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Quaternary fans and terraces in the Khumbu Himal south of Mount Everest: their characteristics, age and formation

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Abstract: Large fans and terraces are frequent in the Khumbu Himal within the high Himalayan valleys south of Mt. Everest. These features are composed of massive matrix- and clast-supported diamicts that were formed from both hyperconcentrated flows and coarse-grained debris flows. Cosmogenic radionuclide (CRN) exposure ages for boulders on fans and terraces indicate that periods of fan and terrace formation occurred at *c*. 16, *c*. 12, *c*. 8, *c*. 4 and *c*. 1.5 ka, and are broadly coincident with the timing of glaciation in the region. The dating precision is insufficient to resolve whether the surfaces formed before, during or after the correlated glacial advance. However, the sedimentology, and morphostratigraphic and geomorphological relationships suggest that fan and terrace sedimentation in this part of the Himalaya primarily occurs during glacier retreat and is thus paraglacial in origin. Furthermore, modern glacial-lake outburst floods and their associated deposits are common in the Khumbu Himal as the result of glacial retreat during historical times. We therefore suggest that Late Quaternary and Holocene fan and terrace formation and sediment transfer are probably linked to temporal changes in discharge and sediment load caused by glacier oscillations responding to climate change. The timing of major sedimentation events in this region can be correlated with fans and terraces in other parts of the Himalaya, suggesting that major sedimentation throughout the Himalaya is synchronous and tied to regional climatic oscillations. Bedrock incision rates calculated from strath terrace ages average *c*. 3.9 mm a^{-1}, suggesting that the overall rate of incision is set by regional uplift.

High Himalayan landscapes provide excellent natural laboratories to examine the interactions between tectonics, surface processes and climate change within an active continent–continent collision zone (Zeitler *et al*. 2001; Bishop *et al*. 2002). Furthermore, these regions contain excellent geomorphological and sedimentological records of glacial oscillations that provide important insights into the nature of Late Quaternary palaeoclimate change, notably the glacial and hydrological response to oscillations in the south Asian monsoon (Owen & Lehmkuhl 2000; Owen & Zhou 2002; Finkel *et al*. 2003). As a first step in examining the relationship between climate change and landscape evolution, we focus our study on landforms within the valleys of the Khumbu Himal region, south of Mount Everest (Figs 1 and 2). The region was chosen because it is relatively accessible and has well-established glacial chronologies, and contains abundant impressive fans and terraces that partially fill deep valleys downstream from modern glaciers (Muller 1958, 1980; Iwata 1976; Fushimi 1977, 1978; Williams 1983; Benn & Owen 1998; Owen *et al*. 1998; Aoki & Imamura, 1999; Richards *et al*. 2000; Finkel *et al*. 2003). (The fans may be described as 'alluvial fans', but we avoid the use of this term because it implies a genetic (fluvial) origin for the fan-shaped landforms that are present within Himalayan valleys. These landforms predominantly comprise diamictons that may be of debris flow, hyperconcentrated flow and/or fluvial origin. We therefore use the non-genetic term 'fan' to describe these landforms.) These landforms (e.g. Fig. 1) allow us to begin to examine in detail the temporal and spatial relationships between climate change, glaciation, sediment transfer, and fan and terrace formation. In this paper, we report our investigations of these fans and terraces to provide evidence for the timing and rates of the erosional and depositional processes within this high Himalayan environment. We suggest temporal and genetic links between terrace and fan formation, and glacier oscillations. Our study of the fans and terraces in the Khumbu Himal and the related study on glacial stages by Finkel *et al*. (2003) are unique in the large number of samples dated (>100), number of landforms dated (14 fan or terrace surfaces, 15 moraines), great spatial distribution of the sampling (tens of kilometres), and integration with landform sedimentology. This represents the most extensive surface dating project ever attempted in the high Himalaya.

Previous studies suggested that Quaternary fans within the Himalaya formed by rapid sedimentation during times of glacial retreat (Derbyshire & Owen 1990; Owen *et al*. 1995; Owen & Sharma 1998; Watanabe *et al*. 1998; Barnard *et al*. 2004*a*). These studies argued that fan formation occurred during times of glacial retreat and thus could be described as 'paraglacial'. This follows the view of Ryder (1971*a*, *b*) and Church & Ryder (1972) that major episodes of deposition by non-glacial processes in proglacial environments are conditioned by glaciation. Moreover, Church & Slaymaker (1989) argued that enhanced sedimentation may persist for many millennia as landscapes adjust to non-glacial conditions. We aim to test these assertions by determining whether the Khumbu fans and terraces are paraglacial in origin and their formation is thus conditioned by climate, which in turn forces glaciation.

Research area

The Khumbu Himal is located in eastern Nepal, *c*. 200 km NE of Kathmandu (Fig. 2 inset). The south Asian summer monsoon is

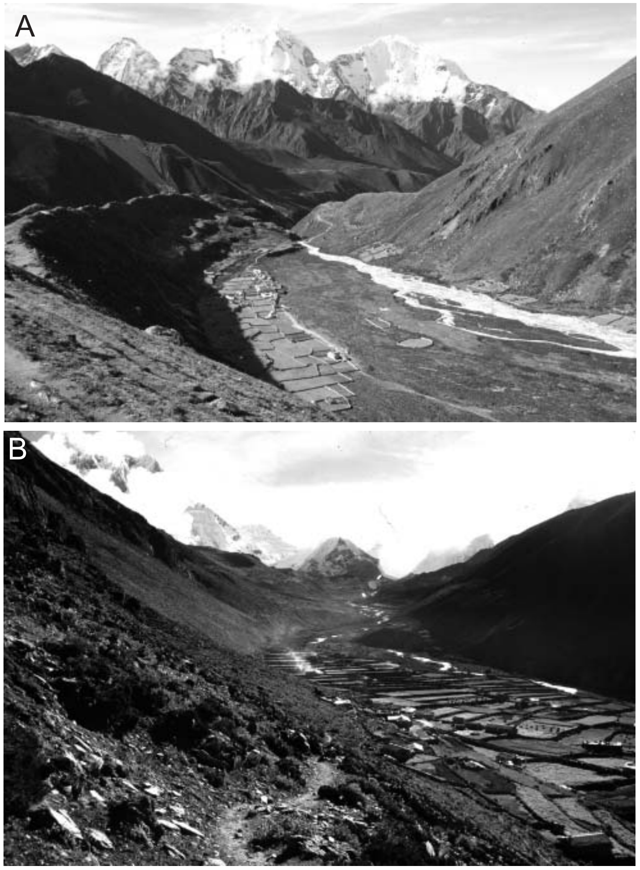


Fig. 1. Typical fans and terraces in the Khumbu Himal. (**a**) View downvalley of an outwash fan below the Khumbu glacier and a major latero-frontal moraine (middle left) dated to *c*. 23 ka by Finkel *et al*. (2003). (**b**) View upvalley of a large terrace at Dingboche downvalley of glaciers and moraines at Chhukhung.

the major source of precipitation in the region. A steep precipitation gradient exists across this region because of topographic effects, ranging from >1500 mm a^{-1} at Lukla (2600 m above sea level (a.s.l.)) in southern Khumbu to *c*. 435 mm a^{-1} at Dingboche (4355 m a.s.l.) in northern Khumbu, in the vicinity of our research area (Nepal Department of Hydrology and Meteorology 1993, 1995, 1996, 1997). The average annual temperature at Dingboche is −0.7 °C (Nepal Department of Hydrology and Meteorology 1993, 1995, 1996, 1997). During the winter months, mid-latitude westerlies transport moisture from the Mediterranean, Black and Caspian Seas toward the Himalaya, but significant snowfall from this source is largely restricted to the western Himalaya (Benn & Owen 1998). At present, most snowfall in the study area accumulates during the summer when moisture is advected north from the Indian Ocean.

The Khumbu Himal contains more than 50 cirque and valley glaciers. Impressive successions of moraines mark the extent of past glaciers (Richards *et al*. 2000; Benn *et al*. 2001; Finkel *et al*. 2003). Building on the work of Richards *et al*. (2000), Finkel *et al*. (2003) documented, using cosmogenic radionuclide (CRN) surface exposure dating, eight separate glacial advances during the Pleistocene and Holocene. These comprise: Thyangboche I (86 ± 6 ka), Thyangboche II (35 ± 3 ka), Pheriche I (23 ± 3 ka), Pheriche II (16 ± 2 ka), Chhukhung (9.2 ± 0.2 ka), Thuklha (3.6 ± 0.3 ka), Lobuche (*c*. 1 ka) and Historical (<0.5 ka). Their results indicate that major glacier advances, such as the Chhukhung Stage, are synchronous with insolation maxima, when increased precipitation delivered by the south Asian summer monsoon fell as snow at high altitudes despite the higher summer temperatures and led to a positive glacial mass balance. During periods of major global cooling, the south Asian summer monsoon was significantly weakened (Sirocko *et al*. 1991), reducing precipitation in the Himalaya. Nevertheless, in some cases, such as during the Pheriche Stages, temperatures were lowered sufficiently to allow glaciers to advance, albeit to a restricted extent (Owen *et al*. 2002*a*; Finkel *et al*. 2003).

Field methods

Three detailed study areas were chosen in the upper catchment of the Khumbu Himal for geomorphological mapping, stratigraphic analysis and CRN dating. These include, in order of increasing altitude up valley: Pangboche, Orsho and Dingboche (Fig. 2). The three study areas contain the most extensive and best-preserved fan successions in the upper Imja Khola Valley, as well as excellent sites for CRN dating, exposed sedimentary sections and well-preserved moraines.

In each area, we used geomorphological and topographic mapping as well as cross-valley profiles to determine the size and relative ages of the fans, terraces and other features. Fans (f) and terraces (t) are designated herein by their morphology and stratigraphic position; for example, t_{p1} is a terrace where the subscript letter refers to the location (p, Pangboche; o, Orsho; d, Dingboche) and the subscript number refers to the relative terrace age (1, youngest; 7, oldest). This mapping also allowed us to reconstruct the former extent of fan and terrace deposits prior to erosion. Sedimentary sections were logged at natural exposures to examine the sediments. Where fan surfaces were not contiguous, correlations were based on relative elevations.

The fans and terraces in the study areas all originate from glacial drainages and have similar morphology and sedimentology, with planar surfaces and coarse diamict deposits. Fans are distinguished from terraces on the basis of slope and position. The Khumbu fans are associated with steep side valley channels and generally have slopes >7°. Terraces have slopes <7°, whereas the terraces are associated with the main trunk valleys.

Dating

A total of 56 samples for CRN dating were collected from the three study sites. Samples were obtained from fan and terrace surfaces, as well as from three modern surfaces. Landforms for CRN dating were chosen to represent the entire chronological range of preserved Quaternary surfaces in the region. The most common rock type sampled was leucogranite. Samples were typically taken from boulder surfaces lying at least 1 m above the fan or terrace surface (to avoid exhumed boulders) and along the distal edges of the landform where the potential complicating effects of erosion, burial, rock fall, or agricultural activity are lowest. A commonly recognized problem with CRN dating is that a sampled boulder may retain a signal of prior exposure inherited from its previous location (i.e. ‘derived’ boulders: Anderson *et al*. 1996; Hancock *et al*. 1999). To help recognize derived boulders, we collected multiple samples from each fan or terrace and looked for potential outliers, that is, exposure ages that fell significantly outside the weighted mean of the landform dated. A second way in which we checked for the possibility of inheritance was to date clasts from the modern floodplain to see whether they gave very low ages (see Anderson *et al*. 1996). We sampled two sand samples from Orsho (E22) and Dingboche (E120), and a boulder along the Orsho floodplain (E21). Dating samples from a landform of known age allowed us to further test the role of inheritance. A flood terrace at Pangboche, t_{p2}, for example, which was deposited in 1977, provided an excellent zero-age surface (Ives 1986; Zimmermann *et al*. 1986; Cenderelli & Wohl 2001). Another problem is boulders that produce erroneously young CRN ages. This is probably caused by boulders that have been exhumed or toppled. We reduce the potential of

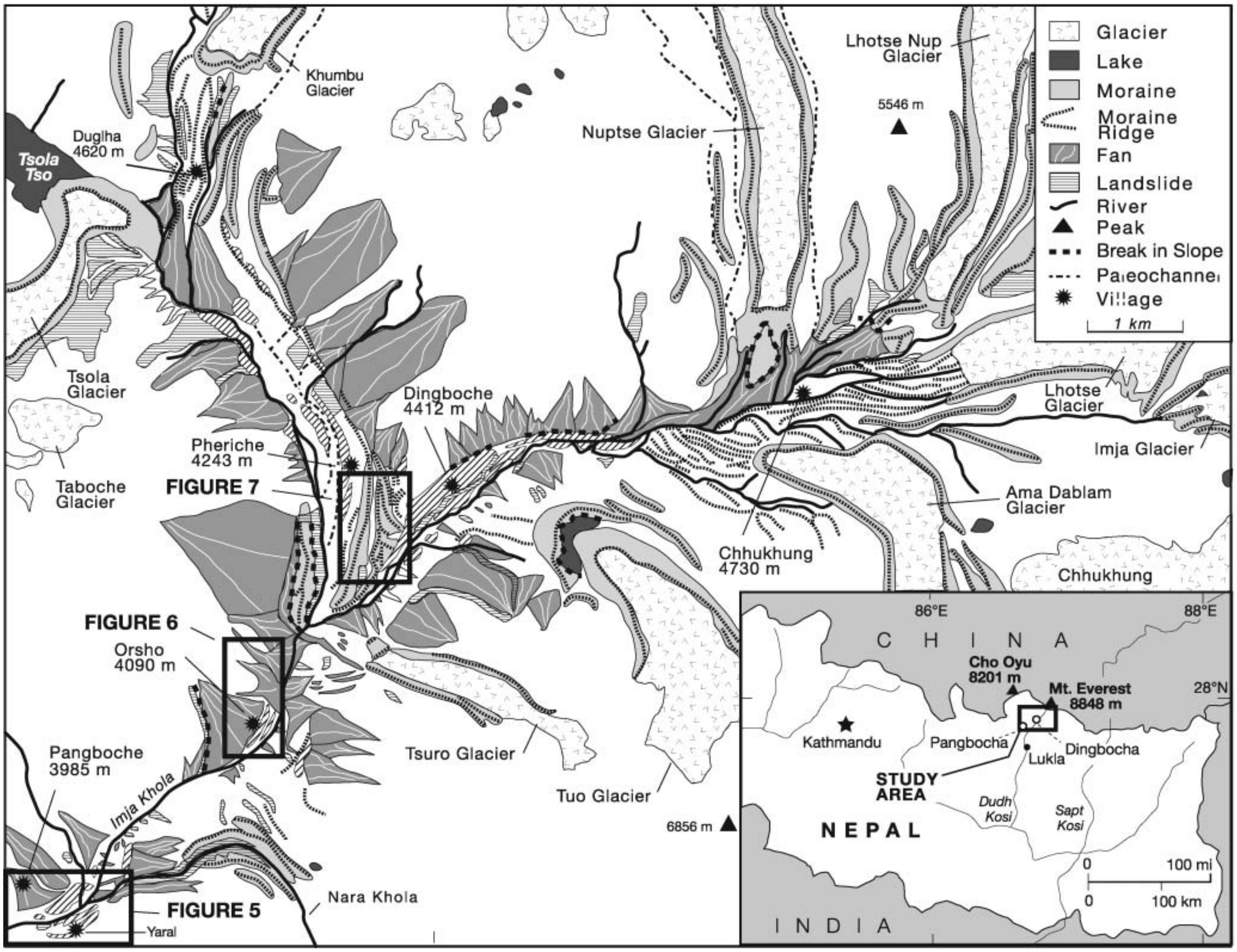


Fig. 2. Geomorphological map of the upper Imja Khola Valley, Khumbu Himal. Boxes define study areas. Mapped at a scale of 1:25 000.

exhumation by choosing the largest boulders on each surface, sampling on ridges (not depressions) on a landform surface, choosing boulders with at least 1 m of relief, and sampling the highest point on each boulder surface. The potential for sampling toppled boulders is reduced by choosing boulders on the distal edges of a landform to avoid toppling from higher surfaces and by sampling boulders that appear well embedded in the landform surface.

In addition to sampling depositional surfaces, one sample was collected for CRN dating from each of four strath terraces lying between 14 and 55 m above the current level of the Imja Khola, 1 km SW of Pangboche.

The CRN samples were analysed for ^{10}Be content in quartz at Lawrence Livermore National Laboratory. First, the samples were crushed and sieved. Quartz was then separated from the 250–500 μm size fraction using the method of Kohl & Nishiizumi (1992). After addition of Be carrier, Be was separated and purified by ion exchange chromatography and precipitation at pH >7. The hydroxides were oxidized by ignition in quartz crucibles. BeO was then mixed with Nb metal prior to determination of the $^{10}Be/^{9}Be$ ratios by accelerator mass spectrometry at the Center for Accelerator Mass Spectrometry in the Lawrence Livermore National Laboratory. Isotope ratios were compared with ICN Pharmaceuticals Inc ^{10}Be standards prepared by K. Nishiizumi (pers. comm.) using a half-life of 1.5×10^6 a. Age determinations were based on the equations and production rates given by Lal (1991) as modified by Stone (2000). A correction for variation in the geomagnetic field was applied to determine the final age of each sample as described by Nishiizumi *et al*. (1989) using the SINT800 geomagnetic intensity assessment (J.-P. Valet, pers. comm.). Full details of the methods used in the age determination have been given by Owen *et al*. (2001, 2002*b*).

Fan geomorphology and sedimentology

With the exception of modern surfaces, each fan and terrace has been incised and partly eroded by progressive downcutting, resulting in nested successions of fans and terraces. The fan and terrace deposits comprise massive beds (2–85 m thick) of matrix-supported cobbles and matrix- and clast-supported boulders. The bouldery diamicts generally have isotropic clast fabrics, but with localized zones of imbrication. The clasts are normally subangular with edges rounded to subrounded, and constitute more than *c*. 50% of the sediment. Clast sizes typically range from 0.5 to 2 m, with some exceeding 5 m in diameter. More than two diamict units are rare in a single exposure. The deposits are indurated and the boulders are transitional between being clast-supported and matrix-supported by pebbly sand with very little silt (*c*. $<10\%$). The cobbly diamicts have clast fabrics with weak to moderate downvalley-preferred orientation. The clasts are subrounded, making up *c*. 20% of the solid fraction, and are supported by a matrix of pebbly sand, with little silt and clay present (*c*. $<5\%$). The cobbly diamicts are poorly sorted, massive and moderately friable. In some deposits the beds are slumped and crudely stratified. Dominant clast sizes range from 10 to 20 cm.

Pangboche–Yaral

We identified 10 distinct fan or terrace levels in the Pangboche–Yaral area. Nine of the 10 surface levels identified are shown in Figure 3, and five surfaces can be traced across the valley (top to bottom: t_{p7}, t_{p6}, t_{p3}, t_{p2}, modern floodplain) (Fig. 3). The upper three levels are fans, which are steeply sloping (>11°) and have abundant large boulders (>5 m) on their surfaces. The fan of greatest surface area, t_{p6}, on the Pangboche side of the valley, is formed of cobbly diamicts overlain by bouldery diamicts transitional between matrix- and clast-supported (Fig. 4). The lower five surfaces are terraces on the Pangboche side of the valley that are inset into the largest fan, and slope parallel to the main valley axis. The lower bouldery terrace surfaces (t_{p2} and t_{p3}) in the Pangboche–Yaral area comprise mostly boulders and are sparsely vegetated (Fig. 5). Sections in t_{p3} show bouldery diamicts, with subangular clasts, some imbrication, and no bedding. The downstream tongue of the surface of t_{p3} consists primarily of moderately well-sorted and subrounded, clast-supported boulders (*c.* 1 m in diameter), with large pore spaces (>10 cm in diameter; Fig. 5c).

Terrace t_{p2} is a fresh boulder deposit with a surface mantled with megaripples (wavelength *c.* 2–3 m), flood chutes and scour pits. This surface formed from a glacial-lake outburst flood that started 8 km upstream on 3 September 1977, when a series of ice-cored moraine dams failed below the Nare Glacier and flood waters surged down the Nare Khola Valley toward Pangboche (Cenderelli & Wohl 2001).

A set of four nested fans and terraces (f_{p3}, f_{p2}, t_{p7} and t_{p6}) originate from the small side valleys above Pangboche village on the Pangboche side of the Imja Khola valley. Additional lower surfaces (i.e. t_{p5} to t_{p1}) are aligned with the main valley axis, having originated as sediments from further up the Imja Khola valley (trunk valley). On the Yaral side, only f_{p1} emerges from a small side valley, originating from a cirque glacier high atop the valley floor. The fan sediments on the Yaral side have their origin from the glaciated valley to the east, the Nare Khola, which drains two glaciers along the southern flanks of Ama Dablam.

Despite being morphostratigraphically equivalent, not all fan levels that are apparently matched on both sides of the valley at Pangboche and Yaral originate from the same source region. This is the case for both surfaces t_{p6} and t_{p7}, where directions of maximum slope on each surface demonstrate that sediment on the two fans on the Pangboche side of the valley originates from two side valleys to the north of the region, whereas the equivalent fans on the Yaral side originate from the Nare Khola Valley to the east. However, the similar elevations and nearly identical sediment types indicate that the fans formed under similar conditions at or about the same time.

Orsho

A prominent set of abandoned fan and terrace surfaces are present at Orsho (4070 m a.s.l.), 3 km up valley from Pangboche (Figs 2 and 6). The Orsho landform succession is located immediately below a large terminal moraine complex of the Khumbu Glacier (Fig. 1a).

A steeply sloping (19–23°) upper fan (f_{o1}) and six gently sloping lower terraces (4–5°) are preserved on the western side of the valley (Fig. 6). Active slope processes have destroyed or covered fan and terrace deposits on the eastern side of the valley at Orsho. The overall geometry of the Orsho surfaces and their sedimentology are similar to those at Pangboche.

The fan (f_{o1}) is the only surface whose axis is perpendicular to the main valley slope. It formed at the foot of a valley that is fed by outwash from the Taboche Glacier (Fig. 2). The lower terrace surface axes are all aligned with the main valley axis and their slopes approximate the main valley slope, indicating sedimentation originating from further up the Imja Khola Valley.

Dingboche

Dingboche is located immediately downvalley from the glacial complex at Chhukhung, which consists of seven converging glaciers. The Dingboche area is highly susceptible to sedimentation events even during periods of only moderate glacial fluctuation because of its upvalley location, near the present glacier margins. A succession of latero-frontal moraines is located up the Imja Khola valley, 2.5 km NE of Orsho (Figs 1a and 2). These represent the former terminus of the Khumbu and Chhukhung glaciers during the Pheriche I (23 ± 3 ka) and Pheriche II (16 ± 2 ka) Glacial Stages (Richards *et al*. 2000; Finkel *et al*. 2003). An extensive axial terrace, t_{d3}, grades to the outermost moraine complex near the village of Dingboche (Fig. 7). Two large terraces, t_{d2} and t_{d1}, are present further up the valley toward Chhukhung but are morphostratigraphically lower and younger than the largest Dingboche surface (t_{d3}). The Dingboche surfaces are much broader and at lower elevations relative to the valley bottom than those at Orsho and Pangboche, probably because the Chhukhung glacier extended into and beyond this region, most recently during the Late Pleistocene (16 ± 2 ka; Finkel *et al*. 2003), widening the valley and thus creating extra space for subsequent sedimentation.

Thin (<3 m) bouldery and cobbly diamict units dominate the exposed sediment sections in the terraces at Dingboche. However, channel deposits are also present, such as a thin sandy pebble layer that is present in a section from t_{d1} (Fig. 8). Furthermore, clean fine sand is also present in sections examined in t_{d1}, and this probably represents wind-blown sediment from nearby glacial deposits accumulating during the dry periods following glacial stages.

Dating results

An estimate of the age of each fan and terrace surface was determined by calculating the weighted average of the individual exposure ages for each surface using the analytical uncertainty as a weighting factor. Factors other than analytical uncertainty can contribute to the spread of ages on a surface. For example, storm events can dislodge samples from higher surfaces and overbank flow can deposit samples from younger, lower-lying landforms. Therefore, samples yielding exposure ages that were within the range of dates determined from surfaces above or below the surface or significantly different from the general population for the given surface, were not included in the calculation. Ages for 16 fan and terrace surfaces were then determined based on 47 CRN dates (Table 1, Fig. 9). In this study we took only three or four samples from each surface to obtain a sufficient number of dates to allow us to develop a broad framework for the Late Quaternary fan and terrace depositional history of the Khumbu. The small number of samples gathered from each surface precludes calculating statistically significant average ages for each surface, but the breadth of coverage allows us to make general conclusions about the temporal development of fans and

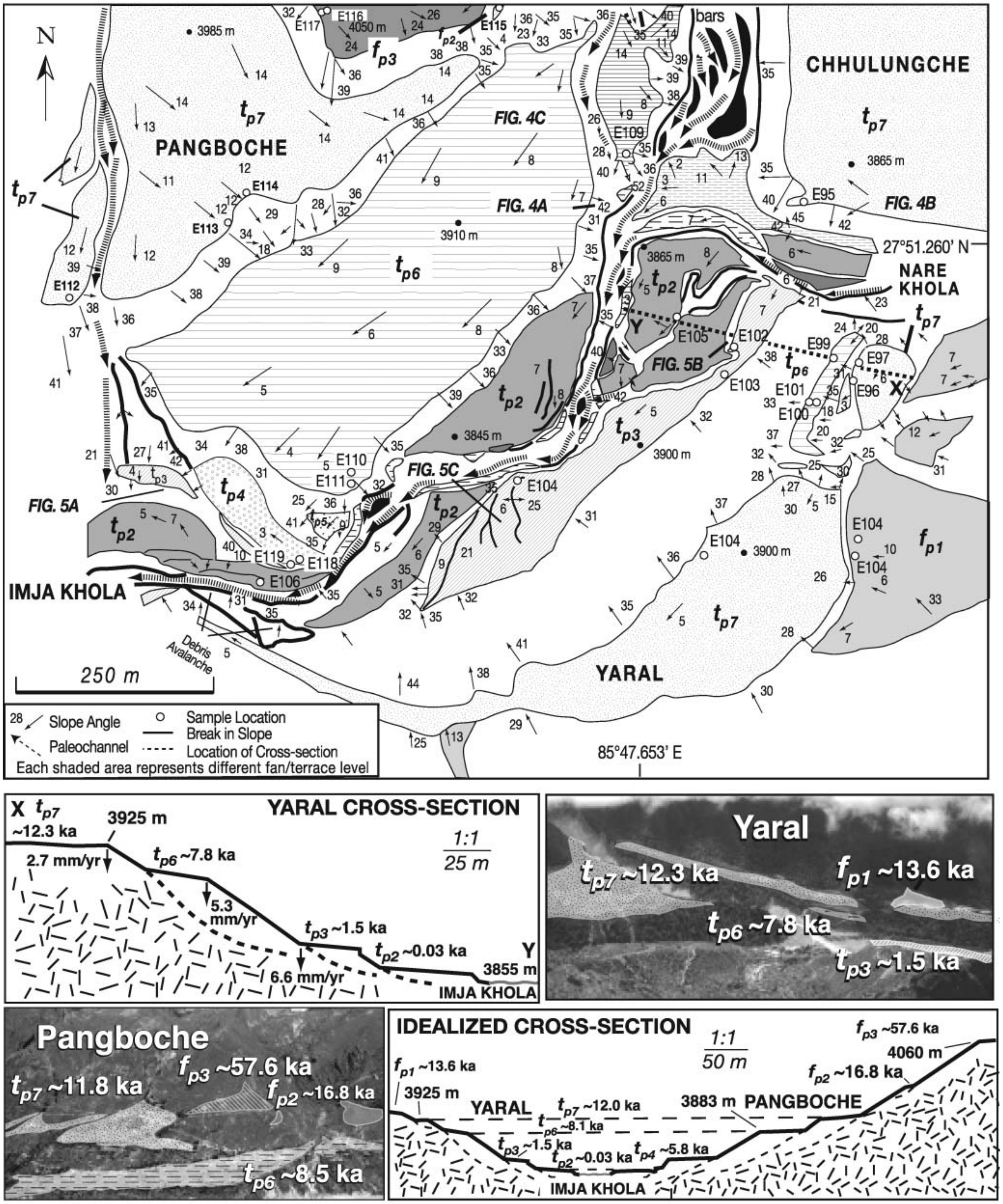


Fig. 3. Geomorphological map of the Pangboche–Yaral study area showing valley profiles and sampling sites. Mapped at a scale of 1:5000. No vertical exaggeration for the cross-sections.

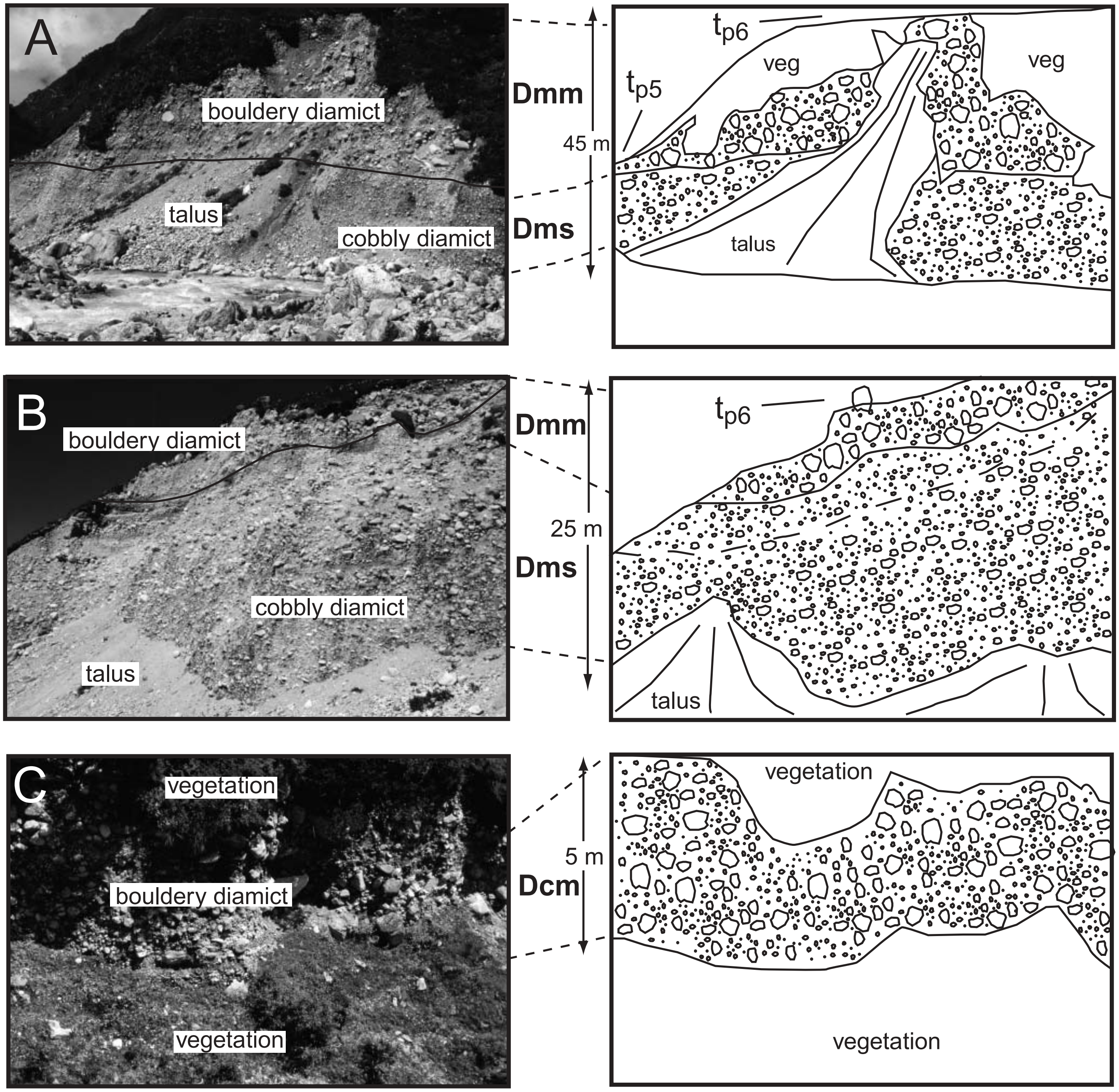
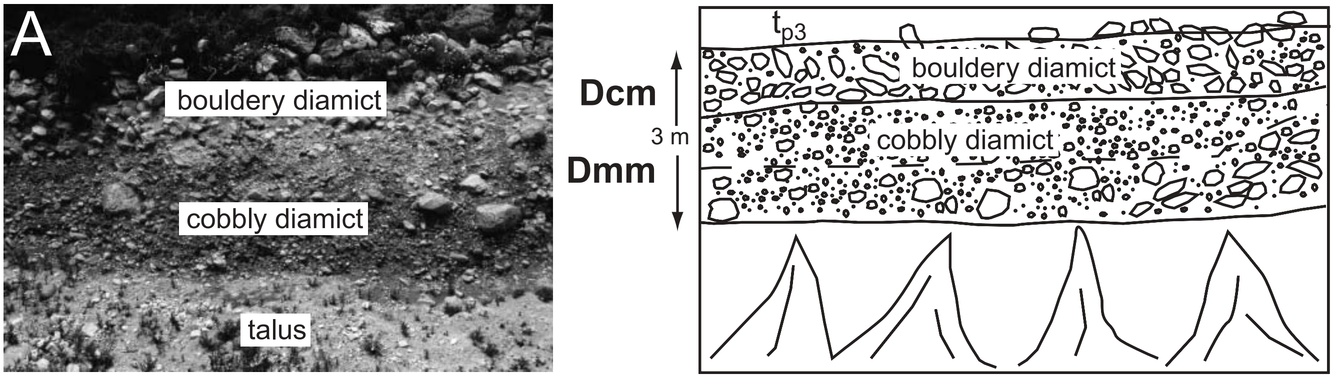


Fig. 4. Typical sedimentary sections from the Pangboche–Yaral study area. (See Fig. 3 for section locations.) (**a**) Thick section from t_{p6} on the Pangboche side of the valley with a bouldery diamict that overlies a cobbly diamict. (**b**) Similar section from t_{p7} below Chhulungche on the Yaral side of the valley. (**c**) Section from t_{p6}, representing a single unit of bouldery diamict. Lithofacies codes after Eyles *et al*. (1983) as modified by Benn & Evans (1998).

terraces. Nevertheless, even if dating errors lie between 10 and 20%, CRN dating is still a vast improvement over relative dating techniques, and the only viable option in an environment where carbon dating is not possible because of the poor production and preservation potential of organic material in the harsh, high Himalayan climate. Whenever practical, the entire range of dates calculated from a given surface is stated and considered. Further information on the methods and calculations employed here has been given by Barnard *et al*. (2001, 2004*a*, *b*), Owen *et al*. (2001, 2002*b*), Burbank (2002) and Finkel *et al*. (2003).

The young CRN ages of 'zero' age inheritance samples ($n = 3$, 0.41 ± 0.03 ka) obtained in our study indicate that the Khumbu Himal sediment probably has a short catchment residence time, which implies that erosion rates are high and thus prior exposure of boulders resting on landform surfaces is, on average, not significant. Ages of samples from the flood deposit at Pangboche (t_{p2}: $n = 2$, 0.72 ± 0.08 ka) illustrate that the average prior exposure of boulders in the Khumbu Himal is <1 ka. Therefore, the exposure ages measured do not significantly overestimate the true age of the landforms.

CRN dates on the morphostratigraphically equivalent surfaces on either side of the Yaral–Pangboche area are tightly clustered



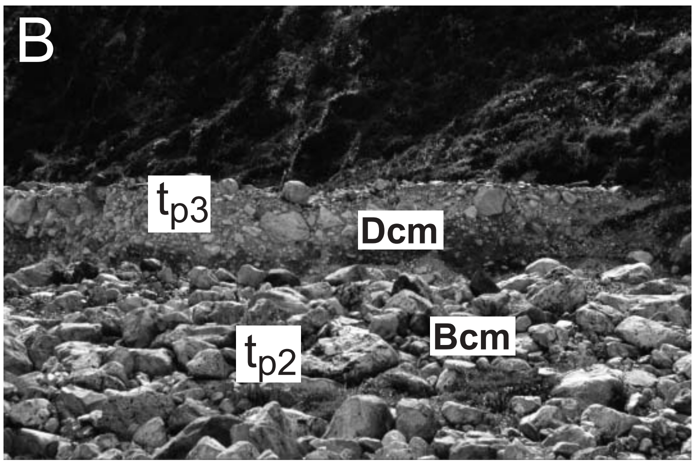


Fig. 5. Typical sedimentary sections from the lower surfaces in the Pangboche–Yaral study area. (See Fig. 3 for section locations.) (**a**) Terrace section beneath t_{p3} on the Pangboche side of the valley. (**b**) On the Yaral side of the valley, a sub-angular, clast-supported bouldery diamict section in t_{p3}. Surface t_{p2} is in the foreground. (**c**) A deposit of moderately well-sorted and subrounded to rounded boulders along the leading edge of t_{p3} on the Yaral side of the valley, looking downflow (i.e. west). Lithofacies codes after Eyles *et al*. (1983) as modified by Benn & Evans (1998).

(Table 1, Fig. 9). Samples from t_{p7}, the highest of the equivalent surfaces, yield an average age of 12.0 ka ($n = 7$, ranging from 10.9 to 13.7 ka). The next lower surface, t_{p6}, is dated to 8.1 ka (n = 5, ranging from 7.7 to 8.2 ka, rejecting E110). Other prominent surfaces formed at 1.5 ka (t_{p3}) and from the AD 1977 glacial-lake outburst flood (t_{p2}: Ives 1986; Zimmermann *et al*. 1986; Cenderelli & Wohl 2001; Fig. 3). A small set of CRN dates on the high fans in the Yaral–Pangboche area suggest episodes of fan sedimentation at *c*. 58 ka (f_{p3}), 17 ka (f_{p2}) and 14 ka (f_{p1}).

Three surfaces were dated at Orsho (Table 1, Fig. 9). The most prominent terrace, t_{o6}, has a weighted average age of 11.0 ka ($n = 3$, ranging from 9.7 to 14.3 ka). The next lower prominent terrace, t_{o4}, dates to 4.8 ka ($n = 6$, ranging from 4.1 to 5.2 ka, rejecting E15, E17 and E25). The rejected (not included in the weighted mean calculation) boulders (E15, age 12.1 ± 0.3 ka; E17, age 35.2 ± 1.5 ka; E25, age 10.1 ± 0.3 ka) are considered to be pre-exposed, because their ages are significantly older than the tightly clustered set of three CRN ages that seem to define the age of this terrace and they are equivalent to or exceed the CRN ages from the higher and older surface (t_{o6}). The next lower terrace surface in the succession, t_{o3}, is dated to *c*. 4.4 ka ($n = 3$, ranging from 4.0 to 4.7 ka).

CRN surface exposure dates on boulders on the Dingboche terrace (t_{d3}) provide dates of 12.2 and 14.7 ka (rejecting E26, age 6.2 ± 0.2 ka, morphostratigraphically similar surfaces at Pang-

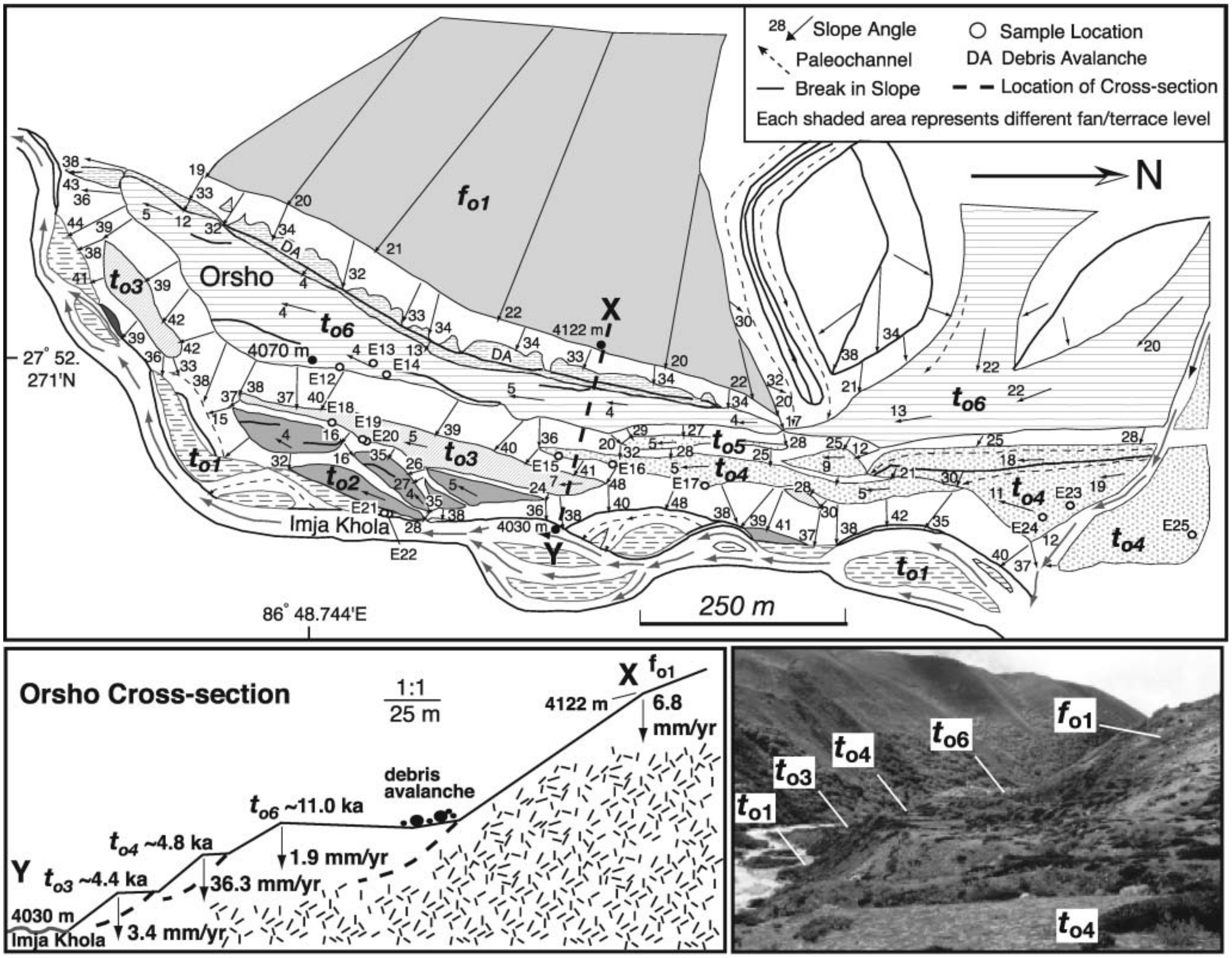


Fig. 6. Geomorphological map of the Orsho study area with a valley profile, landform dates, and cross-section. The photograph shows a view looking downvalley normal to the valley profile. Mapped at a scale of 1:5000. No vertical exaggeration for the cross-section.

boche and Orsho date to >10 ka, truncated moraine dates to 16 ka), which suggest that fan sedimentation ceased by *c*. 12.2 ka. A Late-glacial age for this fan is further supported by the *c*. 16 ka ages on moraines that are overlain by this terrace (Finkel *et al*. 2003; Fig. 7). Furthermore, this terrace is morphostratigraphically equivalent to the prominent surfaces at Pangboche (t_{p6}; see Fig. 3) and Orsho (t_{o6}; see Fig. 6) that are dated to *c*. 12 ka and *c*. 11 ka, respectively. The morphostratigraphic equivalence of each fan or terrace succession was determined by the slope and elevation of each surface, sedimentology, and the surface morphology.

Ages on the two lower Dingboche surfaces, t_{d2} and t_{d1}, range between 4 and 5 ka. The higher terrace, t_{d2}, is dated to *c*. 4.9 ka ($n = 2$, rejecting E65 and E66, both with ages 3.0 ± 0.1 ka, younger than the terrace below it). Fan t_{d1} dates to *c*. 4.1 ka (n = 2, rejecting E68, age 2.81 ± 0.2 ka). The ages of the lower Dingboche surfaces are approximately equivalent to t_{o4} and t_{o3} at Orsho, which are dated to *c*. 4.8 and 4.4 ka, respectively. Alternatively, these two lower fans at Dingboche could date to *c*. 3.0 ka and *c*. 2.8 ka, respectively, if the other samples were rejected instead, but this seems unlikely given the similar succession of surfaces at nearby Orsho.

The Imja Khola valley narrows into a deep gorge immediately downvalley of the Pangboche area (Fig. 10). Four strath terraces cut into the sides of this gorge and have ages of 3.7 ± 0.1 ka, 6.6 ± 0.3 ka, 12.6 ± 0.3 ka and 16.2 ± 0.4 ka (Table 1). These ages indicate incision rates of 3.4–4.3 mm a^{-1}, with an average of 3.9 mm a^{-1} (Table 2). Given that the valley is narrow at this point, it is unlikely that these strath terraces were sites of prolonged sediment storage during the Late Pleistocene (see Pratt *et al*. 2002).

Discussion

Stratigraphic analysis of the Late Pleistocene and Holocene fans and terraces in the Khumbu Himal indicates that the sediments have characteristics of both hyperconcentrated flows and debris flows (Fig. 11). Hyperconcentrated flows are commonly associated with floods containing high sediment loads whereas debris flows are associated with regolith slopes or sedimentary deposits that have become soaked with water during rainstorms or snow melts.

The bouldery diamicts that are prevalent in Khumbu fans and terraces have characteristics common to debris flows (e.g.

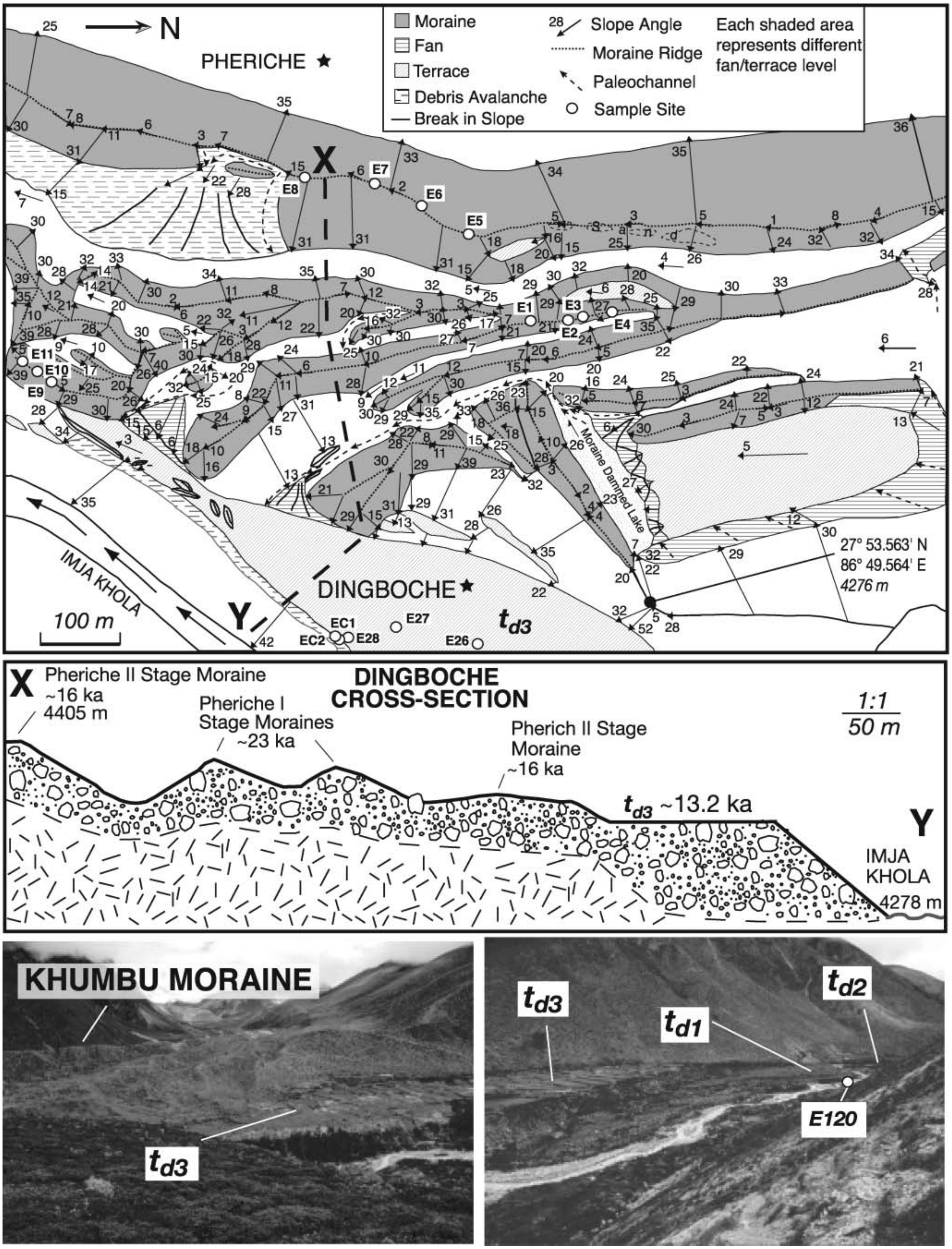


Fig. 7. Geomorphological map of the Dingboche study area with a valley profile and dating results. The photograph shows a northerly view from a ridge on the opposite side of the valley. Mapped at 1:5000. No vertical exaggeration for the cross-section.

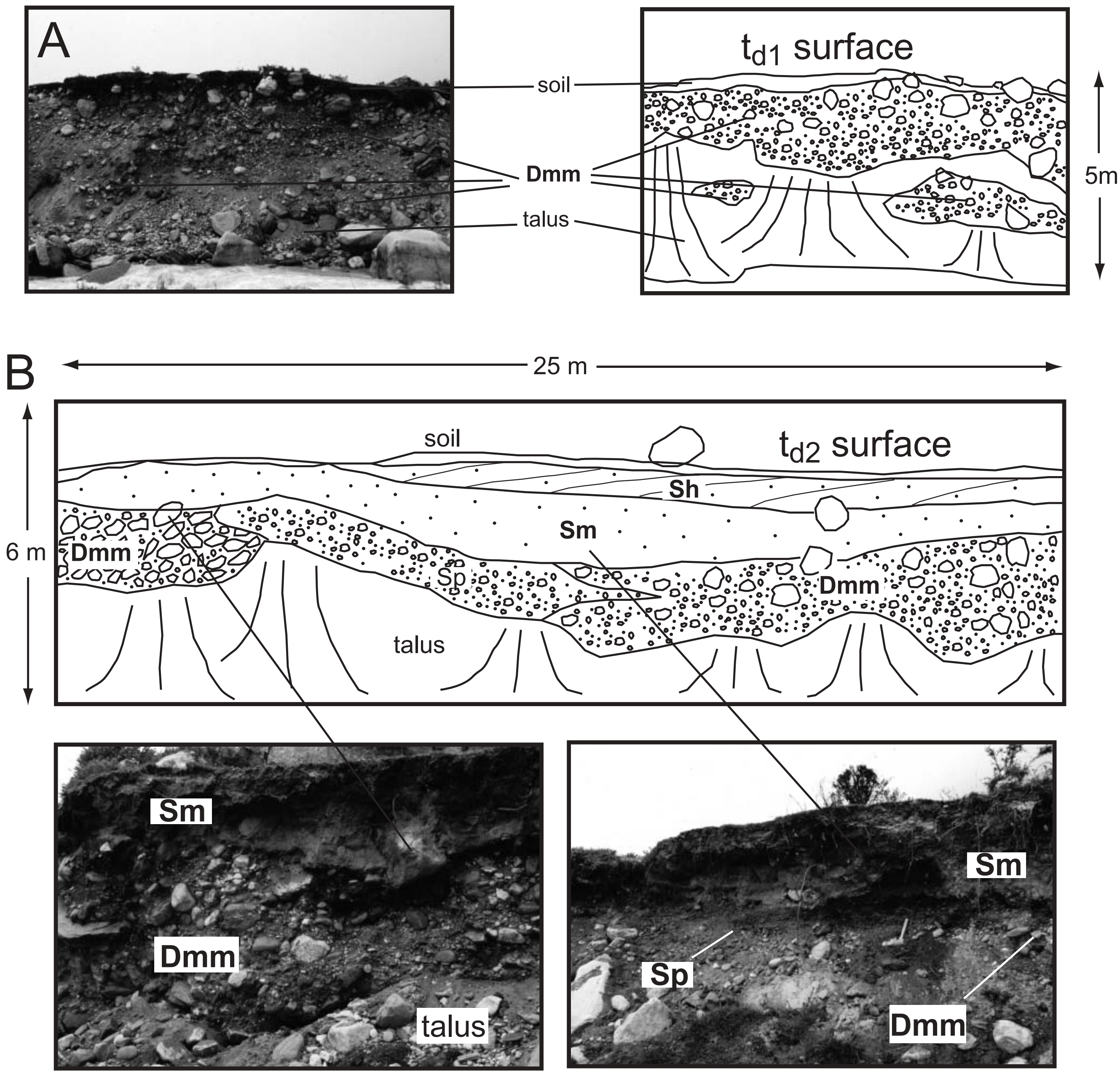


Fig. 8. Sections in the Dingboche study area. (**a**) Diamict in t_{d1} section is massive with subrounded cobbles, borderline matrix-supported by sandy pebbles with occasional boulders concentrated near surface, pockets of extensive imbrication in cobbles and pebbles, 4 m diameter boulders on surface. (**b**) Section in t_{d2}. Lithofacies codes after Eyles *et al*. (1983) as modified by Benn & Evans (1998).

isotropic macroclast fabrics, boulder-dominated, massive, ungraded) that originate from glacial deposits (Beverage & Culbertson 1964; Costa 1988; Ballantyne 1995, 2002, 2003; Zielinski & van Loon 1996; Barnard *et al*. 2004*a*). Zielinski & van Loon (1996) identified similar deposits in their study of fans derived from end moraines in Poland. Using the classification of Schultz (1984), the bouldery diamicts described in this study would be termed clast-rich debris flows, a sediment gravity flow transitional between debris flow and granular flow. Sohn *et al*. (1999) described clast-supported debris flows on alluvial fan deposits in the Yongdong Basin, Korea. By comparison with their study, the bouldery diamicts studied in the Khumbu Himal would fall into the upper end of the debris flow category, more similar to hyperconcentrated flows. The moderate banding, crude stratification, downvalley clast orientation and matrix-supported character of the cobbly diamicts suggest that the sediment was deposited by hyperconcentrated flows (Coussat & Meunier 1996). However, the lack of clast support, sedimentary structures and strong banding indicate that these deposits also contain features characteristic of debris flows. The moderate banding suggests that the sediments were slightly washed, and low mud content and cobble-size clast capacity indicate that fluvial flow conditions (i.e. turbulent flow) were more dominant than debris flow (i.e. laminar flow) conditions (Costa 1988).

Table 1. *^{10}Be ages of fan, terrace and inheritance samples in the study area*

Sample number	Landform number	Latitude (±0.01°) (°N)	Longitude (±0.01°) (°E)	Altitude (m)	Shielding factor*	^{10}Be† (10^6 atoms/g)	Exposure age, ^{10}Be† (ka)	Exposure age with geomagnetic correlation‡ (ka)
Orsho								
E12	Terrace; t_{o6}	27.87	86.81	3971	0.98	0.734 ± 0.018	13.41 ± 0.32	14.26 ± 0.34
E13	Terrace; t_{o6}	27.87	86.81	3998	0.98	0.515 ± 0.013	9.27 ± 0.23	9.74 ± 0.24
E14	Terrace; t_{o6}	27.87	86.81	3998	0.98	0.537 ± 0.019	9.67 ± 0.34	10.15 ± 0.36
E15	Terrace; t_{o4}	27.87	86.81	4009	0.98	0.637 ± 0.016	11.43 ± 0.28	12.10 ± 0.30
E16	Terrace; t_{o4}	27.87	86.81	4126	0.98	0.257 ± 0.007	4.34 ± 0.13	5.02 ± 0.15
E17	Terrace; t_{o4}	27.87	86.81	4159	0.98	2.087 ± 0.088	34.95 ± 1.47	35.21 ± 1.48
E18	Terrace; t_{o3}	27.87	86.81	3927	0.98	0.219 ± 0.007	4.09 ± 0.13	4.74 ± 0.15
E19	Terrace; t_{o3}	27.87	86.81	3927	0.98	0.180 ± 0.007	3.36 ± 0.13	3.97 ± 0.15
E20	Terrace; t_{o3}	27.87	86.81	3927	0.98	0.204 ± 0.008	3.81 ± 0.15	4.45 ± 0.17
E21	Inheritance	27.87	86.81	3828	0.99	0.056 ± 0.004	1.09 ± 0.08	1.13 ± 0.09
E22	Inheritance	27.87	86.81	4123	0.99	0.016 ± 0.003	0.27 ± 0.05	0.24 ± 0.04
E23	Terrace; t_{o4}	27.88	86.81	4140	0.98	0.207 ± 0.007	3.47 ± 0.12	4.11 ± 0.14
E24	Terrace; t_{o4}	27.88	86.81	4140	0.98	0.268 ± 0.007	4.49 ± 0.12	5.17 ± 0.14
E25	Terrace; t_{o4}	27.88	86.81	4105	0.98	0.560 ± 0.014	9.56 ± 0.24	10.05 ± 0.25
Dingboche								
E26	Terrace; t_{o3}	27.87	86.83	4482	0.99	0.393 ± 0.010	5.54 ± 0.14	6.16 ± 0.16
E27	Terrace; t_{o3}	27.87	86.83	4482	0.99	0.972 ± 0.024	13.72 ± 0.34	14.63 ± 0.36
E28	Terrace; t_{o3}	27.87	86.81	4482	0.99	0.814 ± 0.020	11.48 ± 0.29	12.19 ± 0.30
E64	Terrace; t_{d2}	27.90	86.84	4497	0.97	0.253 ± 0.008	3.59 ± 0.12	4.26 ± 0.14
E65	Terrace; t_{d2}	27.90	86.84	4475	0.97	0.182 ± 0.006	2.61 ± 0.08	3.02 ± 0.09
E66	Terrace; t_{d2}	27.90	86.84	4425	0.97	0.177 ± 0.006	2.60 ± 0.09	3.00 ± 0.11
E67	Terrace; t_{d2}	27.90	86.84	4413	0.97	0.348 ± 0.010	5.14 ± 0.15	5.80 ± 0.17
E68	Terrace; t_{d1}	27.90	86.84	4317	0.97	0.159 ± 0.009	2.46 ± 0.13	2.81 ± 0.15
E69	Terrace; t_{d1}	27.90	86.84	4278	0.97	0.215 ± 0.006	3.39 ± 0.10	4.03 ± 0.12
E70	Terrace; t_{d1}	27.90	86.84	4270	0.97	0.226 ± 0.006	3.58 ± 0.10	4.23 ± 0.12
Tsadorje								
E90	Strath	27.85	86.78	3781	0.92	0.146 ± 0.005	3.14 ± 0.12	3.68 ± 0.14
E91	Strath	27.85	86.78	3792	0.94	0.291 ± 0.015	6.07 ± 0.31	6.60 ± 0.34
E92	Strath	27.85	86.78	3870	0.96	0.605 ± 0.016	11.86 ± 0.31	12.57 ± 0.32
E93	Strath	27.85	86.78	3880	0.96	0.780 ± 0.020	15.23 ± 0.39	16.15 ± 0.41
Yaral								
E95	Terrace; t_{p7}	27.86	86.80	3952	0.98	0.673 ± 0.017	12.39 ± 0.32	13.15 ± 0.34
E96	Terrace; t_{p7}	27.85	86.80	4122	0.98	0.665 ± 0.017	11.24 ± 0.29	11.91 ± 0.30
E97	Terrace; t_{p7}	27.85	86.80	4207	0.98	0.672 ± 0.017	10.89 ± 0.28	11.52 ± 0.30
E98	Terrace; t_{p7}	27.85	86.79	3969	0.98	0.654 ± 0.017	11.99 ± 0.31	12.71 ± 0.33
E99	Terrace; t_{p6}	27.85	86.80	4114	0.98	0.434 ± 0.011	7.37 ± 0.19	7.80 ± 0.21
E100	Terrace; t_{p6}	27.85	86.80	4058	0.98	0.414 ± 0.011	7.23 ± 0.19	7.67 ± 0.20
E101	Terrace; t_{p6}	27.85	86.80	4058	0.98	0.423 ± 0.013	7.40 ± 0.22	7.83 ± 0.23
E102	Terrace; t_{p3}	27.85	86.80	3963	0.98	0.088 ± 0.005	1.62 ± 0.10	1.75 ± 0.11
E103	Terrace; t_{p3}	27.85	86.79	3963	0.98	0.090 ± 0.005	1.64 ± 0.10	1.78 ± 0.11
E104	Terrace; t_{p3}	27.85	86.79	3963	0.98	0.067 ± 0.004	1.24 ± 0.07	1.30 ± 0.08
E105	Terrace; t_{p2}	27.85	86.79	3903	0.98	0.009 ± 0.000	0.16 ± 0.00	0.15 ± 0.00
E106	Terrace; t_{p2}	27.85	86.79	3815	0.97	0.062 ± 0.004	1.23 ± 0.08	1.29 ± 0.08
E107	Fan; f_{p1}	27.85	86.80	4059	0.98	0.729 ± 0.021	12.78 ± 0.37	13.58 ± 0.40
E108	Fan; f_{p1}	27.85	86.80	4033	0.98	0.479 ± 0.045	8.50 ± 0.80	8.96 ± 0.84
Pangboche								
E109	Terrace; t_{p6}	27.86	86.79	3985	0.98	0.496 ± 0.023	8.97 ± 0.42	9.45 ± 0.44
E110	Terrace; t_{p6}	27.85	86.79	3970	0.98	1.119 ± 0.034	20.55 ± 0.62	21.66 ± 0.66
E111	Terrace; t_{p6}	27.85	86.79	3979	0.98	0.429 ± 0.013	7.81 ± 0.24	8.22 ± 0.25
E112	Terrace; t_{p7}	27.85	86.79	3960	0.98	0.700 ± 0.017	12.86 ± 0.32	13.66 ± 0.34
E113	Terrace; t_{p7}	27.85	86.79	4021	0.98	0.602 ± 0.018	10.72 ± 0.32	11.32 ± 0.34
E114	Terrace; t_{p7}	27.86	86.79	4061	0.98	0.592 ± 0.015	10.33 ± 0.27	10.89 ± 0.28
E115	Fan; f_{p2}	27.86	86.79	3956	0.98	0.859 ± 0.024	15.86 ± 0.43	16.82 ± 0.46
E116	Fan; f_{p3}	27.86	86.79	4028	0.98	7.282 ± 0.169	132.57 ± 3.08	127.32 ± 2.96
E117	Fan; f_{p3}	27.86	86.79	3941	0.98	2.739 ± 0.054	51.19 ± 1.00	49.98 ± 0.98
E118	Terrace; t_{p4}	27.85	86.79	3818	0.98	0.261 ± 0.009	5.17 ± 0.17	5.79 ± 0.19
E119	Terrace; t_{p4}	27.85	86.79	3875	0.98	0.518 ± 0.000	9.97 ± 0.00	10.49 ± 0.00
Dingboche								
E120	Inheritance	27.89	86.84	4286	0.99	0.034 ± 0.004	0.52 ± 0.06	0.47 ± 0.06

*The topographic shielding factor was determined using the methods of Nishiizumi *et al*. (1989).
†Uncertainty includes only uncertainty in accelerator mass spectrometry.
‡Corrected for time-varying geomagnetic field as described in text. The uncertainty is carried over from that in the exposure age. No additional uncertainty was assigned arising from correction for geomagnetic field change. These ages were calculated with a sea-level high-latitude production of ^{10}Be of 5.16 atoms/g of quartz/year grain using the scaling factors of Lal (1991) as modified by Stone (2000).

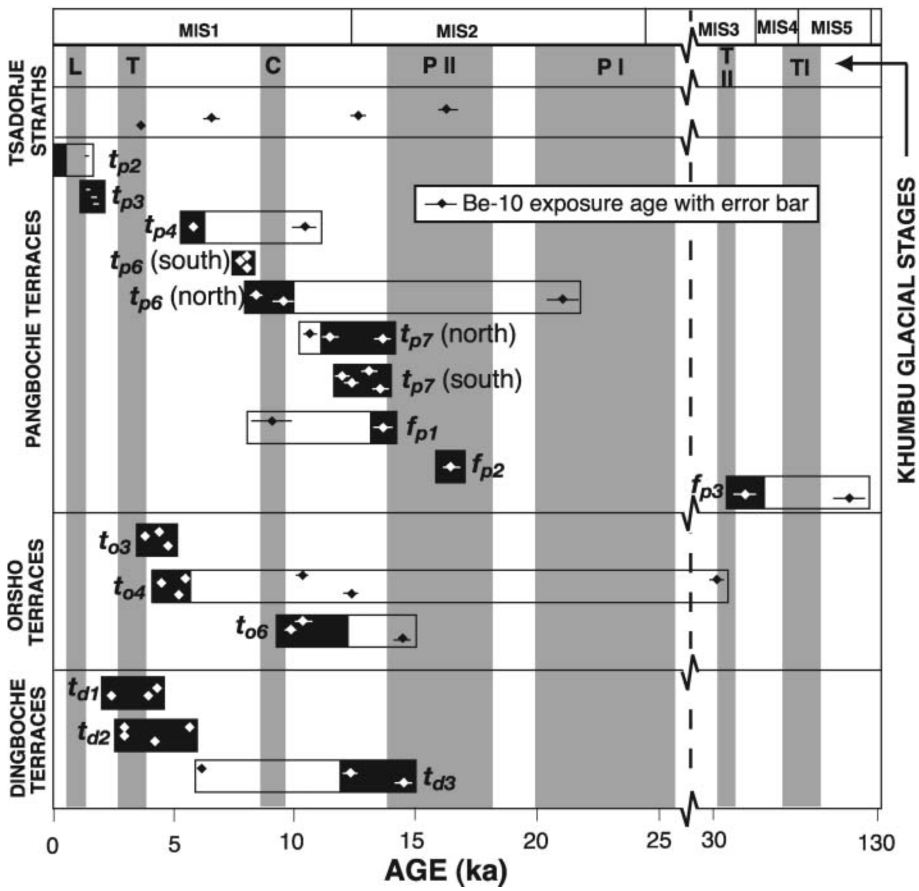


Fig. 9. The correlation of fan or terrace ages for each of the Khumbu Himal study areas compared with the strath terraces ages and the glacial stages of Finkel *et al*. (2003). The areas shaded in dark grey is the inferred age for each fan. Glacial stages: L, Lobuche; T, Thuklha; C, Chhukhung; PII, Pheriche II; PI, Pheriche I; TII, Thyangboche II; TI, Thyangboche I.

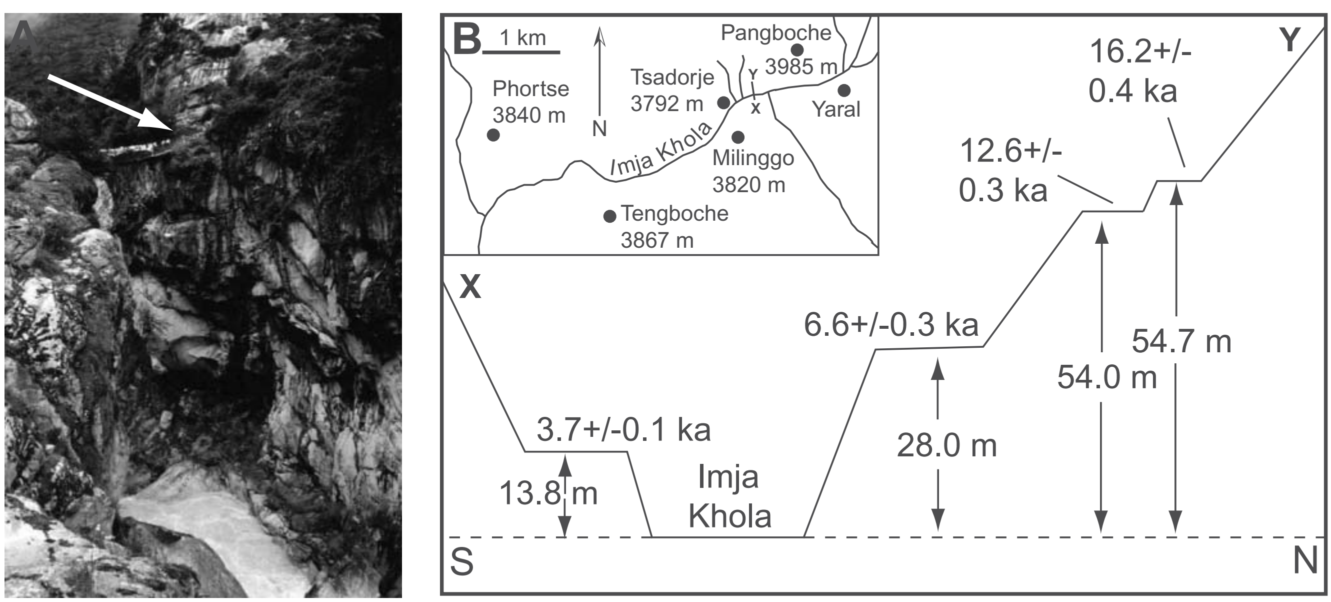


Fig. 10. (**a**) The 28 m deep gorge cut by the Imja Khola beneath the second lowest strath terrace. White arrow points to location of sample E91). (**b**) Schematic representation of strath terrace sampling locations and calculated CRN ages in the Imja Khola Valley at Tsadorje.

These observations suggest that the Khumbu fans and terraces comprise a combination of debris-flow and hyperconcentrated flow deposits. However, it is difficult to assign an unequivocal causal mechanism to individual units, particularly because of the continuum of processes and forms that characterize hyperconcentrated and debris flows and their products (Fig. 11).

The CRN dating suggests that for all but one (at 12 ka) of the major cycles of strath terrace, terrace and fan formation, which

Table 2. *Incision rates calculated from the CRN exposure ages of strath terraces at Tsadorje*

Landform number	Altitude (m)	^{10}Be exposure age (ka)	Height (m)	Rate (mm a^{-1})
E90	3781	3.7 ± 0.1	13.8	3.8
E91	3792	6.6 ± 0.3	28.0	4.2
E92	3870	12.6 ± 0.3	54.0	4.3
E93	3880	16.2 ± 0.4	54.7	3.4
			Average = 3.9	

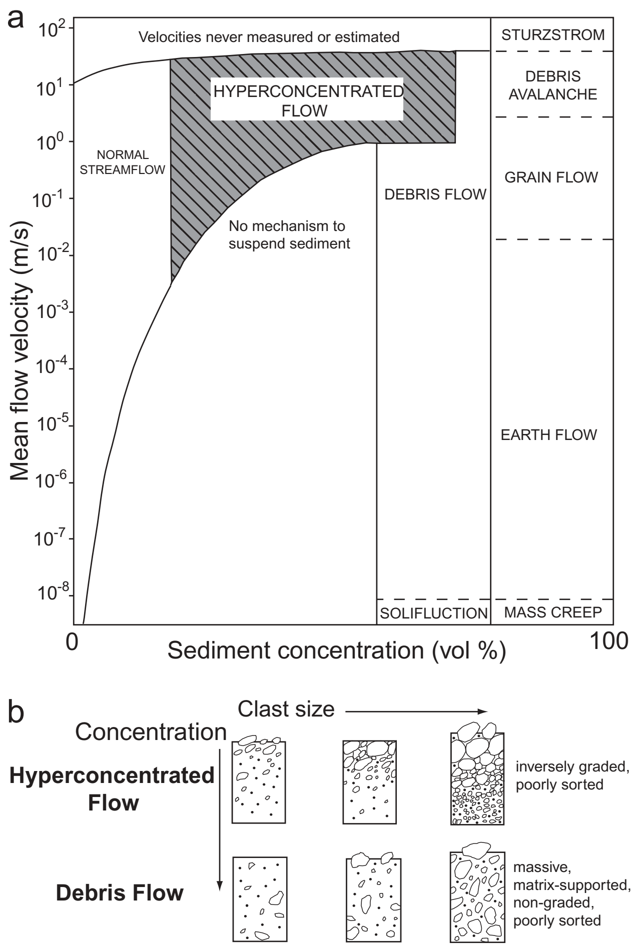


Fig. 11. A comparison of hyperconcentrated flows and debris flows. (**a**) A rheological classification of subaerial sediment–water flows. The striped, shaded region represents the area of transition between true Newtonian fluid type flow behaviour (stream flow) and non-Newtonian or plastic flow (debris flow) (modified from Pierson & Costa (1987) and Svendsen *et al*. (2003)). (**b**) Examples of the fabrics of typical coarse debris flows and hyperconcentrated flows. These are similar to those described from fans or terraces in the Khumbu Himal (modified from Maizels 1993).

occurred at *c*. 16 ka, 12 ka, 8 ka, 4 ka, and 1.5 ka (Fig. 12), there is a tentative correlation with each glacial stage (Fig. 9, Table 3). Therefore it is likely that the formation of these surfaces can be linked with the termination of the glacial stages as established by Finkel *et al*. (2003) when glacial and associated sediments are

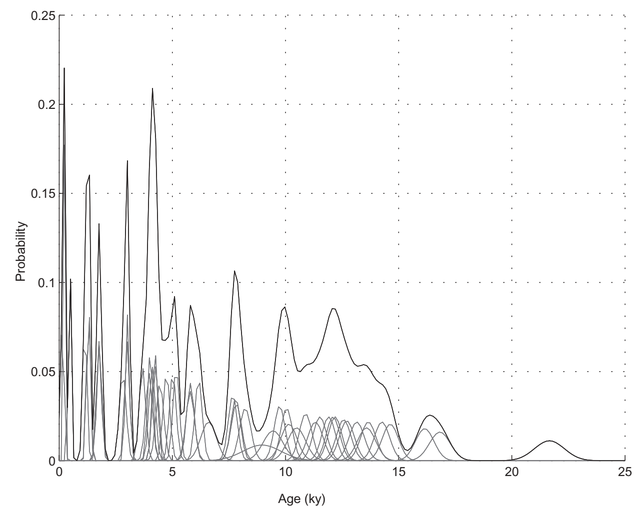


Fig. 12. Age distribution probability density function plot (also known as a 'camel' plot) for the landforms dated in this study.

eroded and resedimented by paraglacial processes such as glacial-lake outburst floods and landsliding. Hence it follows that terrace and fan formation is linked with regional and global climatostratigraphic stages.

CRN dating of the fan and terraces in the Khumbu Himal supports the hypothesis that major sedimentation events follow glacier advances within a few thousand years. The unbedded, thick diamict deposits, representing debris flow and hyperconcentrated flow deposits, perhaps indicate that glacial retreat was rapid, resulting in rapid glacial-lake build-up and eventually catastrophic flooding from subsequent moraine dam breaching, flooding that affected large areas of the Khumbu Himal. CRN dating and sedimentological evidence linking deglaciation with large-scale fan or terrace sedimentation has been suggested by work in the Lahul and in Garhwal Himalaya (Owen *et al*. 2001; Barnard *et al*. 2004*a*).

At Pangboche, f_{p2} formed at *c*. 16.8 ka, approximately coincident with the beginning of the Pheriche II Stage (16.0 ka), or possibly the end of the Pheriche I (Finkel *et al*. 2003). Also at Pangboche, five of six CRN samples indicate that t_{p6} was deposited (*c*. 8.1 ka) broadly with the termination of the Chhukhung Stage (*c*. 9.2 ka) and its sediments display typical paraglacial features (e.g. striated clasts). The existence of several terraces dated at 4–5 ka, at both Dingboche and Orsho, suggests that the mid-Holocene was a time of heightened sediment flux. Poor dating control on a surface at Pangboche (t_{p4}, two samples, dated at 5.8 and 10.5 ka), however, prevents this fan from being correlated with mid-Holocene landforms that formed upvalley. Nevertheless, glacial fluctuations during the Thuklha Stage (*c*. 3.6 ka: Finkel *et al*. 2003) probably resulted in significant fluxes of sediment during the mid-Holocene, possibly controlling the formation of the two sets of mid-Holocene fans at Dingboche and Orsho that date between *c*. 4.1 and 4.9 ka (Table 3). The geomorphological mapping and sedimentological analysis that suggest rapid incision and large-scale resedimentation events during the mid-Holocene support this view. Terrace t_{p3} (*c*. 1.5 ka) may relate to the Lobuche Stage (*c*. 1 ka) (Finkel *et al*. 2003). Modern flood deposits at Pangboche (t_{p2}) may be the result of Little Ice Age retreat.

The prominent set of fans and terraces (t_{p7}, t_{o6}, t_{d3}) that are

Table 3. *Correlation of landform ages in the Khumbu Himal with termination of glacial stages, as presented by Finkel* et al. *(2003), and climatostratigraphic stages*

	Tsadorje		Pangboche–Yaral			Orsho			Dingboche				
Landform	Name	Approx. age (ka)	Landform	Name	Approx. age (ka)	Landform	Name	Approx. age (ka)	Landform	Name	Approx. age (ka)	Glacial stage (after Finkel *et al*. 2003)	Climatostratigraphic correlation
			Terrace	tp1	Recent	Terrace	to1	Recent					
			Terrace	tp2	0.03	Terrace	to2	?				Historical	Little Ice Age
			Terrace	tp3	1.5							Lobuche	Little Climatic Optimum
Strath	E90	3.7				Terrace	to3	4.4	Terrace	td1	4.1	Thuklha	Early Neoglacial
			Terrace	tp4	5.8	Terrace	to4	4.8	Terrace	td2	4.9	Thuklha	Mid-Holocene
Strath	E91	6.6	Terrace	tp5	?	Terrace	to5	?					
			Terrace	tp6	8.1							Chhukhung	Early Holocene
Strath	E92	12.6	Terrace	tp7	12.0	Terrace	to6	11.0	Terrace	td3	13.2		Younger Dryas Stadial
			Fan	fp1	13.6							Pheriche II	Late Glacial Interstadial
Strath	E93	16.2	Fan	fp2	16.8	Fan	fo1	?				Pheriche I–II	Last Glacial Maximum
			Fan	fp3	57.6							Thyangboche I	Late MIS 4–Early MIS 3

dated at *c*. 12 ka in each of the three major study areas may not be glaciogenic in origin because there is no evidence for *c*. 12 ka old source moraines for the fan sediments. The fan sedimentology and stratigraphy are indicative of the same debris and hyperconcentrated flow deposits that make up the bulk of the other fans in the Khumbu Himal. The CRN dates are tightly clustered; of the 14 samples that were taken from this surface across the study area, all but one was dated between 9.8 and 14.3 ka. The ages span the Younger Dryas Stadial, but no glacial advances are recognized in the Khumbu Himal anywhere near this time (Finkel *et al*. 2003). However, lack of evidence for Younger Dryas-age moraines does not necessarily suggest absence of a Younger Dryas glacial advance. It is possible that a glacial advance at *c*. 12 ka did exist and that subsequent advances eroded the moraine ridges. Fluvial incision downvalley could have helped preserve the correlative surfaces. Alternatively, a major lake burst might have occurred at *c*. 12 ka, and the resulting flood formed extensive deposits throughout the Khumbu Himal, including Pangboche, Orsho and Dingboche. This may explain how vast fans could be deposited outside 'paraglacial times', which were once thought to exist for only hundreds of years following glacial retreat (Ballantyne 1995; Owen & Sharma 1998). The potential long-term response of the Khumbu system to the new hydrological conditions associated with deglaciation, although speculative in this case, causes us to reconsider the potential temporal range of landscape response to deglaciation.

With the exception of f_{p3} (*c*. 58 ka), no fan or terrace surfaces in the study area are older than Late Pleistocene. Fan deposits in the outwash plain of Khumbu glaciers rarely persist for more than 16 ka before they are eroded away. The setting beneath a glacier front is subject not only to slope and weathering processes, but can also be affected by floods, debris flows, etc. All these processes reduce the likelihood that fans or terraces will survive long in this environment. The oldest landform dated by CRN methods in the study area is a *c*. 91 ka moraine high above Duglha (Fig. 2: Finkel *et al*. 2003). This suggests that glaciofluvial landforms have not persisted for more than *c*. 100 ka in the Khumbu Himal, because of fluvial, slope and weathering processes.

Supraglacial lakes are at present forming east of Chhukhung on the Imja Khola Glacier (Figs 2 and 13a) and at Gokyo on the Ngozumpa Glacier, 15 km due west of the terminus of the Khumbu Glacier (Benn *et al*. 2001). These lakes are related to historical glacial retreat from advanced positions of the LIA. Dead ice zone lakes build rapidly during the initial rapid glacial retreat associated with the end of glacial stages (Benn *et al*. 2001) and thus when dams fail the resulting glacial-lake outburst flood may be a causal mechanism of fan or terrace formation throughout the Imja Khola Valley. Proglacial lakes, such as the one currently building at the base of the Tsola Glacier (Figs. 2 and 13b), can lead to similar episodes of catastrophic sedimentation.

During deglaciation, high discharge and sediment loads promote strath terrace formation where bedrock is exposed. These same conditions in a wider valley can produce fan sequences. In a narrower, steeper portion of the valley, a smaller channel carrying a comparable discharge and sediment load results in higher bed velocities and thus favours strath formation (Foley 1980; Anderson 1994; Merritts *et al*. 1994; Personius 1995; Leland *et al*. 1998).

Incision rates calculated from strath terraces can be used as a proxy for the long-term denudation and uplift rates of a region, whereas the age of the terrace can yield a deglaciation age

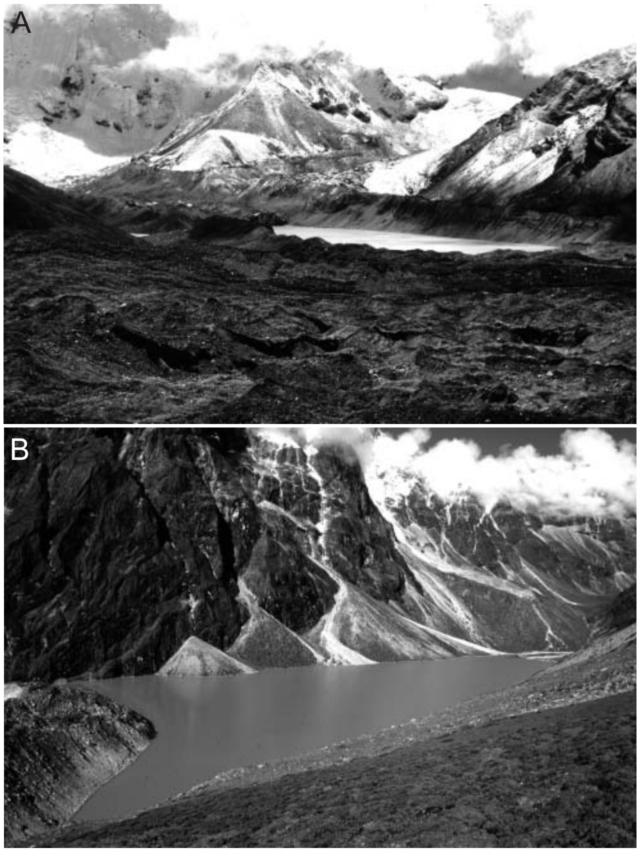


Fig. 13. Lakes forming at present in the Khumbu study area. (See Fig. 2 for locations.) (**a**) Glacial lake trapped in the maze of moraines and glaciers to the east of Chhukhung. Lake is *c*. 1 km in length. (**b**) Tsola Lake trapped behind the Tsola Glacier (left) and an abandoned Khumbu glacier moraine (right).

(Barnard *et al*. 2001). The older the strath terrace, the closer the derived incision rates will approximate the long-term uplift rate (Leland *et al*. 1998). The incision rates derived from four strath terraces in the Khumbu Himal, averaging 3.9 mm a^{-1} (ranging from 3.4 to 4.3 mm a^{-1}), are consistent over the last 16 ka (Table 2). This average rate is similar to the denudation rates calculated from other Himalayan regions that average *c*. 5.7 mm a^{-1} (e.g. ranging from 0.3 to 15.9 mm a^{-1}: Brunsden *et al*. 1981; Zeitler 1985; Valdiya & Bartarya 1989; Burbank & Beck 1991; Gardner & Jones 1993; Burbank *et al*. 1996; Leland *et al*. 1998; Shroder *et al*. 1999; Barnard *et al*. 2001, 2004*a*, *b*; Vance *et al*. 2003). Burbank (2002) showed that erosion by rivers, landslides and glaciers can exceed 5 mm a^{-1} and these rates can be sustained over time periods of the order of 10^2–10^5 a. Mountain uplift rates in the Himalaya during the last 0.5 Ma have been estimated at 1–3 mm a^{-1} by Leland *et al*. (1998), based on CRN dating and apatite fission-track measurements from strath terraces in Nanga Parbat region of the NW Himalaya. Uplift rates have been estimated at 2–5 mm a^{-1}, during the last 7 ka, based on strath terrace dating in the middle gorge of the Indus River near Nanga Parbat (Burbank *et al*. 1996). Uplift results in the net lowering of base level and thus is a major factor driving incision. Leland *et al*. (1998) documented an acceleration of average bedrock incision rates during the last 15 ka in Nanga Parbat, considered to be the locale of maximum incision rates in the Himalayas (Zeitler *et al*., 2001), and attributed this acceleration to an increase in discharge and/or sediment load related to deglaciation in the surrounding mountains following the major glacial advances of the Last Glacial. They also noted a substantial increase in incision rates during the last 7 ka, from 1–6 mm a^{-1} prior to 7 ka to 9–12 mm a^{-1}.

Three of the strath terraces we dated have ages similar to those of the fans dated in this study and to three of the glacial stages of Finkel *et al*. (2003). These are 3.7 ka (Thuklha Stage 3.6 ka; and at Orsho 4.4 ka for t_{o3} and 4.8 ka for t_{o4}, and at Dingboche 4.1 ka for t_{d1} and 4.9 ka for t_{d2}), 12.6 ka (at Pangboche 12.0 ka for t_{p7}, at Orsho 11.0 ka for t_{o6}, and at Dingboche 13.2 ka for t_{d3}) and 16.2 ka (Pheriche II Stage 16.0 ka, and at Pangboche 16.8 ka for f_{p2}). This potential relationship between glacial stages and the formation of strath terraces and fans suggests that there is a glacial control on pulses of erosion and sedimentation downvalley. However, the strath terrace dated to 6.6 ka (sample E91; Table 1) cannot be morphostratigraphically correlated to any of the glacial stages or fan and terrace surfaces at Pangboche, Orsho or Dingboche. We tentatively link the formation of this strath either with t_{p6} at Pangboche (*c*. 8.1 ka) or with the termination of the Chhukhung Stage (*c*. 9.2 ka). This discrepancy may be due to errors in the dating, periods of high discharge and sediment loads that are not related to glacier fluctuations, or an unrecognized glacial stage.

Large-scale sedimentation and erosion events would be expected to occur more frequently in the Dingboche area than further downvalley because the potential for flooding is higher in an area more directly affected by the varying fluctuations and outwash of numerous glaciers. The larger number of individual beds recorded in the sediment logs in the Dingboche terraces, as compared with the fans and terraces in the Orsho and Pangboche areas, which contain similar exposure thicknesses, demonstrate the greater frequency of events or distal deposits. The large existing volumes of the fan and terrace deposits indicate that these landforms may be the most stable location for the long-term storage of sediment. Therefore, the style of formation and erosion of fans and terraces in the Himalaya is largely controlled by their proximity to glacial fluctuations.

Conclusions

Fan and terrace formation occurred during five times in the Late Quaternary: *c*. 16 ka, *c*. 12 ka, 8 ka, 4 ka and 1.5 ka. With the exception of the 12 ka episode, these depositional events can be linked temporally and sedimentologically to the glacial stages defined by Finkel *et al*. (2003). Fans and terraces in the Khumbu Himal primarily comprise bouldery and cobbly diamicts deposited by debris flows and hyperconcentrated flows. This morphology and sedimentology suggest that incision, sediment transfer and deposition are driven by short-term variations in discharge and sediment load conditioned by glacial oscillations. Thus fan and terrace formation and incision are related to sporadic, catastrophic events that are intimately tied to rapid glacial fluctuations. Fans and terraces in other parts of the Himalaya probably respond in a similar fashion to those in the Khumbu Himal, resulting in common forms of landscape evolution. This suggests that our fan and terrace chronologies might be used for regional correlations throughout the monsoon-influenced Himalaya. Furthermore, the chronologies provide some of the first data to aid in quantifying the timing and rates of moraine denudation and sediment transfer within the Himalaya.

Longer-term rates of incision of the Khumbu Himal approximate to typical Himalayan uplift rates. Calculations of bedrock incision rates from the CRN dating of strath terraces in the Khumbu Himal are consistent with rates for other parts of the Himalaya, averaging *c*. 3.9 mm a^{-1}.

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