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GEOMORPHOLOGY OF THE CENTRAL AND FRONTAL RONGBUCK GLACIER AREA (MT. EVEREST, TIBET)

ABSTRACT: PECCI M., PIGNOTTI S., SMIRAGLIA C. & MORTARA G., *Geomorphology of the central and frontal Rongbuk glacier area (Mount Everest, Tibet)*. (IT ISSN 0391-9838, 2010).

This report details the results of some recent geomorphological studies, surveys and mappings of the higher parts of the northern (Tibetan) area of Mount Everest, along the Rongbuk glacier. Its retreat is causing extensive gravitational phenomena involving both ice/snow and rock/debris. At the same time, the spatial reduction and the retreat of the glacier tongues are promoting new conditions for superficial and supraglacial run-off, concentrated in the terminus area, generating a direct transition from glacial to paraglacial processes over short distance and time scales. The monitoring and mapping of processes and landforms, carried out in the field with GIS technology, provided early-control of survey data. The availability of digital data collected or specifically implemented (Digital Elevation Model or satellite imageries) and survey data, also in real time and at low-cost, made possible the reconstruction of the morphological evolution, as a «field pre-view», as well as providing a safe approach to field activity. The results of the surveys are presented as cartography and descriptions of processes and landforms, with particular attention to active geomorphological hazards, such as ice falls, rock/slope instability, small GLOFs (Glacial Outburst Floods) at ice termini and to consequent risk.

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KEY WORDS: GIS and glacial, Periglacial and paraglacial mapping, Cryosphere shrinking, Glacial risk, GLOF, Mount Everest, Rongbuk glacier.

RIASSUNTO: PECCI M., PIGNOTTI S., SMIRAGLIA C. & MORTARA G., *Geomorfologia dell'area centrale e frontale del ghiacciaio di Rongbuck (M. Everest, Tibet)*. (IT ISSN 0391-9838, 2010).

Il lavoro presenta i risultati di recenti rilievi, elaborazioni cartografiche e studi condotti nell'alta quota del versante settentrionale (Tibetano) del Monte Everest, lungo il ghiacciaio di Rongbuck. Il ritiro delle lingue glaciali sta comportando estesi fenomeni gravitativi che coinvolgono sia il ghiaccio e la neve, sia la roccia e il detrito. Allo stesso tempo, la veloce riduzione glaciale sta promuovendo nuove condizioni per lo scorrimento idrico superficiale e supraglaciale che si va concentrando nella zona frontale ed è in grado di provocare una transizione diretta dai processi glaciali a quelli paraglaciali in un breve lasso di tempo e in un ambito spaziale ristretto. Il rilievo e la cartografia di processi e forme effettuata in ambiente GIS ha consentito un controllo del dato direttamente sul terreno. La disponibilità di dati digitali su Internet o implementati per l'occasione (come nel caso di Modelli Digitali del Terreno o di immagini da satellite, anche ad alta risoluzione) a costi contenuti se non gratuiti insieme alla contestuale ed immediata possibilità di archiviare e gestire in modo digitale i dati di terreno, ha reso possibile la ricostruzione dell'evoluzione geomorfologica recente nei termini di una interessante ed utile "anteprima di terreno". Questa, anche, ha contribuito a gestire in maniera più sicura le attività di terreno, intrinsecamente pericolose. I risultati delle attività sono presentati (sia nella cartografia, sia nel testo), tenendo presente nella descrizione di processi e forme una prospettiva altimetrica, in grado di evidenziare nel progressivo innalzamento della quota il passaggio da ambienti periglaciali e paraglaciali ad un franco ambiente glaciale. Una particolare attenzione è stata rivolta, anche nella rappresentazione cartografica, agli elementi di pericolosità geomorfologica, come, ad esempio, seraccate glaciali, crolli e frane, piene per rotte glaciali (GLOFs), in particolare nella zona frontale, ed ai relativi rischi.

TERMINI CHIAVE: Sistemi Informativi geografici e cartografia glaciale, periglaciale e paraglaciale, Riduzione della criosfera, GLOF, Monte Everest, Ghiacciaio di Rongbuk.

INTRODUCTION

In recent decades the scientific community has paid increasing attention to the higher mountain ranges of Asia, the so called «Third Pole», with studies dealing with geomorphological and environmental issues. In fact, high altitude remote areas represent ideal sites for studying and monitoring environmental and climate-induced processes (*sensu* Jenkins & *alii*, 1987 and Wake & *alii*, 1994). The cryosphere can be considered an environmental matrix highly sensitive to global changes; as a consequence, in particular, of glacier shrinking and permafrost degradation, the paraglacial system (*sensu* Ballantyne, 2002) is developing wide phenomena of risk and instability.

In such a framework the availability, often on the web, of free digital terrain data and high resolution images enables more efficient management of logistics, field activities and even surveys, including updates of the geo-database in real time and directly in the field.

On the other hand, the results of traditional geomorphological surveys are becoming increasingly important and necessary in order to find the best conditions for location of camps in safe places, given the higher risk due to increasing geomorphological hazard (*sensu* Brandolini & *alii*, 2007) and human frequentation.

Taking into account all these inputs, in this paper the authors present the geomorphological map and the results of geomorphological surveys and research carried out in the Rongbuk (*Ronpu* in Tibetan) glacier area, located on the northern slope of Mount Everest.

The aim of the research and field activity was reconstruction of the geomorphological evolution of the glacier and surrounding areas, with the use of modern technologies, also highlighting potential risks affecting trekkers and mountaineers.

RESEARCH REVIEW

A rich fund of literature has been published on a wide range of multi-disciplinary studies concerning the area studied, with the common background of mountaineering support and, usually, related to mountaineering expeditions starting from the second half of the last century.

Geological studies started with the preliminary and pioneering studies (e.g. Wager, 1934; Odell, 1948) passing through monographic works (e.g. Gansser, 1964; Yin & Kuo, 1978) and mono-disciplinary works (e.g. Carosi & *alii*, 1998; Bortolami, 1998) up to the more recent and exhaustive study (Searle, 2003).

From the geomorphological point of view, previous studies deals with glaciological and geomorphological issues (see principally Shih & *alii*, 1980; Nakawo & Young, 1982; Kuhle, 1986; Kuhle, 1997; Zheng, 1988; Derbyshire & Owen, 1989; Burbank & Kang, 1991; Kalvoda, 1992; Benn & Owen, 1998; Owen & *alii*, 1998; Kayastha & *alii*, 2000; Khule, 2005; Owen & Benn, 2005; Rai, 2005; Man & *alii*, 2007; Owen & *alii*, 2008; Hambrey & *alii*, 2008), geomorphological evolution based on remote sensing (see, e.g. Messerli & Ives, 1997; Kääb & *alii,* 2002; Zomer & *alii*, 2002; Gspurning & *alii*, 2004; Berthier & *alii*, 2007), risk implications (e.g. Ives, 1986; Yamada, 1998; Mool & *alii*, 2001; Pecci, 2005), climate and recent paleoclimate framework (Rao, 1981; Ludeke, 1983; Stravisi & *alii*, 1998; Kang & *alii*, 2001; Ren & *alii*, 2006) and paraglacial processes and landforms (*sensu* Iturrizaga, 2008).

GEOGRAPHICAL, GEOLOGICAL AND CLIMATIC OUTLINE

Mount Everest (*Sagharmata* in Nepali e *Chomologma* in Chinese) reaches an elevation between 8848.82 m (bedrock) and 8852.10 m (snowy summit). The summit snow thickness was measured by GPR (Ground Penetrating Radar) surveys in May 2004 (Poretti & *alii*, 2005) and varies according to the season. The «Top of the World» overtakes the closer 8,000s (Lhotse - 8516 m, Makalu - 8463 m and Cho Oyu - 8201 m asl.) in the area of major uplift of the Himalaya range, located in the centre of the Asia (fig. 1).

Due to the altitude, the main footprint of the studied area is imposed by glacial and periglacial processes, following by the paraglacial. The Rongbuk glacier flows for about 18 km down to the proglacial plain at 5200 m asl, usually used as Base Camp by mountaineering expeditions. The upper glacial basin can be divided almost symmetrically Eastward and Westward into two important streams: the Eastern and the Western Rongbuk glaciers. Both are typical debris-covered tongues, a condition very common in the Himalayas, Karakorum and Pamir (Nakawo & *alii*, 2000; Smiraglia, 1998).

The glacier is clean and crevassed along the first 5 km of length, becoming debris-covered from an elevation of about 5750 m asl, close to the confluence with the western stream, also masked by the debris.

At present, only this confluent stream feeds into the principal tongue, no longer directly linked to the eastern one. This is why the path climbing up to the North Col of Everest snakes along the eastern Rongbuk Glacier.

The geological outline of the High Himalayan region is summarized (after Gansser, 1964; Bortolami, 1998; Carosi & *alii*, 1998; Searle, 2003) in the geological sketch (fig. 2), displaying the spatial distribution and outcrops of the principal lithologic units (grouped into principal units according to common lithologic features and *facies*).

From the climatic point of view, the Tibetan-Himalayan area and, more generally, the Qinghai-Tibet Plateau, are located in the inter-tropical convergence zone, showing well-known and defined features**.** In fact the weather conditions are strictly conditioned by the contact and the interaction of cold (polar) air masses with the Monsoon winds (Lùdeke, 1983).

According to the four distinctive periods distinguished by Rao (1981), the rainy season is dominated by the South-West Monsoon, moisture-laden as it comes from the Indian Ocean and the Bay of Bengal.

Monsoon circulation is complicated by important local factors, mainly dependent on: orographic effects, principal edges and valley pattern, altitude, insulation (and related formation and periodicity of breezes), and presence and action of glacier and jet streams (Stravisi & *alii,* 1998*)*. The air temperatures are generally low during the whole year both on the mountain and the plateau, with strong winds blowing. At higher altitudes jet streams prevail and do not

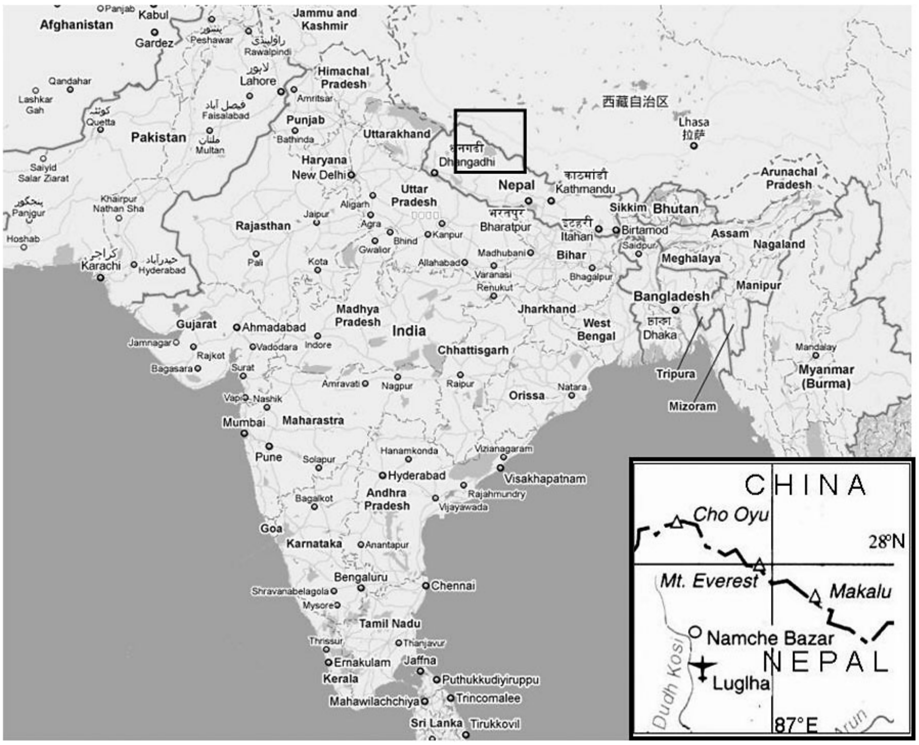

FIG. 1 - Location of the study area, with a detailed view in the box (Google map 2010).

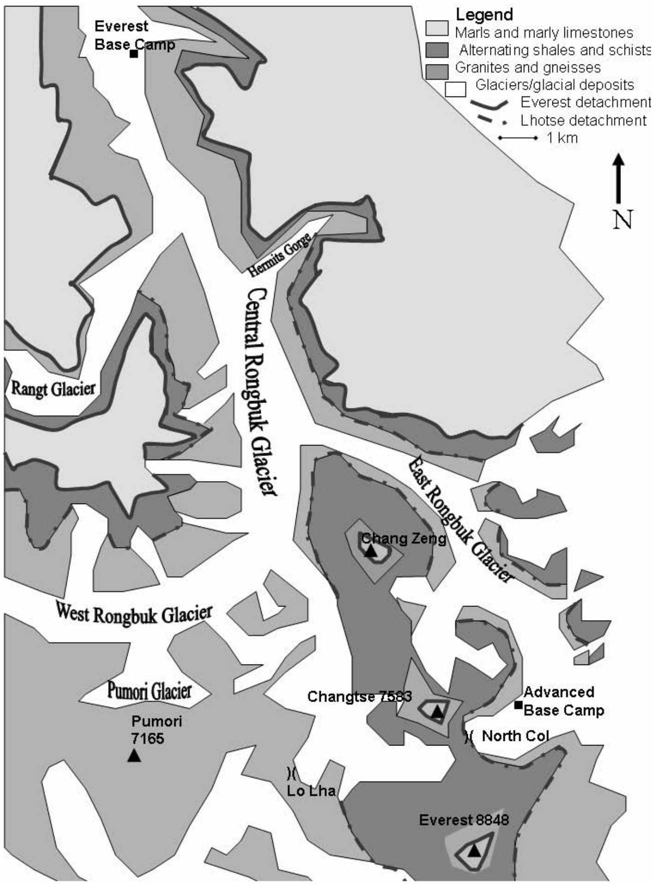

FIG. 2 - Geological sketch of the area (redrawn and modified after Searle, 2003).

favour suitable weather conditions for outdoor activities, with wind-peaks of more than 25 m/s.

METHODOLOGY AND TOOLS

DATA SURVEY AND ELABORATION

The geomorphological map was drawn using an integrated approach based on field surveys, topographic and morphometric modelling in a GIS environment and analysis of satellite images. The topographic 1:50,000 «Mount Everest» map, drawn and published by the National Geographic (1988), was the basis for surveys and *in situ* measurements; in addition, the topographic 1:50,000 «*Khumbu Himal*» (Siebenlechner, 1999) was used. GPS points were also taken on the surface of the glacier and on the paraglacial surrounding areas: a Trimble GeoXT was used for single point positioning and for mapping lines and polygons, within the working limits declared for the device.

The WGS84 UTM 45N coordinate system was used not only for survey activity, but also for implementing the GIS project.

During preparation of the expedition, digital data available on the web was collected, in order to produce and to make available (directly in the field and in real time) GIS outputs and digital cartography, such as for example, field pre-view maps and field geo-databases: the preliminary results of the geomorphological surveys and mapping were corrected and stored directly in the field, continuously updating the cartography.

The resulting image of the area studied (included in the geomorphological map) was obtained using the mosaic of the Quickbird image captured from GoogleEarth, and processed as a digital orthophoto (scale 1:10,000), used for controls and mapping of the landforms. In the post-elaboration phase, a SRTM-DEM was used.

During the GPS survey campaigns, a set of Ground Control Points (GCP) was collected in order to verify the quality and the confidence of the DEMs acquired in the subsequent data elaboration phase.

As regards the accuracy level of all the informative layers, the GPS data have an average precision of 5.5 m in the x and y co-ordinates, and 10.2 m in z, with a PDOP contained around 4.0. The DEM presents a RMS (Root Mean deviation) of 54 m (x, y); from the digital elaboration point of view, the DEM 86x86 SRTM was an excellent starting point for the geomorphological analysis of remote high altitude areas; although the resolution does not allow detail of each single landform, the DEM provides a preliminary identification of the principal morphologic and territorial patterns.

The following primary attributes (*sensu* Wilson & Gallant, 2000) were used in the Rongbuk area: slope, roughness, local relief and topographic irregularity; they were compared with the results of field surveys in order to verify their suitability in describing, on a large scale, some peculiar features of the instability areas.

LEGEND AND CARTOGRAPHY

The use of a shared (from the Literature), useful and practical (in the field) legend was one of the principal needs. In the present work recent cartographic experiences were taken into account, integrated by special needs to represent features typical of high altitudes (Pecci, 2004).

In relation to the geology and the structural pattern of the bedrock the authors' decision was to include in the map (and in the legend) only the strongly jointed metamorphic rocks. Surface deposits have been indicated by symbols representing, if possible, the grain size and the genesis; the colour of the symbols represents the morphogenetic process producing the deposits themselves.

Data and features of the hydrographical network and of the glaciers are drawn in cyan. A different colour is assigned to each morphogenetic process, depending on the prevalent genesis of the landform.

In the whole area four principal geomorphological processes have been identified: the glacial, the periglacial, the gravitational, and the fluvial; the latter three, even though well-distinguishable in the resulting landforms, form part of a paraglacial framework in the sense of «nonglacial earth-surface processes, sediment accumulations, landforms, landsystems and landscapes that are directly conditioned by glaciation and deglaciation» (Ballantyne, 2002). In such a perspective, a specific «paraglacial» legend heading was not created, due to the applicational aim of the study, even though the particular features and cases are discussed in the text.

Particular attention was also focused on ephemeral features due to hydrological patterns (produced by the melting of the ice) and to the ice features (produced by differential ablation), both distinguished in the Legend. Each landform has been classified under erosional or depositional classes and defined active or inactive from the morpho-developmental point of view. The principal morphometric data were derived directly from the topographic base; some peculiar features, such as, for instance, scarp edges or fans, have been distinguished according to morphometric criteria (different heights, typical dip). No Absolute chronological age has been attributed.

RESULTS

The principal result is represented by the geomorphological map of the Rongbuk glacier area (Mount Everest), scale 1: 30,000, integrated by the satellite image of the snout area. Processes and landforms are described below, principally according to an altitudinal criterion in terms of relief energy (*sensu* Khule, 2007), also taking into account a paraglacial perspective.

GEOLOGICAL AND STRUCTURAL FEATURES

The principal structural features are represented by two low angle normal faults, cutting the Mount Everest massif at the top of the Greater Himalayan slab, drawn in the geological sketch of figure 2 as the two principal detachments; the earlier, lower Lhotse detachment, bounds the upper limit of massive leucogranite sills and sillimanite-cordierite gneisses, and has been locally folded. The upper Everest (*Qomolangma*) detachment is well-exposed in the summit pyramid of Everest and dips northwards at angles of less than 15° (Searle & *alii*, 2003). The structural features are well detectable on the vertical walls of the summits (often covered and masked by deposits along the glacier tongues and the lower slopes), proving problematic to survey and map on a detailed scale; this is why they are mapped only in the geological sketch of fig. 2. The structural evolution of the area is complicated by different time-dependent and interconnected tectonic phases, still active; according to Searle & *alii*, 2003, the South Tibetan Detachment normal faults roughly coincide with initiation of strike-slip faulting and east-west extension in south Tibet.

Only strongly jointed rocks are mapped, due to their intrinsic predisposition to produce debris, enhanced by frost wedging. In the lower slopes of the Rongbuk valley they are both affected by the Everest and Lhotse detachment.

HIGH ALTITUDE PROCESSES AND LANDFORMS

The high altitudes here considered and presented are strictly dependent on environmental conditions, particularly wind (jet streams), temperature and precipitation, and on the presence and action of ice and snow. It is the typical landscape modelled by glacial and, subordinately, periglacial processes, both active from the higher edges and summits of the mountains down the slopes to an average elevation of about 6000 m a.s.l., which represents in the area the lower limit of clean ice, also according to Quincey & *alii*, 2009.

The clean-ice is widely outcropping and has been distinguished from the supraglacial debris: the glacier snouts were also surveyed (with GPS technologies for the Rongbuk tongue) and mapped, in order to fix a referential glacial frontal limit for future comparisons and evaluation of glacial variations. Typical evidence of the transition between clean and debris-covered ice is initially highlighted by the presence of seracs, rapidly evolving to ice sails. Some spectacular sails are shown in fig. 3, illustrating the action of differential ablation on the glacier surface. Two important transfluence saddles have been previously reported in the literature (Kuhle, 2006) at the *Rabu-La* 6548 m and the Chang La (North Col) *Bei'ao* - 7066 m: in the first case well evident and active and in the second case still active but transforming to rock saddle with shrinking of the ice threshold.

The glacial processes are active and strongly condition the high altitude Himalayan environment. They have also left an evident footprint on the landscape, both with still active erosional (upstream) and depositional (downstream, in the valley) landforms.

Among the erosional landforms, the glacial cirques are widely distributed and dominate the high altitude geomorphological landscape and skyline.

The upstream glacial cirques (fig. 4), including the buried ones, present typical morphologies, with steep walls, covered and filled by glaciers, often with seracs in the upper sectors and with an overburden (and probably overdeepened) bedrock below.

With melted ice bodies, the bottom of the lower cirques generally host landslide bodies generated by falls and caused by the post-glacial tensional release.

The cirque edges have been displayed on the map using as a basis available satellite images in which the landforms were relatively easy-to-detect at the representation scale.

The lateral and medial moraine pattern follows the presence and the action of the tongues. The evolution of active and well organized moraines was surveyed only in limited upper sectors of the East Rongbuk glacier in the Advanced Base Camp (ABC) and surrounding area, along with other debris-producing processes, in particular avalanches (lateral active moraine ridge of fig. 5).

FIG. 3 - Great ice sails along the trek between Intermediate Camp and Advanced Base Camp of Mt. Everest, about 6000 m asl.

FIG. 4 - The compound high altitude basins of the eastern Rongbuk ice stream.

FIG. 5 - View from the North Col (7066 m asl) of the ABC area spread on a lateral active moraine ridge that is highlighted in full black line and is also mapped on the geomorphological map, as well as an valanche deposit (dashed black line) just upstream (Eastern Rongbuk higher basin).

VALLEY PROCESSES AND LANDFORMS

Lower areas are characterized by depositional landforms and deposits, mainly located along the glacial valleys and slopes, in turn occupied by the debris-covered Rongbuk retreated tongues. In such a framework of a paraglacial landsystem, still evolving, the gravitational processes rapidly affect the free-ice slopes with rock falls, landslides and slope instability. They represent the more evident footprint in the landscape, only locally characterized by some spectacular glacial, periglacial, fluvio-glacial and running waters landforms, as highlighted in the geomorphological map.

Edges of degradation scarps and scree slopes/talus cones, without doubt, represent the active gravitational landforms that mainly characterize the area. Talus cones are generally with heterometric and polygenetic clasts, showing planar arrangements with inclinations between 30° and 40° and characterized by edged grains and stability conditions close to the equilibrium limit, due to a slope angle close to the friction angle. They have been surveyed below and at rock couloirs, emerging from the scree slopes as «in relief» landforms.

Rock fall accumulation areas are also composed of heterogenic and heterometric debris. The more evident non-active rockfall bodies affect the First Camp which was frequently used after Hillary's expedition (no longer used at present) and along the trek joining the Rongbuk monastery and the Base camp area, on the true right.

The fluvial-glacial environment accompanying the glacier-melt runoff (Singh & Singh, 2001) is located just below and downstream of this area, where the torrent runs in a braided pattern; all the valley slopes of the three streams of the Rongbuk glacier are affected by running water, producing gullies, wide superficial erosion and, above all, striking earth pyramids (fig. 6), mainly depending on the

FIG. 6 - Earth pyramids within the LIA inactive moraine ridge hanging on the Base Camp and produced by running water.

slope dipping and on the dimension, distribution and mechanical features of the debris.

Several debris flow fans border the lower tongue, sometimes covering it. In some cases the upper channel is present and well detectable, as well as a differentiation within the fan into a proximal and active sector and a distal less active area.

The field features and the morphologic evidence of at least two GLOFs and of the subsequent debris flows have been surveyed with particular attention to their risk significance and implications. They are both located on the debris-covered lateral (Eastern, in fig. 7) side of the Rongbuk glacier snout.

In both cases the GLOF deposits cover an estimated area about 20,000 m^2, with the alluvial fan elongated along the glacier stream direction, passing next to the snout and enlarging in the proximal proglacial plain, also interacting with the snout dynamic.

Even if not directly reported in the literature (i.e. Campbell, 2005; Mool & *alii*, 2001), the evolution of lakes, still limited in surface area in 2004 on the Rongbuk glacier, is common to other glacier valleys in the Himalayas and prone to rapid changes in risk conditions, at least at the Mt. Everest base camp greater areas.

The grain size composition of the erosional channel ranges between grains and large blocks (also of some m^3, as in the boulder of fig. 6) with absent matrix: erosional landforms appear in a fresh state.

From the hydrographical point of view the lower debris-covered and downwasted glacial tongues are cha-racterized by ephemeral supraglacial lakes and streams, when possible surveyed directly in the field using GPS (fig. 8).

All the features are ephemeral, due to the activity taking place only during the melting season (usually from the end of April to October), intermittent in the short period (day/night cycle) and long term temporal scale and sometimes affected both by typical processes and actions, such as micro sub-aerial ripples (fig. 8), promoted by the wind action. No springs were surveyed or reported in the area as well as the deposits, due to the energy relief; only one system of fans appears well-organized, just in the area of the base camps, where the fluvial processes have re-organized the original till and where the two already described little GLOF fans converge.

Ephemeral ice landforms have also been surveyed, mapped and distinguished from glacial landforms *tout court*, including in relation to the important role in defining the glacial landscape, and, above all, in generating seasonal risk for mountaineers and expedition infrastructures, as reported in the initial and descriptive part of the Legend (Hydrography).

The other features surveyed and displayed (ice cliffs of fig. 9, hanging serac edges and deposits) were not mappable, because of the limited surface development, but indicated with points.

They were important in defining the natural hazard framework and in the occurrence of the phenomenon shown, as an example, in fig. 10.

In fact, during the expedition (Mortara & Pecci, 2005) a serac fall affected the trek, although without causing damage, probably detached from the *Changtse* edge during the night 1-2 May 2004 (Mortara & Pecci, 2005), between the base camp and the intermediate base camp (about 5800 m asl).

Along the active glacial tongues or in the surrounding areas and directly above, all sediments still affected by the glacial process or on the borders, have been mapped as «Glacial deposits» and «Supraglacial debris», respectively.

FIG. 7 - Eastern recent GLOF deposit in the snout area, currently carved by running waters.

FIG. 8 - Ephemeral supraglacial stream with evident shore and ripples.

FIG. 9 - Ice cliff bounded pond (inner part of the main Rongbuk stream, elevation of about 5400 m asl) illustrating debris layers within the approx. 10 m high cliff and the 1-2 m thick drape of supraglacial debris.

Glacial deposits, surveyed active and inactive, also include in the latter case all the sediments and debris involved in the glacial process in past geo-morphodynamic conditions: LIA (Little Ice Age), Holocene-Neoglacial and, probably in the upper slopes, Late Glacial-Pleistocene.

The glacial deposits are widely cropped out in the area, not organized in well detectable landforms, such as the case of structured inactive edges of *kame* and in well defined moraine ridges. A case of well conserved south-oriented edges of *kame* is illustrated in fig. 11.

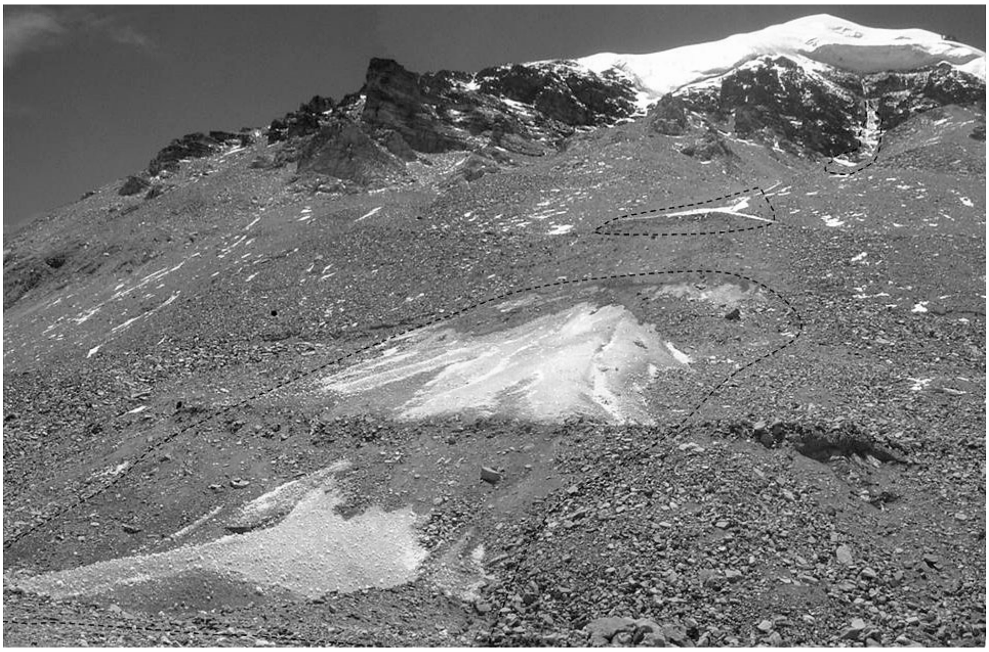

FIG. 10 - Hanging ice serac on the edge of the Changtze and, in the foreground, the ice accumulation caused by a fall in the night 1-2/05/2004.

FIG. 11 - Evident and continuous *kame* edge on the Rongbuk glacier (main stream), below the last confluence.

The re-elaboration of the glacial deposit (both active and inactive) and the convergence of different and further geomorphological processes are frequent in the frontal and peripheral areas of the glacier, also contributing to the presence of a highly active para-glacial environment.

No cartographic distinctions have been made among LGM (Last Glacial Maximum), Neoglacial and LIA ridges, because of the scale rate. In fact, the glacier is laterally bordered by two orders of moraine ridges (practically overlapping on the map): the upper (Burbank & Kang, 1991) attributed to the «Rongbude Neoglaciation» and located in the Base Camp area at an altitude of about 5400 m asl, and the lower to the Little Ice Age.

Furthermore, scientific discussion is still open concerning the Equilibrium Line Altitude of the LGM in the Everest area and the attribution of the chronology to the moraines. A preliminary chronological attribution was obtained during the Chinese expedition in 1966-68 (Zheng, 1988) and followed by the different scientific views about the last Tibetan glaciation (Kuhle, 1986; Kuhle, 1997; Benn & Owen, 1998); Burbank & Kang (1991) reinterpreted the glacial chronology in the Rongbuk valley on the basis of relative weathering state. Finally, Mann & *alii* (2007) provided minimum ages for the moraines, limited to the Holocene, using boulder weathering studies, lichenometry and radiocarbon dating of calcium carbonate coatings in moraine soils.

The Neoglacial retreat resulted, mainly, in a reduction of the tongue ice thickness in the area studied: the ice-free slopes, mostly South and East oriented as in case of fig. 12, promoted and still promote gravitational movement of the debris, also with the contribution of avalanches, adding to the deposition of the lateral moraine (fig. 12).

Avalanches, even if localized, are one of the most important processes modifying the slopes and affecting human presence and expedition infrastructure. Several channels and related deposits (fan) have been surveyed on the left true slope of the East Rongbuk stream, potentially affecting not only the trek to the higher camps but also the Advanced Base Camp semi-permanent settlement. The deposits are chaotically distributed in a debris fan or cone, depending on the interaction of gravity and melted running waters; periglacial process prevail in the case of fig 12, despite the absence of an active pro-talus rampart, due to the action of the East Rongbuk glacier tongue.

FIG. 12 - Snow avalanche accumulation, just above the ABC area (6500 m asl).

Further periglacial landforms mainly consist in two well developed active rock glaciers and in localized turf banked terrace surfaces.

Two well-developed and active rock glaciers have been surveyed: the lower (fig. 13), with the probable ice core very deep, showed a well-defined festoon-ridge, a still developing structuring and grain size selection with a resulting chaotic sedimentary pattern and with a surface area calculated at about 56,000 m^2; the upper rock glacier developed in an area without moraine*s*, but in chaotic glacial deposits and surrounded by scree slopes, showing a structure in festoon ridges oriented downstream; estimated surface area is about 223,000 m^2.

The only turf-banked terrace area observed was identified on the left true slope near the hanging snout of the East Rongbuk glacier, with a relatively limited outcrop,

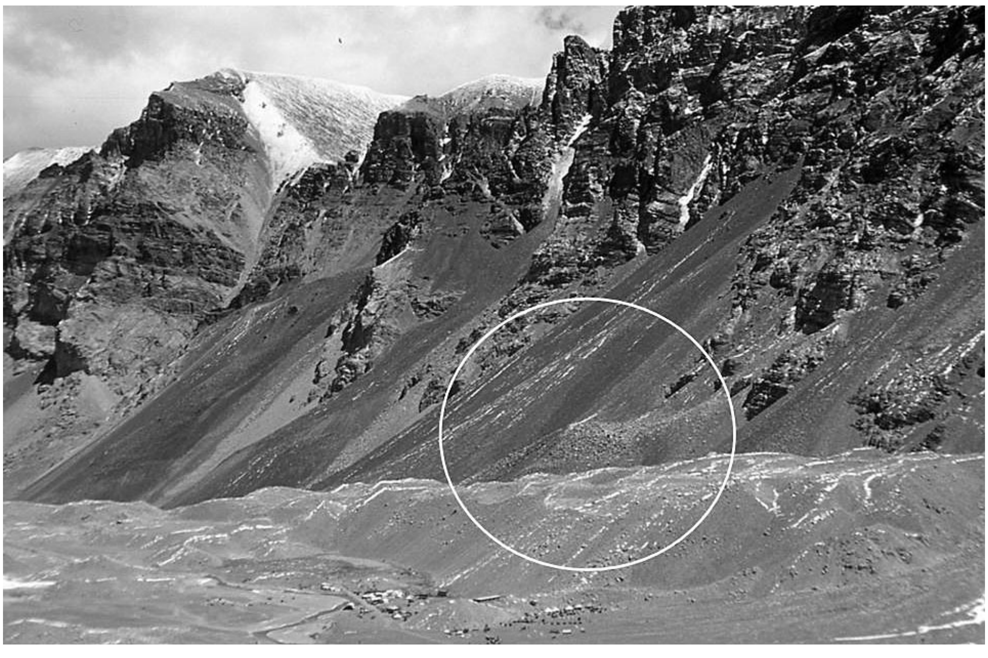

FIG. 13 - The lower and active rock glacier (within the white circle) above the Base Camp area and the closing true right moraine ridge, above the limit Neoglacial moraine-scree slope.

surface not mappable, with clay and silt composition, with slope dipping of about 30°-35° and with marked anastomising and characteristic inter-bedded features.

Finally, human presence is limited to tourism and mountaineering. Herds of yak live only in the area of the Base Camp, where some semi-permanent small constructions and structures are present. The tourist flow is centred on the well defined trek to the summit of Mt. Everest, with significant risk. Continuous use of the most frequented trails in the area has led to evident erosion effects.

TIME-DEPENDANT EVOLUTION OF THE GLACIERS

The Rongbuk glaciers are among the most significant, important and frequented *apparata* of the northern slope of Mount Everest. The principal morphologic parameters and features are summarized in table 1.

TABLE 1 - Principal features of the Rongbuk glacier system, after National Geographic (1988).

Glacier	Max length (m)	Max altitude (m)	Type	Note
Central Rongbuk	About 14.500	LhoLa (6026)	Mountain, compound basins	Completely debris covered downward, stationary, but thinning
Eastern Rongbuk	About 10.359 (confluence)	Beìao (7066) (North Col)	Mountain, compound basins	Clean ice in the upper part, thinning and retreating from the confluence
Western Rongbuk	About 9700 (confluence)	Altitude 6833	Mountain, compound basins, confluent (central Rongbuk)	Clean ice in the upper part, thinning and debris covering in the lower
Pumori	About 4000 (confluence)	Pumori 7165	Mountain, compound basins, confluent (Western Rongbuk)	Clean ice, thinning

At present, the glacier system is shrinking, as shown by the non active moraine dam pattern containing the tongue (in the valley sector) and linkable to the Holocene-Neoglacial and LIA cycles. The evident and fresh lateral inactive moraine clearly defines the extension of the tongues and their altitudinal limits, also indicating a substantial continuity among the three tongues comprising the glacier.

The shrinkage of the glacier is strictly a function of the rise in ELA, different in the southern and northern slopes: the modern ELA of the East Rongbuk glacier was estimated (Burbank & Kang, 1991) around 6400 m asl, while the ELA depression to the south of the range −950 m was about twice as great as to the north −400 m (Owen & Benn, 2005).

The more recent reduction of the glacier since the end of the Little Ice Age has produced the growth of a further and lower pattern of moraine ridges, internal to the Neoglacial one, as reconstructed in the interpretative sketches and profiles of fig. 14.

The shrinkage of the glacier system has also produced general tensional release on the mountain slopes, inducing still active gravitational phenomena, localized in very few large rock falls and more widely rock, debris, ice and snow, promoting new risk conditions.

THE APPLIED OUTPUTS: FROM DIGITAL ELABORATION TO HAZARD MAP

A further important output of digital elaboration is the interpretative natural hazard map (fig. 15), describing the

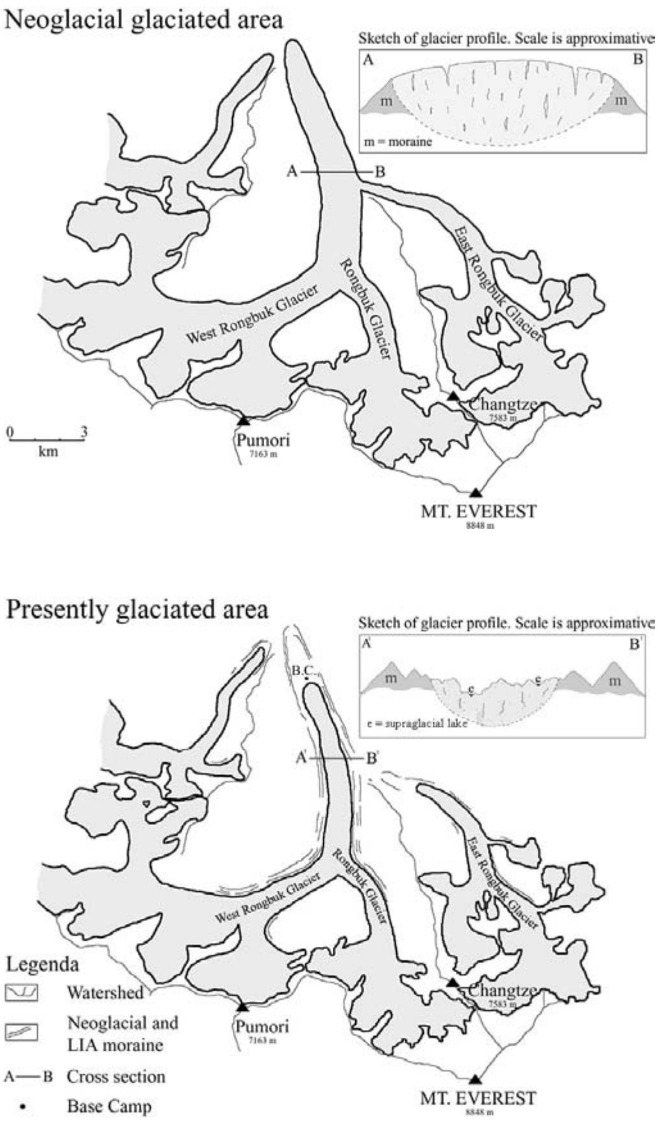

FIG. 14 - Geomorphological sketches and profile of Holocene retreat of the mountain compound basin glacier of Rongbuk. Scale is approximate (after Burbank & Kang, 1991, modified).

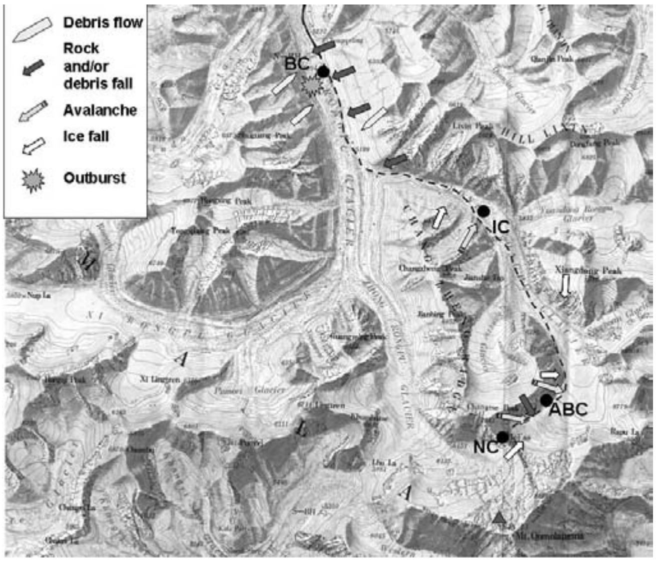

FIG. 15 - Interpretative hazard map of the area studied (topographic base 1:50,000, redrawn from National Geographic Magazine, 1988). Location of the risk-prone sites along the trek (dashed black line) from the Base Camp (BC) to the Intermediate Camp (IC) and to the Advanced Base Camp (ABC), up to the mountaineering path towards North Col (NC).

risk elements and sources. The legend differentiates the sources, depending on the genesis.

It is important to highlight that identification of such landforms and features and their relative degree of hazard is not immediately perceptible only from mountaineering experience. Some of these landforms, in fact, are easily detectable in the field (debris flow channel, fans and landslide accumulations), but the processes generating hazards, and then risks in the case of human presence, can be activated by particular meteorological or climatic events, sometimes completely unpredictable. On the other hand, some other processes directly linked to the rapid evolution of the terminus, or such as GLOFs, are hardly detectable in the «dormant» state and unpredictable in terms of time. In fact, in the terminus area geomorphological evidence of recent GLOFs has been mapped. Furthermore the evidence of the evolution of a GLOF «in progress» has been surveyed on top of the tongue snout, leading to risk conditions for the mountaineering camp site below.

The spatial extension of these landforms has been mapped and correlated with the location of the tents, as surveyed in the spring 2004.

The increasing human presence in the fragile Mount Everest environment also implies the need for a different perspective taking account of and evaluating the new risk conditions (Pecci & Mortara, 2005). The human presence is usually concentrated in the periods April-May and October-November, but anomalous early or delayed Monsoon periods can generate a serious landslide and debris flow hazard along the path from the Rongbuk Monastery to the Base Camp, as well as to the large and unregulated tent settlement on the proglacial plain. The trek to the upper camps is also subject to well known gravitational phenomena of the mountain slopes, such as avalanches and landslides, but also to increasing and unpredictable events such as ice falls from hanging seracs. Given the logistic difficulty in lowering the risks conditions, in the authors' opinion, knowledge of, and respect for, the high altitude environment is the essential condition in preventing damage and victims.

FINAL REMARKS

The 1:30,000 scale study of the Rongbuk glacier basin enables reconstruction of the geomorphological outline. The surveyed area shows a clear glacial footprint on a structural predisposed bedrock, within a paraglacial framework of evolution and dynamism.

The principal features also include ephemeral landforms linked to melting waters and/or differential ablation on the glacier surface. The frost wedging on the jointed bedrock favours high production of frost-shattered clasts, which feed drift-mantled slopes. The gravitational and fluvial/wash processes are particularly active in free-ice areas within a paraglacial context, but are less significant in comparison to the principal ones; in fact, glacial and periglacial process produced the principal erosional and depositional landforms presented. Most of the landforms identified in the area should be considered active.

The human presence is only seasonal and linked to tourism, chiefly mountaineering expeditions. The risks conditions are increasing and must be thoroughly assessed in the future.

A useful and correct approach to accomplish in situ researches in remote areas, especially if glaciarized and in high altitude, implies previous knowledge of the field and the environment and, therefore, the availability of remote sensing and terrain images. The initial availability of a geodatabase enables construction of a «field preview», necessary, in the authors' opinion, to plan and manage not only field research, but also tourist and mountaineering activities; moreover, the availability of low-cost or free digital images and data also allows the implementation of a dedicated GIS (during the preparation activity), ready-to-use for real time surveys, controls and updating, directly on the spot, and for identification of hazards for human settlements and research activity.

In this study, such a GIS system enabled all the georeferencing operations (with GPS technologies), the correct digitalization of the landforms and the field elements and their backup as «field data» ready to be used. Moreover the «field preview» and the preliminary *in situ* controls allowed us to set up the base camp under safe conditions, thanks principally to the availability of a preliminary field glacial-geomorphological map.

Such a conceptual path, besides providing an essential support for research on the evolution of geomorphological processes at high altitude, could lead in a relatively limited time to the assessment, the choice and eventual re-location of future camps in scientific and mountaineering expeditions with a low-cost geodata use.

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