water formation in the North Atlantic, with more moisture reaching high latitudes. From 3-2.5 Ma B.P., it has been suggested that obliquity (and therefore insolation) fluctuated increasingly, switching this „ocean conveyor belt" on and off like a flip-flop mechanism and



initiating the ice ages (BROECKER 1995, HAUG & TIEDEMANN 1998, MASLIN et al. 1998). What is problematic about this causal nexus is the direct link between ocean circulation and insolation fluctuations: ice ages ought therefore to follow a cycle of 41 rather than 100 ky. Second, the decrease in obliquity variations between 0.9 and 0.6 Ma B.P. to low levels corresponding to pre-ice age values between 3.2 and 3.0 Ma B.P. might be expected to be accompanied by a waning of the glacials. Yet the opposite is the case – from 0.8 Ma B.P. onwards the ice ages showed a clear increase in intensity (Fig. 12).

It has been suggested that ice age changes in ocean circulation affected the biological productivity of the surface oceans and thus the atmospheric CO_2 content (BARNOLA et al. 1987, BROECKER 1995). In fact, as the Vostok ice core records for the last 250 ky show, the CO_2 content of the atmosphere fluctuates between a minimum of 180 ppmv during glacials and more than 300 ppmv during interglacial stages (FISCHER et al. 1999). However, the rise in CO_2 content at a glacial/interglacial transition occurs with a time lag of 600 ±400 years of warming, and at the transition to glacial stages high CO_2 values may be maintained for several thousands of years in

Fig. 12: (a)Astronomical parameters of the earth's orbit and rotation and corresponding insolation values for 65 °N for the last 6 million years according to BERGER & LOUTRE (1991).
(b) Benthic oxygen isotope records from Ocean Drilling Program Site 659 according to TIEDEMANN et al. (1994). The fluctuations in the $\delta^{18}O$-content of the foraminifera reflect the fluctuations of the global ice volume, with high values corresponding to the glacials and low values to the interglacials.
(c) Comparison of (a) and (b) shows that orbital variations cannot be the primary cause of the ice ages and have merely a modulating function. The closure of the Panama gateway (HAUG & TIEDEMANN 1998) occurred too early to serve as a terrestrial cause. The uplift of the Tibetan plateau, as far as it can be reconstructed from the onset of the summer (TIEDEMANN et al. 1994, QUADE et al. 1989, PRELL & KUTZBACH 1992, DE MENOCAL 1995) and winter (JIN XIAOCHI 1999, DING et al. 1992, KUKLA & AN 1989, AN et al. 1990) monsoons, and, derivable from this, the begin of an autochthonous glaciation of Tibet from (2.5 Ma B.P. onwards, was synchronous with the onset of the global ice ages. Evidence that variations of the summer and winter monsoon intensity documented by marine dust flux records (EMEIS et al. 1995, ANDERSON & PRELL 1993, TIEDEMANN et al. 1994, DE MENOCAL 1995) and loess-palaeosol sequences (RUTTER & DING 1993, XIAO et al. 1995, DING et al. 1992, DING et al. 1995) occurred in phase with glacial/interglacial cycles (~40 ky and (100 ky periods), strongly suggest the existence of a Tibetan glaciation (EMEIS et al. 1995, ANDERSON & PRELL 1993). Gradual uplift of the Tibetan Plateau towards the ELA level enabled an ice sheet of 2.4 million km^2 to grow from (1 Ma B.P. onwards; the resulting cooling effect permitted a maximum expansion of the Nordic lowland ice sheets (-1200 m ELA). The now beginning glacio-isostatic depression, deglaciation and subsequent uplift of the plateau resulted in interglacial/glacial cycles at 100 ky periods.

Abb. 12: (a) Parameter der Erdumlaufbahn und entsprechende Einstrahlungswerte bei 65 °N für die letzten 6 Millionen Jahre nach BERGER & LOUTRE (1991).
(b) Benthische Sauerstoffisotopwerte ($\delta^{18}O$) der Ocean Drilling Program (ODP) site 659 nach TIEDEMANN et al. (1994). Die Schwankungen des $\delta^{18}O$-Gehaltes der Foraminiferen entsprechen den Schwankungen des globalen Gletschervolumens, wobei hohe Werte den Glazialen und niedrige Werte den Interglazialen entsprechen.
(c) Der Vergleich von (a) und (b) zeigt, daß Variationen der Erdumlaufparameter nicht die primäre Ursache der Eiszeiten sein und lediglich eine modulierende Funktion besitzen können. Die Schließung der Meeresenge von Panama (HAUG & TIEDEMANN 1998) erfolgte zu früh um als terrestrische Ursache infrage zu kommen. Die Hebung des tibetischen Plateaus, soweit sie bisher über das Einsetzen des Sommer- (TIEDEMANN et al. 1994, QUADE et al. 1989, PRELL & KUTZBACH 1992, DE MENOCAL 1995) und des Wintermonsuns (JIN XIAOCHI 1999, DING et al. 1992, KUKLA & AN 1989, AN et al. 1990), rekonstruiert werden konnte und die damit einhergehende Vereisung Tibets seit ~2 Ma B.P., erweist sich als synchron mit dem Beginn der globalen Eiszeiten. Intensitätsschwankungen des Sommer- und Wintermonsuns, die von Meeressedimenten (EEMEIS et al. 1995, ANDERSON & PRELL 1993, TIEDEMANN et al. 1994, DE MENOCAL 1995) und Lössablagerungen (RUTTER & DING 1993, XIAO et al. 1995, DING et al. 1992, DING et al. 1995) dokumentiert werden, sind korreliert mit den Glazial-/Interglazial-Zyklen (~40 ky und ~100 ky Perioden) und weisen damit auf die Existenz einer tibetischen Vereisung hin (EMEIS et al. 1995, ANDERSON & PRELL 1993). Die Hebung des tibetischen Plateaus in das Niveau der ELA erlaubte seit ~1 Ma B.P. die Entwicklung eines ca. 2.4 Mio km^2 großen Inlandeises; der resultierende Kühleffekt führte zum maximalen Aufbau der nordischen Flachlandeise (-1200 m ELA). Aus der folgenden glazio-isostatischen Depression, Deglaziation und wiederum Hebung des Plateaus ergeben sich Glazial-/Interglazial-Zyklen mit ~100 ky Perioden.

spite of large temperature decreases (FISCHER et al. 1999). This shows that both ocean circulation and atmospheric CO_2 content can amplify an incipient ice age, but do not cause primary temperature reduction. Linked functionally to insolation fluctuations, they cannot be the reason for onset, intensification or 100 ky periodicity of the ice ages. To assume that an - as yet unproven (PAGANI et al. 1999, PEARSON & PALMER 1999) - linear drop in the atmospheric CO_2 content from 320 ppmv to 200 ppmv between 3 Ma B.P. and today was the promoter of the ice ages, as BERGER et al. (1999) propose, is to confuse cause and effect. This model shows that the ice volumes known to have existed during the glacial stages of the past ~1 Ma form at a CO_2 level of 240 ppmv and less. Given a Holocene, pre-industrial CO_2 level of 267 ppmv (FELZER et al. 1998), this difference of -27 ppmv is equivalent to a GMT anomaly of -0.8 °C (OGLESBY & SALTZMAN 1992). This is indirect confirmation that the growth of a Tibetan ice sheet starting at ~1 Ma which, according to our calculations, causes a GMT anomaly of -0.8 °C (see above), could be the primary terrestrial cause of the ice ages. Tibet's uplift is entirely independent of earth orbital variations, which would account for the singularity of ice age onset. The course of uplift and the chronology of the ice ages correlate positively over time. The climatic effectivity of the Tibetan plateau is linked with the attaining of stringently definable threshold values, so ecological effects occur abruptly, as do the ice ages. Above a certain plateau elevation, between 4600 and 5000 m asl, large-scale ice sheets can also survive phases of positive insolation anomalies and force the glacial phases into a ~100 ky cycle in contrast to orbital variations. Tibet's influence on global climate results from its vast area, its high altitude and subtropical latitude (KUHLE 1987, 1998; Fig. 11). The promoter of one of the largest atmospheric circulation systems, Tibet plays a decisive role in regulating the climatic zones of the Northern Hemisphere. Being an albedo surface with significant subtropical energy values during the ice ages, the Tibetan plateau affected the absolute heat balance of the earth.

Up to now, general circulation models have been based on the ice-sheet configurations shown by CLIMAP (1981) and COHMAP (1988), which do not yet include any glaciation of Tibet. However, in these climate models, Tibet shows the basic tendency to develop a permanent snow cover and thus signals that the development of large-scale glaciation was inevitable in the climatic context (KUTZBACH et al. 1998). It is suggested that what has previously been considered to be an unavoidable error in the climate models (VERBITZKY & OGLESBY 1992, MARSIAT 1994, KUTZBACH et al. 1998) actually corresponds to reality, as indicated by field evidence (KUHLE 1982-1999).

The crucial role played by the Tibetan plateau for our understanding of Quaternary climatic change is undisputed (HUGHES 1998, KARLEN et al. 1998). Due consideration of a Tibetan ice sheet may be expected to significantly increase the realism of climatic simulations.

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