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SPATIAL ANALYSIS OF TOPOGRAPHY FOR GLACIER MAPPING IN THE WESTERN HIMALAYA

A Thesis Presented to the
Department of Geography and Geology
and the
faculty of the Graduate College
University of Nebraska
in Partial Fulfillment of the Requirements for the Degree
Master of Arts
University of Nebraska at Omaha

by

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FOR GLACIER MAPPING
IN THE WESTERN HIMALAYA

Acceptance for the Faculty of the Graduate College,
University of Nebraska, in partial fulfillment of the
requirements for the degree Master of Arts,
University of Nebraska at Omaha.

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John F. Shroder 11/30/2006

Chairperson / Date

SPATIAL ANALYSIS OF TOPOGRAPHY FOR GLACIER MAPPING IN THE WESTERN HIMALAYA

(Abstract)

Ľubica Čverčková, MA
University of Nebraska, 2007
Advisor: John F. Shroder

Understanding climate change requires accurate assessment of the Earths cryosphere, as glacier fluctuations directly and indirectly reflect changes in radiative forcing and temperature and precipitation patterns. Direct assessment of alpine glaciers in high-mountains is notoriously difficult, and assessment from space represents the only practical alternative for assessing regional and global ice-fluctuation patterns. The mapping of debris-covered glaciers is especially problematic, as glacier surfaces exhibit spectral reflectance patterns similar to surrounding rock and sediment. Therefore, multispectral analysis of satellite imagery does not permit accurate delineation.

Consequently, the use of satellite-derived topographic information and spatial analysis were evaluated for mapping the Raikot and Sachen Glaciers at Nanga Parbat mountain in the Pakistan Himalaya. Geomorphometric analyses were used to generate first- and second-order topographic parameters. These were utilized to generate homogeneous elemental-form objects, which were evaluated for glacier mapping. Topo-sequence information was also examined and represents the slope-angle altitude function within slope facet objects.

The results indicate that it is difficult to characterize the hierarchical topographic organization of glaciers using topographic parameters and elemental form objects. Even though only one level of the topographic hierarchy was attempted, elemental form objects appear to be more useful than topographic parameters, as they represent a combination of topographic information. In addition, elemental-form objects can be used to identify and map selected glacial features without further aggregation to another level in the hierarchy. Toposequence information was found to be of value in differentiating glacier versus non-glacier surfaces. Collectively these results indicate that spatial analysis of the topography can be used for glacier mapping, although accurate digital elevation models are required, along with more sophisticated approaches for quantitatively characterizing the topography. It is suggested that specific topographic primitives and glacier landforms be individually characterized and integrated into a landscape topographic hierarchy in order to accurately characterize and map debris-covered glaciers. Finally, special attention to the concept of scale must be formally accounted for in analysis procedures.

The main role of scientists is to investigate what reality is as well as to understand the past and present in order to figure out what the future holds. Despite science's efforts to provide objective, trustworthy answers to difficult questions, it is not always able to gain public faith. Understanding reality can be a never-ending process with no start and no end, full of faults as well as progress. But the main question still remains: ***Is human kind prepared to know what reality is?***

To my parents

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Chapter 1

Introduction

At the beginning of the Pleistocene Ice Age large glaciers covered part of the Earth's surface, and formed at least 30% of today's landscape. Glaciers play a significant role in landscape evolution for the areas north of 40° latitude, and in mountains and high plateaus at all latitudes. Mountain glaciers, together with ice caps and snowy mountain ranges, hold 2% of the fresh water of the Earth. They represent a significant water resource, especially in arid and semi-arid climates. Consequently, it is important to monitor glaciers to determine how they are responding to climate forcing.

Even in today's era of general glacier recession (Shroder et al., 2000b), $\sim$ 10 percent of the land surface is under glacier cover (Bloom, 1998). Research documents the significant influence of modern glaciation on landscapes, especially in high altitude environments, where glaciation plays a major role in relief production (Bishop and Shroder, 2000a; Bishop et al., 2003). On the north side of the Nanga Parbat mountain in Pakistan, for example, Gardner and Jones (1993) calculated the rate of glacial denudation to be $4 - 6$ mm a^{-1}. Such rapid denudation reduces the lithospheric mass and results in isostatic and localized tectonic uplift. With increasing elevation, climate change and glaciation modify the topography by further reducing lithospheric mass, which increases topographic relief even more (Bishop et al., 1998b). This represents complex interactions between tectonic, climate and surface processes (figure 1.1) (Bishop and Shroder, 2000a; Zeitler et al., 2001a; Zeilter et al. , 2001b).

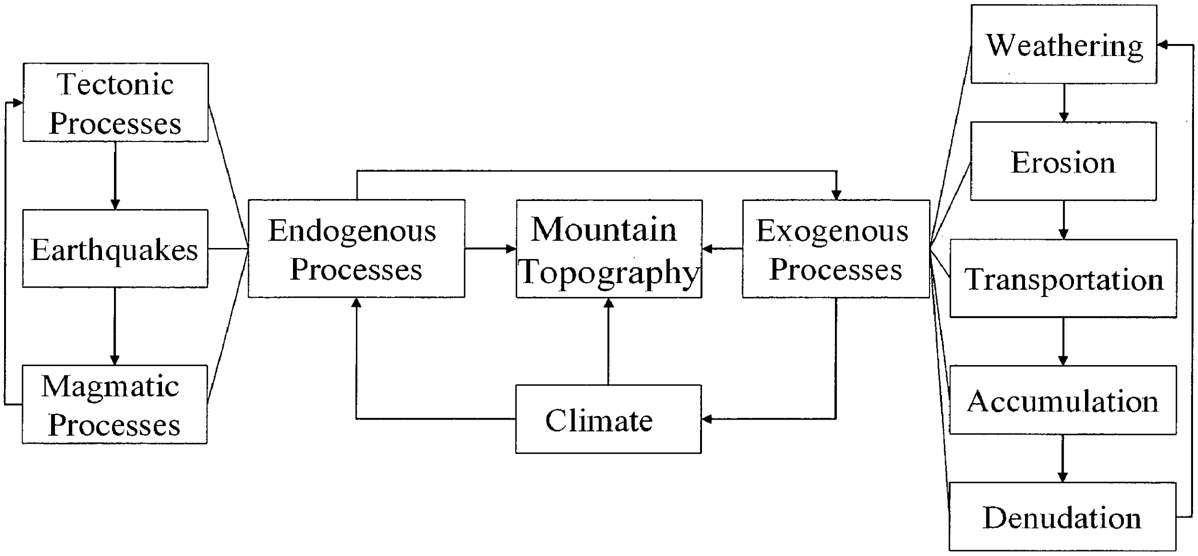


Figure 1.1: Conceptual model of mountain geodynamics. Mountain topography is the ultimate result of endogenous, exogenous processes and climate.

Glaciers, especially the Himalayan ice masses, are thought to be very vulnerable to climate warming due to high altitudes and highly variable debris cover. They are "summer accumulation types" that strongly depend on summer monsoonal precipitation and cool summer temperatures (Ageta and Higuchi, 1984). It follows, therefore, that glaciers are one of the best indicators of climate change (Sharp, 1960). Furthermore, rapid glacier advances and retreats can lead to major slope failures (Bishop et al., 1998a). In addition, supraglacial ice-dammed and moraine-dammed lakes, formed in the terminus region of a glacier, commonly lead to a chaotic potential for glacier lake outburst floods (GLOFs), destruction of property and loss of human life in areas downstream (Wessels et al., 2002).

Understanding mountain geodynamics and climate change require accurate assessment of the Earth's cryosphere. Glacier fluctuations directly and indirectly reflect changes in radiative forcing, temperature and precipitation patterns (Bishop et al., 2001). Direct assessment of alpine glaciers in high mountains is notoriously difficult, and assessment from space represents the only practical alternative for assessing regional and global ice-fluctuation patterns (Bishop et al., 2001). Remote sensing technology today, however, provides a potential solution for the monitoring of mountain glaciers, but it cannot be used easily for complete glacier mapping, as the lower debris-covered parts of Himalayan glaciers exhibit spectral reflectance patterns similar to surrounding rock and sediement. Therefore, multispectral analysis of satellite imagery does not permit accurate mapping and assessment (Čverčková et al., 2004).

Bishop et al. (2001) and Bonk (2002) evaluated scale-dependent information derived from satellite remote sensing to map glacial surfaces, by incorporating detailed field measurements and geomorphometric analysis into mapping efforts. They found morphometric parameters to be very useful in delineating glacial features and some landforms. Over time, the use of morphometry or 'orometry' (Sonklar, 1973) has shifted from comparison of mountain shapes to morphometric characterizations that represent process-form relationships (Montogomery et al., 2001) as well as to the extraction and classification of terrain features from digital elevation models (DEMs) (e.g., Bishop et al., 2001; Hammond, 1964; Wood and Sneel, 1960). Despite the proliferation of empirical research in geomorphometry, there is still no systematic approach to effectively model the complexities of mountain topography (Rasemann et al., 2004).

Numerous scientists have tried to utilize morphometric parameters to automate geomorpological mapping at different scales, and are using physically-based models for estimating rates of erosion and simulating landscape evolution (Hofierka and Šúri, 1999; Minár, 1998; Mitašová et al., 1996a,b). While physically based models have produced promising results (Hofierka and Šúri, 1999), they do not consider the hierarchical organization of the topography.

Characterizing the spatial organization of mountain topography is essential for understanding self-organization mechanisms of landscape evolution. Furthermore, we need to address the issue of scale and the various hierarchical levels of organization that are usually neglected, although critical for understanding spatial relationships and patterns (Albrecht and Car, 1999).

Assessing scale-dependent surface processes and topography can be addressed using geographic information system (GIS) technology and digital elevation models (DEMs). Analysis and modeling of the topography have provided new insights into erosion processes, possible feedback mechanisms, and the polygenetic nature of topographic evolution, which control relief production and the spatial complexity of the landscape (Bishop and Shroder, 2000a; Brozovik et al., 1997; Burbank et al., 1996; Shroder and Bishop, 1998a).

Bishop et al. (2001) and Bonk (2002) were among the first to investigate the theoretical and practical aspects of hierarchical organization of topography for glacier mapping, using object-oriented data modeling, geomorphometry, and scale-dependent analysis. Their automated approach using a two-level hierarchical model was reasonable enough to delineate portions of the Raikot Glacier on the Nanga Parbat massif. They suggested, however, that additional analysis was required to characterize complex glacier topography.

1.1 Nature of the Problem

The analysis of Western Himalayan topography involves understanding the feedback mechanisms that control topographic evolution (Bishop and Shroder, 2000a). To be able to understand landscape evolution, we need to understand the underlying processes that create them (Phillips, 1999). The study of geomorphic processes can be difficult because they are highly scale-dependant (spatio-temporal) (Mark and Aronson, 1989).

A common way of dealing with scale (see appendix) in scientific research is the hierarchical approach. Hierarchy theory (see appendix) was formally described by Koestler (1967) as an alternative to the application of classic reductional experimental science in the study of human behavior. He used the term 'hierarchy' for a tree-like structure of a system, which can be subdivided into smaller subsystems that in turn can be subdivided into next smaller subsystems and so on. The smallest subsystems from a morphology perspective can be referred to as 'elemental terrain form objects (ETFO)', which exist at a small geographic scale, and which may exhibit homogeneous morphometric properties, such as slope, slope-aspect and curvature (figure 1.2)

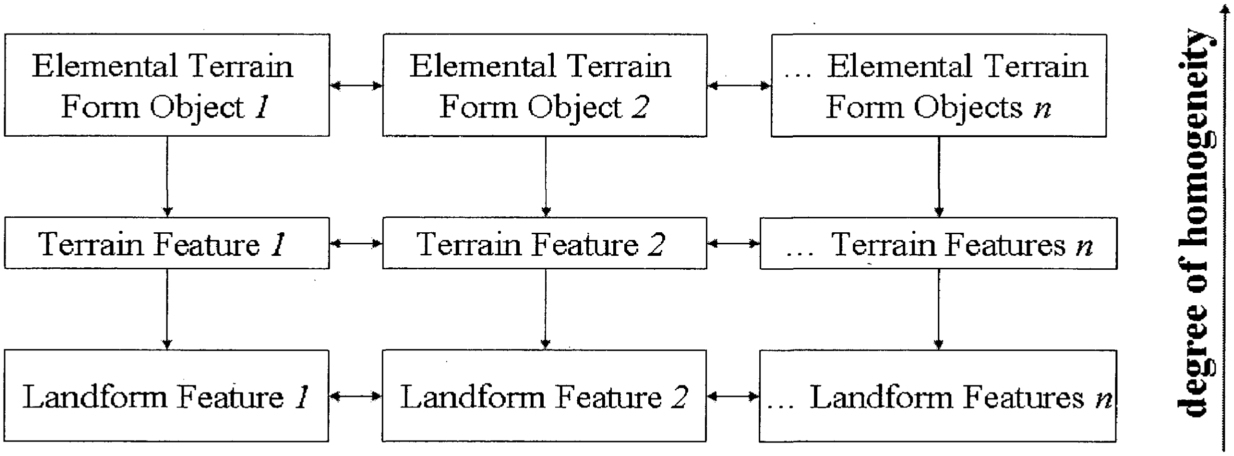


Figure 1.2: Hierarchical characterization of mountain landforms. The topography is a hierarchy, such that elemental terrain forms objects represent the lower-level terrain-form objects. At higher level, terrain-features are defined based upon the spatial aggregation of multiple elemental terrain-form objects, and subsequent higher-order feature, landform features result from the spatial aggregation of objects from the appropriate lower level.

It follows then, that hierarchy theory can be used in the characterization of landforms, as the topography is a hierarchy, such that ETFOs represent one relatively low-level object. At higher levels, terrain-features, such as moraines and ice cliffs can be defined based upon the spatial aggregation of ETFOs, and subsequent landform features, such as a glaciers result from the spatial aggregation of objects from the appropriate lower levels (Bishop et al., 2001).

In addition, hierarchy theory attempts to reduce the level of complexity and explain the spatial hierarchical structure of the topography (Bishop et al., 2001). Reducing the complexity does not always result in losing too much information, but it is related to techniques of managing the complexity and multi-scaled dependency of hierarchically structured attributes (Suryana and Hoop, 1994).

Another advantage of using a hierarchical description of landscape is that it gives information about the topology of topography. The knowledge of spatial topology provides a basis for utilizing geomorphometric characteristics in mapping surface processes that operate at various hierarchical levels. Furthermore, there maybe unique relationships associated between object attributes at each hierarchical level as well as across them that potentially contain information about the polygenetic evolution of a landscape (Bishop et al., 2001).

A new methodology, as well as new morphometric parameters, need to be developed and evaluated that capture the morphogenetic information associated with these forms and their scale-dependency. Furthermore, the approach needs to account for the changing morphometry of a glacier's surface as it advances or retreats, as well as the similarity of topographic characteristics generated by other surface processes.

1.2 Research Objectives

The topographic complexity at Nanga Parbat results from dynamic interactions between climate and tectonics that consequently affect surface processes. Alpine glaciers at Nanga Parbat, however, differ in their activity as a result of climate change and local topographic variation, and they exhibit unique topographic characteristics at various scales that can be captured by spatial analysis. Development of a space-based approach allows for glacial monitoring and the study of mountain dynamics that are the result of multi-scale feedback mechanisms. Mapping of alpine glaciers using satellite imagery is not feasible due to similar spectral reflectance patterns of debris-covered glaciers and surrounding rocks.

Geomorphometric analysis has the potential to investigate the complexities of mountain geomorphology and topography. Consequently, the overall objective of the research is to evaluate the utility of topographic information and spatial analysis for mapping alpine glaciers at Nanga Parbat, Pakistan.

Specific research objectives include:

- Evaluation of topographic parameters for characterizing glacier surface characteristics. This includes traditional first-order and second-order derivatives and new morphometric parameters that include a scale-of-analysis such as openness.
- Evaluation of toposequence information for characterizing glacier/non-glacier surfaces. Glacier features contain unique geometric properties that can be described by using suitable combinations of morphometric parameters and elemental form objects. The slope-altitude function within a basin will be compared to determine if it can uniquely be used to identify glacier surfaces.
- Evaluation of the utility of object-oriented analysis for characterizing alpine glaciers. Object-oriented data modeling and analyses will be used to study the efficacy of diagnostic landform mapping, as the object-oriented data model can represent the real world on the conceptual level, such as it seeks to characterize conceptual entities (e.g. elemental forms, terrain features, and landforms) as objects and can be used to characterize topological relationships.

1.3 Hypotheses and Rationale

There is a need for better understanding landscape organization and topographic evolution. It has been surmised that mountain topography is hierarchical and exhibits reoccurring patterns of forms, such that the glacial surface can be divided into small homogeneous units, elementary terrain form objects, which can be further connected into larger, more complex, less homogeneous units, that constitute landform features (figure 1.2). This hypothesis is based upon hierarchy theory, which emphasizes the spatial organization of topography as a result of climate, tectonic, and surface processes. Surface processes are spatially and temporally constrained, such that processes that generate ETFOs operate at local scale (i.e. internal topographic forcing). Furthermore, processes that generate higher-order forms operate at larger scales and incorporate more processes (i.e. external forcing of climate and tectonics). By anticipating that there are unique attributes associated with scale-dependent hierarchical structures of mountain topography, such as internal morphometric variability, it should be feasible using geomorphometry to depict the spatial patterns associated with topographic structure at a variety of scales. The work of Bishop et al. (2001) and Bonk (2002) has demonstrated the feasibility of this concept.

A description of topographic complexity involves developing additional geometric and contextual information, such as spatial topology. Topological relations such as adjacency and connectivity are important aspects of morphogenetic relationships that dictate differences in matter, process and topographic complexity. Furthermore, shape indices should enable identification of terrain features and assist in characterizing terrain objects. This overall hypothesis is based upon the assumption that mountain topography inherently contains morphologic, morphogenetic and morphodynamic information related to the polygenetic nature of landscape evolution, and that this information can be extracted from DEMs using geomorphometric analysis (figure 1.3).

Specific hypotheses and rationales as related to the specified objectives are as follows:

- It is hypothesized that traditional first- and second-order topographic parameters cannot be directly used to accurately map glaciers. This is because the magnitudes of the metrics are not unique for glacier surfaces, and a multitude of surface processes generate similar topographic conditions. It is anticipated that their greatest value will be in the generation of topographic primitives such as ridges, and in the generation

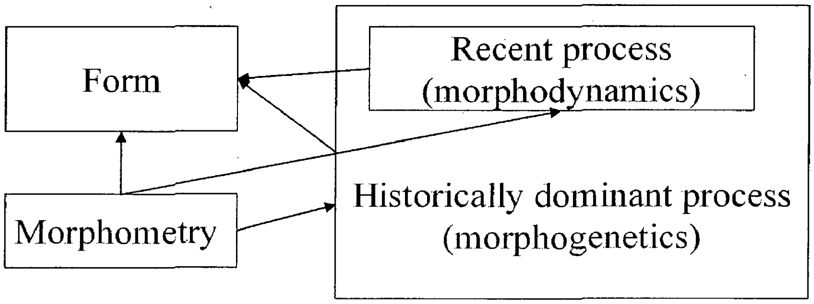


Figure 1.3: Relations among basic geomorphologic categories (modified from Minár, 1992).

of elemental form objects. It is also anticipated that the topographic parameter called openness will be of minimal value as it represents a globally-controlled metric whose magnitude is dependent upon the scale-of-analysis. Because the inherent scale-of-analysis for a particular glacier is not accurately known, its utility for automated mapping is limited, unless it is uniquely combined with other topographic information.

- It is hypothesized that toposequence information has the potential to be used effectively to differentiate between glacier and non-glacier surfaces, because it represents the slope-altitude function for the slope-facet structure of the topography. The slope-facet structure of glaciers surfaces should be highly variable compared to alpine basin topography because the glacier surface is highly active and slope facets should be relative small in size compared to large steep slope alpine basin slope facets. Given these differences, glacier slope facets should exhibit relatively lower slope angles and relief in the ablation area.

- Finally, it is hypothesized that object-oriented data modeling and analysis can be used to accurately characterize various aspects of the hierarchical structure of mountain topography. Specifically, spatial analysis and object-oriented data modeling should enable the study of spatial patterns on glaciers. Although very little work has been done on formalizing the object hierarchy and on the methodology for generating objects at various hierarchy levels, it is anticipated that elemental form objects generated from individual topographic parameters will be of limited value, although objects generated from multiple topographic parameters will be very useful. It is expected that unsupervised cluster analysis will be an effective approach for enforcing the homogeneity rule in the generation of elemental form objects.

1.4 Significance of Research

The Western Himalayas represent the world's highest mountains that exhibit active tectonics and climate change. They are home to some of the largest and most active glaciers on Earth. Accurate assessment and mapping of these glaciers is required in order to understand climate change, landscape evolution, natural hazards and water resources.

Glacier characterization and mapping requires a multidisciplinary approach. It is necessary to use remote sensing, geomorphometry, geomorphology and GISscience to address issues of surface characteristics, topography, and scale-dependence. This requires application of data modeling and spatial analysis.

This research should provide insight into the feasibility of using hierarchy theory for complex topographic characterization, and consequently give us more information about landscape self-organization as it relates to process and form (i.e. morphogenetics). Development of data models and computer analysis used in this research should provide better information about glacier morphology and the use of morphometric parameters generated from DEMs.

Perhaps the most significant benefit of this research will be to assist in the accurate delineation of glaciers to permit monitoring and change detection. Glaciers in Pakistan have already significantly impacted settlement, communications, natural resources, and economies. In Pakistan, there are approximately $1,214$ glaciers that dominate the hydrology of many basins (Bishop et al., 1995). Better assessment and monitoring is essential so that information can be used for hazard assessment and management of resources for people living in these high-altitude environments.

Chapter 2

Literature Review

Mapping debris-covered glaciers is a difficult task (Čverčková et al., 2004). It involves utilization of knowledge such as spatial organization of landscapes, glacier geomorphology, geomorphometry, and the utility of geographic information technology and digital elevation models (DEMs). Therefore, a review of the literature will focus on the following topics:

- **Nanga Parbat Massif** - climate, tectonic and surface processes conditions.
- **Hierarchy Theory and Mountain Topography** - Spatial organization of mountain landscapes.
- **Glacier Mapping** - Geomorphometric analysis, GIS spatial analysis and remote sensing.

2.1 Nanga Parbat Massif

The extreme topography of Nanga Parbat mountain has been recognized as unusual in terms of active surface processes that result in ferocious denudation rates. Zeitler (1985) was among the first scientists who studied exhumation rates using fission-track dating of bedrock at Nanga Parbat, one of the fastest growing mountains in the world (Burbank et al., 1996; Shroder and Bishop, 1998a). He calculated exceptionally rapid rates of uplift of ≈ 10 mm yr^{-1} over the past few million years (Bishop et al., 1998b). The later work of Zeitler (1989) and Winslow et al. (1994) estimated exhumation rates of 4 to 8 mm yr^{-1}. Burbank et al. (1996), using cosmogenic-radionuclide exposure ages, calculated bedrock incision rates by the antecedent Indus River. His research brought the estimates of incision rates to about $2 - 12$ mm yr^{-1} (Shroder et al., 1999). Shroder et al. (1999) made 15 preliminary measurements of glacier and river incision rates based upon which they calculated valley incision rates that average $\sim 2.2 \pm 1.1$ cm yr^{-1}.

Gardner and Jones (1993) concluded that glacial processes were responsible for removing large amounts of sediments from Nanga Parbat mountain. They estimated glacier denudation as high as 4.6 - 6.9 mm yr^{-1}. During the last decade Shroder (1998b); Shroder et al. (1999) and Shroder and Bishop (2000a) explored unroofing and glacial characteristics of different glaciers at Nanga Parbat mountain. They pointed out that unroofing of Nanga Parbat is caused not only by differential denudation but also by differential incision that was responsible for the huge knife-edged massif with the steepest relief on the planet.

Slope failures were recognized to be responsible for unroofing of the massif as well (Shroder, 1998b; Shroder et al., 1999). They were examined very precisely by Code and Sirhindi (1986); Owen (1989) and Goudie et al. (1984) in the Raikot-Astor region of Nanga Parbat and the Atabad Hunza area. There were also other authors who studied uplift and consequently denudation rates at the Nanga Parbat massif, e.g. Amano and Taira (1992); France-Lanord et al. (1993) and Montogomery (1994), who concluded that high rates of denudation result in a reduction of lithospheric mass, which can cause isostatic uplift that results in increases in elevation, climate change and glaciation.

The advent of geographic information systems (GIS) technology, as well as new development in remote sensing, created opportunities for advanced glaciological and geomorphological studies. Among the first GIS approaches to studying Nanga Parbat mountain were reported by Bishop et al. (1998b). It was multidisciplinary research investigating the relationship between tectonic and surface processes, denudation and uplift using remote sensing for image acquisition, and multispectral analysis and geomorphometric analysis of a digital elevation model, derived from a satellite imagery. GIS and pattern recognition procedures were applied to analyze topographic complexity and the geomorphology of the massif. The results of the geomorphometric approach, specifically slope analysis, applied to the Raikot basin showed high variation of slope with altitude. The high variation is associated with various processes; such that maximum slope angles were associated with faulting and river incision, whereas minimum slope angles were associated with glaciation.

Considerable potential exists for the classification of remotely sensed data and spatial data with the use of artificial neural network (ANN) technology (Civco, 1993; Foody et al., 1995; Zhou and Civco, 1996). Bishop et al. (1999) investigated the utility of ANN for classifying supraglacial characteristics of alpine glaciers and to identify spectral patterns that were associated with the surface topography of glaciers at Nanga Parbat. ANN technology was also utilized to classify categories of debris-load classes for some of the glaciers at Nanga Parbat. They trained each ANN to recognize between: (1) bare glacier ice; (2) shallow debris on white ice; (3) moisture-laden, shallow debris; (4) thick debris-topographic high and; (5) thick debris-topographic low.

Also important were the findings of Bishop and Shroder (2000a) who used virtual reality coupled with morphometric analysis to analyze complex topography at Nanga Parbat. The results revealed a hierarchical organization of topography as well as extreme relief as a result of tectonic uplift, extreme denudation, and lithology/structure. Furthermore, they used satellite imagery to identify geomorphic events by examining erosion and deposition features. In addition, they recognized the significance of the shape of valleys modified either by river incision or glaciation using terrain-curvature analysis. The spatial distribution of extreme concavity was associated with river incision that shaped the valleys into the characteristic "V" shape. On the other hand, glaciation modified the valleys into significant "U" shapes.

They concluded there was a significant influence of glaciation on the landscape and the relief structure at Nanga Parbat.

The effect of glaciation was further investigated in the research of Bishop et al. (2003). A better capability of deriving the information from satellite imagery was achieved by radiometric calibration, specifically by using the Minnaert-correction method, to account for topographic effects. Both river incision and glaciation proved to be major geomorphic agents responsible for relief production at Nanga Parbat, although glaciation generates the greatest mesoscale relief at high altitudes. At intermediate altitudes, warm-based glaciation decreases meso-scale relief. The results show a differential influence of glaciation on the relief structure of the landscape.

The multidisciplinary research conducted at Nanga Parbat shows that the massif has undergone extreme environmental change over a very short period of geological time. Glacial, fluvial, and slope processes have played very important roles at different times in unroofing of the massif. Therefore, Nanga Parbat is not in a topographic steady state. New parameterizations for numerical modeling are needed to investigate microclimate, surface runoff, and glacial processes that influence erosion and relief production. In addition, new information extraction approaches from satellite imagery are required. This can be accomplished by developing and utilizing spatio-temporal theories of mountain topographic organization and developing new GIS-based techniques for modeling these complexities (Bishop et al., 2002, 2003; Shroder and Bishop, 2000a).

2.2 Hierarchy Theory and Mountain Topography

Characterization of terrain spatial organization is essential in understanding landscape self-organization mechanisms. In an attempt to characterize the complex nature of landscapes, a theoretical foundation should guide data modeling and analysis efforts. There are several issues that need to be met once hierarchy theory is used for landscape mapping, such as formalizing hierarchy theory, encountering the scale-dependency of geomorphic forms or mapping units, and developing a procedure for spatial aggregation of forms. Mapping of spatially organized topography begins with the characterization of the topographic primitives that include first- and second-order derivatives of the elevation field. It then involves identification of fundamental spatial units that compose the landscape. Numerous theories and viewpoints about spatial organization of topography have been developed by various scientists of different nations, for example, by geoecologists of the German-Swiss school (e.g., Baume, 1991; Hasse, 1969; Mossimann, 1990) who initiated the theory of fundamental units or elemental forms in the early 1970's and 1980's. They referred to the basic, or the most homogeneous elemental forms as a '*geotop*'.

In geomorphology the nature of elemental forms was often described using geometry, for example, Krcho (1973, 2001) and Lastočkin (1987) characterized elemental forms on the basis of homogeneous geometric parameters. The approach of Krcho has been based on the morphometric homogeneity of the surface by using morphometric parameters calculated for a single location on the basis of its nearest neighbors, such as slope, aspect, profile, tangential and planimetric curvatures (Etzelmüller and Sulebak, 2000). Krcho's approach continued with the theoretical combination of morphometric parameters to create elemental forms. The problem with the procedure is that defined surfaces are morphometrically homogeneous inside, but their boundaries often do not correspond to the inner georelief structure (Minár, 1992). The problem of indeterminate boundaries represents one of the issues in the complexities of characterization of elemental forms (Borrough and Frank, 1996).

Geometry, however, often used in defining morphometric properties of terrain, has not been thoroughly investigated for mapping of glacial surfaces. Bishop et al. (2001) was among the first to define forms or hierarchical structures of glacial surfaces using morphometry. The results indicated that slope-angle and slope-aspect have the potential to delineate the boundaries of glaciers. Similarly, curvature was found to be of value for identifying glacier features such as moraines and ice cliffs. Overall, the result of using morphometric parameters proved to be valuable, but not completely adequate for automated mapping. An improved approach is needed to produce elemental forms that that are the result of the combination of morphometric parameters. Furthermore, it is important that automated modeling of landforms accounts for the inherent scale-dependency of elemental forms and landform features.

Bishop et al. (1998a) investigated the use of scale-dependent variation, derived from satellite imagery, to characterize glacier features that are the result of, for example, ice movement, ablation and supraglacial fluvial action. The result of scale-dependent analysis indicated that reflectance variation from fractured white-ice (seracs) exhibits a fractal pattern, whereas reflectance variations from other glacier surfaces exhibit a fractal pattern only within specific scale ranges (i.e. multi-fractality).

It is essential that the idea of spatial scale be viewed in a hierarchical context (hierarchical scale), such that a system consists of a group of lower-level subsystems, while each subsystem is composed of lower-level subsystems, thereby defining a hierarchical organization. It follows then that spatial scale plays an important role in defining a hierarchical description of landscape. Given that an important objective is to define the hierarchical organization of topography, it is essential to identify those morphometric parameters that are most useful in defining the nature of elemental form objects.

Yokoyama et al. (2002) developed the metric 'openness', which is a relatively new morphometric parameter that accounts for the meso-scale curvature characteristic of the topography. Openness expresses dominance (exposure) versus enclosure of a location on an irregular surface (Pike, 2002). Etzelmüller and Sulebak (2000) provided an overview of morphometric parameters concerning permafrost distribution and periglacial processes, which could be related to hierarchical levels. They distinguished between point parameters, catchment-related parameters, compound parameters, and topography-based distributed models as follows:

- **Point parameters** - altitude, slope, aspect, curvature. From these, other parameters are derived, such as focal statistical measures (e.g. slope mean), relief/roughness measures (e.g. curvature standard deviation), and hypsographic measures (e.g. altitude skew).

- **Catchment-related parameters** - run-off response, glacier flow, slope geomorphology
- **Compound parameters** - involve combinations of point with catchment related parameters, such as wetness-index, erosion index and roughness index.
- **Topography-based models** - are physical-based models involving specific topographic parameterizations that can be used to generate other landscape variables such as surface temperature, irradiance and other energy balance parameters presented in Kumar et al. (1997).

On the other hand, Dikau (1989, 1992) defined a hierarchical space into different levels of relief, such that features and landforms exist at scales representative of picorelief, nanorelief, microrelief, mesorelief, and macrorelief, up to megarelief.

The concept of elemental forms is only one such idea that could represent a basic level in hierarchical organization. The concepts of genesis and dynamics are two other properties that should be taken into consideration in complete landscape mapping. Minár (1995), as a representative of the Slovak geomorphic school, argued that the current nature of a geomorphologic systems dictates the existing organization of the topography. He presented the theory of elemental forms as morphometrically, morphogenetically and morphodynamically homogeneous basic terrain elements. He concluded that it is difficult to provide an exact expression of connection among these elementary form properties using a general geomorphologic equation, although the approach has potential and can be used for regional geomorphological mapping. It is interesting that despite all the definitions of elemental forms and/or hierarchy theory, there are no formal mathematical guidelines or rules established to define the organization structure (Brändli, 1996). In addition, computation has not kept pace with the development of theory to test and evaluate various concepts. Examples include indeterminate boundaries, spatial aggregation of terrain-form objects and the formulation of functional levels not adequately stated in theory.

Hughes (1991) defined aggregation as an object-oriented abstraction, in which a relationship among objects is represented by a higher level, composite or aggregated objects. Bishop et al. (2001) evaluated the cluster analysis technique to create higher-order landform objects based upon their attributes. The chosen approach proved to be useful only if the attributes are unique for different landforms. Consequently, they questioned the nature of relationships between object attributes to be used as a basis for spatial aggregation. Furthermore, they stated that an obstacle in accurate characterization of elemental forms is not associated with the concept of homogeneity, but it is related to ontological issues and the problem of defining the topology of elemental forms.

Such a topological model was developed by Falcidieno and Spagnuolo (1991). The model, however, can be tested and verified on large sets of real data, but the samples that the authors used are rather artificial, and do not exhibit the problem cases that are abundant in real data (Brändli, 1996). Clearly, more research is required to examine all aspects of hierarchy theory as applied to topography.

2.3 Glacier Mapping

Early Exploration

The first authentic description of glaciers appears in the writing of Münster (1544). The fact that glaciers are in motion was first noticed *en passant* by Josias Simler in 1574. These studies, however, remained unknown for over a century until Swiss J. J. Scheuchzer recorded his investigations in his Itinera Alpina (1705) in which he cites Simler's earlier observations (Seligman, 1949).

Europe and especially Switzerland originated the studies of alpine glaciers and continental ice-sheets. Recognized is the work "Essai sur la Constitutuion Géognostique des Pyrenées" by Jean de Charpentier, and especially well known is "Étude sur les Glaciers" by Jean Louis Rodolphe Agassiz who preceded a rather superior work by Charpentier by one year (Fairbridge, 1968).

In Karakoram and Northwest Himalaya Dainelli (1922) pioneered the observation of quaternary glaciation. He mapped and speculated about glacial effects down the Indus and northward into Hunza (Shroder, 1989a). On Nanga Parbat Mountain, beginning 1934, the German expedition attempted to climb the mountain and produced a detailed topographic 1:50, 000 map of Nanga Parbat. Its glaciological surveys provide the basis for all subsequent glaciological research in the region (Finsterwalder, 1935). Subsequent observations at the Raikot glacier were made by Troll (1938), Pillewizer (1956) and Gardner (1986) (Shroder, 1993).

Geomorphometry, GIS and Remote Sensing

A better understanding of glacier denudation, morphology and glacier mass balance can be obtained by glacier feature detection and mapping (Bishop et al., 2000b). Geomorphometry played an important role in defining mathematical features of terrain before the advent of GIS and remote sensing capabilities.

Morphometrical characterization of topography was developed by Gauss (1827) and by Maxwell (1870). Gauss (1827) created the basis of modern differential geometry of surfaces, which is a theory of surface geometrical forms described locally, that is, by curvatures. Maxwell (1870) developed the theory of "land surface and gravitational field", which considers the land surface for the whole Earth and its gravitational field. The problem with the theory is that it does not account for land surface boundaries. Speight (1973) wanted to solve this problem using the concept of regions which represented restricted land surface areal analysis.

Independently, Evans (1972) and Krcho (1973) studied local morphometric variables, such as profile, planimetric and profile curvatures that are absent in the theory of Gauss (1827). Curvature is an important parameter, because it depicts important information regarding the shape of an object resulting from surface processes (Mackay et al., 1992).

With the advent of geographic information systems (GIS) and digital elevation models (DEMs), morphometric parameters can be routinely generated and incorporated into an analysis. Wilson and Gallant (2000) provided an excellent overview of theoretical and mathematical techniques for extracting features for geomorphologic, hydrologic and biologic applications. Among the first GIS-based approaches to studying the Nanga Parbat massif were reported by Bishop et al. (1998b).

GIS technology coupled with new data from satellite sensors has generated new opportunities for advanced glaciological and geomorphological studies (Bishop et al., 2002). Launching of the weather satellite TIROS-1 in 1960 demonstrated that snow-covered areas could be delineated from space (Bishop et al., 1998a). Thus, remote sensing studies have added much to understanding alpine-glaciers and ice fields in numerous environments (e.g. Bayr et al. (1994); Hall et al. (1988, 1989); Williams et al. (1991) and Bishop et al. (1995, 1998a)). Nakawo et al. (1993) made one of the first remote sensing studies of a Himalayan debris-covered glacier in an attempt to improve estimates of surface ablation. With the use of multi-spectral satellite data combined with detailed field measurements, they were able to classify the ablation area of the Khumbu Glacier in Nepal, into snow, bare ice, and thin and thick debris. With the launch of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) in late 1999, the GLIMS (Global Land Ice Measurement from Space) Project was designed as an international project to ascertain the extent and condition of the world's glaciers (Bishop et al., 2000b).

Monitoring the cryosphere from space can produce valuable information about glacier mass balance, spatial extent, terminus location and glacier facies. Accurate mapping of glaciers can be problematic, however, because of difficulties in spectral variation, clouds, and differential illumination (Bishop et al., 2000b; Cao and Liu, 2001). Bishop et al. (2000b) examined various approaches to evaluate the feasibility for automated analysis of glaciers at Nanga Parbat. They utilized geomorphometric analysis to assist in glacier-extent mapping, spatial analysis to describe glaciers with geomorphic criteria, and pattern-recognition for mapping supraglacial features. Their results indicated that integration of the above approaches enables accurate characterization of debris-covered glaciers in high Asia.

Remote sensing and geomorphometric analysis of DEMs are also used to investigate the complexities of mountain geomorphology and topography (Bishop et al., 1998a,b, 1999; Chase, 1992; Koons, 1995). For example, ANN have been used for classifying supraglacial characteristics of alpine glaciers and to identify spectral patterns that are associated with the surface topography of glaciers (e.g.,Bishop et al., 1999). Considerable potential exists using artificial neural network (ANN) technology (Civco, 1993; Foody et al., 1995; Zhou and Civco, 1996).

Among the first to characterize and map glacial features and/or glacial versus non-glacial surfaces using hierarchy theory is the work by Bishop et al. (2001) and Bonk (2002). They presented a two-level hierarchical approach. This did not, however, accurately characterize the glacial surface, but their results did prove the inherent feasibility of the approach for glacier mapping.

Collectively, the literature demonstrates the need for further research into all aspects of landform mapping. Numerous issues associated with organization theory, scale, numerical techniques, computation and empirical validation need to be formalized and evaluated. This research will focus on the evaluation of morphometric parameters and the generation of elemental form objects.

Chapter 3

Study Area

Nanga Parbat mountain is perceived by many as a unique topographic, lithologic and structural feature (Seeber and Pêcher, 1998; Zeitler and Chamberlain, 1991). It is a knife-edged, east-west-trending ridge that stands out alone from the main Himalaya and Karakoram ranges in northern Pakistan (Bishop et al., 1998b). The great height of 8125 m, makes Nanga Parbat not only the ninth highest mountain in the world, but also a great challenge for mountaineers.

Nanga Parbat represents the generalized study area, but specifically, the Raikot Glacier located on the north side, and the Sachen Glacier on the eastern side are the focus of this work (figure 3.1). The Raikot and Sachen Glaciers were selected because they are fundamentally different in their character, which will allow for comparison of results. Raikot Glacier is a typical alpine-type glacier, with a continuous ice-stream from the accumulation area to the ablation area. Sachen Glacier, on the other hand, does not have its accumulation and ablation zones physically connected, and ice and snow avalanches are the only source of nourishment into its ablation area (Čverčková et al., 2004). In addition, Sachen Glacier belongs to the least efficient glaciers on the mountain, with its associated rock glaciers, versus Raikot Glacier, which is representative of the most active glaciers with rapid plug flow

(Shroder et al., 2000b). Lastly, the topographic position of these glaciers causes solar irradiance variations that have a significant impact on glacier dynamics. Sachen Glacier located on the eastern side, receives more solar radiation, which causes ablation at much higher elevations.

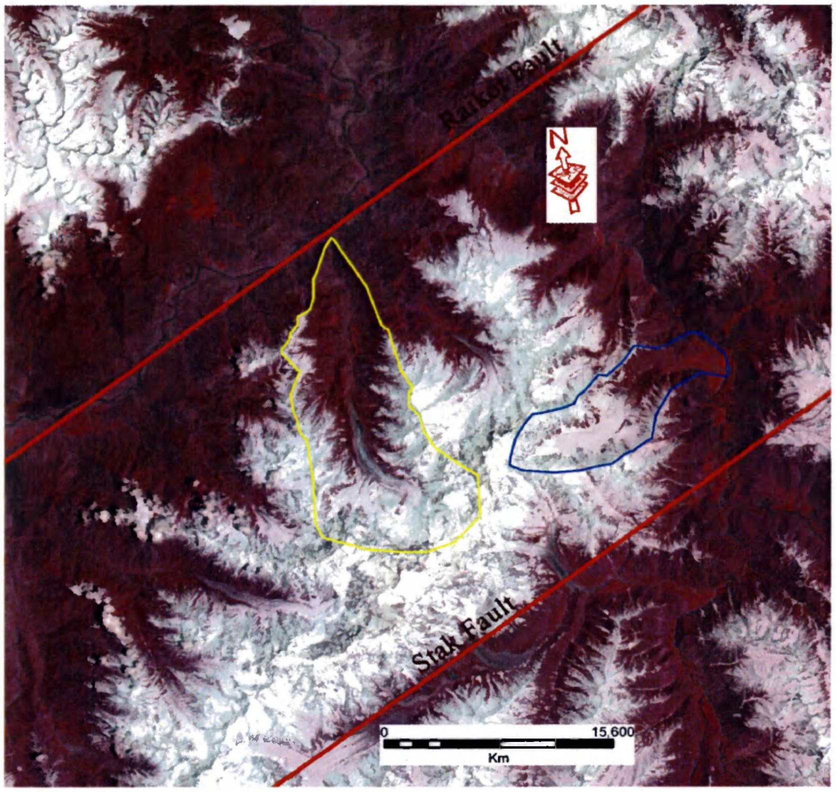


Figure 3.1: SPOT 3 ortho-rectified NIR image of Nanga Parbat. Raikot Basin (yellow line) and Sachen Basin (blue line) are depicted. Fault lines are diagrammatic.

3.1 Nanga Parbat

Evolution and Surface Processes

At about 120 Ma ago the convergence of the Indian and Asian continents started (Rolland, 2002). Following the continental collision of India with Asia ~ 50 Ma ago, the Indian plate continued to move north to force up the Hindu Kush and Himalaya chain from Afghanistan to Burma (Seeber and Pêcher, 1998). The Nanga Parbat pop-up structure was initiated at

$\sim$ 12 – 10 Ma, as a tectonic aneurysm caused by the rapid incision of the Indus River (Burbank et al., 1996; Shroder and Bishop, 2000a; Zeitler et al., 2001a; Zeilter et al. , 2001b). Rapid incision resulted in high surficial denudation rates, rapid uplift $\approx$ 10 mm yr^{-1}, and extreme relief with the steepest relief on the planet; a $\sim$ 7 km rise up on the north side of the mountain over a 21 km horizontal distance (figure 3.2), *c.* 6 km on the eastern side, and *c.* 5 on the south side. (Bishop and Shroder, 2000a; Zeitler, 1985).

Figure 3.2: Nanga Parbat, as seen from the north. Nearly 7000 meters of relief is visible between the summit and the Indus River at its base. Photograph by Anne Meltzer.

Besides river incision, other surficial processes also contributed to denudation of the massif, such as glaciation, floods and mass movements. The most typical mass movement processes that occur are slope failures that initiate the sediment-transfer cascade (Shroder and Bishop, 2000a). It has been concluded that major glaciation during the Pleistocene, as well as minor fluctuations during Holocene (table 3.1), increased the opportunity for undercutting of slopes (Cornwell and Hamidullah, 1992; Hewitt, 1964; Shroder, 1989a,b). The largest rockfalls and rockslides occur on all sides of the mountain in the Diamir, Rupal, Astor and Indus valleys. Some are associated with the peripheral faults. All types of mass movement are the main source of the thick debris cover on the glaciers radiating from the massif. The main slope failures include Tap, Doian, Mushkin rockslide, the well known catastrophic Liachar-Indus landslides, the Raikot-Biale debris avalanches and the Rupal alpine basins with debris fans (Shroder et al., 2000b).

Western Himalaya	**Nanga Parbat**	**Time**	**Dating Method**
Holocene			
Pasu II	Modern	20^{th} century (Ct.)	WS, D, G
Pasu I	Little Ice Age	Several Cts. ago to late 19^{th}Ct.	WS, D, G,^{14}C
Batura	Neoglacial	Early-Middle Holocene	G, WS, ^{10}Be, ^{14}C, IRSL
Pleistocene			
Ghulkin II	?Drang	34 – 38 ka	^{10}Be
Ghulkin I	?High Moraine?	47 ka	G, TL
Borit Jheel	High Moraine?	50 – 65 ka	G, TL, ^{3}He
Yunz	(Gorikot?)	139 ka	TL
Early Middle Glaciation	(Jalipur?)	*c.* 250 ka?	S
Shanoz-Bunthang		1.1 – 1.25Ma	G, S, PM

Table 3.1: Tentative glacial chronology during the Quaternary in the Western Himalaya and Nanga Parbat (after Derbyshire et al., 1984; Derbyshire, 1996; Shroder, 1993). Dating Methods: D - dendrochronology; G - geomorphic position; IRSL - infrared stimulated luminescence; PM - palaeomagnetic estimate; S - stratigraphic position; TL - thermoluminescence dating; WS - weathering and soil development; ^{14}C - radiocarbon dating; ^{10}Be and ^{3}He - cosmogenic nuclide dating.

Glaciers represent one of the most important geomorphic agents responsible for denudation of high mountain topography. At Nanga Parbat, glacier denudation is estimated at 4.6 - 6.9 mm yr^{-1} (Gardner and Jones, 1993). Nanga Parbat is extensively glacierized by 69 separate glaciers that cover an area of 302 km^2 with an ice volume of 25 km^3 (figure 3.1; 3.4) (Kick, 1980). Thus, glaciers play an important role in sediment transfer, and have very high supraglacial debris-load variability (Bishop et al., 1995, 1998a,b).

Morphometric description of the Nanga Parbat Massif

The hypsometry of Nanga Parbat (figure 3.3) reveals that around 69% of the landscape lies within the 3000 – 6000 m range (Bishop and Shroder, 2000a). Cumulatively, a very small percentage (4%) of land lies at an altitude higher than 6000 m (Bishop et al., 2002). The average elevation is *c.* 3600 m (Bishop and Shroder, 2000a).

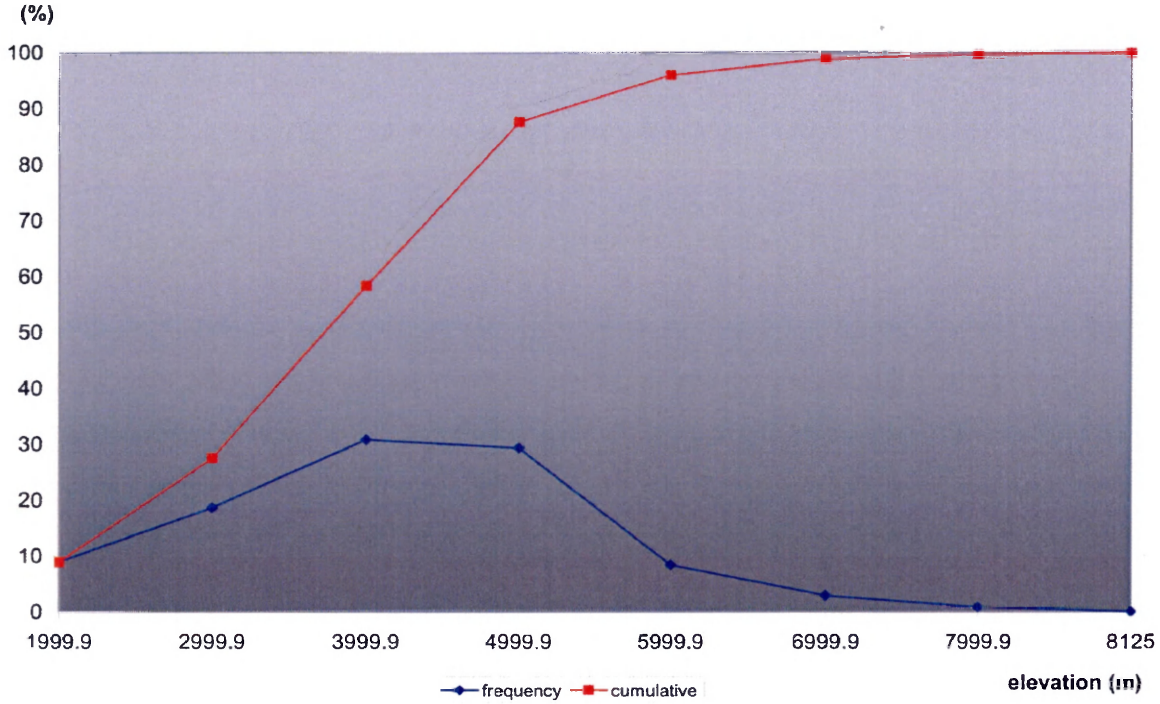


Figure 3.3: Altitude distribution of the landscape at Nanga Parbat (Bishop and Shroder, 2000a).

Modern glacierization is the most extensive on the north side of the massif, with the mean elevation of the glaciers at ~ 5140 m. On the south side, the mean glacial altitude is 4720 m, with ice reaching down to 3000 m (Bishop et al., 2002; Shroder and Bishop, 2000a). The altitude distribution statistics at Nanga Parbat reflect the dominance of a glacial landscape and the knife-edged ridge of the massif at high altitude. Figure 3.4 summarizes elevation characteristics of the massif.

Slope characteristics reveal valuable information about the effects of various geomorphic agents on the landscape; for example shallow slope angles are usually associated with broad flat valley floors with a typical U-shape, modified by glaciation and glacierization. The relationship between slope angles and altitude is not linear, and the maximum slope angles are high over all altitudes at the massif. Maximum mean slope angles ~ 45° are associated with the Raikot Fault Zone, slope failures and active river incision with typical V-shaped valleys at elevations ranging from 1500 - 2000 m. At intermediate altitudes from 3000 - 5000 m, minimum slope angles decrease as the result of erosion by warm-based glaciers and deposition of hummocky moraines (Bishop et al., 2000b). With increasing elevation mean slope angles again increase due to a decrease in temperature, cold-based, non-erosive ice, and the dominance of mass movement. The mean slope angle over Nanga Parbat is *c.* 32° (Bishop and Shroder, 2000a).

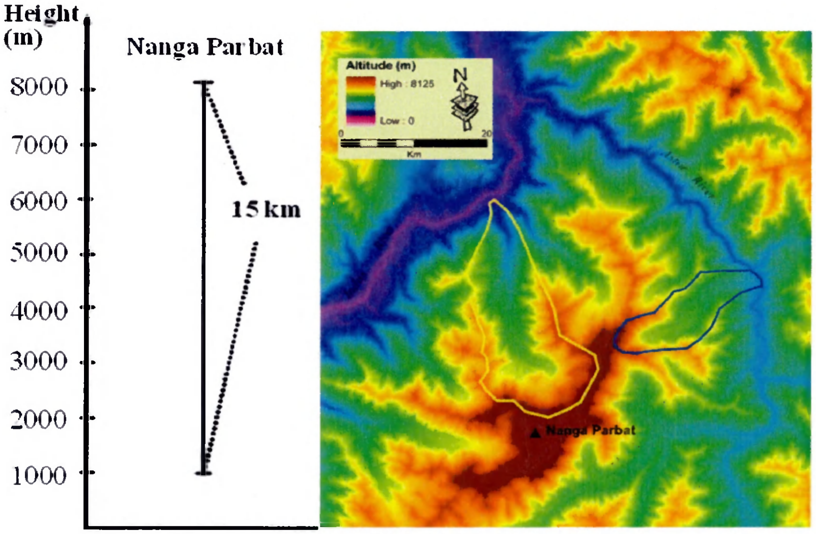


Figure 3.4: Digital elevation model (DEM) of Nanga Parbat, depicting Raikot Basin (yellow line) and Sachen Basin (blue line). Graph (on the left) summarizing the basic elevation characteristics.

Tectonics and Geology

Many scientists have studied faults of the Nanga Parbat massif, specifically the Raikot and Stak faults (figure 3.1) (Butler and Prior, 1988; Lawrence and Ghauri, 1983; Madin, 1986; Searle, 1991). They found that the recent rapid uplift has been caused by the faults. Further, much of the recent uplift of Nanga Parbat, or more than 10 km of exhumation in the last 10 Ma, of which over 6 km has occurred in the last 1.3 Ma (Chamberlain et al., 1989; Zeitler, 1985), has been a result of thrust culmination on the Raikot Fault-Liachar Thrust (Searle, 1991).

Two new major shear zones have been identified by Schneider et al. (1999): the north- and west-dipping Rupal shear, and the southeast-to east-dipping Diamir shear. The two shear zones represent a conjugate pair of reverse faults that defines a crustal-scale pop-up structure. The pop-up structure thus provides a straightforward mechanism to accommodate the major upward displacement of Nanga Parbat, along with very rapid cooling, young plutonism, and deeply exposed basement. Further, they suggest that the Nanga Parbat pop-up structure initiated *c.* 10 Ma on the basis of crystallization ages of granites, and the mica cooling ages located adjacent to the principal bounding shear zones (e.g. Schneider et al., 1997, 1999a,b).

Nanga Parbat has been also recognized as an unusual portion of the crust that has areas of exceptionally young metamorphic and igneous rocks (Shroder and Bishop, 2000a). Three main geologic units have been identified from structurally lowest to highest:

- *The Shengus Gneisses* - fine-grained and finely laminated with amphibolite-grade pelitic and psammitic gneisses and subordinate amphibolites and calc-silicate gneisses. The present minimum thickness of the unit is 5 km. The protolith of the Shengus Gneiss was probably shale, marl, arkosic sandstone, and limestone (Madin et al., 1989).

- *The Iskere Gneisses* - is predominantly coarse-grained, coarsely layered amphibolite-grade biotite gneiss, with subordinate biotite schist, amphibolite, and calc-silicate gneiss with thickness at least 8 km, but no complete section exists. The protolith of the Iskere Gneiss is interpreted as intermediate-composition plutonic rocks intruded into a sequence of arkosic and greywacke sandstones with minor marl and limestone (Madin et al., 1989).

- *The Haramosh Schist* - is a unit of medium to coarse-grained amphibolite-grade biotite schist and gneiss, with marble, calc-silicate gneiss, and subordinate amphibolite. The various lithologies occur in layers that range from 1.0 cm to 1.0 m thick. Although the range of lithologies and mineralogy is the same as that of the Iskere Gneiss, the two units can be distinguished by the relative lack of coarse biotite orthogneiss in the Haramosh Schist. The minimum measured thickness of the unit is 2.5 km, but as much as 10 km may be exposed on the inaccessible north face of Haramosh massif. The protolith of the Haramosh Schist is interpreted as a sequence of sediments similar to the sedimentary component of the Iskere Gneiss (Madin et al., 1989).

Climate

The great height of Nanga Parbat serves as a climatic divide between the continental air masses of cold and arid central Asia and the monsoonal maritime air mass of the Arabian Sea, leaving various regions of the massif in rainshadow. In general, the southeast slopes are affected by northwest monsoon winds, leaving the southwest and northwest slopes in rainshadow (Scott, 1992). Further, climatic gradients represent strong control over the denudation processes on Nanga Parbat (Hewitt, 1993).

Local microclimate varies considerably with altitude, aspect and local relief. The valley floors have very dry, near-desert conditions with mean annual precipitation of less than 200 mm (Scott, 1992), versus on the peaks where precipitation can exceed 2000 mm (Gardner, 1986). Above $\sim$ 5000 m, precipitation falls as snow (Bishop et al., 2002). Maximum summer temperatures are up to $50°C$ (Gardner, 1986). Westerly winter storms also strongly impact the mountain. Precipitation is less than 120 mm yr^1 at altitudes below 2500 m, but rises to more than 8000 mm yr^1 at elevations above 4500 m (Kick, 1980).

3.1.1 Raikot Glacier

The dynamic nature of the 14-km-long Raikot Glacier (figure 3.5) produces significant glacier topographic relief (Bishop et al., 2001). It is located on the steep north side of the mountain, and it decends into a series of tumbled ice cliffs at an angle of about 51° at an altitude of 5000 m (Shroder, 1989a). Because of this upper steep gradient, the upper portions of the glacier exhibit very high ice-flow velocities (Bishop et al., 2001). From the elevation of 5000 m to its terminus at $\sim$ 3175 m, the glacier exhibits a more gentle slope of about 9° (Shroder et al., 2000b).

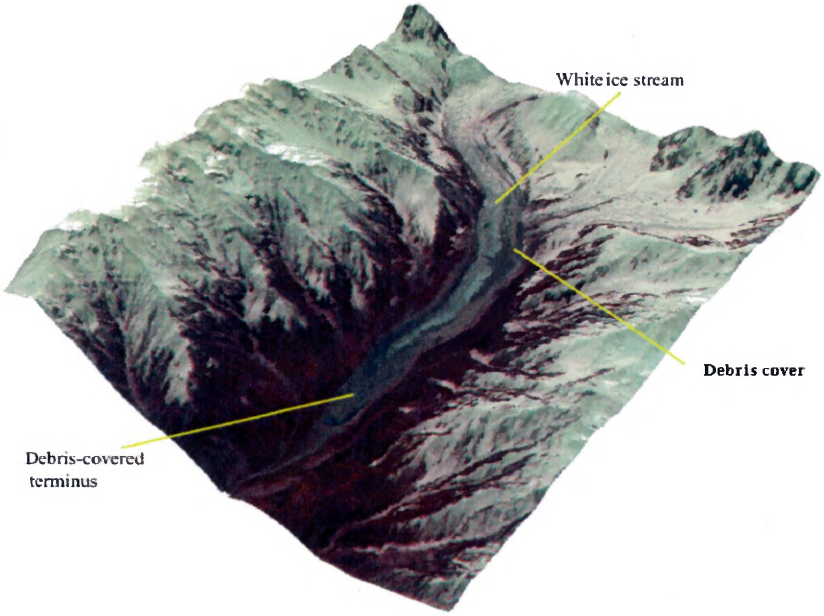


Figure 3.5: 3D visualization of SPOT 3 ortho-rectified NIR image of Raikot Basin.

The Raikot Glacier has an area of 32 km^2 (table 3.2) (Shroder et al., 2000b). Its equilibrium line altitude (ELA) lies at $\sim$ 4800 m above sea level (asl) (Owen et al., 2003), and exhibits an accumulation/ablation area ratio of 0.60 (Gardner and Jones, 1993). Daily ice velocities range from 12 to 39 cm per day (Shroder et al., 2000b) with erosion rates $\sim$ 5 mm per year in the 1980's (Gardner and Jones, 1993). The position of the Raikot basin on the north side of Nanga Parbat mountain creates very good conditions for glacier growth to very high as well as very low elevations due to lower solar radiation on northern mountain slopes. The upper parts of the watershed extend to 7845 m, and the lowest areas reach 1125 m. It follows, that the relief of the Raikot watershed is 6720 m (see figure 3.7) (Bishop et al., 2002).

Basin	Planimetric area (km^2)	Surface area (km^2)	Perimeter (m)
Raikot	174.1	220.7	77,110.9
Sachen	57.7	71.6	45,578.0

Table 3.2: Comparison of Raikot and Sachen basin statistics (Bishop et al., 2002)

The maximum basin slope angles are associated with the lowest altitudes, where the basin reaches the Indus Valley around 1700 m, with mean slope angles up to 45°. In the middle parts of the Raikot Glacier mean slope angles decrease, as a result of active glacial processes that cause the creation of U-shaped valleys. Mean slope angles continue to rise with increasing elevation and reach the maximum $\sim$ 50° near the summit, at a small plateau called the Silver Saddle.

The terminus of the Raikot Glacier, however, exhibits extensive debris cover up to 5 m in thickness (Bishop et al., 2001). The glacier exhibits efficient sediment transfer mechanisms, whereby moraines are eroded away and transported to the fluvial system by glacial meltwater and catastrophic flooding (Bishop et al., 1999).

3.1.2 Sachen Glacier

The Sachen Glacier (figure 3.6), is $\sim$ 8 km in length, with the upper parts of the terminus at an elevation of *c.* 3500 m. The Sachen Glacier is a medium-size glacier on the massif (see table 3.2). Wide and flat accumulation zones are at elevations above 5000 m. The lowest elevation of the Sachen basin is at 2127 m and the watershed exhibits 4268 m of relief (see figure 3.7).

The Sachen Glacier exhibits a low gradient, especially in its wide ablation area at *c.* 5°, has lower ice velocities and produces limited meltwater that cause a very inefficient transfer mechanism for the removal of debris. This results in huge moraines at Rama in its forefield and a pronounced digitate terminus with four lobes. The lobes were formed from breakout through lateral and end moraines as rock glaciers with pronounced transverse ridges, furrows, and steep fronts at the angle of repose (Bishop et al., 1999; Bishop and Shroder, 2000a; Shroder et al., 2000b).

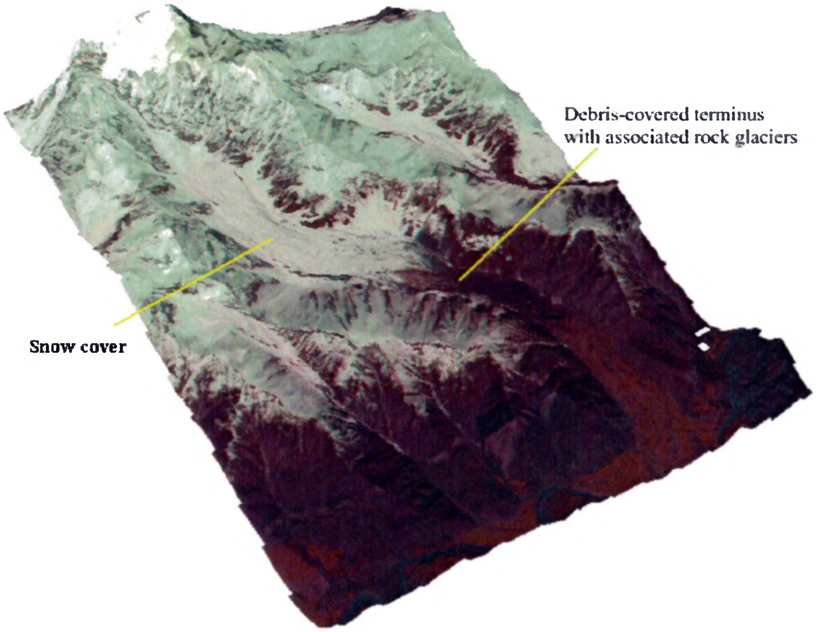


Figure 3.6: 3D visualization of SPOT 3 ortho-rectified NIR image of Sachen Basin.

Kick (1962) was the first to note no change in the movement of the Sachen Glacier since first described in the 19^{th} ct. It is presumed the Sachen Glacier is in the process of formation into a rock glacier as the glacier exhibits poor sediment transfer to meltwater and very low ice velocity, which decreases gradually downward into the mass, and forms typical transverse ridges and furrows. Low ice velocity and sediment transfer favors formation of rock glaciers (Shroder et al., 2000b).

Low sediment transfer efficiency, downwasting and low ice velocity of the Sachen Glacier results from having very little cold-based ice and plentiful warm-based ice. No presence of firn-fields contributes to formation of rock glaciers at the glacier. Sachen Glacier has a very small meltwater discharge with rare outburst floods that causes accumulation of debris from unvegetated slopes and thick supraglacial debris. In addition, the Sachen Glacier has no trunk river at the terminus and very static, small drainage portals. It is still unknown whether the internal ice of the rock glaciers that make up part of the Sachen Glacier is glacier ice or permafrost.

Four rock glaciers have been identified at Sachen Glacier. The West Sango rock-glacier lobe has a classic rock-glacier form, with a large number of transverse ridges and furrows across it. It has been observed that the lobe broke through the lateral moraine, and has deflated, probably because of reduced avalanche nourishment or recent climate warming. The East Sango lobe is not that well developed, and actually it has been overrun by large amount of debris and ice resembling a kinematic wave. A third rock glacier was developed across from the Gurikal icefall at an altitude of *c.* 3800 m. The last rock glacier evolved above Sango lake, and it has been observed that since 1936 the feature had ablated a great amount with no ice left on its surface and instead only a debris cover occurs now (Shroder et al., 2000b).

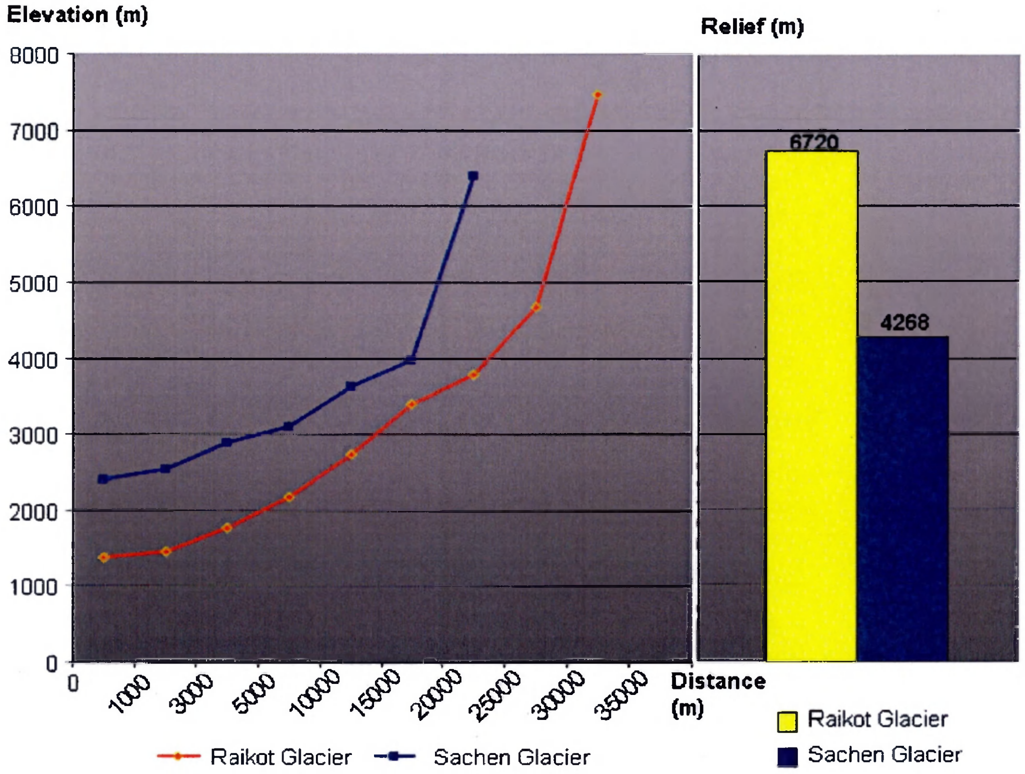


Figure 3.7: Raikot and Sachen watersheds comparison of elevation characteristics (Bishop et al., 2002) The graph on left shows elevation curves of the two watersheds. The minimum elevation of Raikot Basin (red line) is at 1125 m and its maximum is at 7845 m. The lowest areas of Sachen watershed (blue line) reach 2127 m and the upper parts extend to 6395 m. The graph on right plots relief characteristics for both watersheds. Raikot Basin (yellow) exhibits 6728 m of relief and Sachen basin (blue) 4268 m.

Chapter 4

Methodology

Application of hierarchy theory requires a rigorous methodological design that will define topographic elements and incorporate a scale-dependent hierarchical organization of elements. Such a methodological framework has been partly developed to test the potential of using topographic information derived from a digital elevation model (figure 4.1) and includes an object-oriented analysis approach (figure 4.2) for geomorphological mapping of alpine glaciers.

4.1 Digital Elevation Model and Data Preprocessing

Surface processes play a fundamental role in dictating the nature of the Earth's surface. Consequently, the topography contains information about the polygenetic evolution of the landscape. An important objective is to be able to extract information about the landscape from digital elevation models, although point, spatial and topological information and relationships must be used (Wilson and Gallant, 2000).

With the emergence of new imaging sensors such as SPOT and ASTER, digital elevation models can be routinely generated. The DEM used in this analysis comes from Bishop et al. (1998b). It was generated from a SPOT 3 panchromatic stereo-pair acquired on 27 and 28

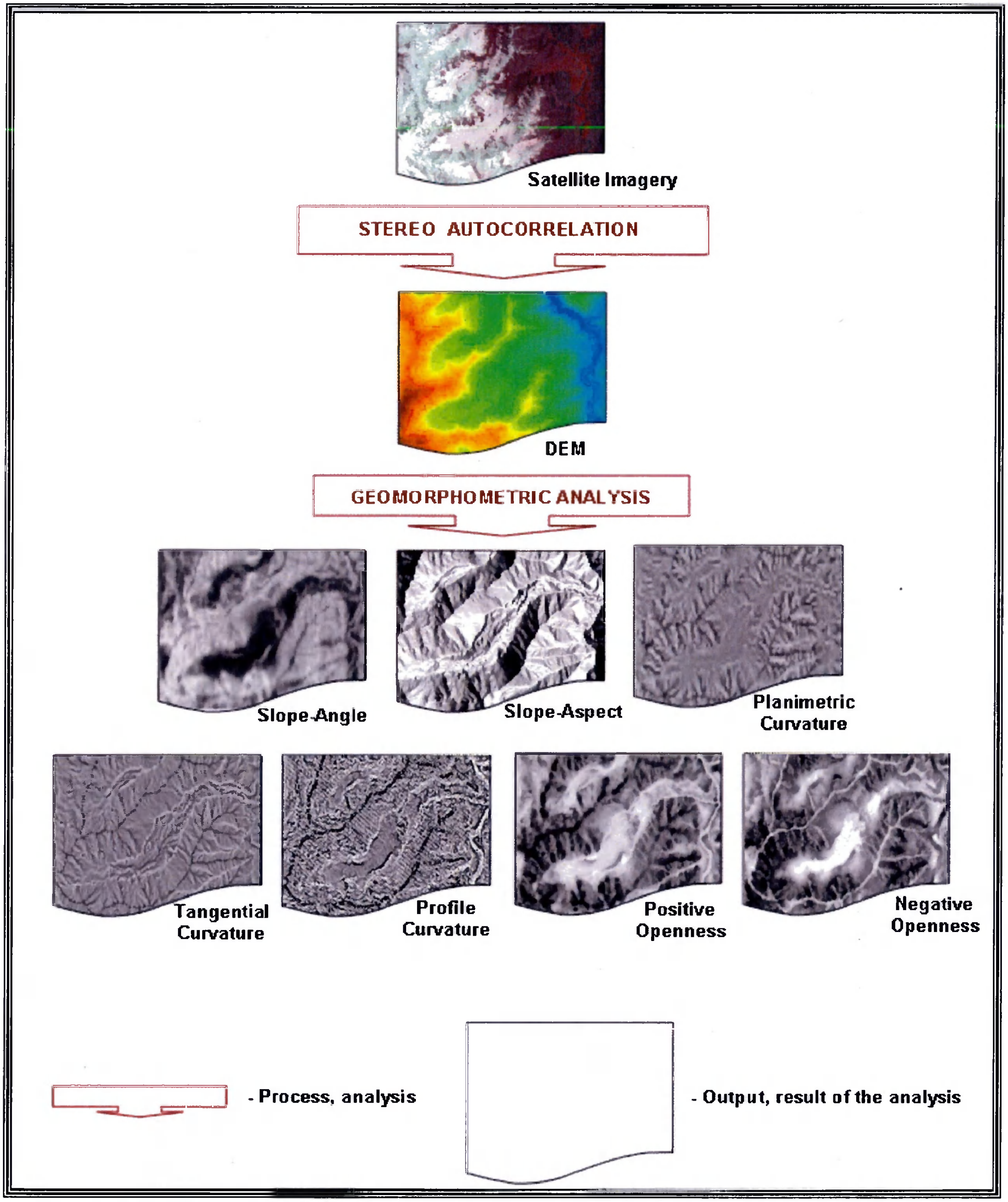


Figure 4.1: Methodological design (part I.) Geomorphometric analysis is applied to DEM to produce morphometric properties.

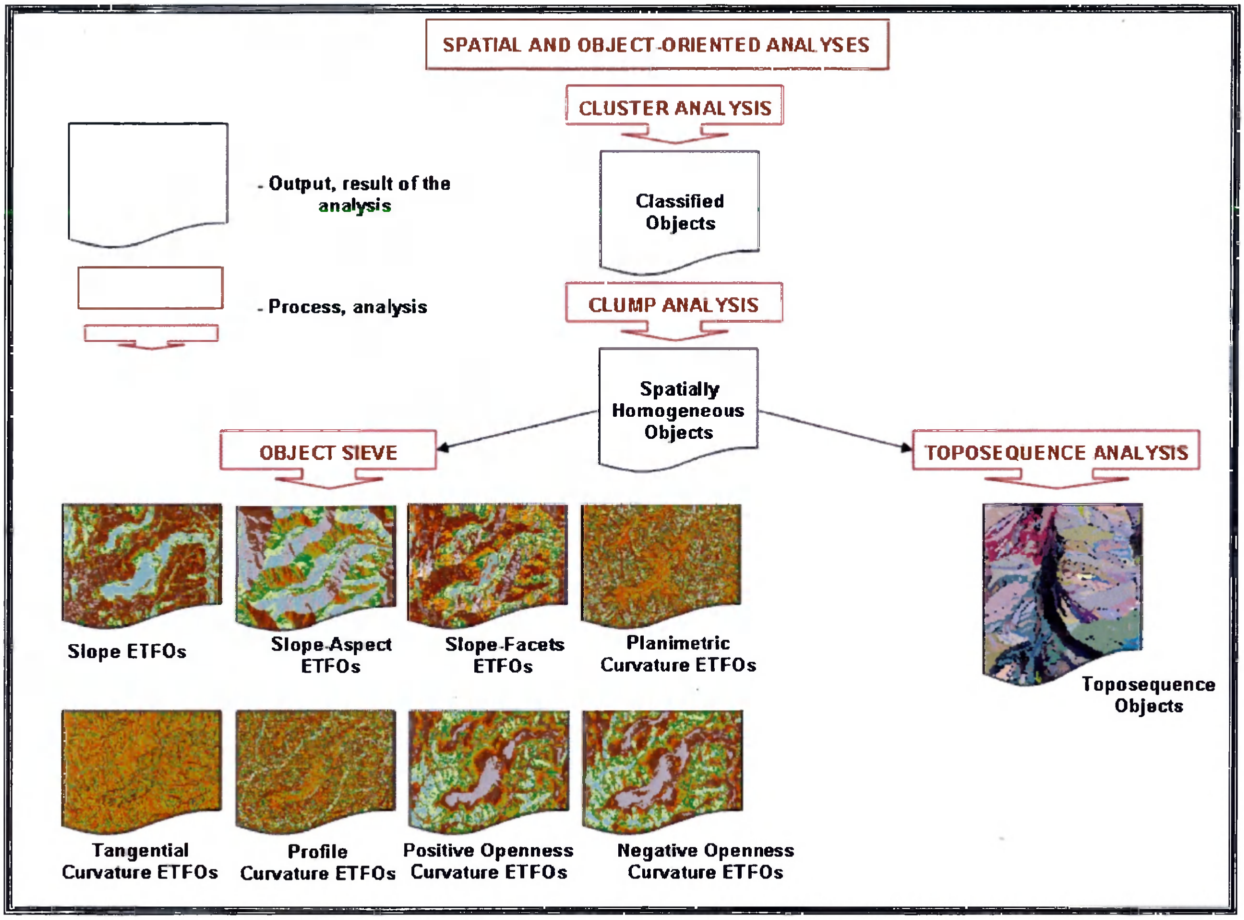


Figure 4.2: Methodological design (part II.) The second part of methodological design consist of series of analysis where the final product is focused on producing sieved objects of the first level in hierarchy (ETFOs) and toposequence objects.

October 1996.

DEM preprocessing was used to reduce high-frequency variation in altitude and enhance the lower-frequency information content. In order to obtain a high quality DEM at high altitudes, morphometric information from a relatively large scale topographic map was used to account for problem areas caused by spectral saturation. Correlation failures result from highly reflective features, such as snow and ice that reduce spectral variation. A 1:50,000 scale map was used, although spectral saturation was confined to the highest portions of the massif and these areas do not influence the analysis or mapping results. This resulted in a DEM with a spatial resolution of 20 m and an absolute vertical accuracy of ±8 - 12 m. The

DEM covers a radius of $\sim$ 30 km centered over Chongra Peak on the Nanga Parbat massif (Bishop et al., 1998b, 2003).

4.2 Geomorphometric Analysis

The Earth's surface can be considered a static spatial surface over a selected time interval $\Delta\, t_i$ in a Cartesian coordinate system O,x,y,z described as a function of two variables (a function without t) that can be expressed in the general form:

$$z = f(x, y), \tag{4.2.1}$$

where z is the altitude ([m]), and x and y are the two-dimensional spatial coordinates (Krcho, 2001).

Because the particular analytic form of equation 4.2.1 is actually not known, the unknown function in a DEM is usually substituted by an interpolation function which can take on numerous mathematical properties. With spatial interpolation it is possible to estimate the distribution of altitudes given that an adequate sample has been obtained. Numerous approaches to spatial interpolation exist and each algorithm produces unique results.

Every topographic surface has unique properties about the spatial variability of z. Following the work of Krcho (1973, 1991, 2001), we can define the first partial derivatives of the surface in the form:

$$z_x = \frac{\partial z}{\partial x}, \quad z_y = \frac{\partial z}{\partial y}, \tag{4.2.2}$$

such that z_x and z_y are the first derivatives.

The second partial derivatives (the partial derivatives of second order) of the function (4.2.1) are in the form:

$$z_{xx} = \frac{\partial^2 z}{\partial x^2}, \quad z_{yy} = \frac{\partial^2 z}{\partial y^2}, \quad z_{xy} = \frac{\partial^2 z}{\partial x \partial y}. \tag{4.2.3}$$

4.2.1 First-order Morphometric Parameters

The altitude field can be used to estimate the morphometric parameters, which are the first- and second-order derivatives of the surface. These derivatives measure the rate at which altitude changes in response to changes in the x and y direction. Using the first-order derivative (equation 4.2.2), slope-angle (β) and slope-azimuth (ϕ) of the terrain can be computed. First derivatives are further used for computation of the second-order derivatives (equation 4.2.3), that describe the rate of change of the first derivative in the x and y directions, or the curvature in those directions. The variable z_{xy} represents the second derivative that describes the rate of change of the first derivative in the x and y direction, or the twisting of the surface (Wilson and Gallant, 2000).

4.2.1.1 Slope Angle (β) and size of gradient ($|grad\, z|$)

The slope angle can be defined at at every point and represents the angle between a horizontal plane and the plane connecting two points by the following equation (Minár, 1998):

$$\beta = \arctan \sqrt{z_x^2 + z_y^2}. \tag{4.2.4}$$

Slope angle can be defined as a vector with not only a direction but a quantity or gradient ($|grad\, z|$), defined as:

$$|grad\, z| = \frac{F_1}{F_2} = \tan \beta = \sqrt{z_x^2 + z_y^2}. \tag{4.2.5}$$

where F_1 is a normal vector, perpendicular to surface, and F_2 is a vector for a given point parallel with the surface. F_1 and F_2 are gravitational vectors that approximately point to the center of the Earth. Their size depends on the value of the slope-angle, and they are determined by the intensity of the Earth's gravitational field, which can be expressed as:

$$F = mg. \tag{4.2.6}$$

where m is the weight of an particle and g is the gravitational acceleration for a given point on the Earth's surface that is a function of altitude and latitude. The value of the gradient determines the velocity of moving material, and its spatial variability dictates acceleration or deceleration.

4.2.1.2 Slope-Aspect of the Terrain (ϕ)

Slope-azimuth ϕ, which is commonly referred to as slope-aspect, is the cardinal direction or orientation angle of the slope. Its value ranges from 0 to 360 degrees. It is computed as:

$$\phi = \arctan \frac{z_y}{z_x}. \tag{4.2.7}$$

Aspect values can be converted to transformed sine and cosine values to represent linear east-west and north-south orientation variation. Sine values range from -1 (west direction) to 1 (east direction), while cosine values range from -1 (south direction) to 1 (north direction). The linearization of slope-aspect is demonstrated in figure 4.3.

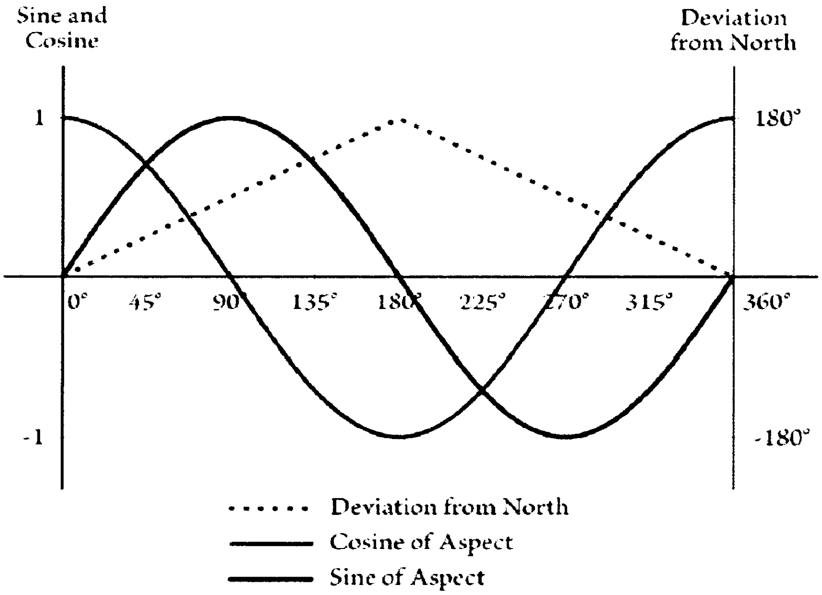


Figure 4.3: Transformations of aspect values (Jenness, 2006).

4.2.1.3 Profile Curvature (K_p)

Profile curvature is the degree of concavity or convexity of a surface in the vertical plane of a flow line (figure 4.4). Flow lines are imaginary lines on the terrain oriented in the direction of maximum slope (Minár, 1998; Mitašová and Hofierka, 1993). The curvature of a flow line in the direction normal to the Earth's surface can be defined as follows (Krcho, 2001):

$$K_p = \frac{z_{xx} z_x^2 + 2 z_{xy} z_x z_y + z_{yy} z_y^2}{(z_x^2 + z_y^2)\sqrt{(1 + z_x^2 + z_y^2)^3}}. \tag{4.2.8}$$

As was mentioned earlier, the gravitational influence F at the Earth's surface can be represented as $\tan(\beta) = |gradz|$, respectively. The importance of utilizing profile curvature is that it reflects the change in slope-angle along the flow direction and thus controls the change of velocity of mass flowing down the slope (Minár, 1998; Mitašová and Hofierka, 1993).

4.2.1.4 Planimetric Curvature (K_c)

Planimetric curvature is the degree of concavity or convexity of the surface, in the horizontal plane, in the direction perpendicular to the direction of steepest slope (figure 4.4). It reflects change in slope-azimuth angle and influences the divergence ($K_c < 0$, concave form in the direction of contours) and convergence ($K_c > 0$, convex form in the direction of contours) of water flow (Mitašová and Hofierka, 1993). It can be expressed as follows (Krcho, 2001):

$$K_c = \frac{z_{xx} z_y^2 - 2 z_{xy} z_x z_y + z_{yy} z_x^2}{\sqrt{(z_x^2 + z_y^2)^3}}. \tag{4.2.9}$$

4.2.1.5 Tangential Curvature (K_t)

Mitašová and Hofierka (1993) have suggested that tangential curvature (K_t) (figure 4.4) is more appropriate than planimetric curvature for studying flow convergence and divergence because it does not take on extremely large values when slope angles are small. It can be defined as the curvature of the normal plane in a direction of tangent to the contour line, which is perpendicular to the gradient. It can be defined as follows (Krcho, 2001):

$$K_t = \frac{z_{xx}z_y^2 - 2z_{xy}z_xz_y + z_{yy}z_x^2}{(z_x^2 + z_y^2)\sqrt{(1 + z_x^2 + z_y^2)}}. \tag{4.2.10}$$

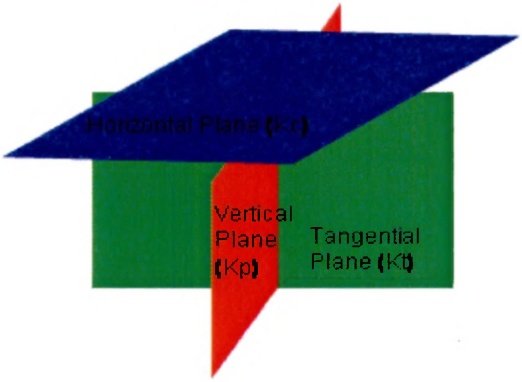


Figure 4.4: Schematic visualization of vertical, horizontal and tangential planes.

4.2.1.6 Scale-Dependent Curvature Analysis

Yokoyama et al. (2002) developed a relatively new image-processing technique that generates an angular measure of surface form that they called "Openness". It characterizes the topographic dominance or enclosure of any location on an irregular surface represented by a DEM. The measure incorporates the terrain line-of-sight (viewshed) principle and is calculated from zenith and nadir angles along eight DEM azimuths (0°, 45°, 90°...315°) (figure 4.5). Openness is expressed in two modes. Positive openness ϕ_L, or "above ground", emphasizes convex features of topography (figure 4.6). Its negative counterpart, ”below-ground” openness ψ_L emphasizes concave features (figure 4.6)(Yokoyama et al., 2002).

The metric can be computed for different values of L, to emphasize fine- or coarse-scale features. In other words, the metric is scale-dependent in how it characterizes surface curvature.

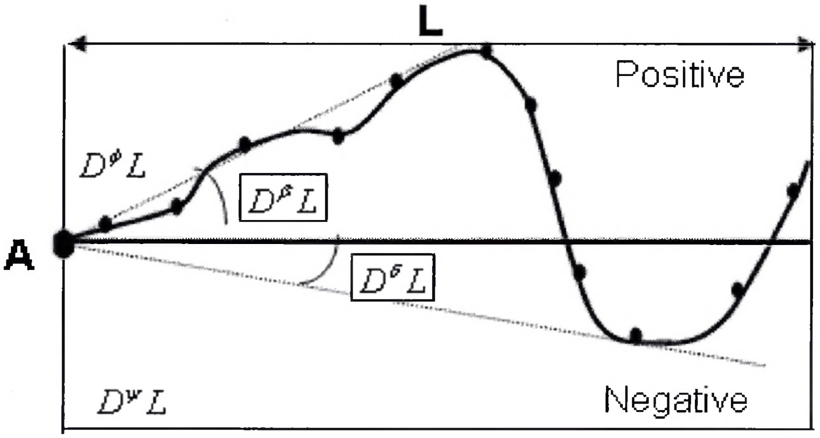


Figure 4.5: Surface openness defined in terms of zenith and nadir angles. Zenith angle $D\phi_L$ or $(90 - D^{\beta}L)$, and nadir angle $D\psi_L$ or $(90 + D^{\delta}L)$, calculated along one of eight azimuths D within L. L is radial limit of calculation for chosen point on DEM. Dots are height along terrain profile. Positive openness is the mean value of $D\phi_L$; negative openness is the mean value of $D\psi_L$. Elevation angles $D^{\beta}L$ and $D^{\delta}L$ can be either positive or negative, depending on the character of the topography around the central point A (Yokoyama et al., 2002).

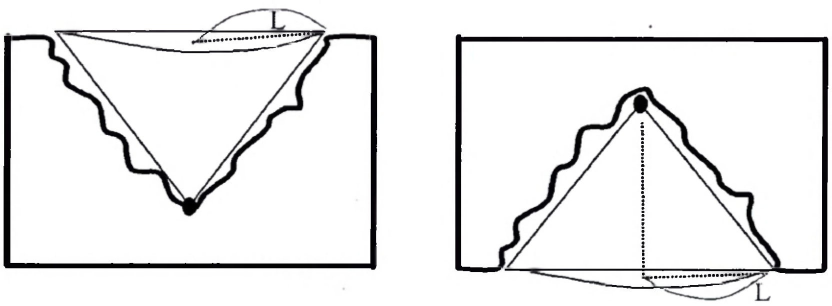


Figure 4.6: Positive (left) and negative (right) openness shown schematically for values $< 90°$. The heavy irregular line is terrain surface; L is the radial limit of calculation for the chosen point (large dot) on the DEM (Yokoyama et al., 2002).

4.3 Elementary Terrain Form Objects

Delineation of elementary terrain form-objects (ETFOs) on the basis of homogeneous morphometric attributes is a first step towards hierarchically characterizing alpine glaciers. For each morphometric parameter an unsupervised classification method using the ISODATA "Iterative Self-Organizing Data Analysis Technique" clustering algorithm was chosen as an aggregating technique. The method groups grid cells based upon the concept of statistical separability using a euclidean distance measure. Consequently, this fulfills the requirement of homogeneity. Through experimentation an appropriate number of cluster classes was chosen for each morphometric parameter.

Bishop et al. (2001) evaluated the previous approach and indicated that morphometric parameters should be combined to generate initial objects. Therefore, various combinations of slope, slope-azimuth, and curvature were utilized and evaluated to generate form-objects. Specifically, slope-facet objects were also generated. In order to generate meaningful form-objects, a series of spatial analysis routines had to be utilized.

4.3.1 Spatial Clumping

The initial aggregated results were submitted to a clumping algorithm. Spatial clumping assigns a unique category value to each localized cluster or clump that exhibits a contiguous cell category value (figure 4.7). This procedure is done for each initial classification, which results in identifying thousands of ETFOs. This is required so that each form-object is uniquely identified thereby permitting object-oriented analysis.

4.3.2 Spatial Sieving

The results from clumping indicated that many clumps or objects are the result of noise in the DEM. To rectify this, spatial sieving was used to filter out form-objects that

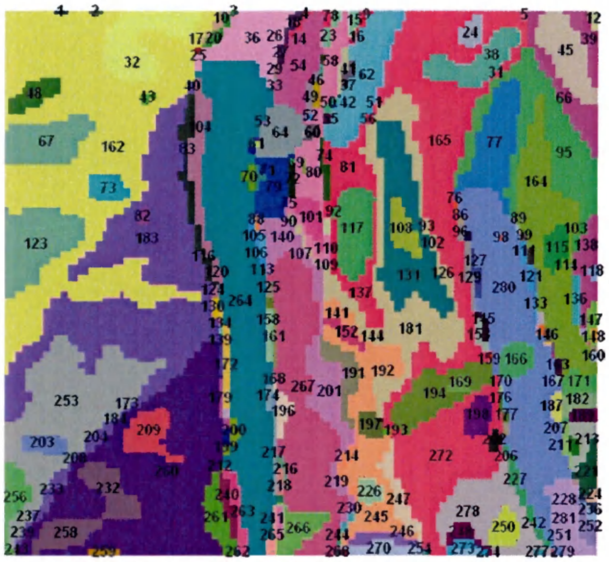


Figure 4.7: Clumping algorithm applied to slope-aspect ETFOs. The colors depict the form-objects and the numbers represent their clump identification value.

were smaller that a minimum specified size (two pixels). The sieve technique identifies form-objects smaller than the threshold and examines the neighborhood form objects. It then assigns neighboring values to the pixels of the form-object in question based upon a dominance rule (figure 4.8).

The sieve technique works very well when the pixels are surrounded by only one neighboring value. There is a dilemma when the pixels are surrounded by more than one neighboring value although the rule of dominance dictates that the form-object in question will be assigned the value of the most dominant neighboring form-object (figure 4.9). In this way, form-objects are made more homogeneous and error is removed from the analysis.

4.4 Object-Oriented Analysis

One research objective was to investigate the utility of object-oriented analysis for mapping of alpine glaciers. This approach involves computing the inherent attributes of each ETFO to support aggregation at the next level of the hierarchy (figure 4.2). It is important to

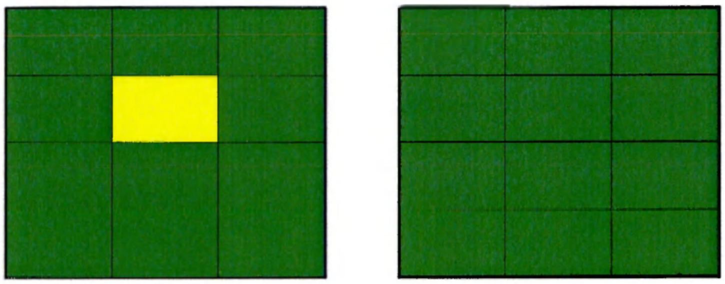


Figure 4.8: Elimination of single or two-pixel form-objects by assigning neighboring form-object identification values to the small form-object.

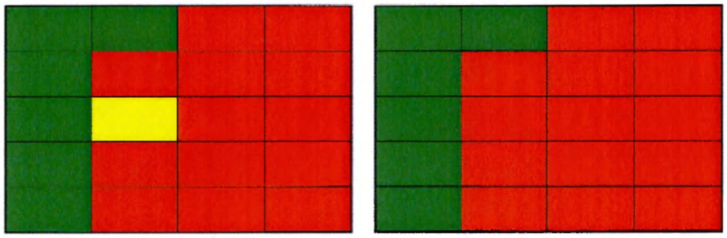
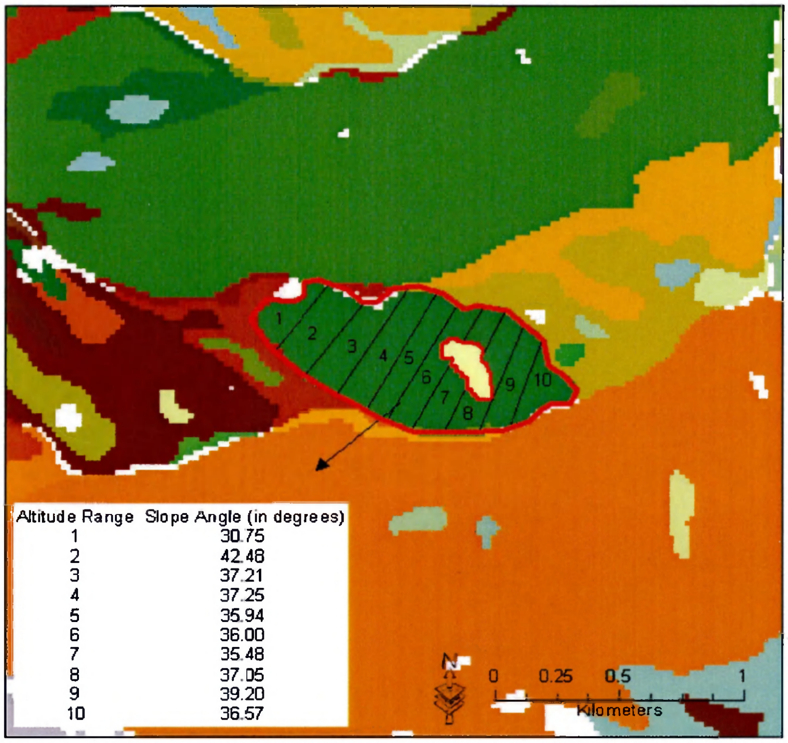


Figure 4.9: Multiple form-object boundary condition. The single pixel form object will be assigned the red-colored form-object identification value.

consider and understand the complexity of the topography that can be represented by various geometric and contextual metrics. That is why the object-oriented approach was utilized to generate toposequence information

4.4.1 Toposequence Information

Toposequence information represents variation of a topographic parameter across altitude. Consequently, toposequence information represents a two variable function. For example, landscape hypsometry is a toposequence function. In this work a toposequence function was generated for each slope-aspect object. The first part of the analysis involved the generation of slope-aspect objects as defined earlier. The second part of the analysis involved the computation of the slope-altitude function, within each slope-aspect object. The relief within each object was divided into ten relative altitude ranges, and the average slope-angle was computed for each altitude range. The procedure resulted in 10 altitude ranges within each slope-aspect object (figure 4.10). Slope-aspect objects of smaller size that did permit the computation of 10 relative altitude bins were not included in the analysis.



Altitude Range	Slope Angle (in degrees)
1	30.75
2	42.48
3	37.21
4	37.25
5	35.94
6	36.00
7	35.48
8	37.05
9	39.20
10	36.57

Figure 4.10: A schematic division of slope-aspect objects into 10 altitude ranges and their slope-angle values.

Chapter 5

Results

5.1 Morphometric Analysis

Visual examination of morphometric parameters for the Raikot and Sachen Glaciers show that variation in the magnitude of some parameters are highly correlated with landscape and glacier features. Figures 5.1, and 5.2 show slope-angle variations for Raikot and Sachen Glaciers that depict steep slope-angles associated with valley walls, lateral moraines and glacier edges, and relatively low slope-angles associated with the glacier surface. Similar results were obtained from Bishop et al. (1998b), Bishop and Shroder (2000a) and Bishop et al. (2001) and low slope-angles are the result of dynamic glacier processes that erode the landscape and redistribute sediment. Glaciers are active erosion agents and therefore modify the hypsometry compared to surrounding terrain, which is more resistant to change and exhibits less effective erosional agents. The slope-angle parameter effectively delineates glacier-modified topography from non-glacial very well, although some glaciated terrain still exhibits relatively high slope-angles. Portions of ablation valleys, and the areas where they meet steep surrounding walls can be delineated. There are, however, discrepancies using this metric in determining the glacier surface from the ablation valleys, moraines, and outwash plain. In addition, the glacier boundaries in the terminus region cannot be effectively delineated using the slope-angle metric.

The slope-aspect parameter (figures 5.3, and 5.4) highlights some glacier boundaries very well, as there is a significant directional difference where the glacier flows perpendicular to steep valley walls. This is more the case with the Raikot Glacier compared to the Sachen Glacier. Sine and cosine transformations of slope-aspect (figures 5.5, 5.6, 5.7, and 5.8) depict this pattern reasonably well. This indicates that the slope-aspect parameter is important in mapping the structural characteristics of the topography, although it cannot be used alone to delineate debris-covered glaciers. In addition, slope-aspect variations depict lateral and medial moraines and other supraglacial characteristics. Figure 5.9 depicts sharp changes in slope-aspect that does highlight a relatively large portion of the boundary of the Raikot Glacier in the ablation area.

Profile curvature does an excellent job in depicting the boundary of the Raikot and Sachen glaciers due to profile convexity and concavity (figures 5.10, and 5.11). Bishop et al. (2001) and Bonk (2002) pointed out the potential of profile curvature to highlight convex ridge tops and lateral moraines. Similarly, the geometric relationships between glacier flow direction and valley wall orientation generates concave curvature which highlights the edge of the glaciers. In addition, concavity delineates the boundaries of past ablation valleys in the Raikot Basin, as well as lobes boundaries at the terminus of the Sachen Glacier.

Planimetric curvature also provides very valuable information about glacier surface topography (figures 5.12, and 5.13). The results of planimetric curvature contain a distinctive homogeneous spatial pattern of relative planarity commonly associated with the glacier surface. This is in contrast to non-glacier surfaces where the landscape exhibits relatively high spatial variability in concavity and convexity. Because of this characteristic of planimetric curvature, variations in the complexity of the landscape can be differentiated. It is also clear that this metric accurately identifies the crests and low points of ridges and valleys, thereby delineating geometric conditions that can be used for delineating glacier boundaries.

It should be noted however, that results for Raikot are better than for Sachen and that not all glacier boundaries can be identified.

Figures 5.14, and 5.15 show heterogeneity of glacier topography as characterized by tangential curvature. In general, the metric highlights the crests of ridges and the low points of valleys. The metric does a reasonable job of enhancing the boundaries of the Raikot and Sachen glaciers. This is demonstrated in tangential curvature boundary maps (figures 5.16, and 5.17), although non-glacier boundaries cannot be differentiated from glacier boundaries without more sophisticated analysis. These results are similar to those obtained from planimetric curvature.

Positive and negative openness metrics computed at various scales characterize the hemispherical curvature of the landscape. Using a radius of 100 m (figures 5.18, 5.19, and 5.20, 5.21), the metric highlights and delineates major portions of the Raikot and Sachen Glaciers. Specifically it highlights all those portions of the landscape that effectively have relatively low slopes including glacier surfaces and ablation valleys. In this way the results are very similar to slope-angle distributions. It does appear, however, that the negative openness metric does a better job of delineating the glacier boundaries. It is difficult to determine if the results from using a radius of 500 m (figures 5.22, 5.23, and 5.24, 5.25) produces significantly different results. In general, the "negative" metric seems to produce better results than the "positive" metric, and more detailed analysis seems warranted to determine what the effective difference of scale-dependent analysis is, and whether it provides useful information.

Collectively, it has been determined that the morphometric parameters characterize a variety of morphological conditions, and that each metric contains useful information about the topography and glacier surfaces. In many cases, each morphometric parameter was found to be valuable in helping to delineate glacier boundaries. It was found, however, that no individual parameter could be used exclusively to precisely delineate glacier boundaries, from a computer-assisted analysis perspective. Conversely, numerous metrics could be used by an analyst to accurately delineate the boundary of the glaciers via human interpretation. This indicates that in order to automate glacier mapping, these parameters must be collectively utilized and combined in a unique way to accurately characterize some aspect of topographic structure not characterized by individual parameters.

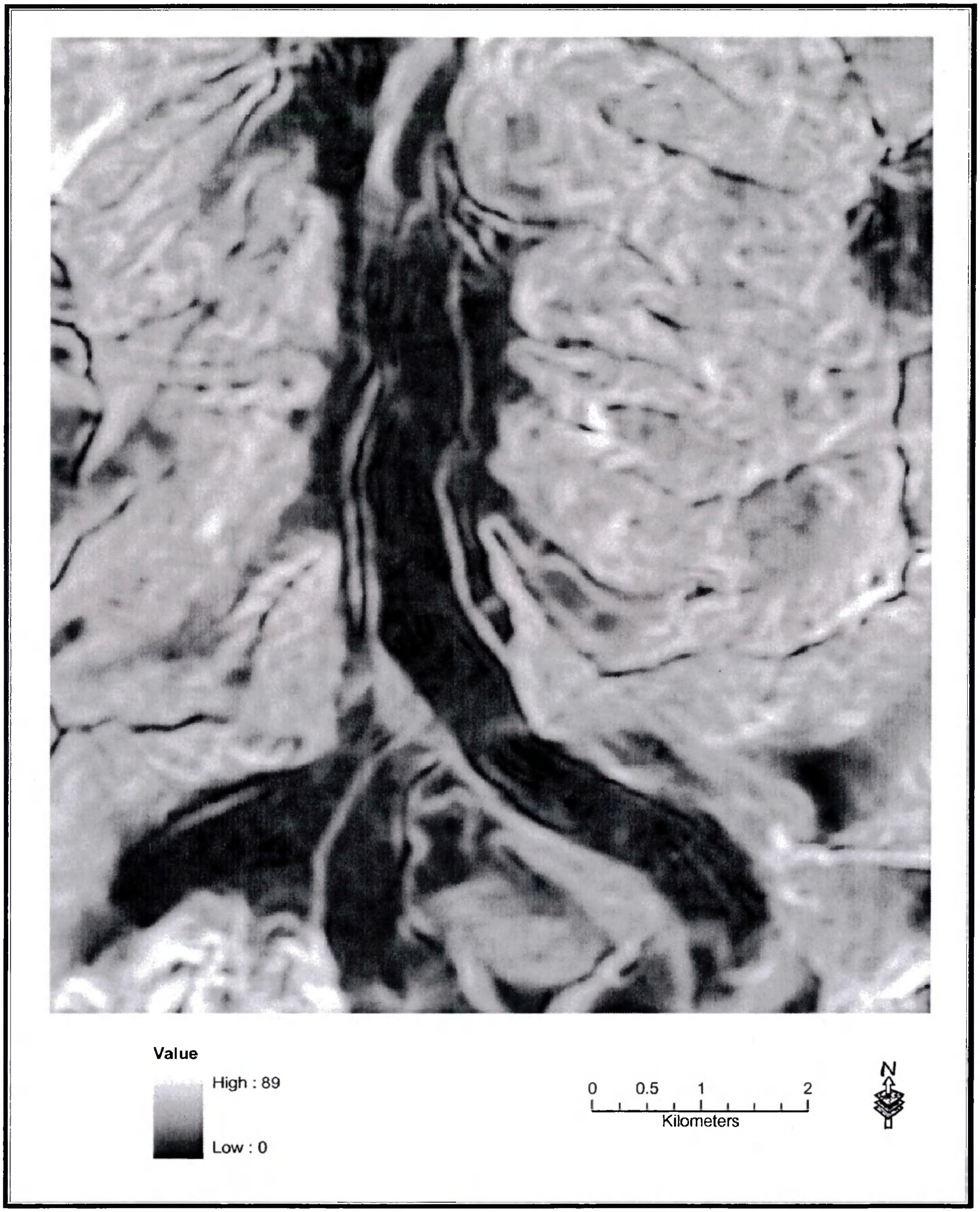


Figure 5.1: Slope-angle map of Raikot Glacier.

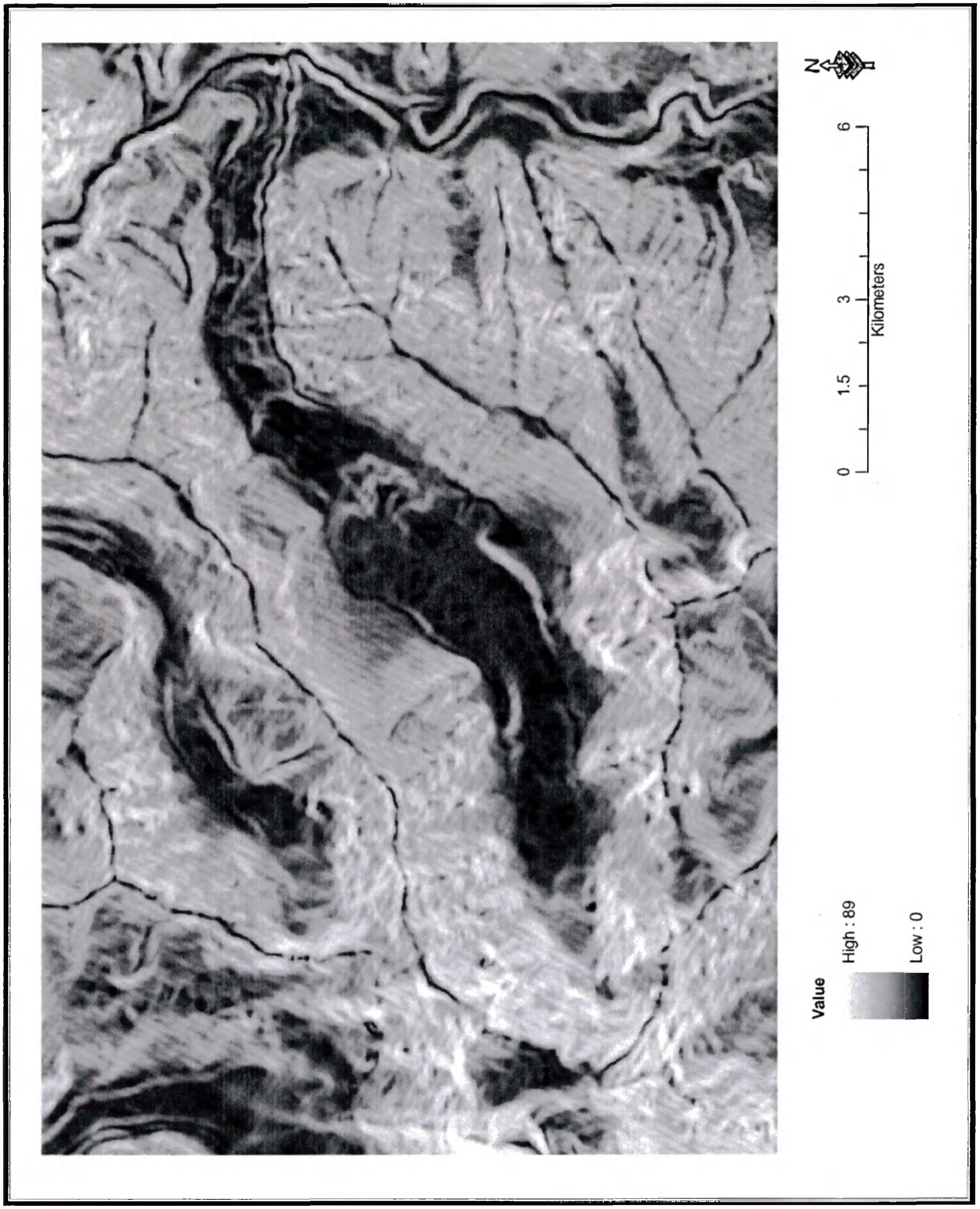


Figure 5.2: Slope-angle map of Sachen Glacier.

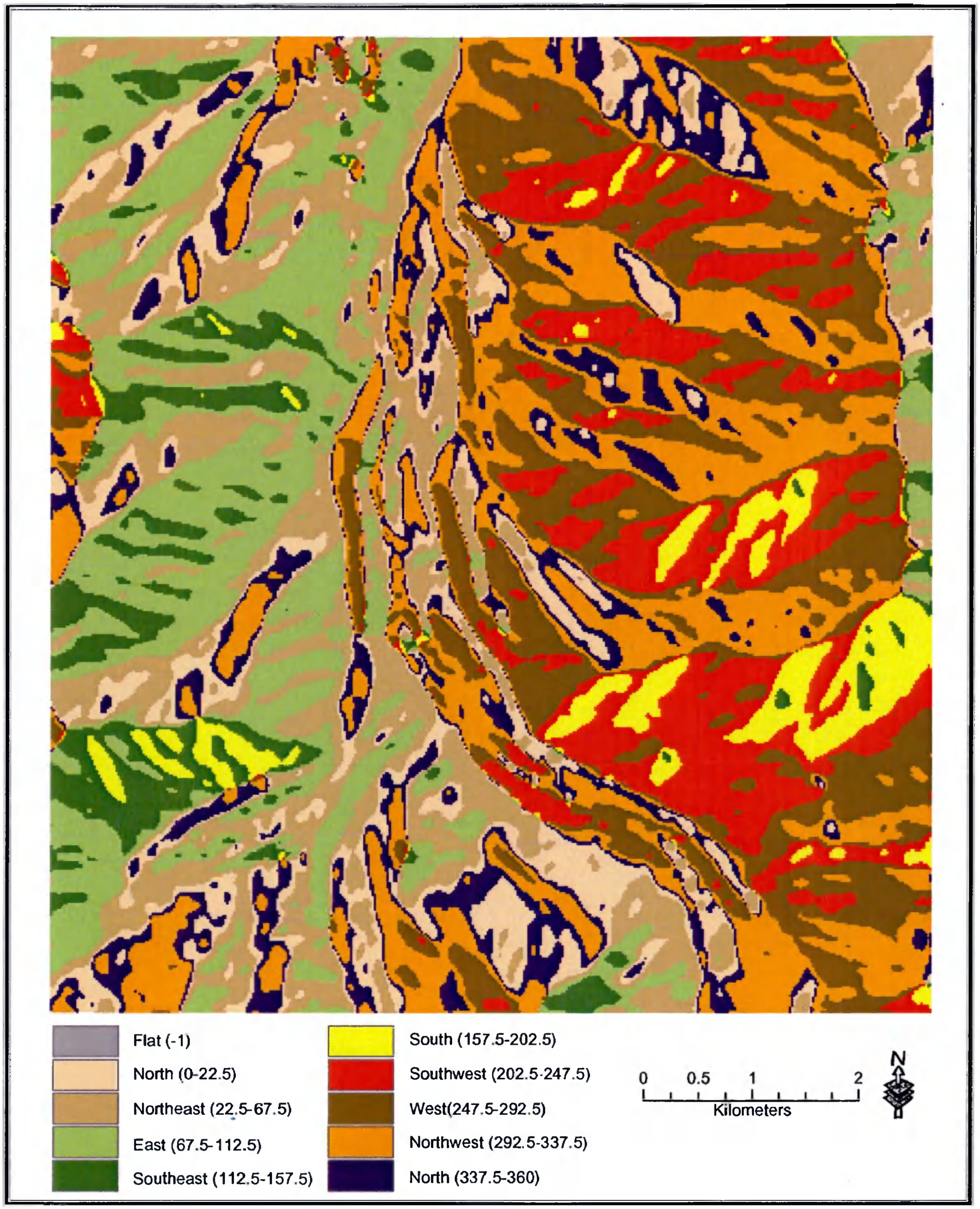


Figure 5.3: Slope-aspect map of Raikot Glacier.

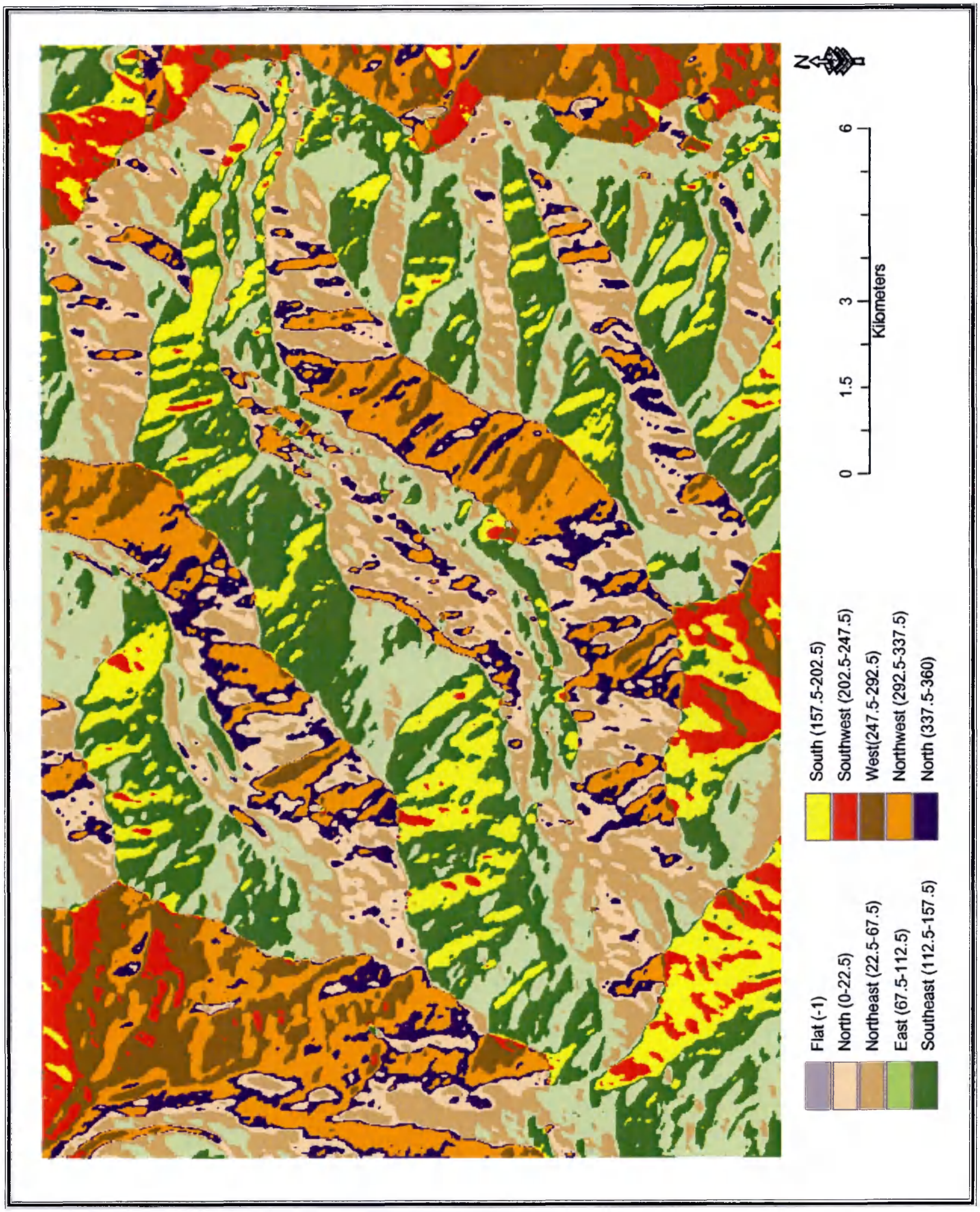


Figure 5.4: Slope-aspect map of Sachen Glacier.

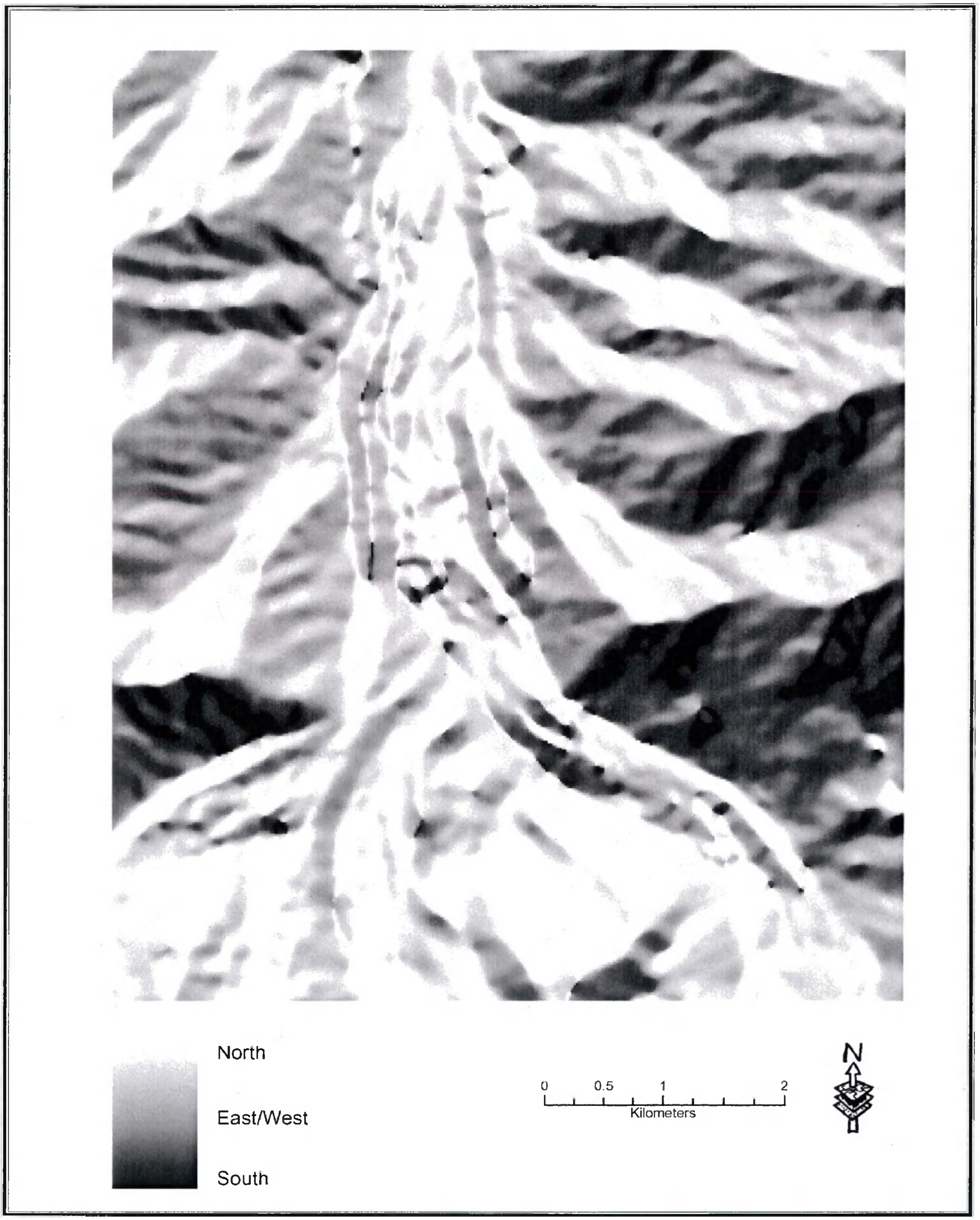


Figure 5.5: Cosine slope-aspect map of Raikot Glacier.

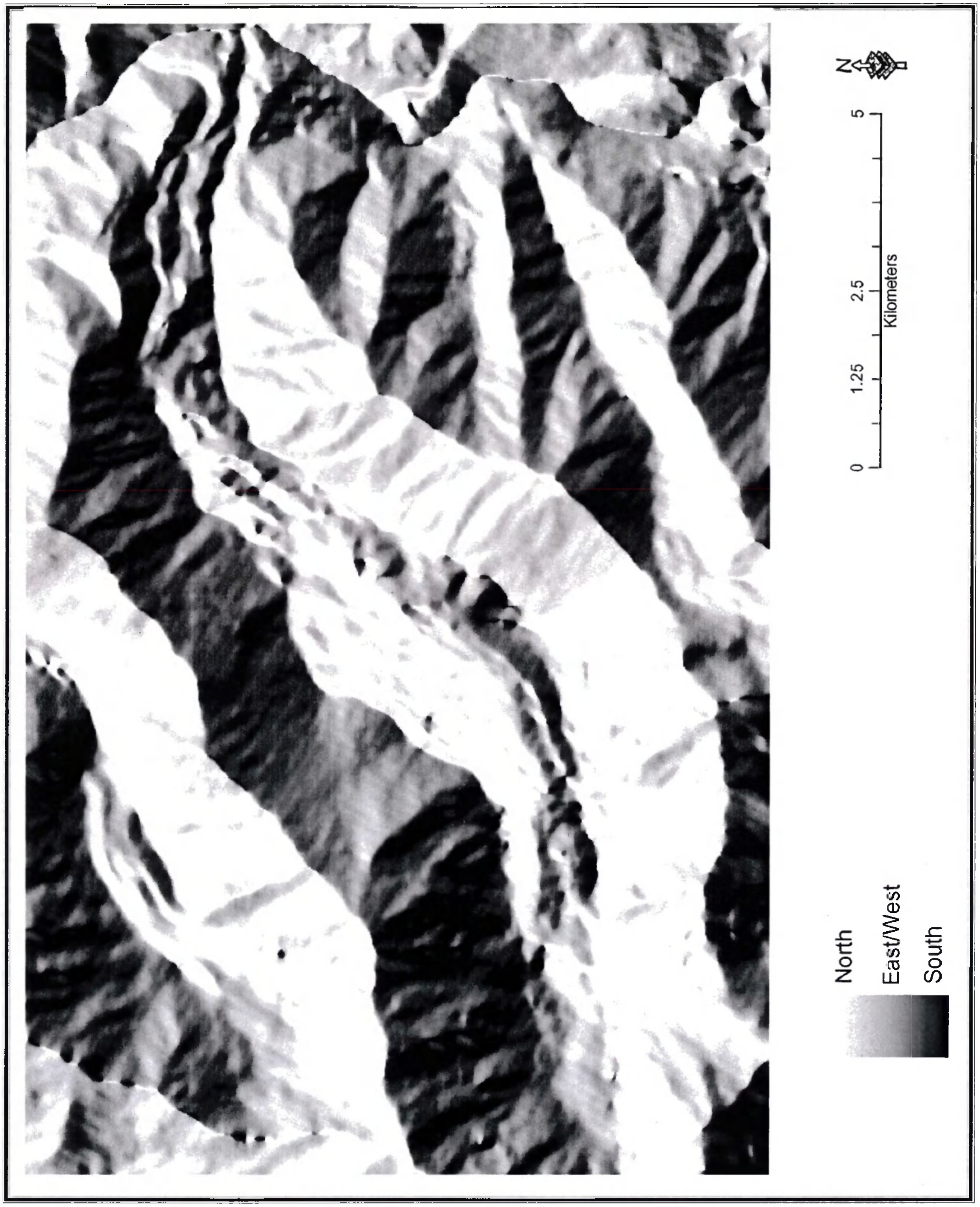


Figure 5.6: Cosine slope-aspect map of Sachen Glacier.

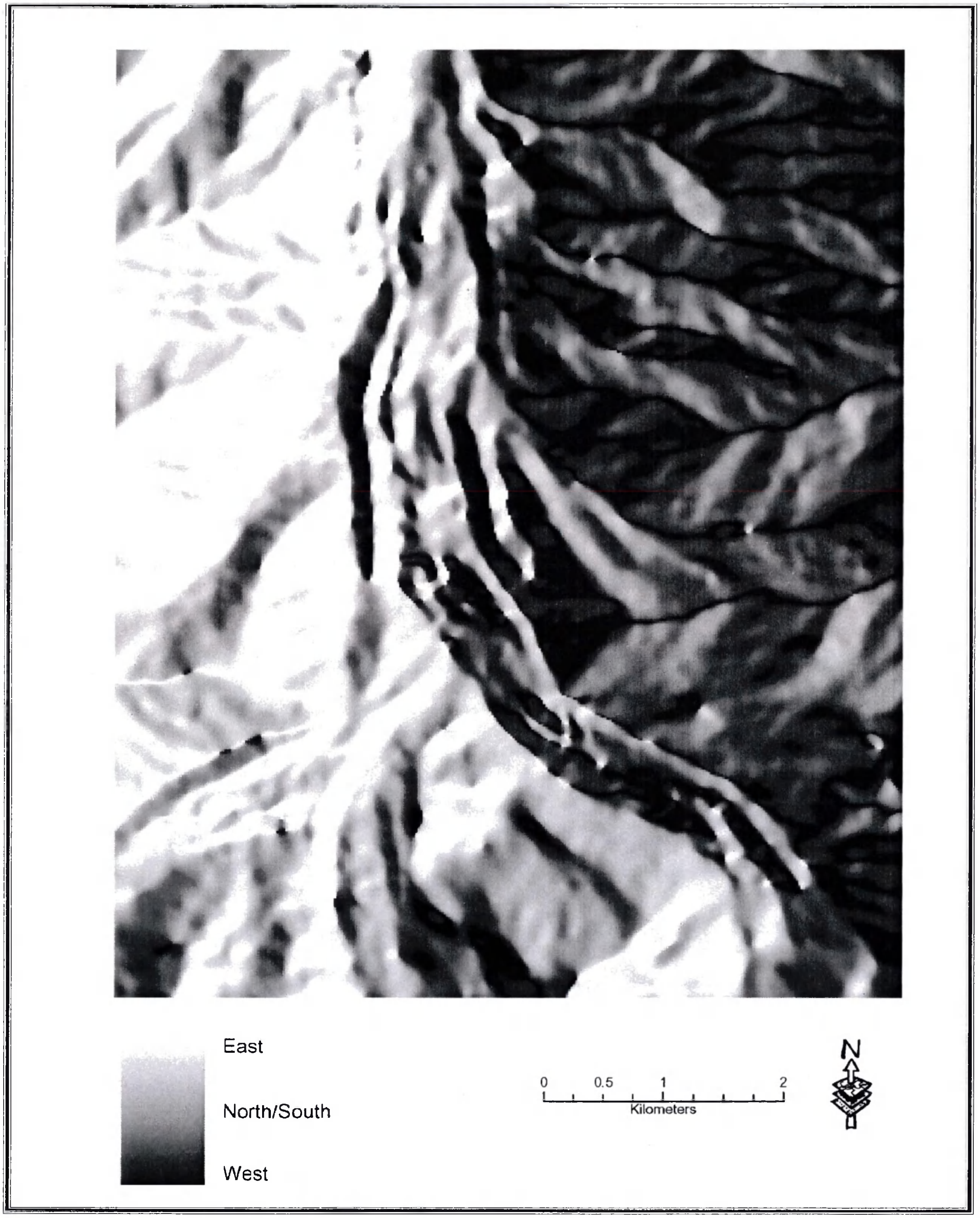


Figure 5.7: Sine slope-aspect map of Raikot Glacier.

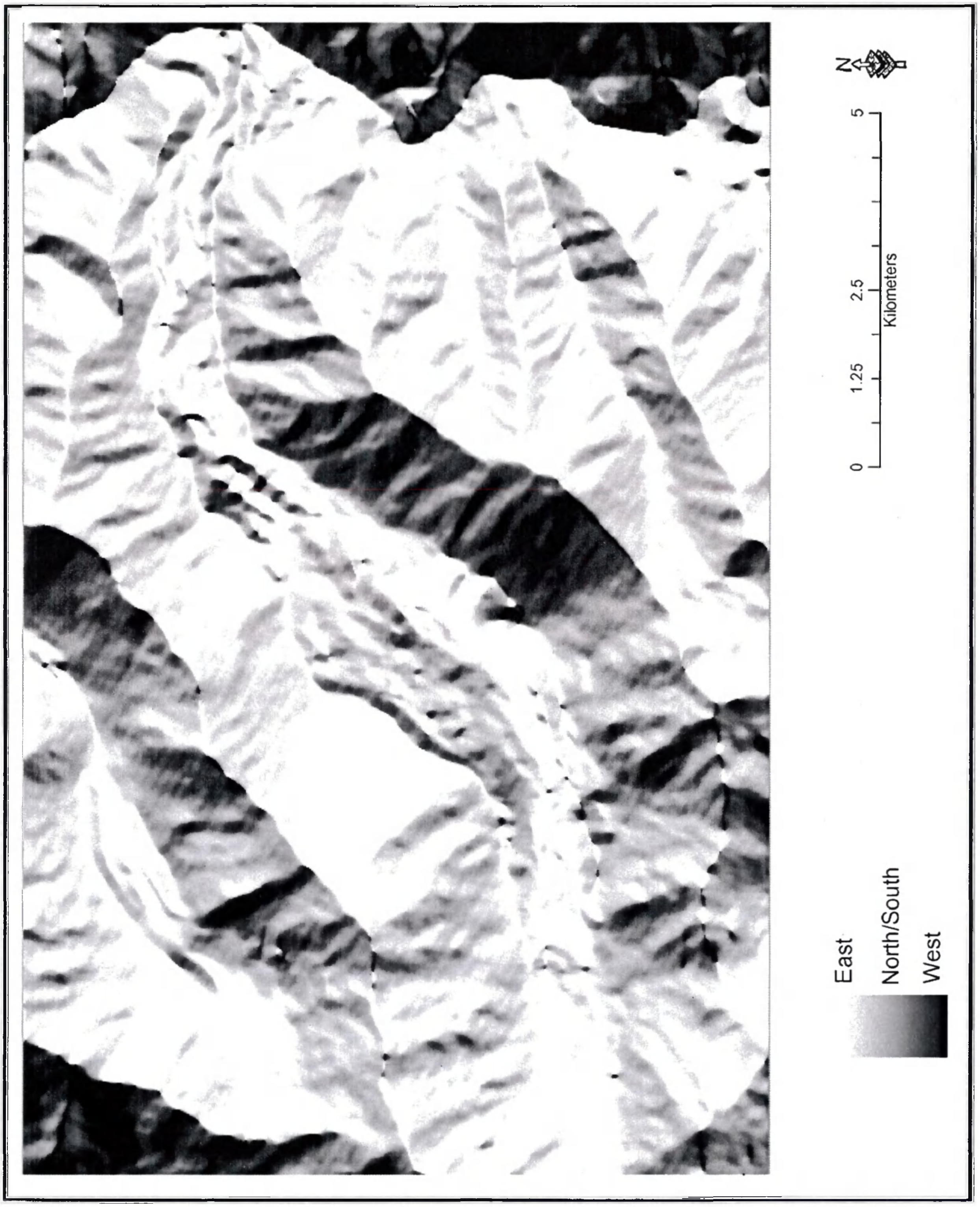


Figure 5.8: Sine slope-aspect map of Sachen Glacier.

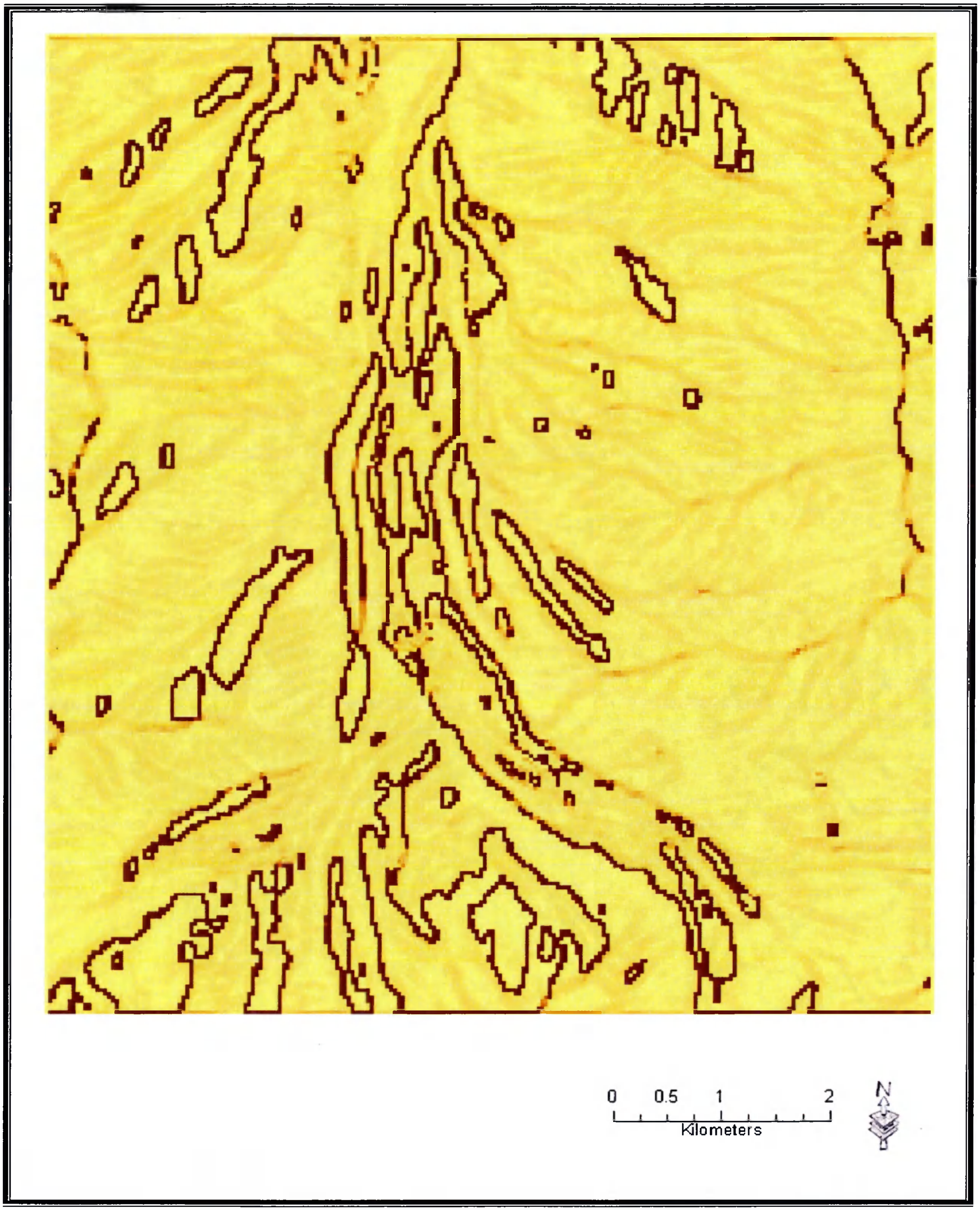


Figure 5.9: Slope-aspect boundaries of Raikot Glacier.

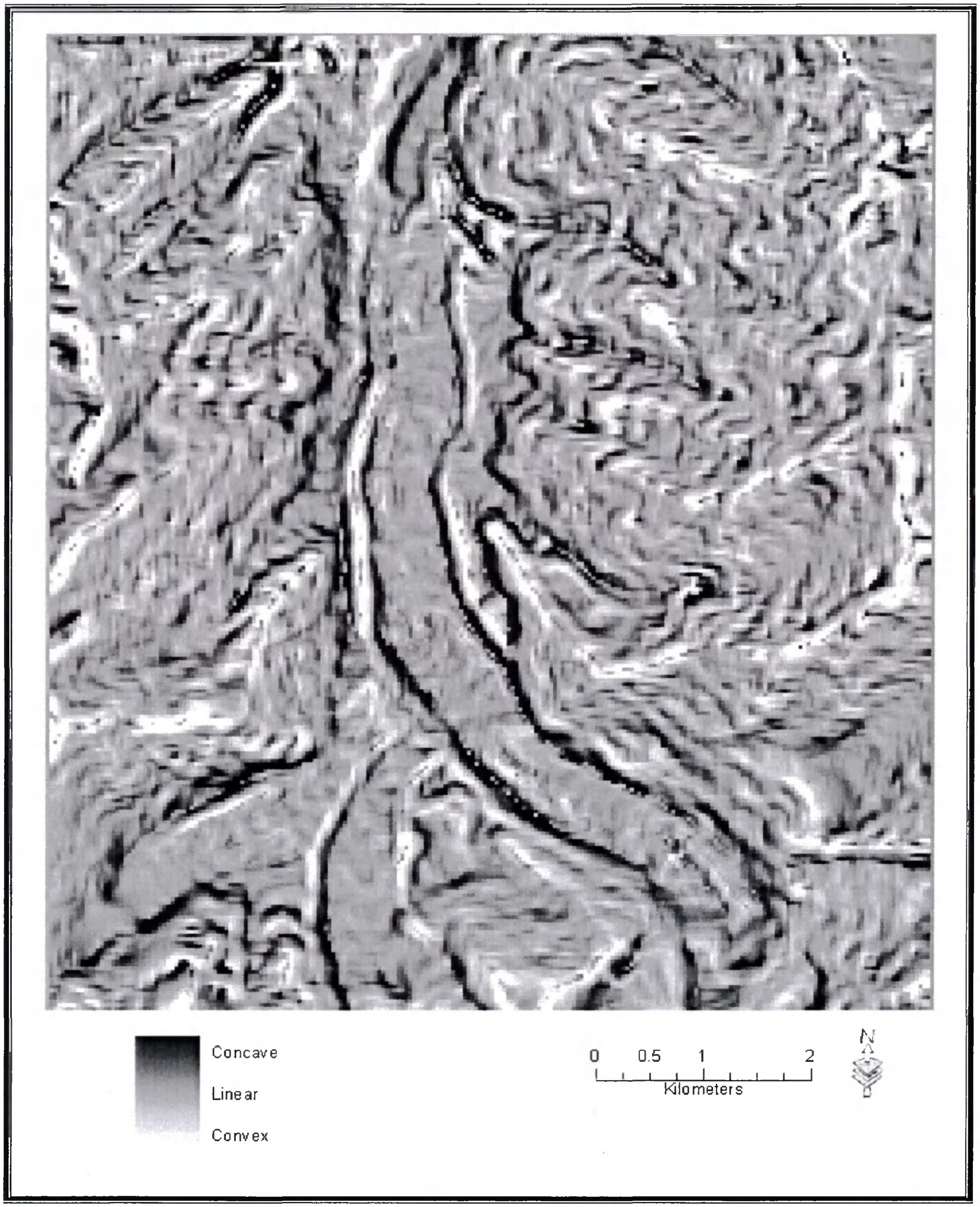


Figure 5.10: Profile curvature map of Raikot Glacier.

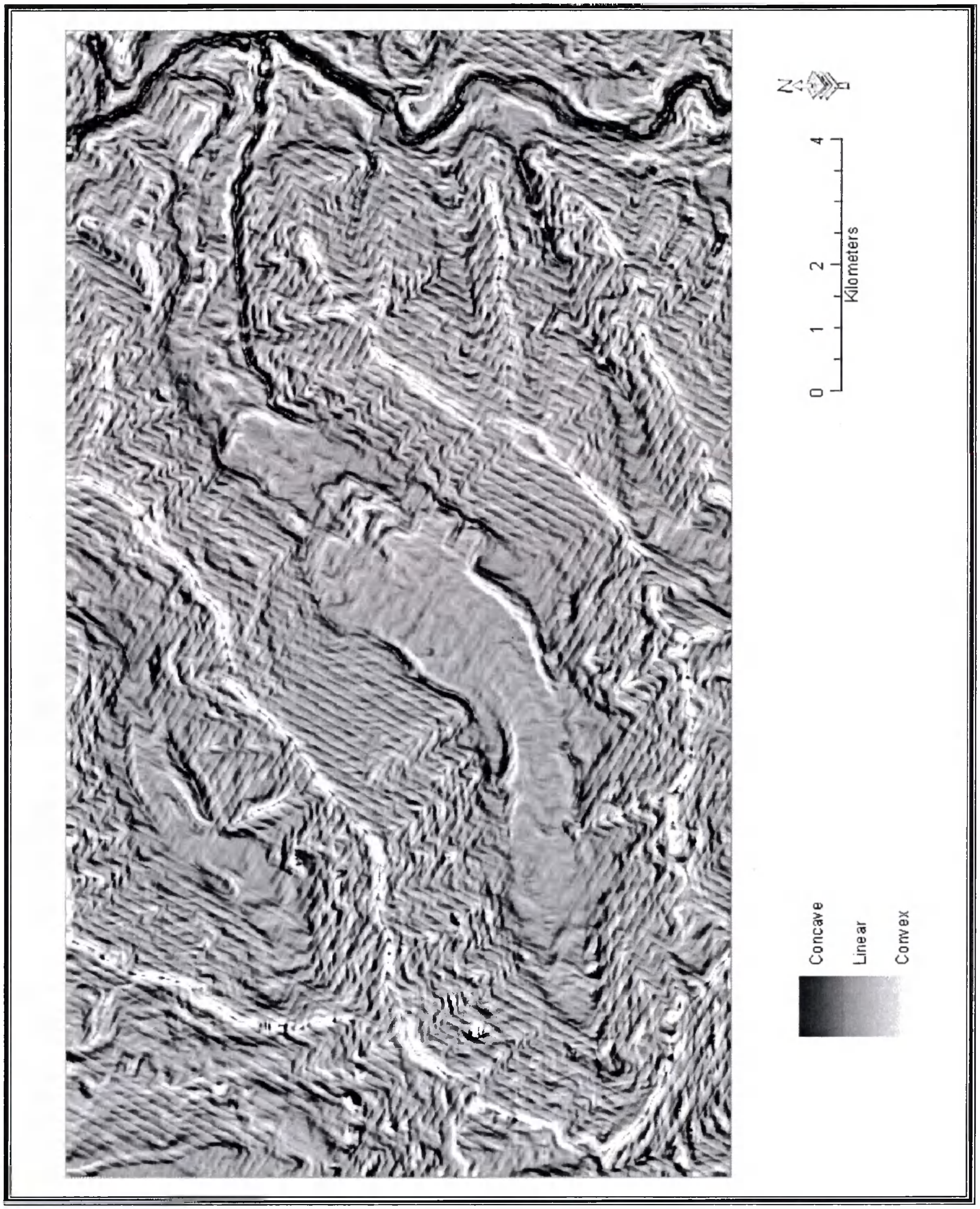


Figure 5.11: Profile curvature map of Sachen Glacier.

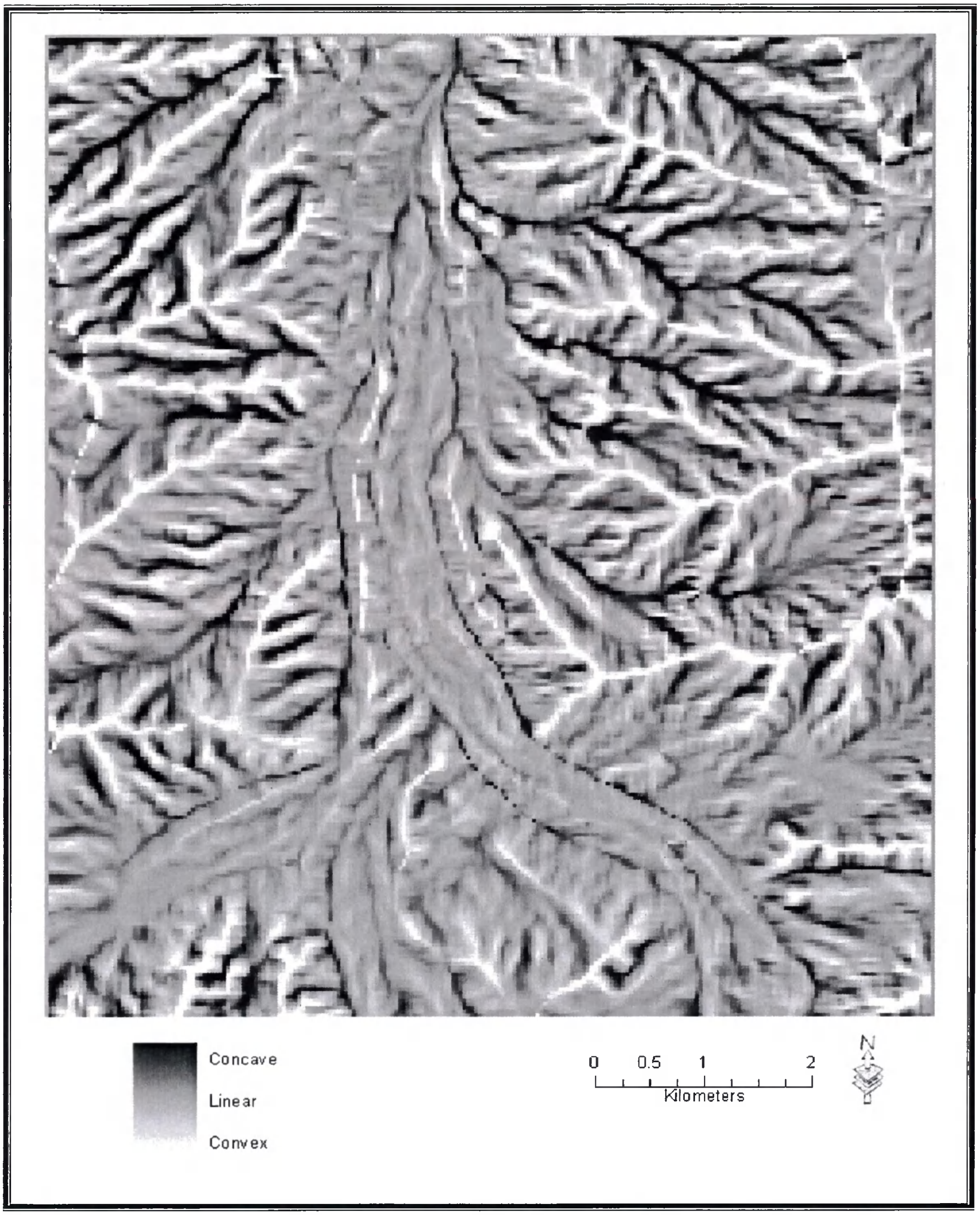


Figure 5.12: Planimetric curvature map of Raikot Glacier.

Figure 5.13: Planimetric curvature map of Sachen Glacier.

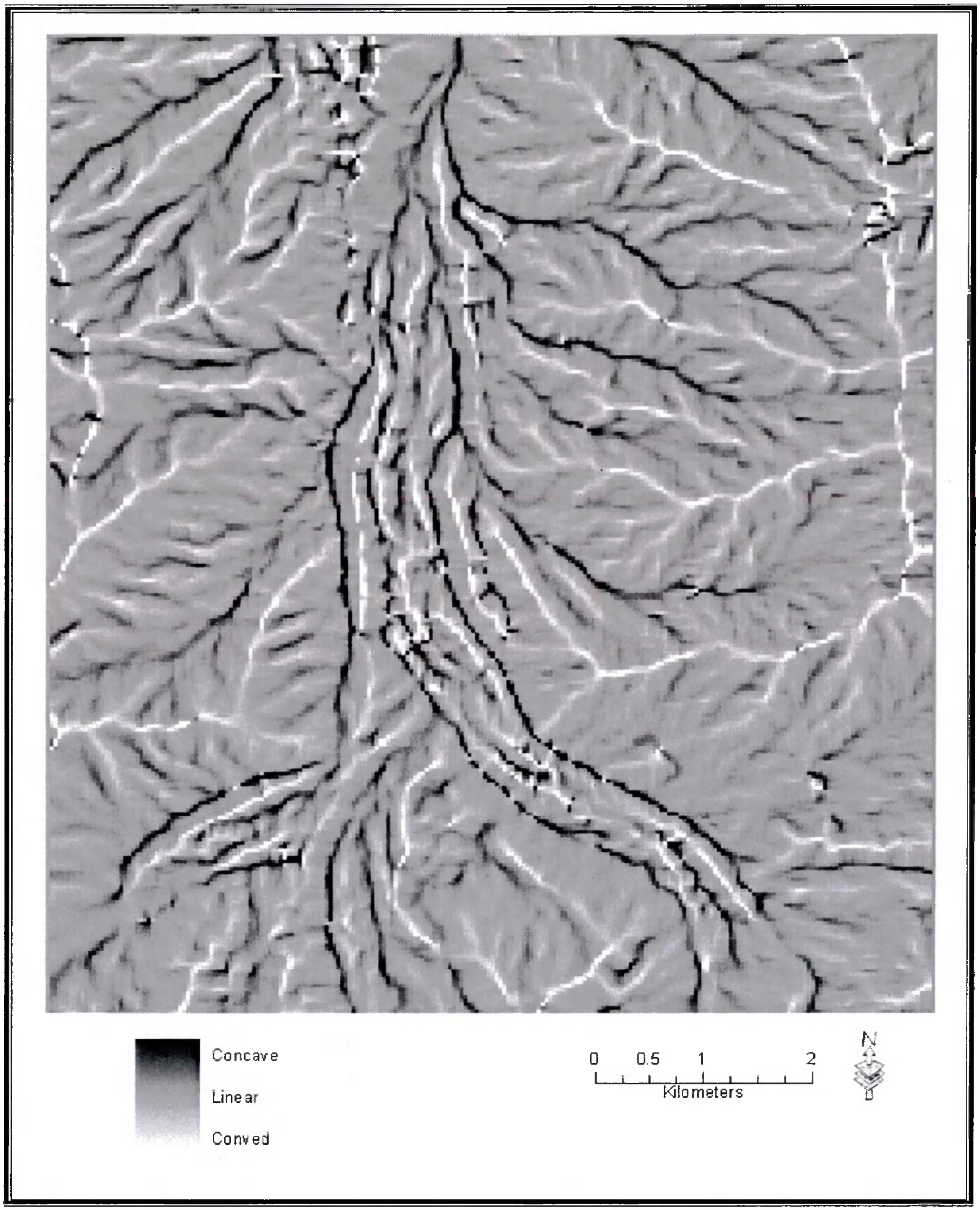


Figure 5.14: Tangential curvature map of Raikot Glacier.

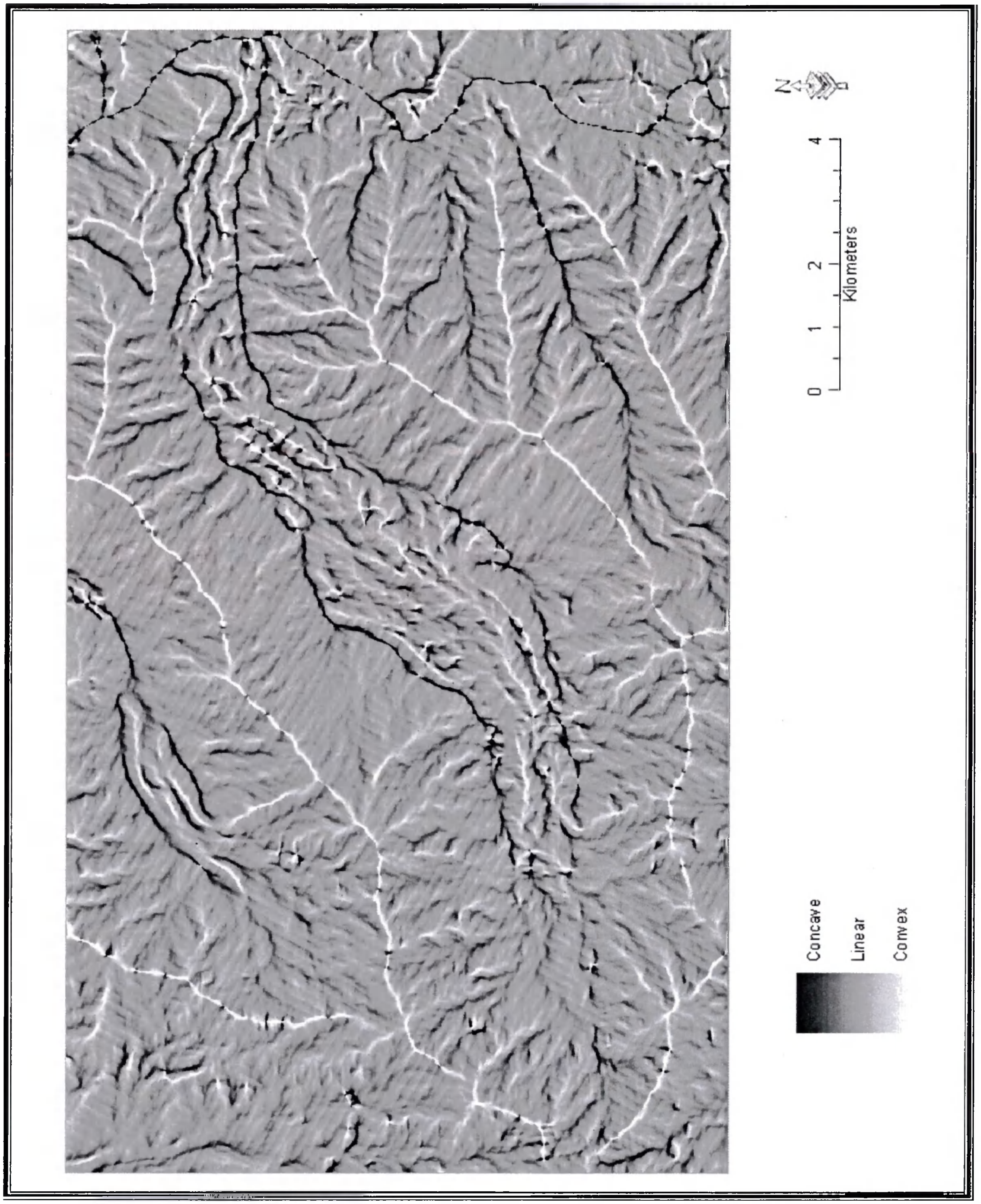


Figure 5.15: Tangential curvature map of Sachen Glacier.

Figure 5.16: Tangential curvature boundaries of Raikot Glacier.

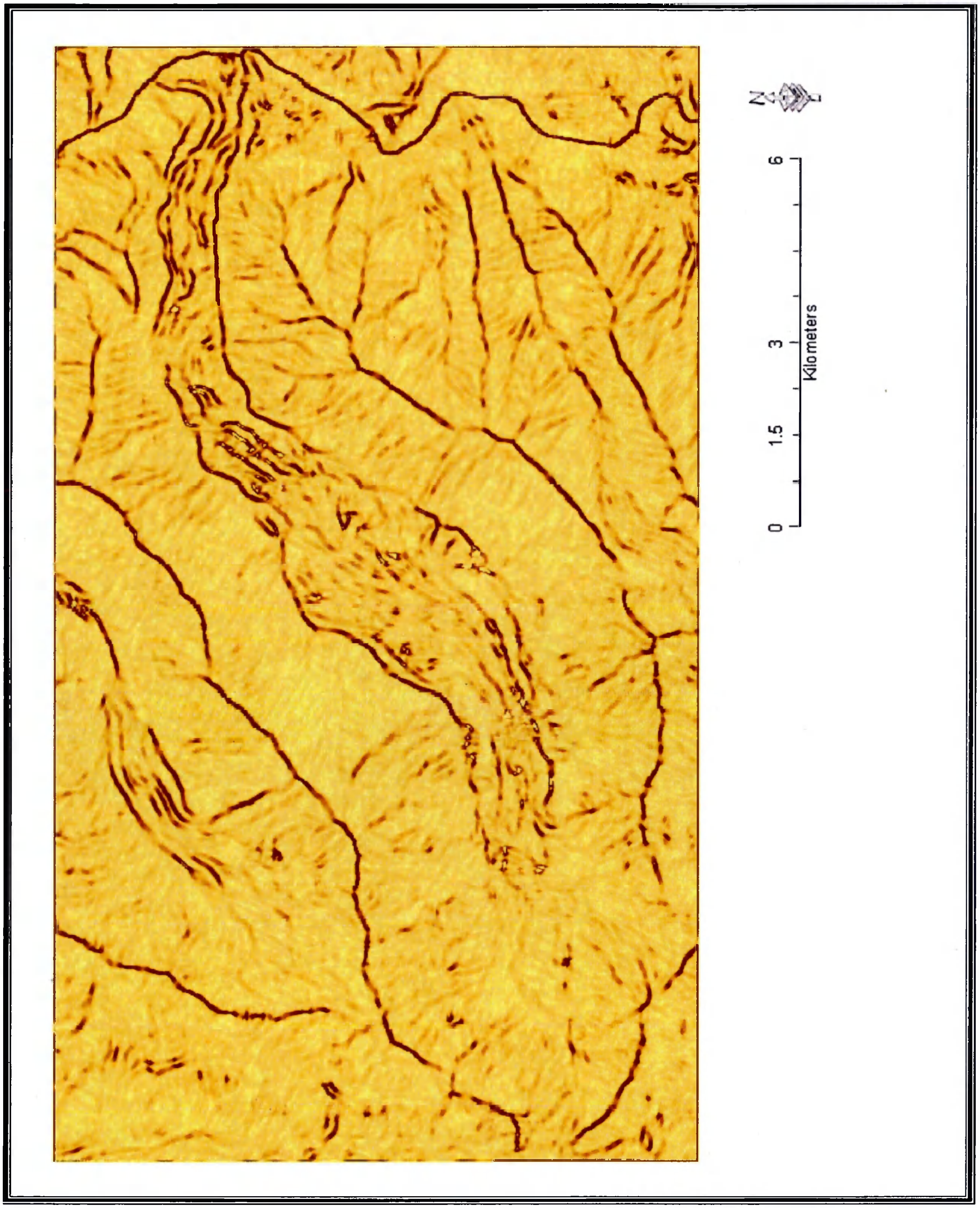


Figure 5.17: Tangential curvature boundaries of Sachen Glacier.

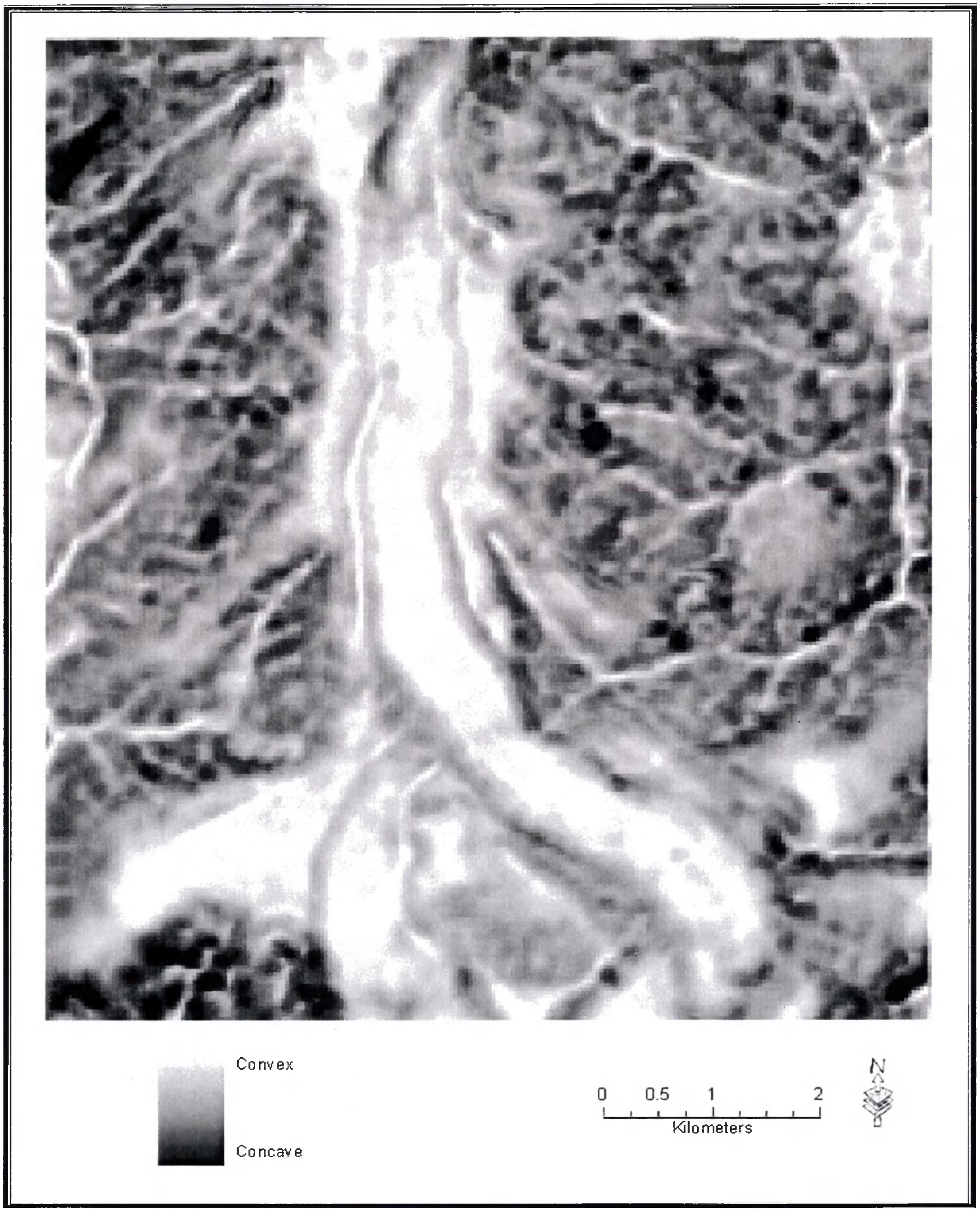


Figure 5.18: Positive openness map of Raikot Glacier with 100 m radius.

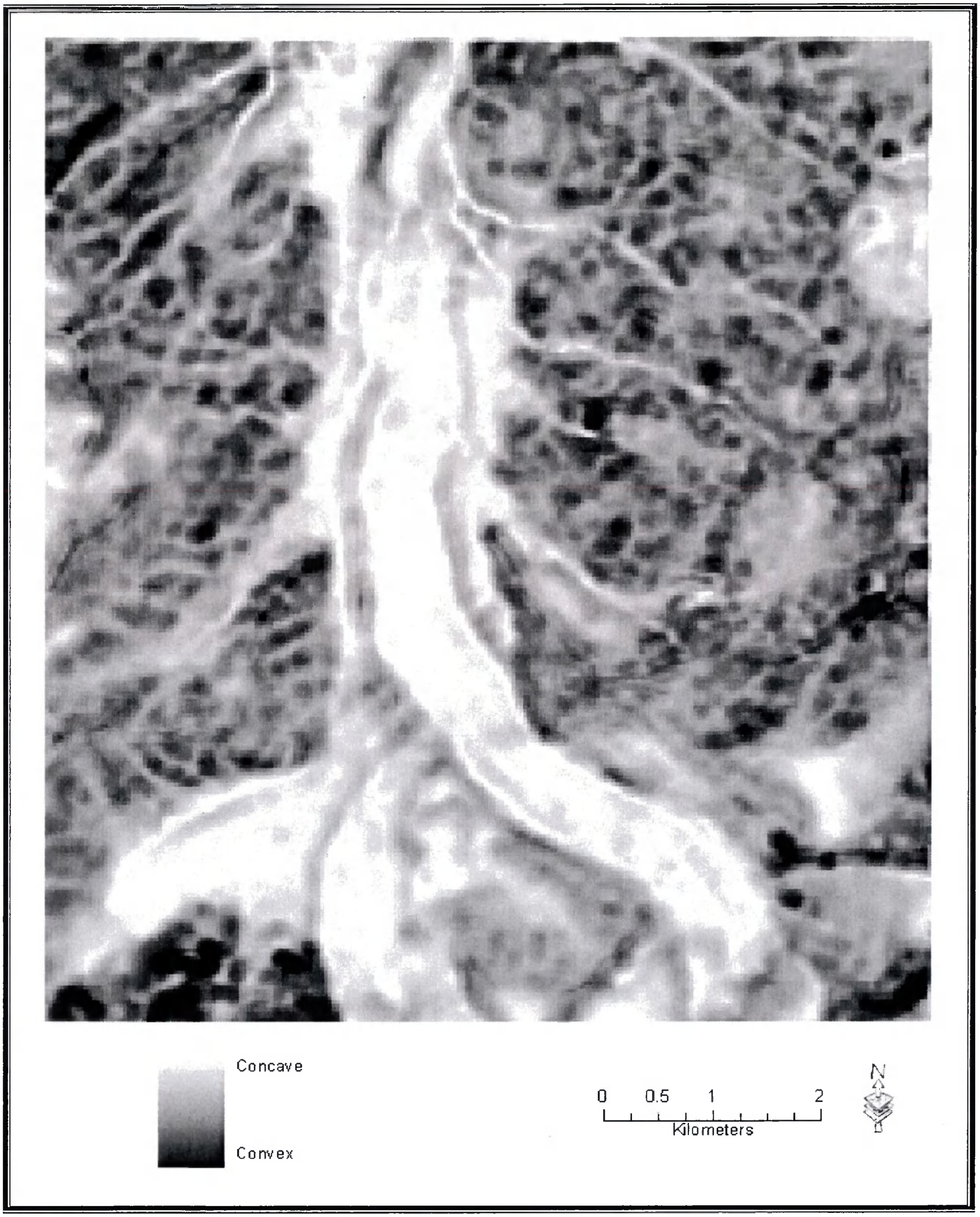


Figure 5.19: Negative openness map of Raikot Glacier with 100 m radius.

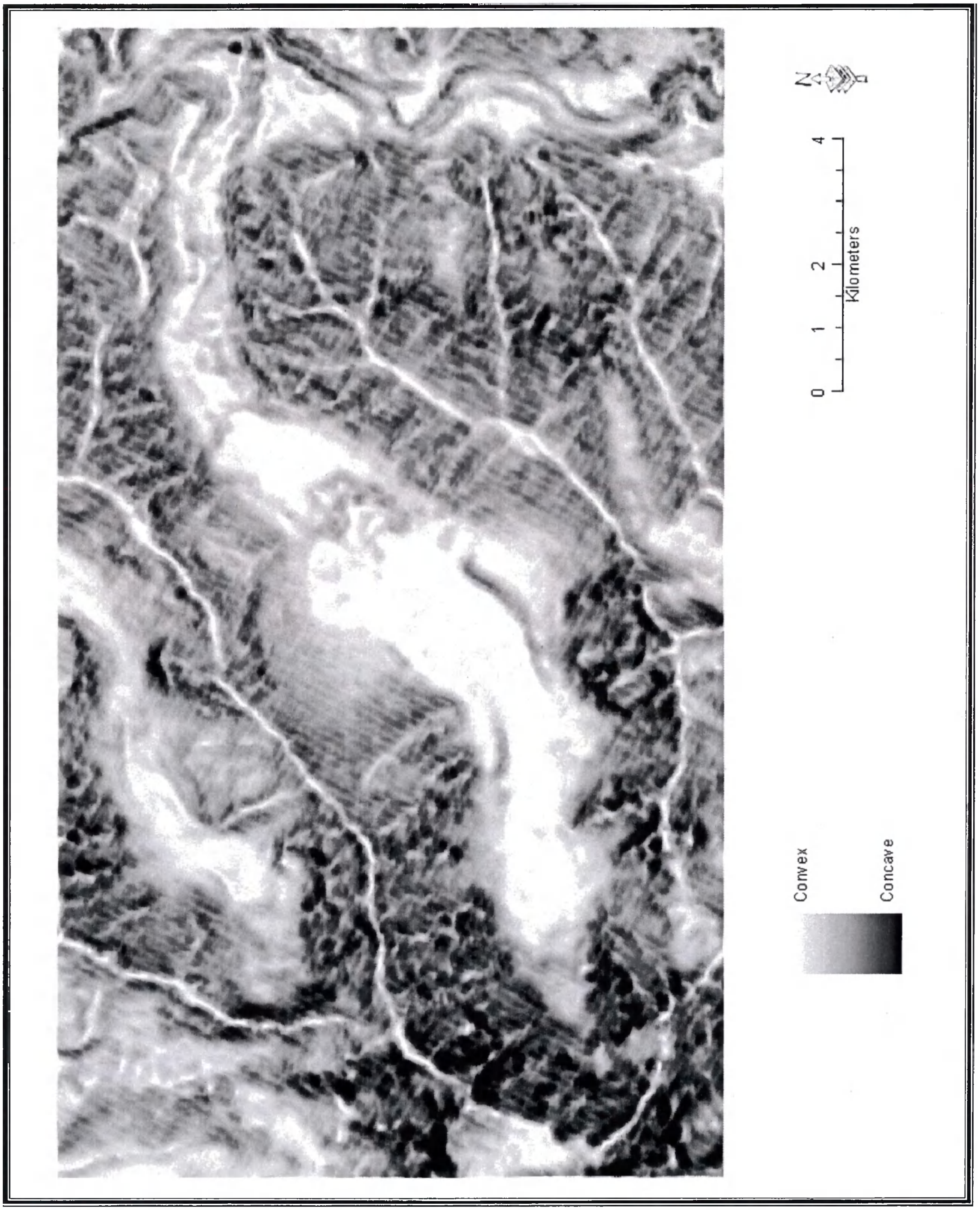


Figure 5.20: Positive openness map of Sachen Glacier with 100 m radius.

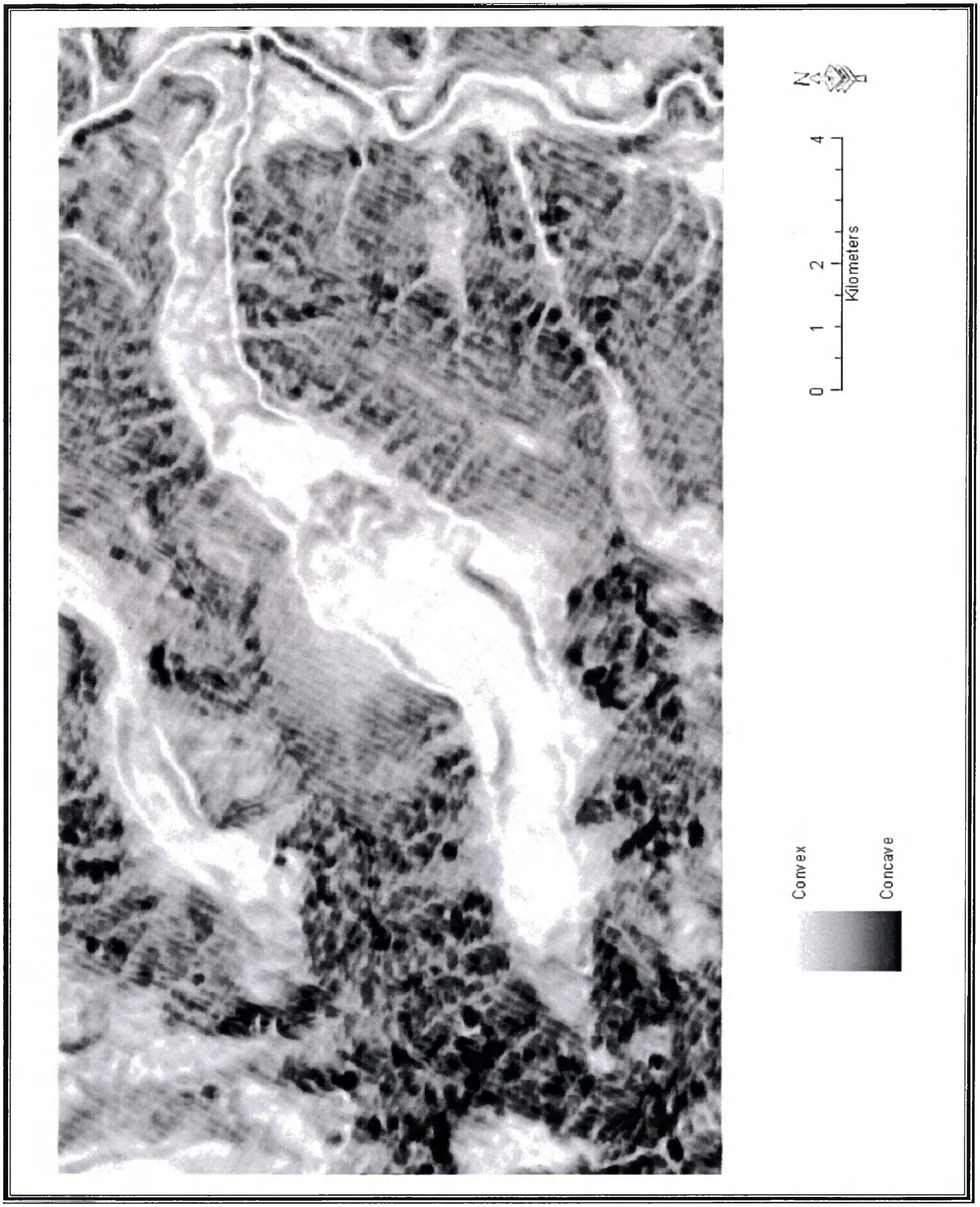


Figure 5.21: Negative openness map of Sachen Glacier with 100 m radius.

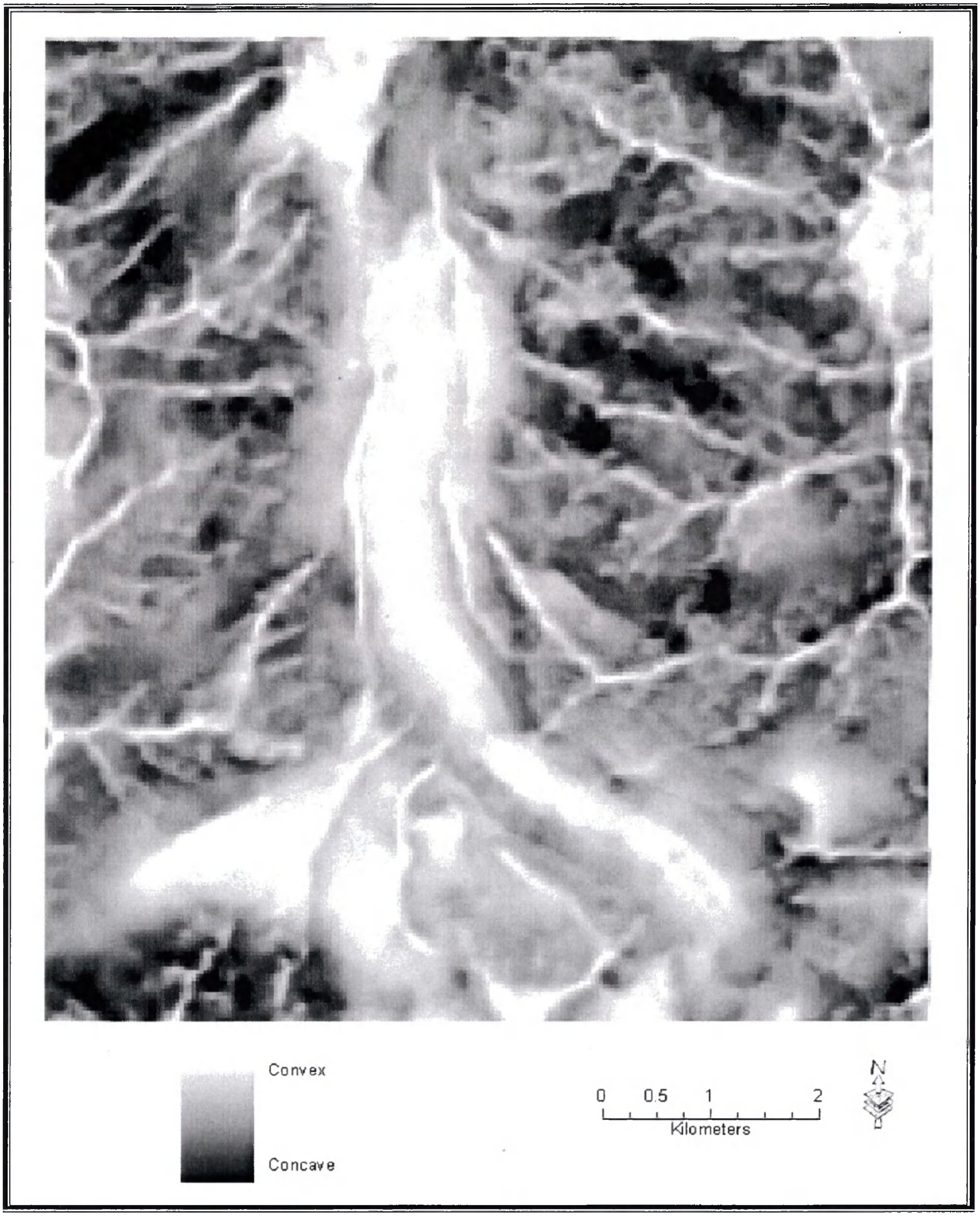


Figure 5.22: Positive openness map of Raikot Glacier with 500 m radius.

Figure 5.23: Negative openness map of Raikot Glacier with 500 m radius.

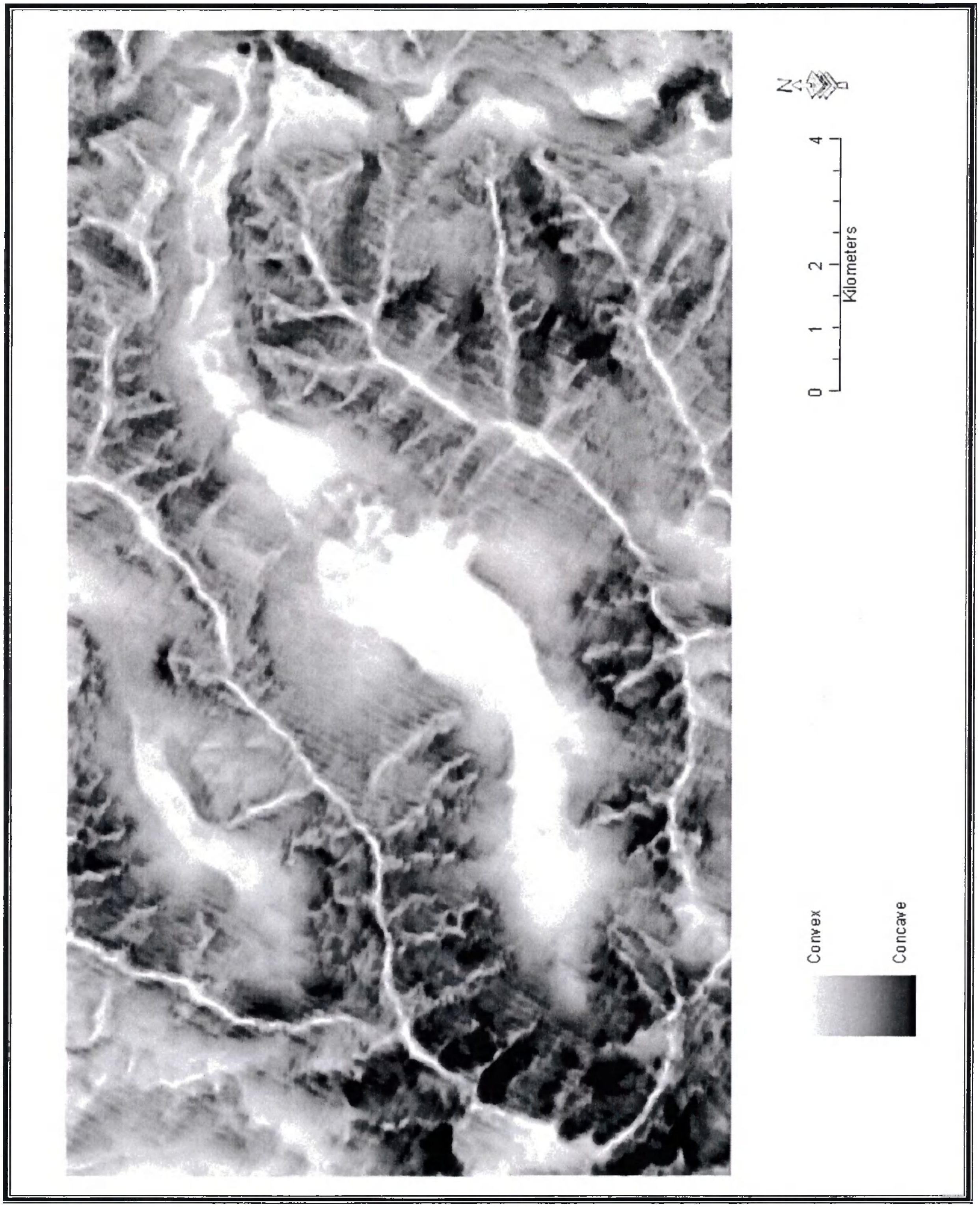


Figure 5.24: Positive openness map of Sachen Glacier with 500 m radius.

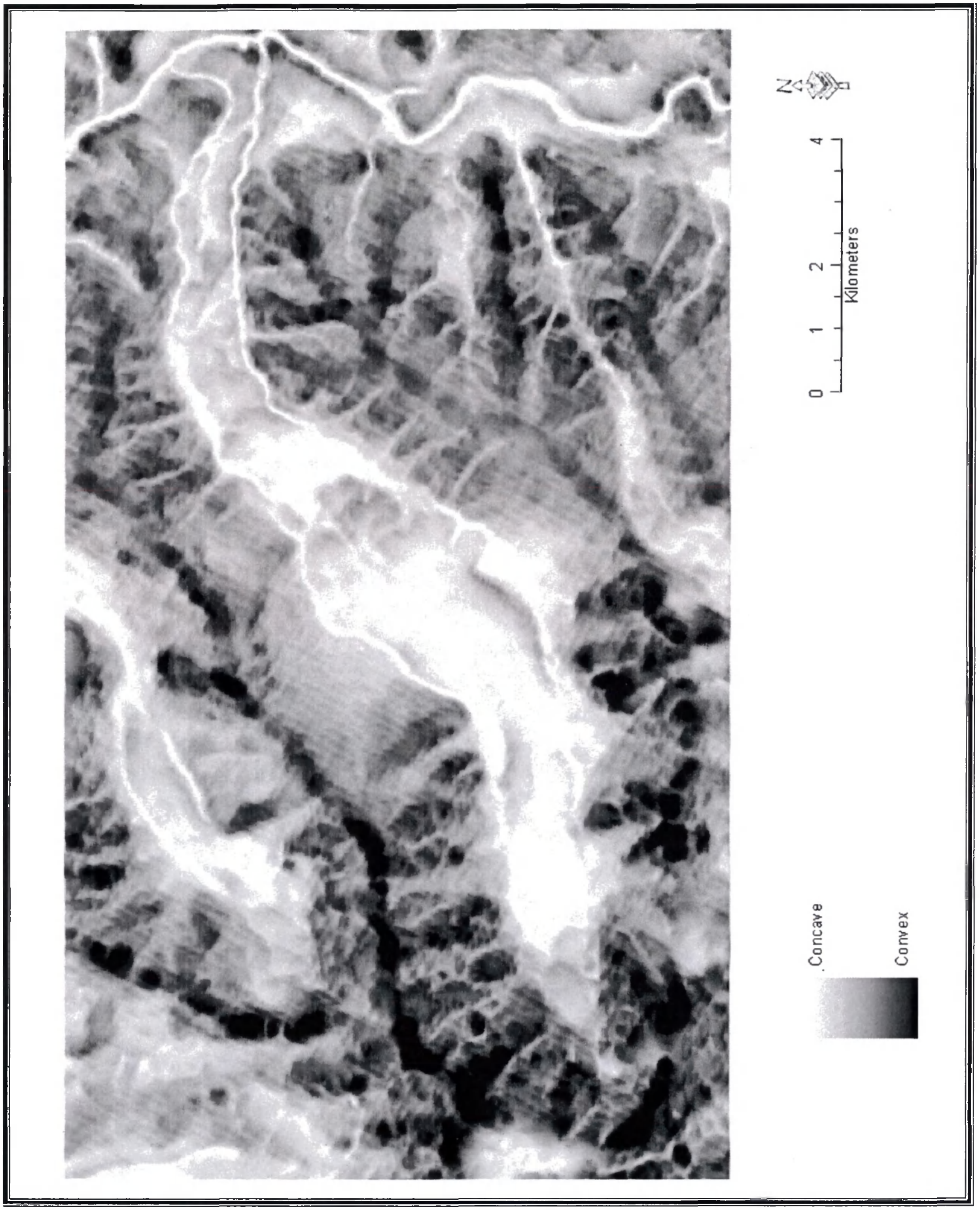


Figure 5.25: Negative openness map of Sachen Glacier with 500 m radius.

5.2 Elementary Terrain-Form Objects

An important research objective is to demonstrate that elementary terrain-form objects (ETFOs) can be used to characterize features on a glacier surface. Implementation of the methodology generates thousands of ETFOs for each geomorphometric parameter. Consequently, visual examination was used to determine which parameters are the most important in generating ETFOs that identify and delineate glacier surface features.

Figures 5.26, and 5.27 show the spatial pattern of slope-angle ETFOs for Raikot and Sachen Glaciers. The results of classifying the slope-angle metric produce very useful information related to the influence of glaciation on topography. The results of this work and Bonk (2002) demonstrate how glacier processes reduce the slope angles of the topography due to glacier erosion and redistribution of sediment. The result of these glacier processes are large homogeneous slope-angle objects that permit the identification of glacier surfaces that are actively eroding, and of low-slope surfaces such as ablation valleys and erosion surfaces resulting from past glaciation. Both the Raikot and Sachen Glacier surfaces are depicted by these large ETFOs. Unfortunately these ETFOs do not accurately delineate the glacier surface because ablation valleys and valley bottoms also exhibit relative shallow slope. Conversely, the topography associated with resistant rocks exhibits smaller ETFOs with a higher spatial frequency of objects. In general, slope-based ETFOs provide an indication of modern glacial versus non-glacial topography.

Glacier surfaces are the result of dynamic interactions involving ice flow, erosion, and mass balance. Consequently, glacier topography is highly varied and can result in significant relief and slope-aspect variations. The results demonstrate this, although there are limits to characterizing this and other properties of glacier surfaces due to DEM resolution. Nevertheless, the results show significant variation of slope-aspect ETFOs compared to the surrounding topography. In addition, this results in smaller objects and high spatial variability of objects over glacier surfaces. This is caused by rapid changes in the glacier surface compared to more resistant rock slopes that do not rapidly change. This is why they exhibit large homogeneous slope-aspect ETFOs. This can be clearly seen in the Raikot basin (figure 5.28). For less active glaciers like the Sachen, the difference in the size and spatial frequency of objects is less pronounced (figure 5.29).

Results for profile curvature-based objects are interesting (figures 5.30, and 5.31). They do not appear to characterize any glacier feature, although they do provide an indication of the flow-direction on the glacier surfaces. This is especially true for the Sachen Glacier.

Similarly, planimetric curvature-based objects do not characterize specific glacier features, although they do exhibit an interesting dendritic pattern that is associated with ridges and local topographic highs (figures 5.32, and 5.33). In the case of the Sachen Glacier, it appears that the magnitude of curvature may be used to differentiate the glacier surface from the surrounding topography.

Given that tangential curvature is highly correlated with planimetric curvature, tangential curvature-based object results are expected to be similar to planimetric curvature-based object results (figures 5.34 and 5.35). This was the case and the objects depict the ridges and valleys of glacier topography. Other important glacier geomorphological features were not characterized. It is clear that the curvature-based parameters and objects cannot be utilized alone to depict glacier surface features, although they are valuable for delineating glacier boundaries in many instances.

The spatial distribution of openness-based objects has a similar pattern to slope-angle-based objects, characterized by relatively large objects over the glacier surface (figures 5.36, 5.37, and 5.38, 5.39, and 5.40, 5.41, and 5.42, 5.43). There is effectively little difference in the results generated from positive and negative openness, given a particular scale parameter value. As with curvature-based objects, openness-based objects do not characterize specific glacier features. Furthermore, the use of a different scale parameter value does not appear to generate significantly different results.

Bishop et al. (2001) suggested that the ETFOs should be generated from the combination of morphometric parameters and not from a single metric. Consequently, slope-facet objects can be generated from the combination of slope and slope-aspect parameters. Slope-facet objects are displayed in figures 5.44, and 5.45. The concept of slope-facets is an extremely important one, as it represents one form of the spatial structure of the topography. The results indicate that slope-facets can be used effectively to characterize glacier boundaries. The Raikot and Sachen glaciers were both reasonably delineated. In some places, however, the boundaries are not delineated, although this is associated with the way in which the slope-angle metric is used to generate slope-facet objects. It is obvious from previous results that curvature is very important in delineating the glacier boundaries. Consequently, the effective integration of curvature into the generation of slope-facet objects should solve the problem of delineating glacier boundaries in the ablation zone.

Collectively, these results along with the outcome of Bishop et al. (2001) and Bonk (2002) studies demonstrate the tremendous potential of generating and utilizing ETFOs in glacier and geomorphological mapping. It is clear, however, that ETFOs generated from a single morphometric parameters are of little utility. It is also clear that finding a way to effectively integrate morphometric parameters may be a challenge. It was found, however, that slope-facets can be used to accurately delineate glacier boundaries.

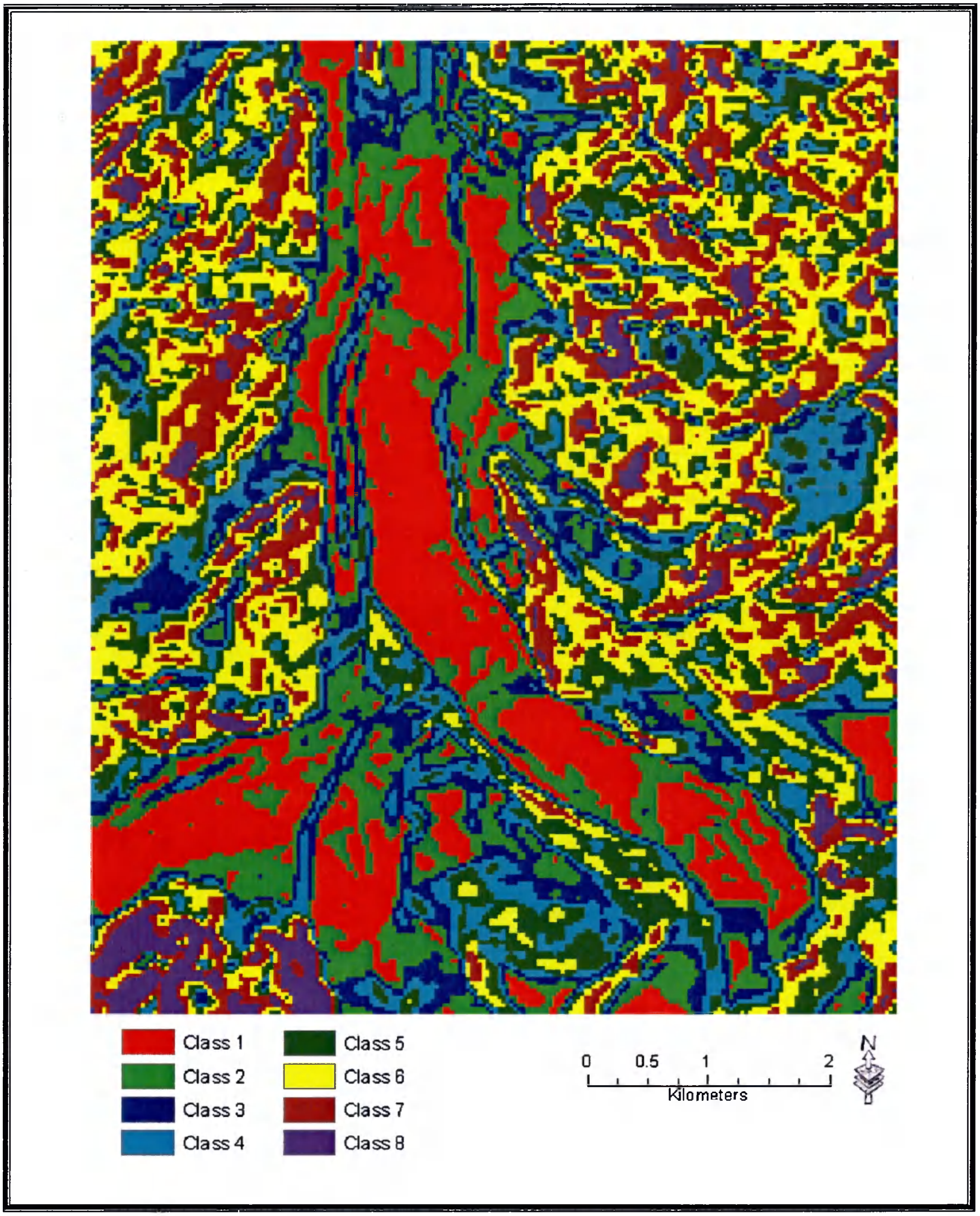


Figure 5.26: Slope-angle ETFOs map of Raikot Glacier.

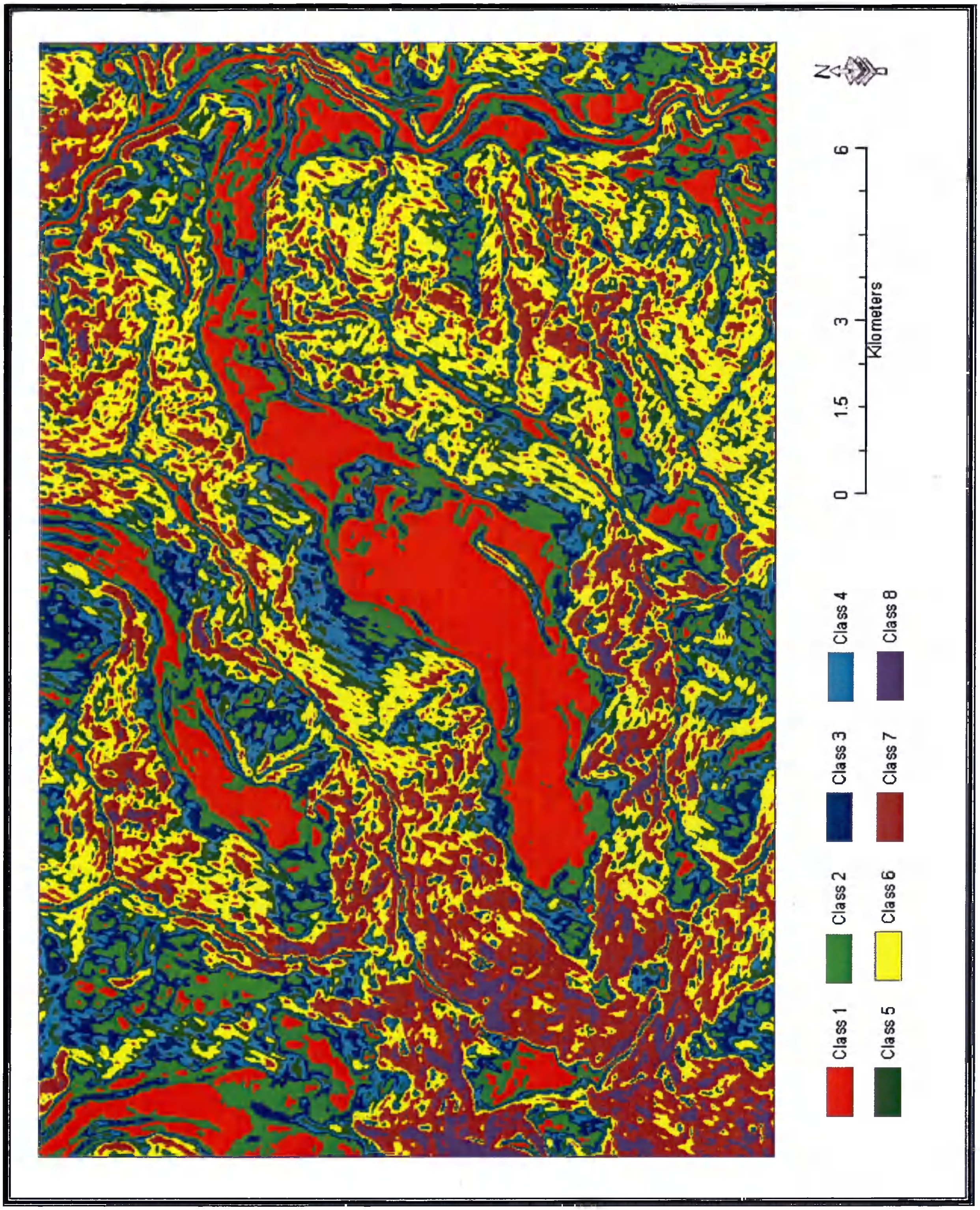


Figure 5.27: Slope-angle ETFOs map of Sachen Glacier.

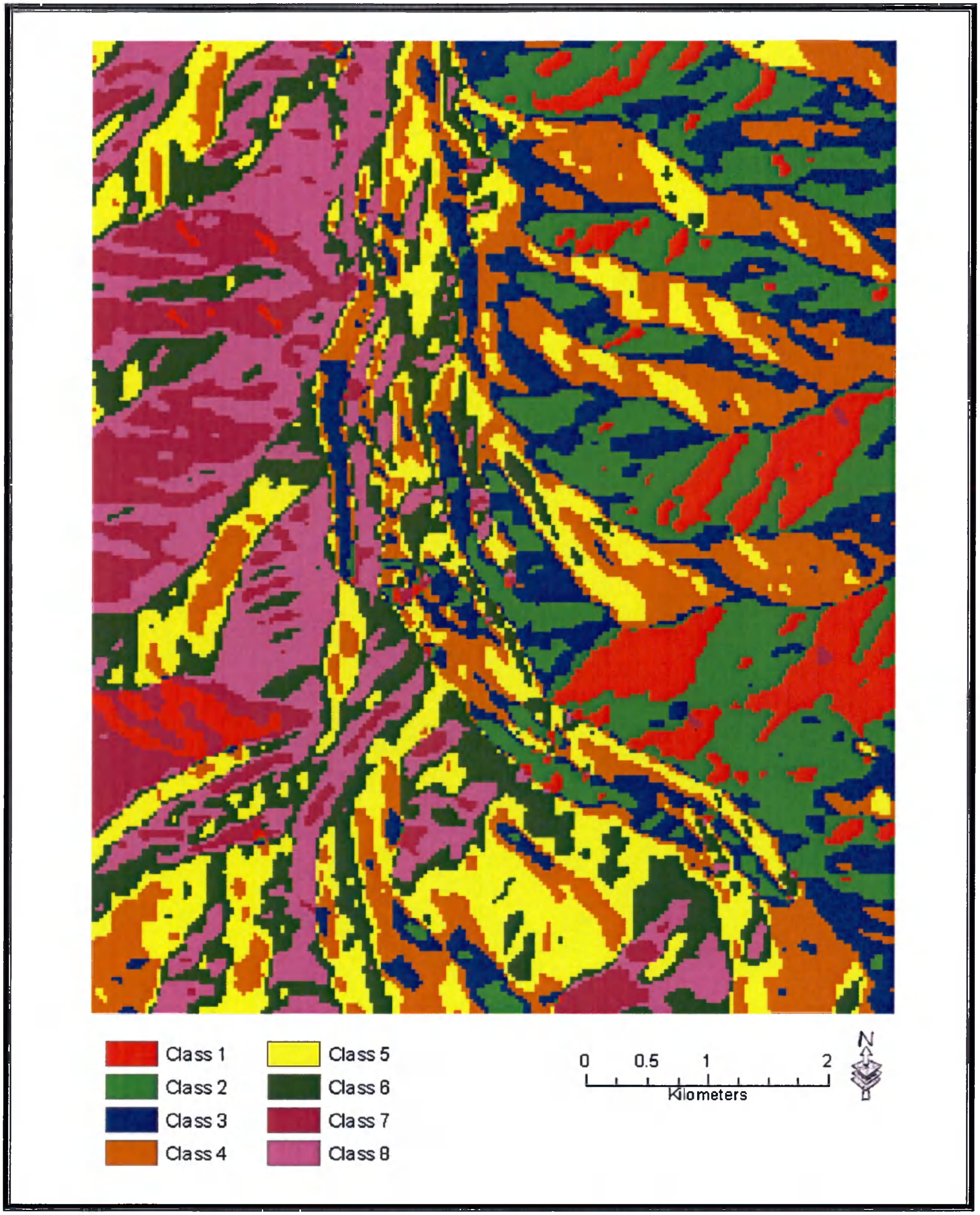


Figure 5.28: Slope-aspect ETFOs map of Raikot Glacier.

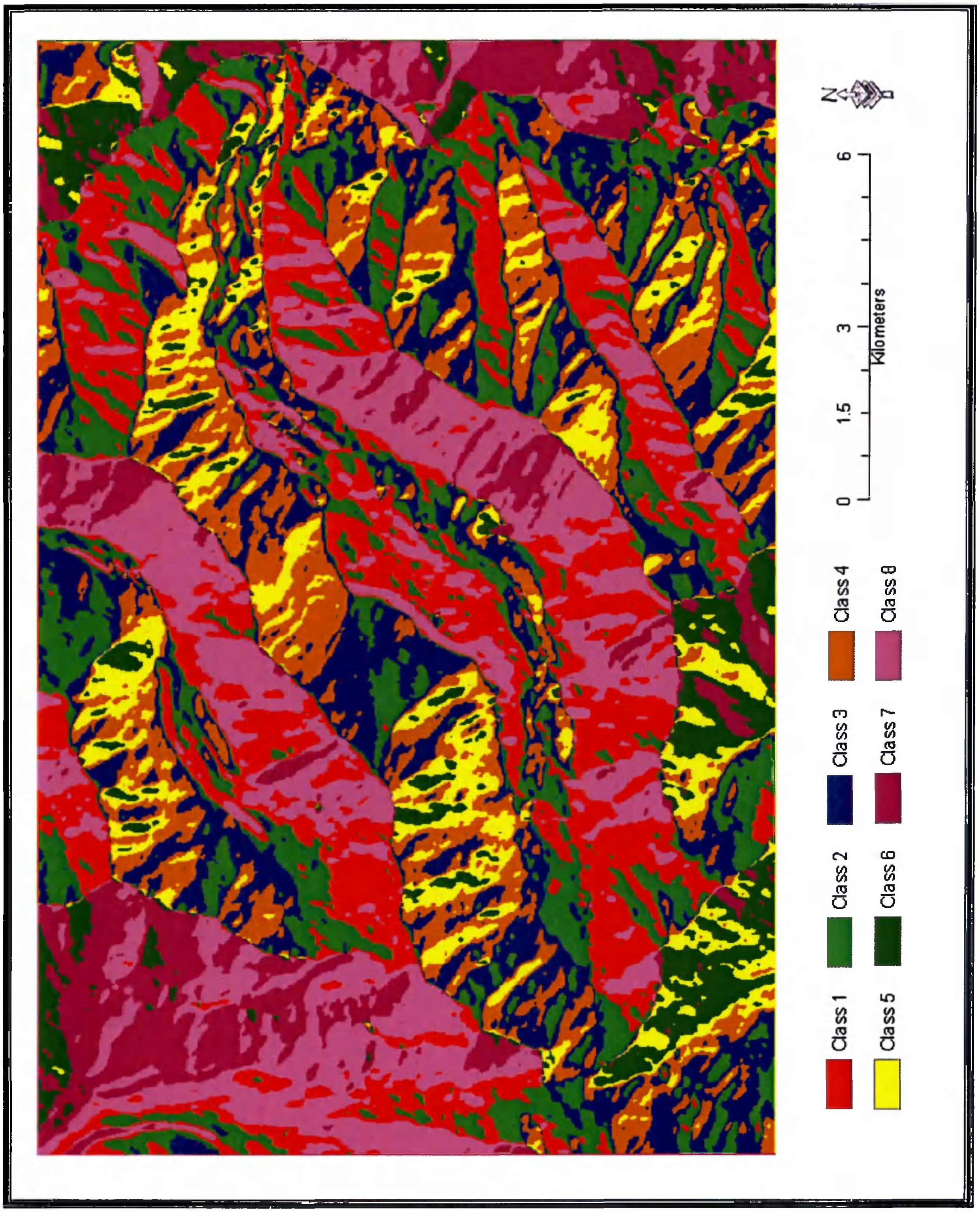


Figure 5.29: Slope-aspect ETFOs map of Sachen Glacier.

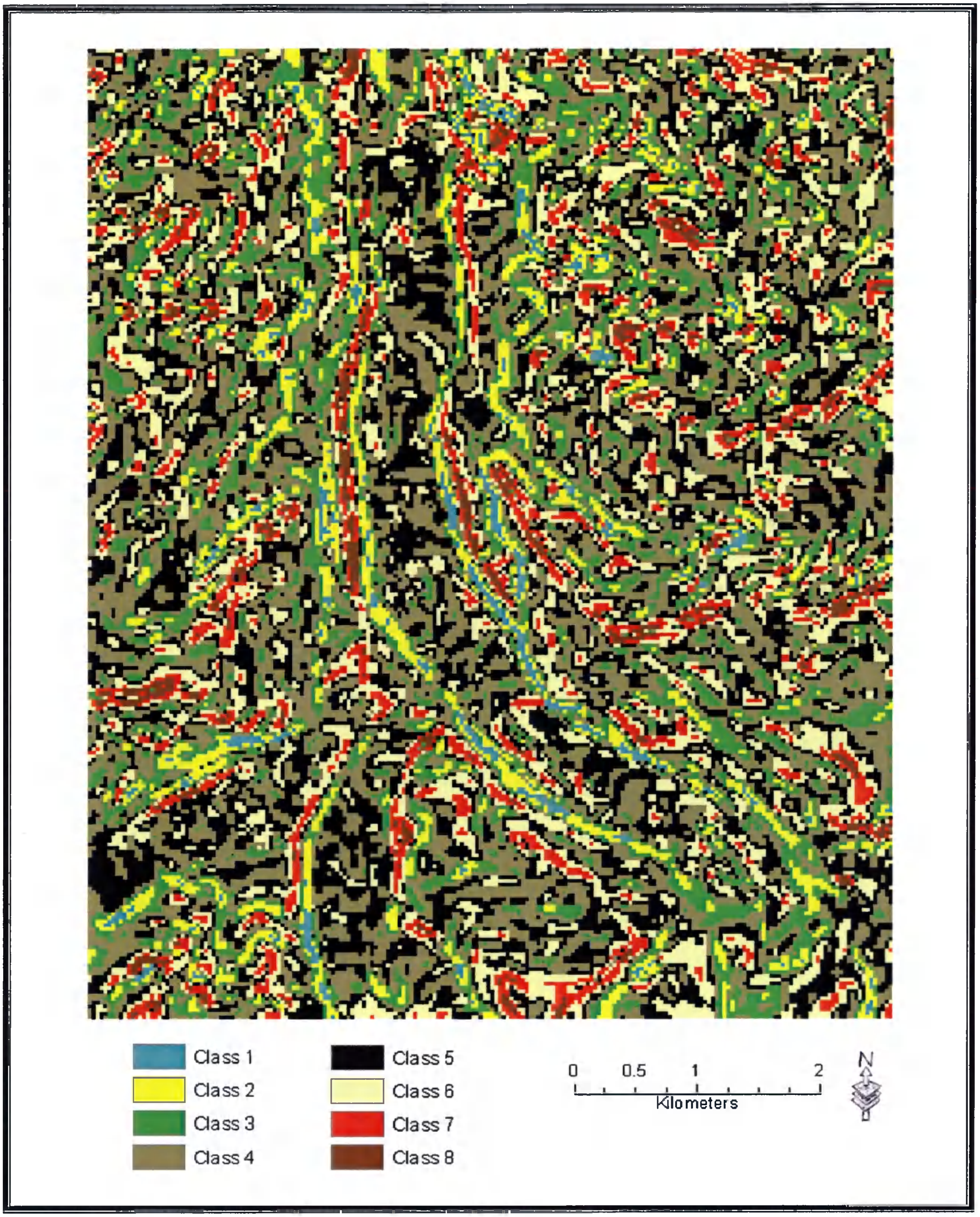


Figure 5.30: Profile curvature ETFOs map of Raikot Glacier.

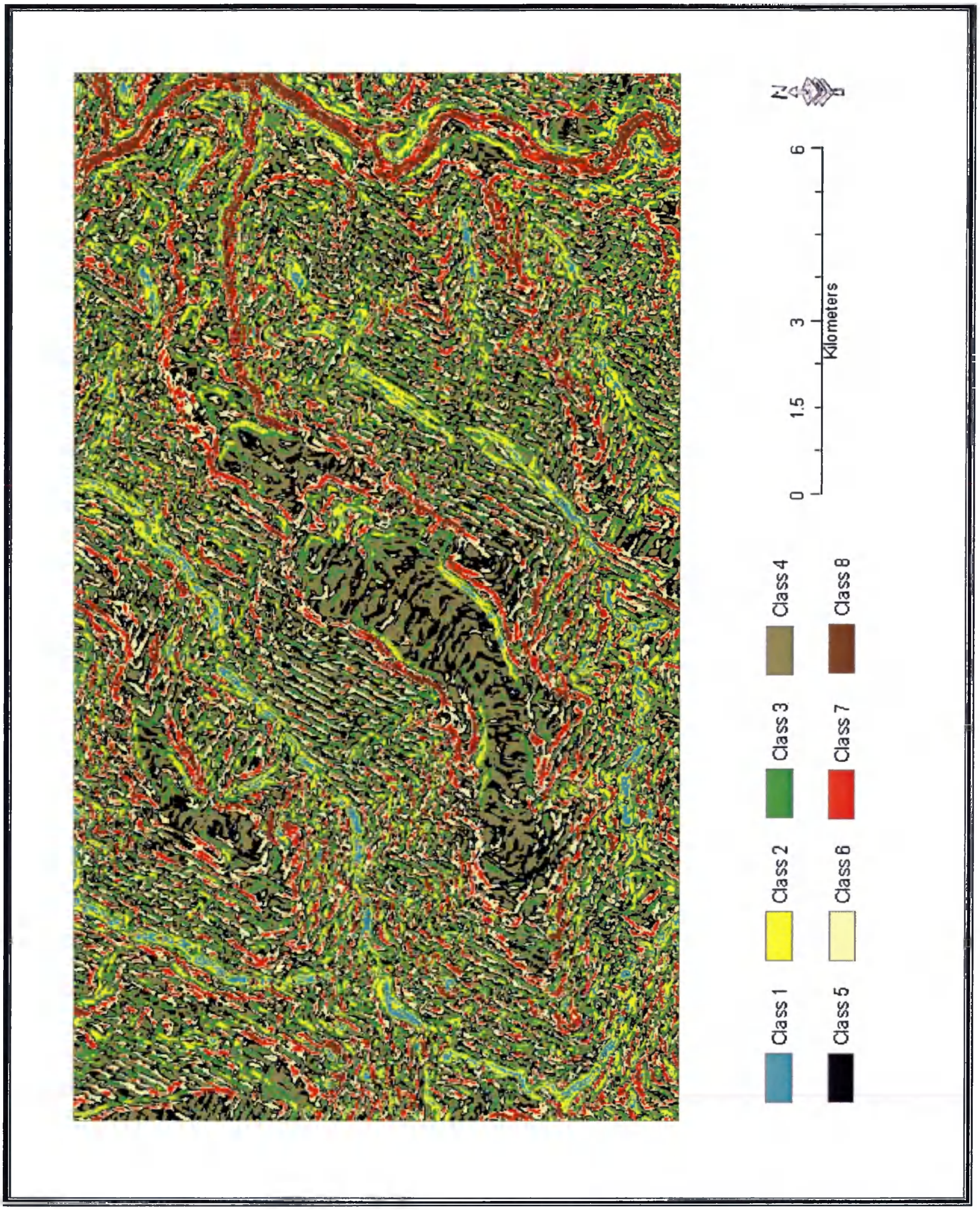


Figure 5.31: Profile curvature ETFOs map of Sachen Glacier.

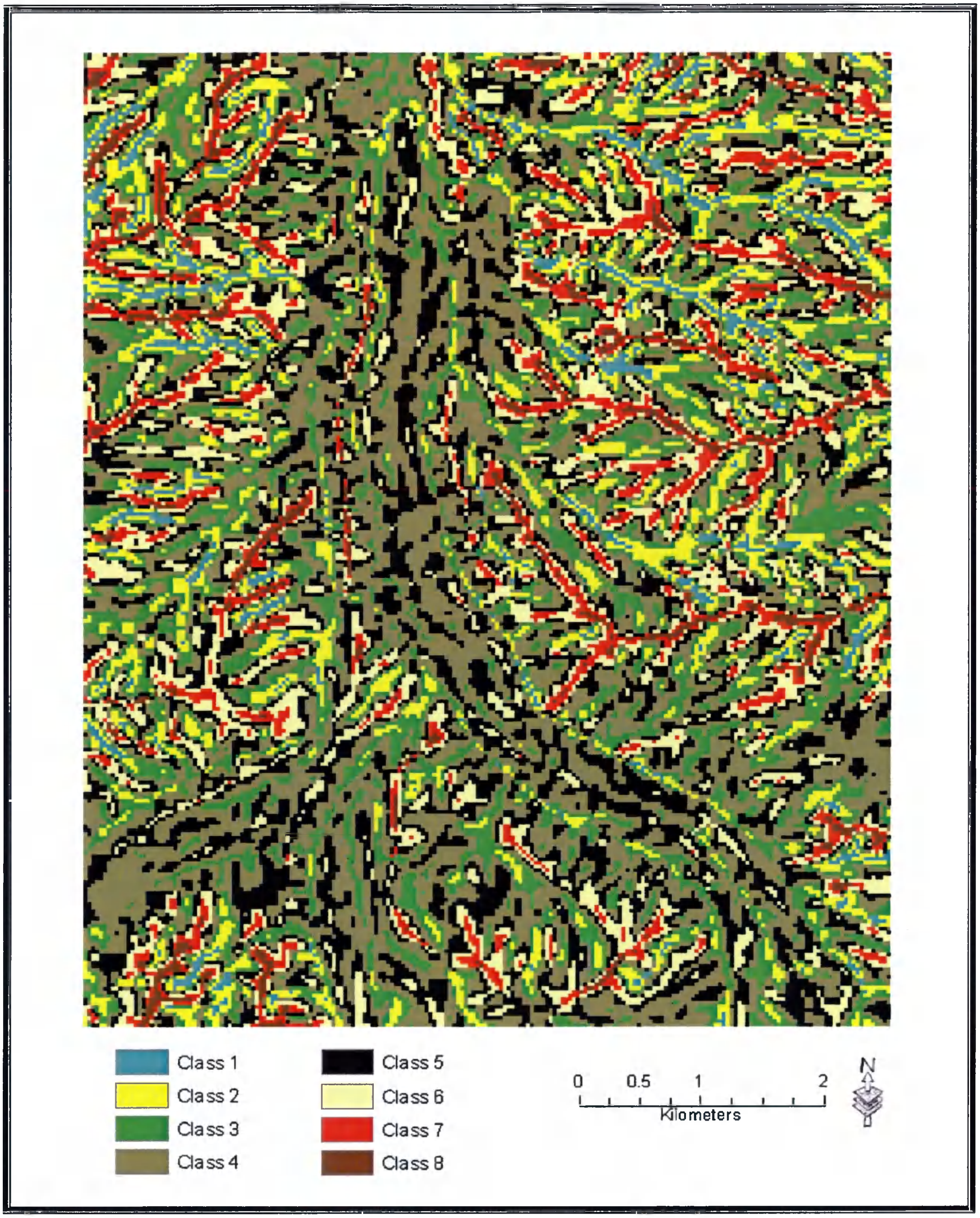


Figure 5.32: Planimetric curvature ETFOs map of Raikot Glacier.

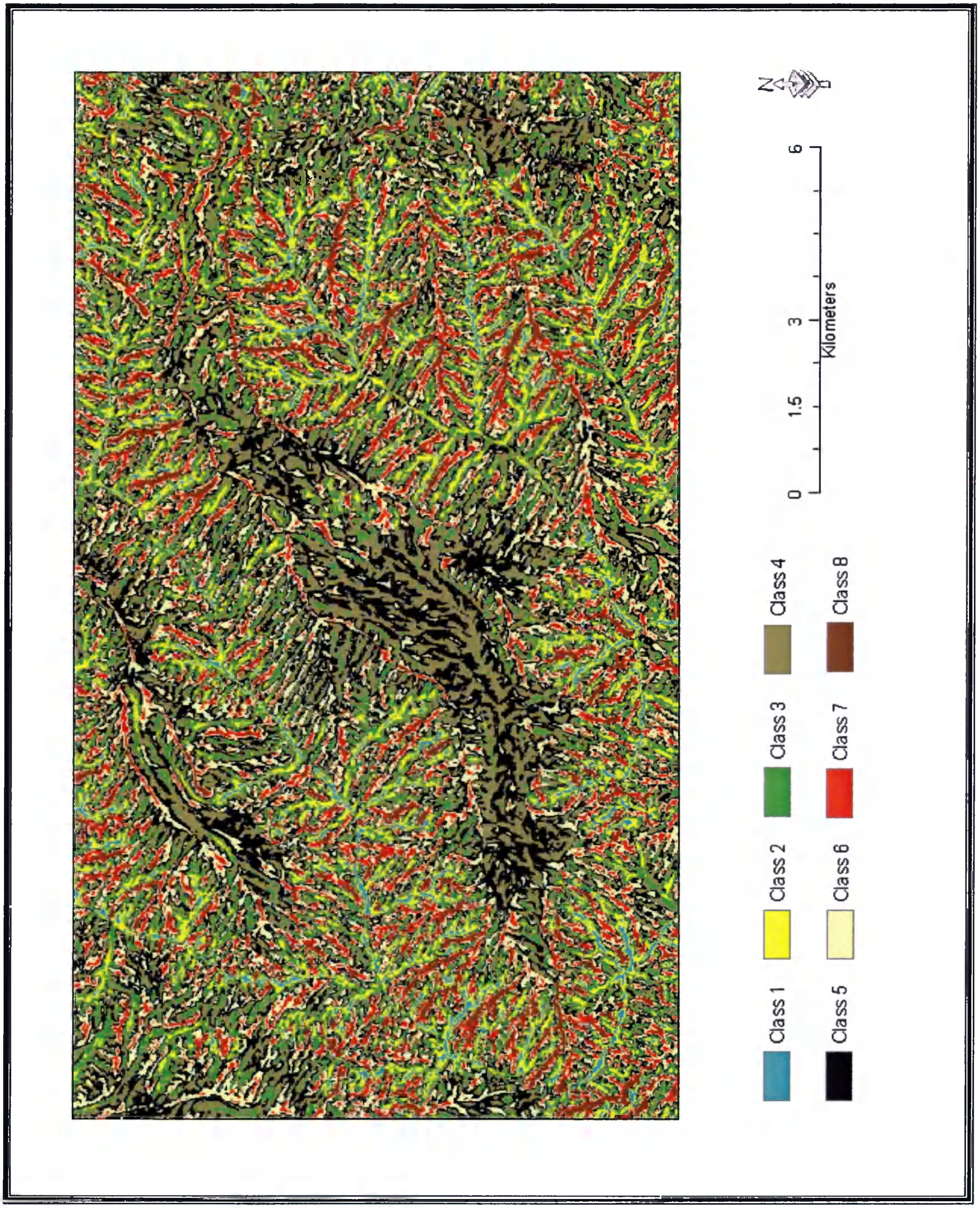


Figure 5.33: Planimetric curvature ETFOs map of Sachen Glacier.

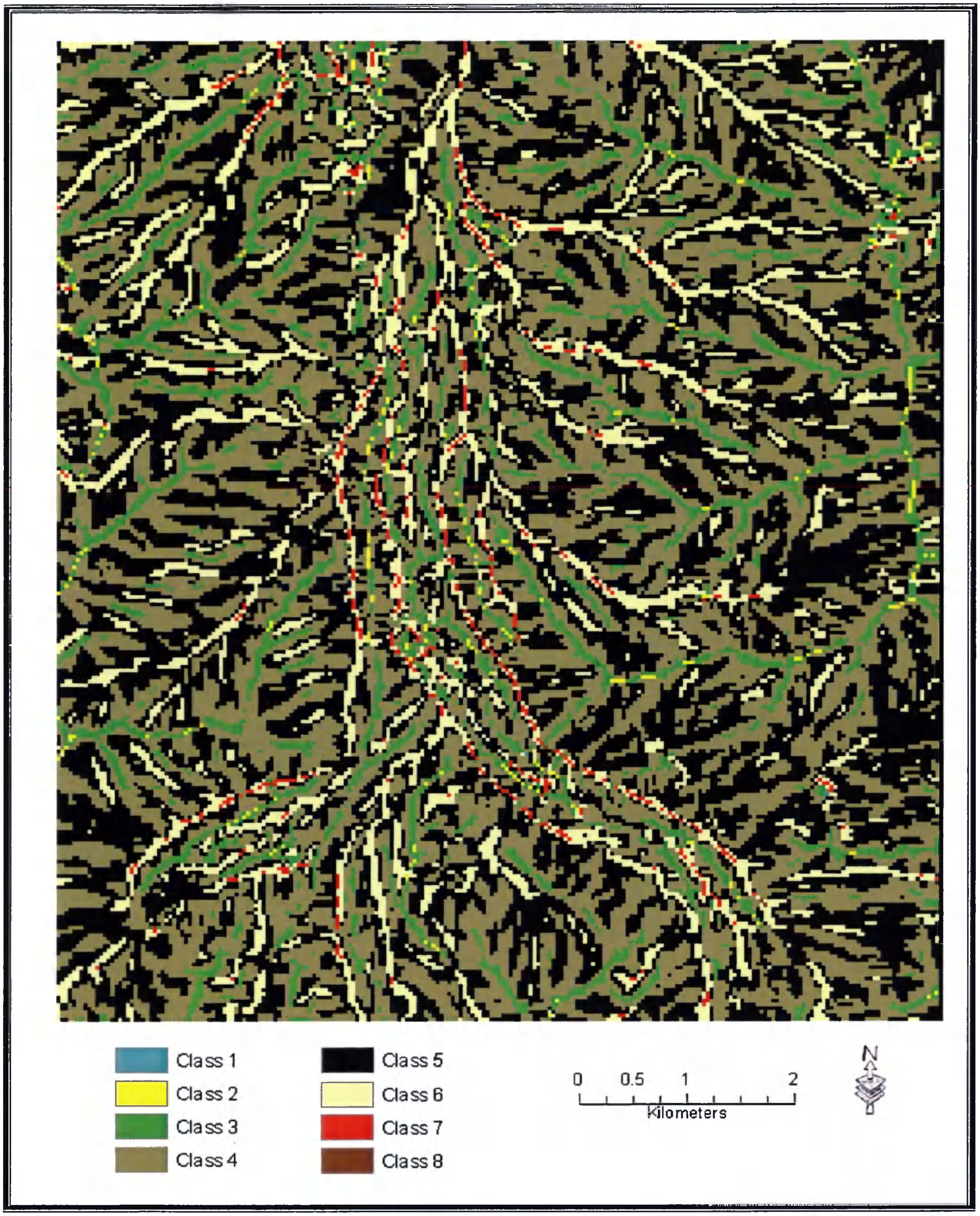


Figure 5.34: Tangential curvature ETFOs map of Raikot Glacier.

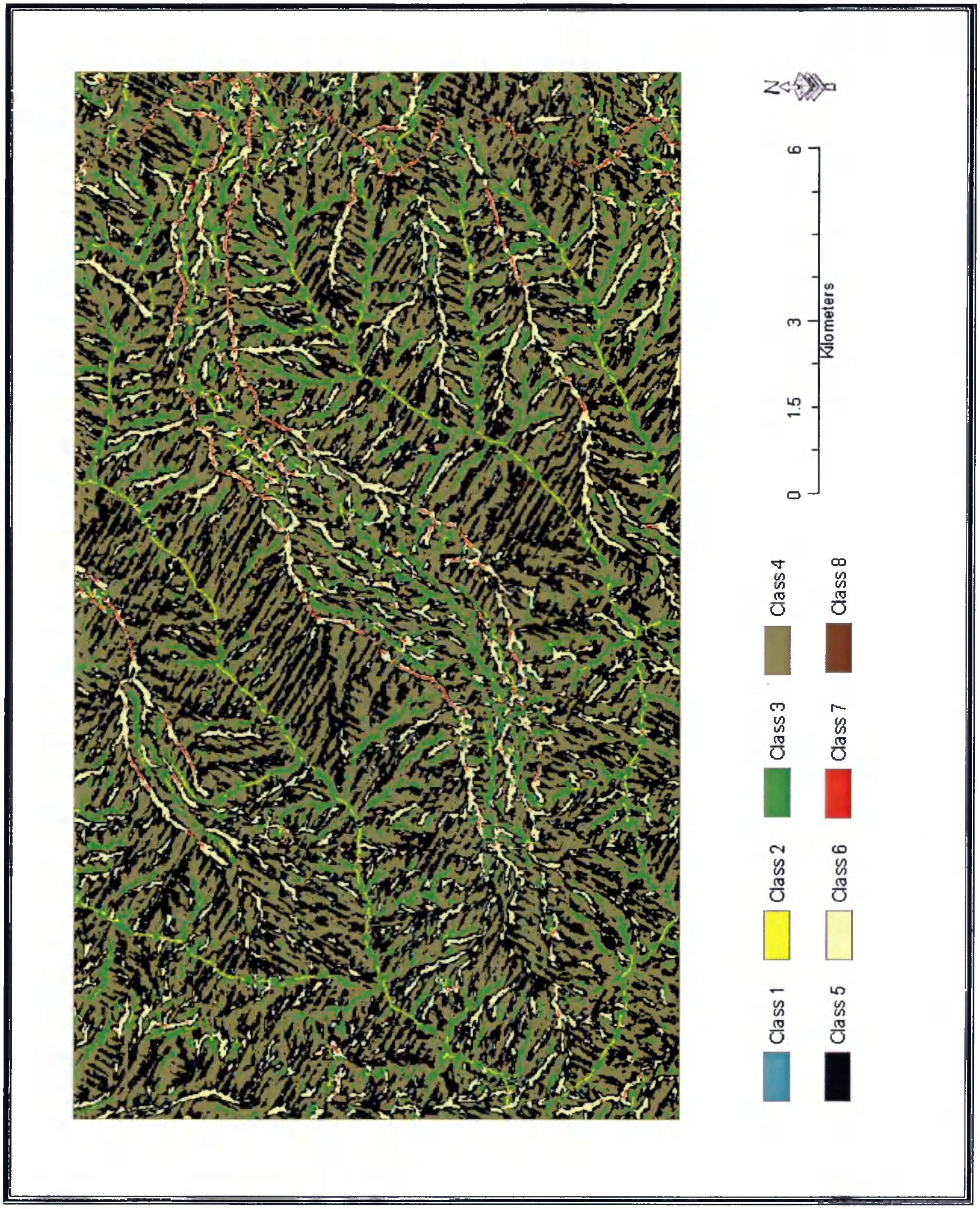


Figure 5.35: Tangential curvature ETFOs map of Sachen Glacier.

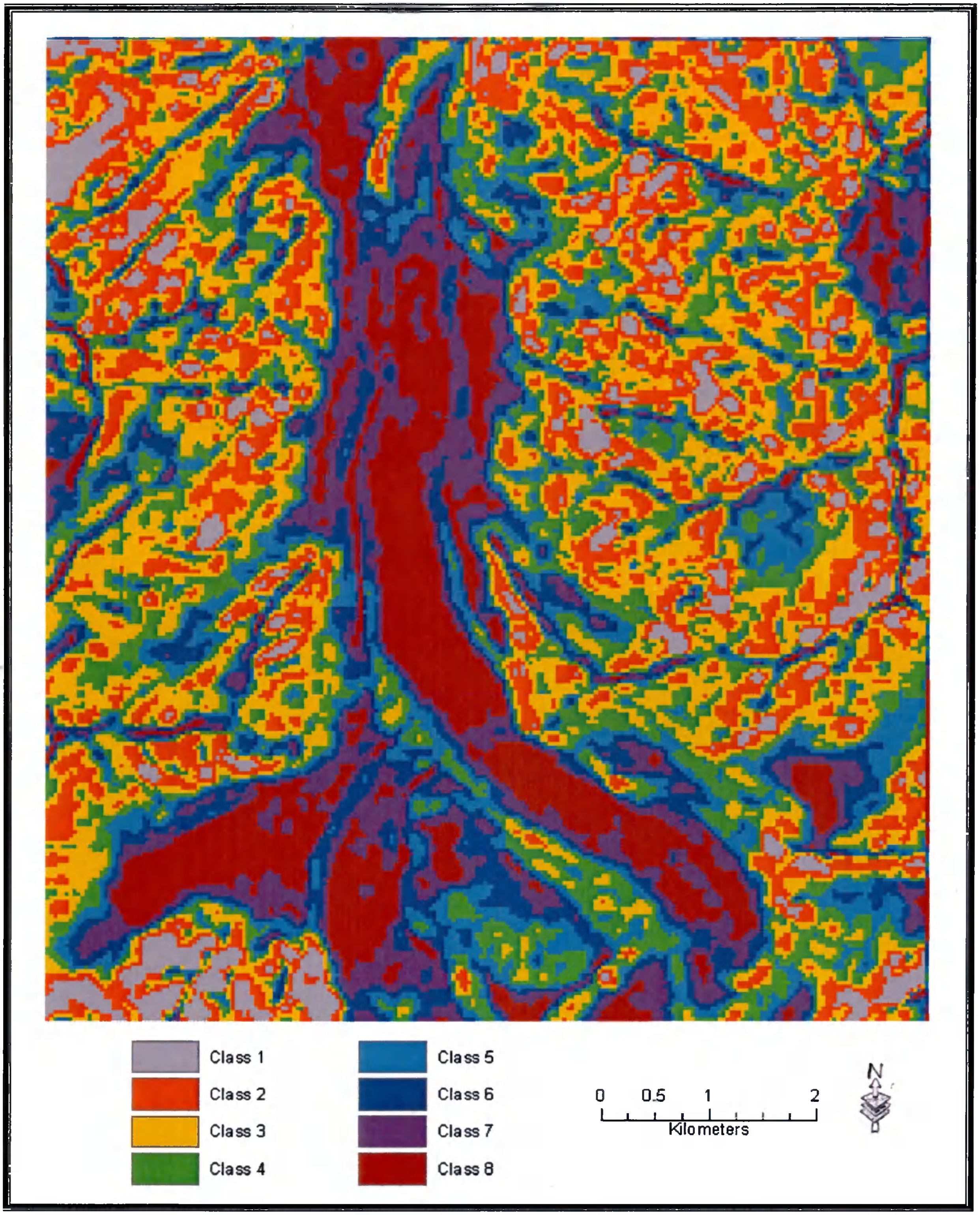


Figure 5.36: Positive openness ETFOs map of Raikot Glacier with 100 m radius.

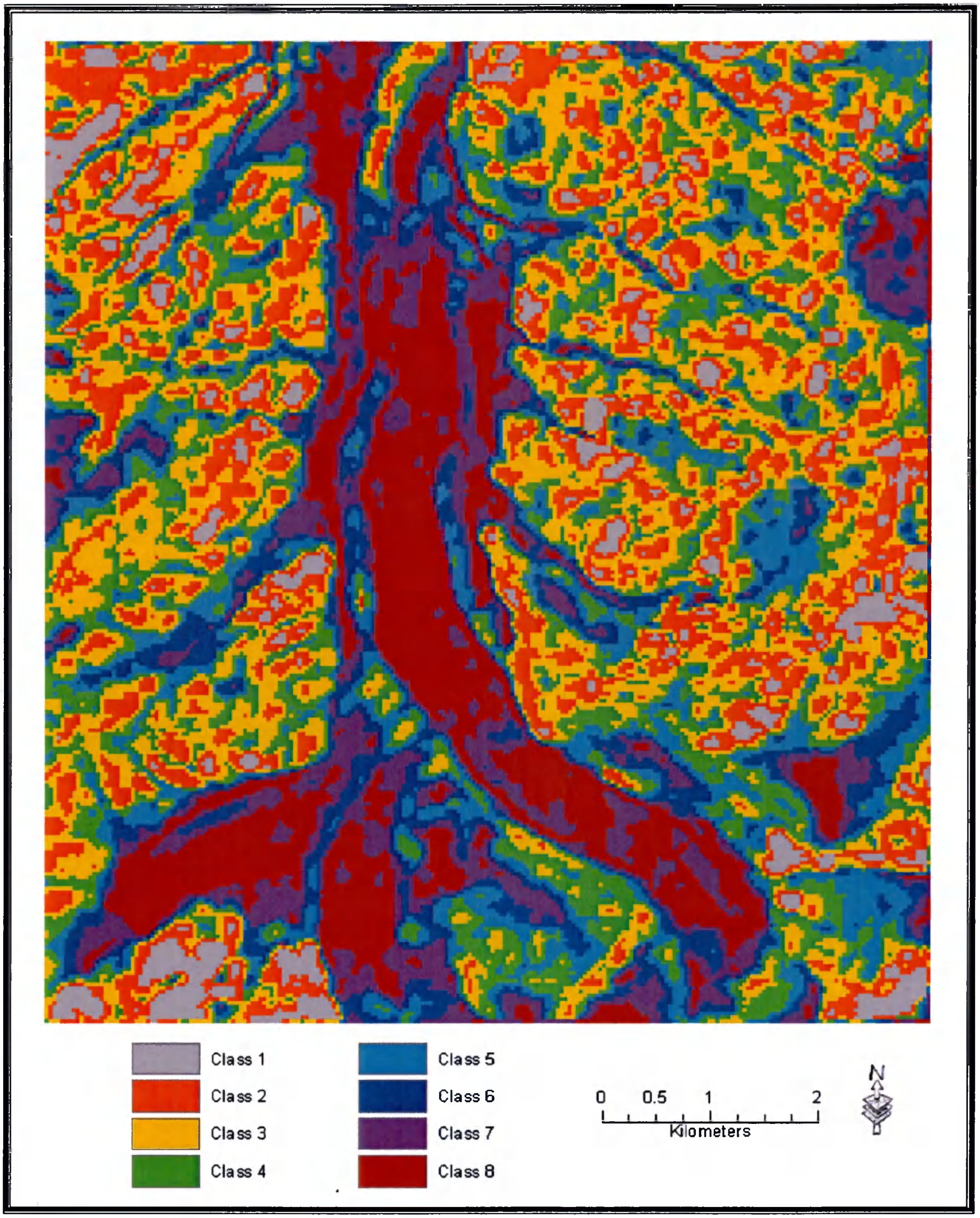


Figure 5.37: Negative openness ETFOs map of Raikot Glacier with 100 m radius.

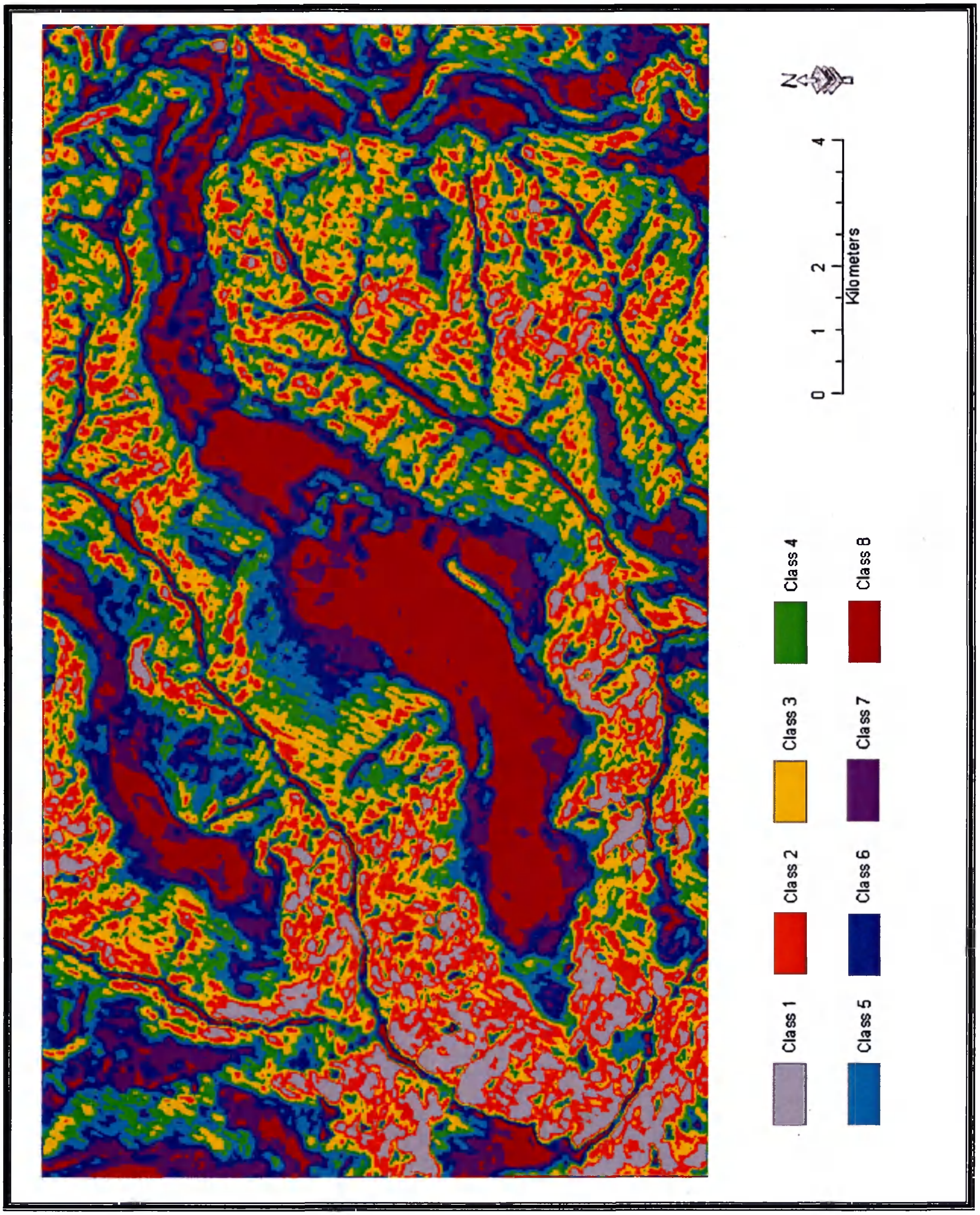


Figure 5.38: Positive openness ETFOs map of Sachen Glacier with 100 m radius.

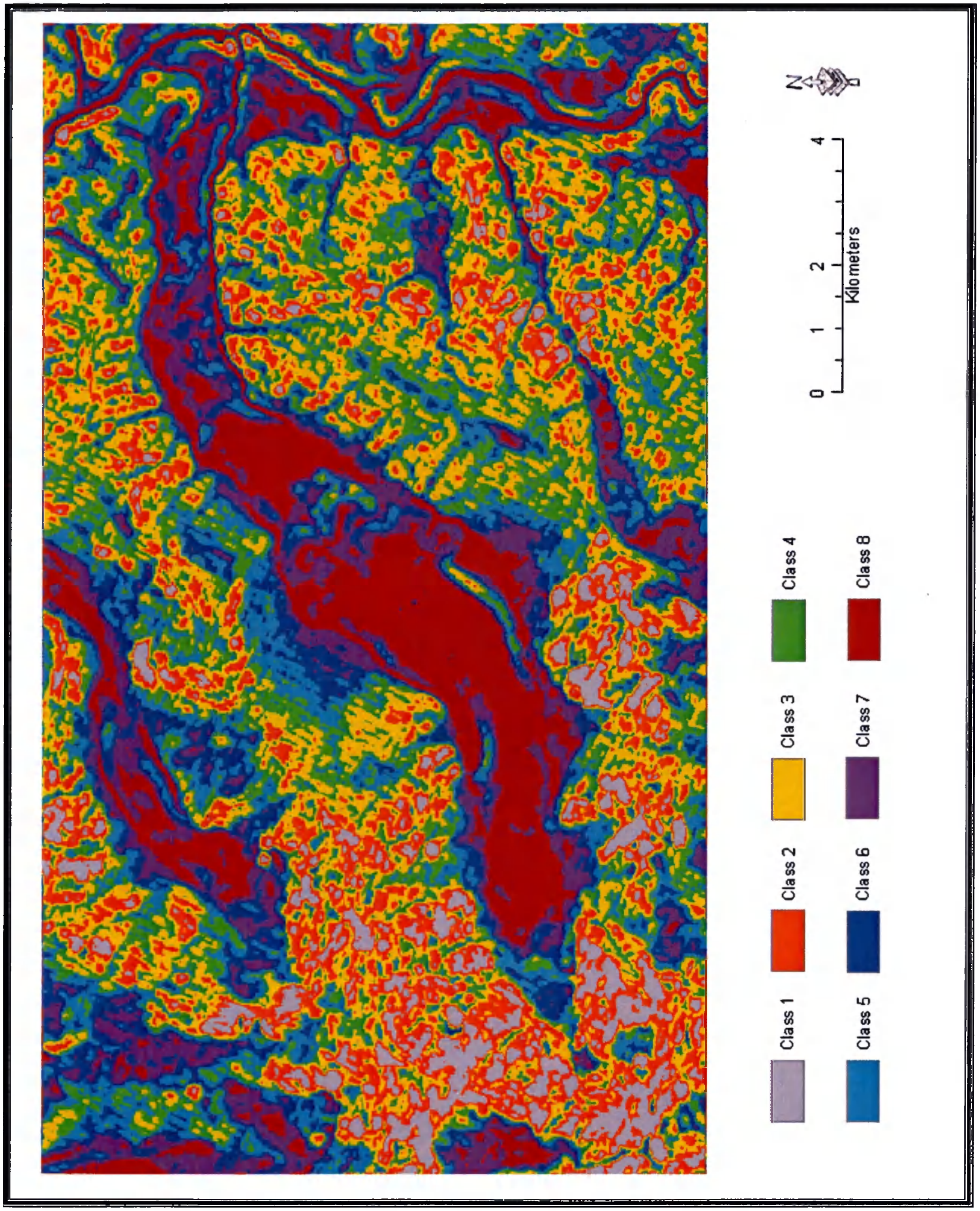


Figure 5.39: Negative openness ETFOs map of Sachen Glacier with 100 m radius.

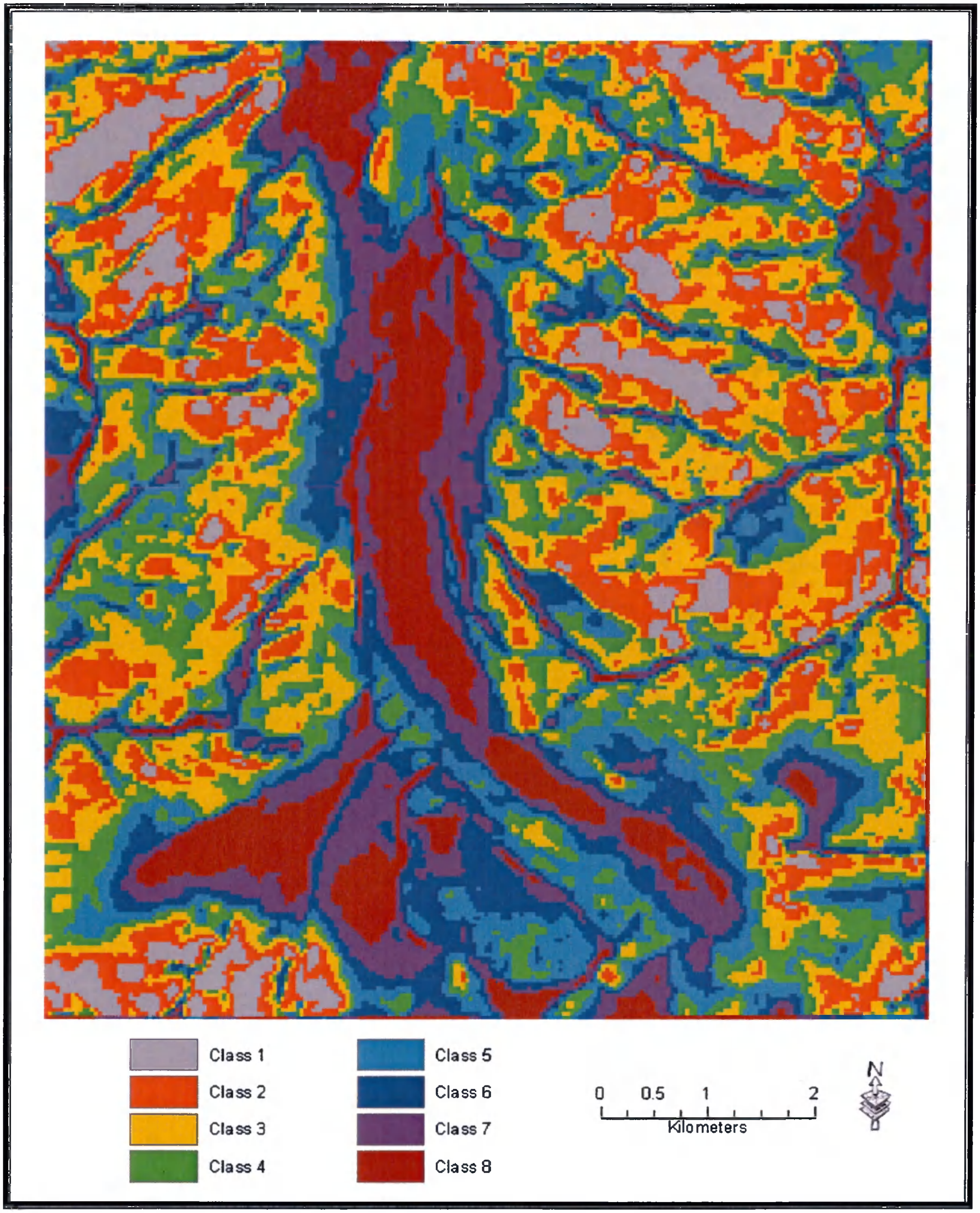


Figure 5.40: Positive openness ETFOs map of Raikot Glacier with 500 m radius.

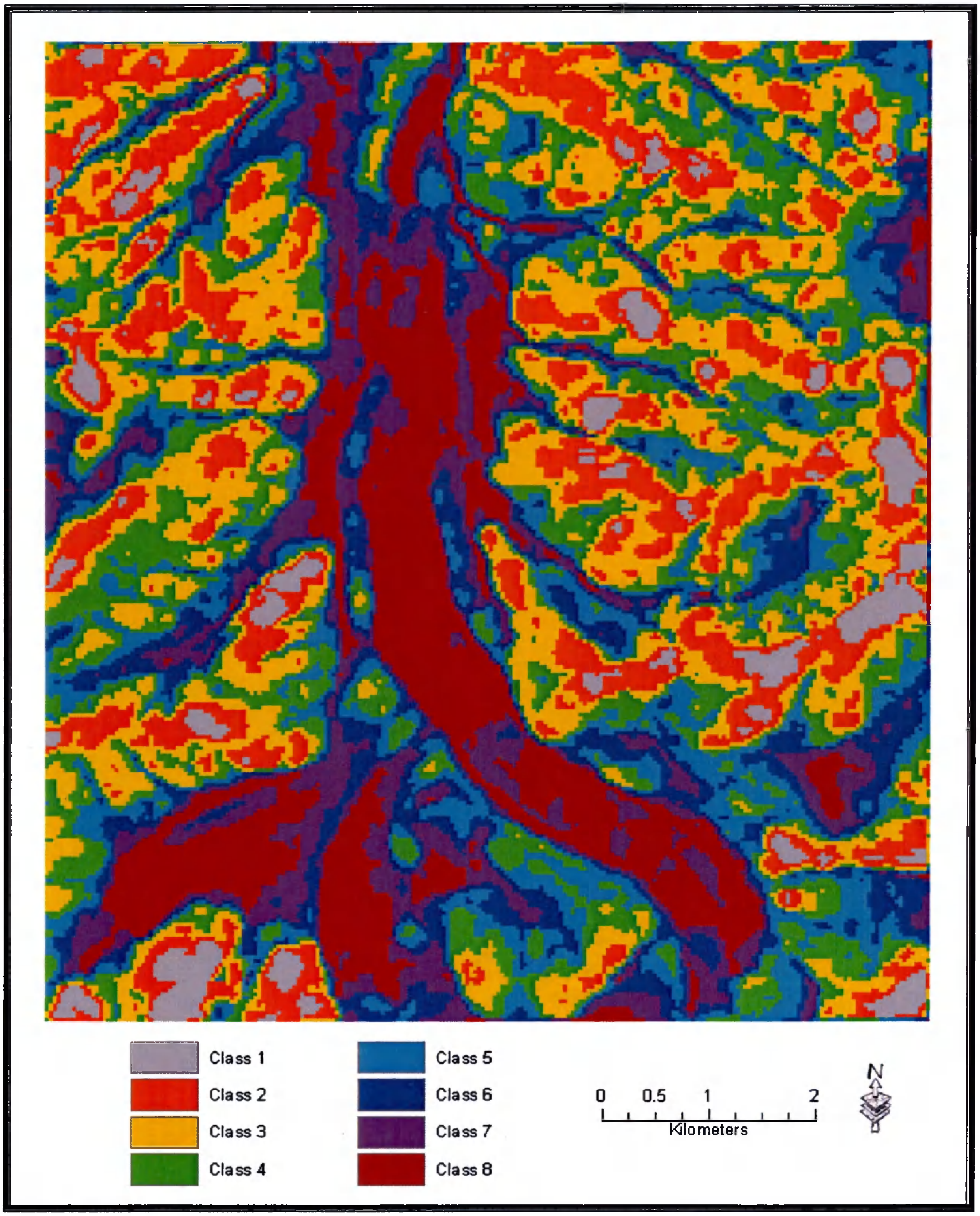


Figure 5.41: Negative openness ETFOs map of Raikot Glacier with 500 m radius.

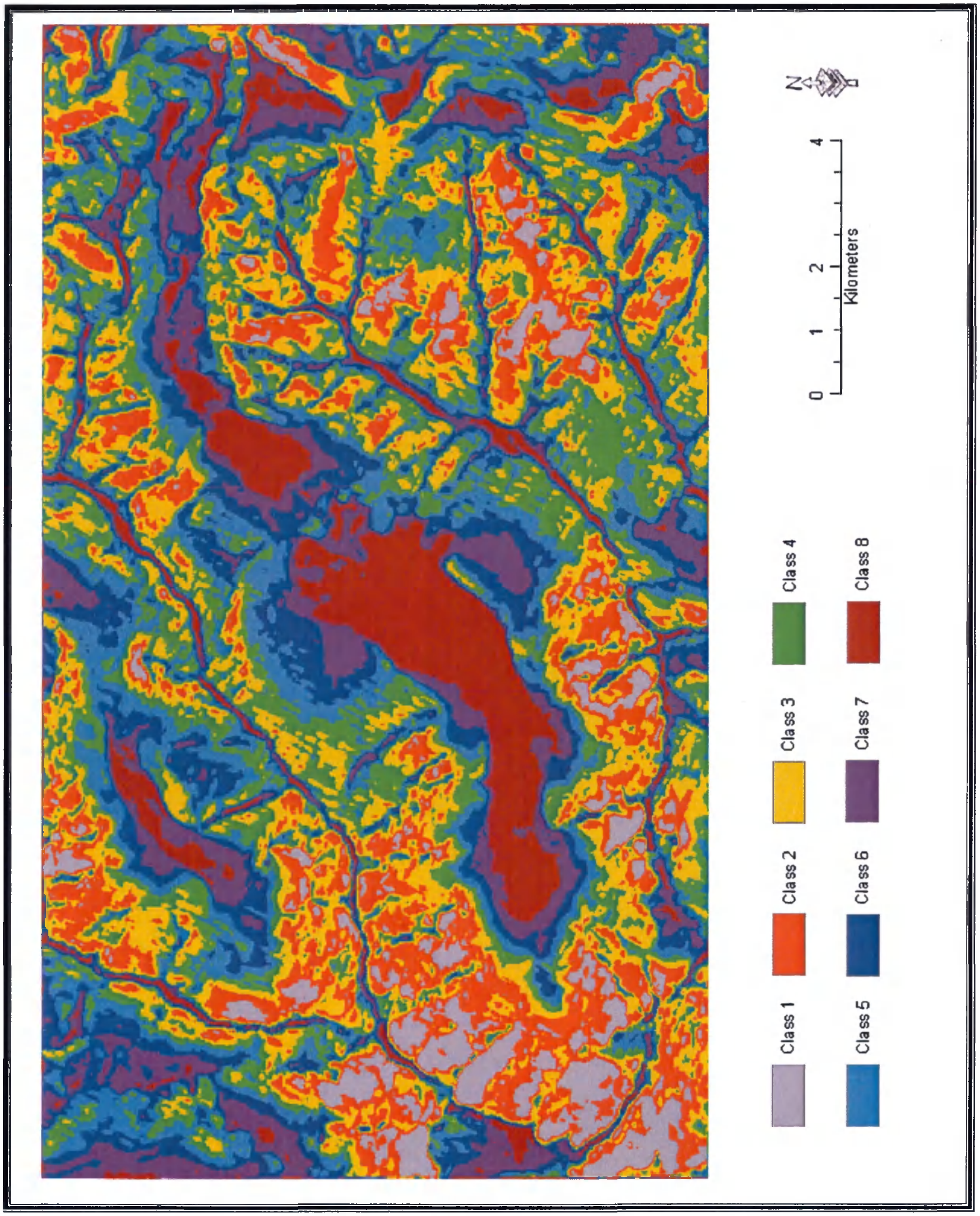


Figure 5.42: Positive openness ETFOs map of Sachen Glacier with 500 m radius.

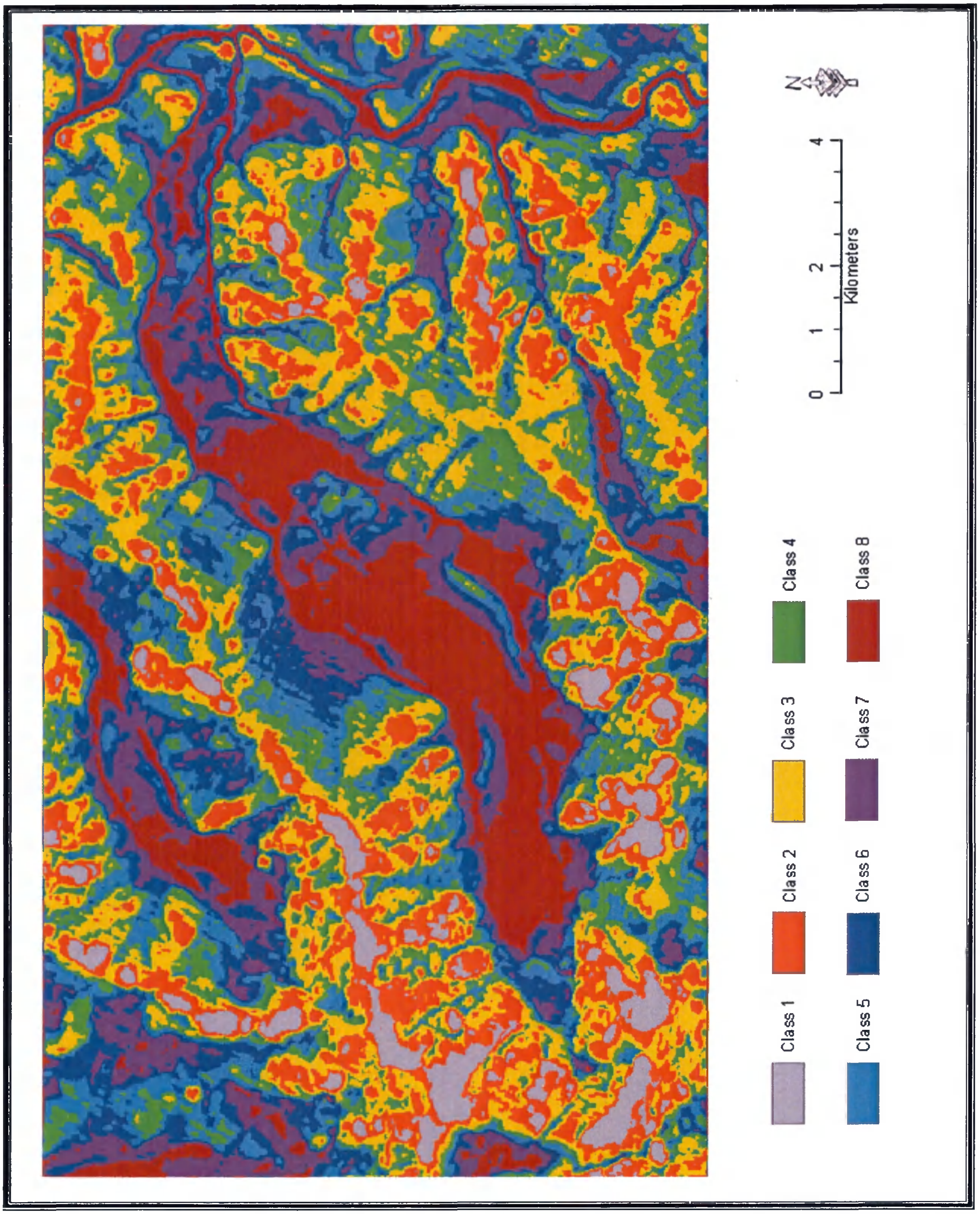


Figure 5.43: Negative openness ETFOs map of Sachen Glacier with 500 m radius.

5.3 Toposequence

Slope-angle profiles from slope-aspect objects demonstrate the potential of the differentiation of an active glacier surface from non-glacier topography. As previous mentioned, glacier surfaces exhibit high spatial variability of slope-facets due to a rapidly changing surface. Consequently, slope-facet slope angles are relatively small compared to the surrounding basin slopes. The object-oriented toposequence analysis was based on slope-aspect objects that are closely related to slope-facets, and generated an altitude-slope-angle function for each object. The results for five locations on the Raikot Glacier are displayed in figures 5.46 and 5.47. Notice that the slope angles are relatively low for the entire glacier surface. Conversely, steep valley-walls exhibit greater relief and high slope-angles. The results of a profile across the valley are displayed in figures 5.48 and 5.49. Notice the difference in slope angles for the relative altitude ranges, with the glacier surface characterized by low slope angles, and the valley-wall characterized by high slope angles. This analysis demonstrates the potential of using object oriented analysis for characterizing the spatial structure of the topography and for identification and classification of landscape features and characteristics. Toposequence information represents a unique type of information that has not been effectively utilized in geomorphological mapping. Its integration into an object-oriented analysis approach needs to be further investigated.

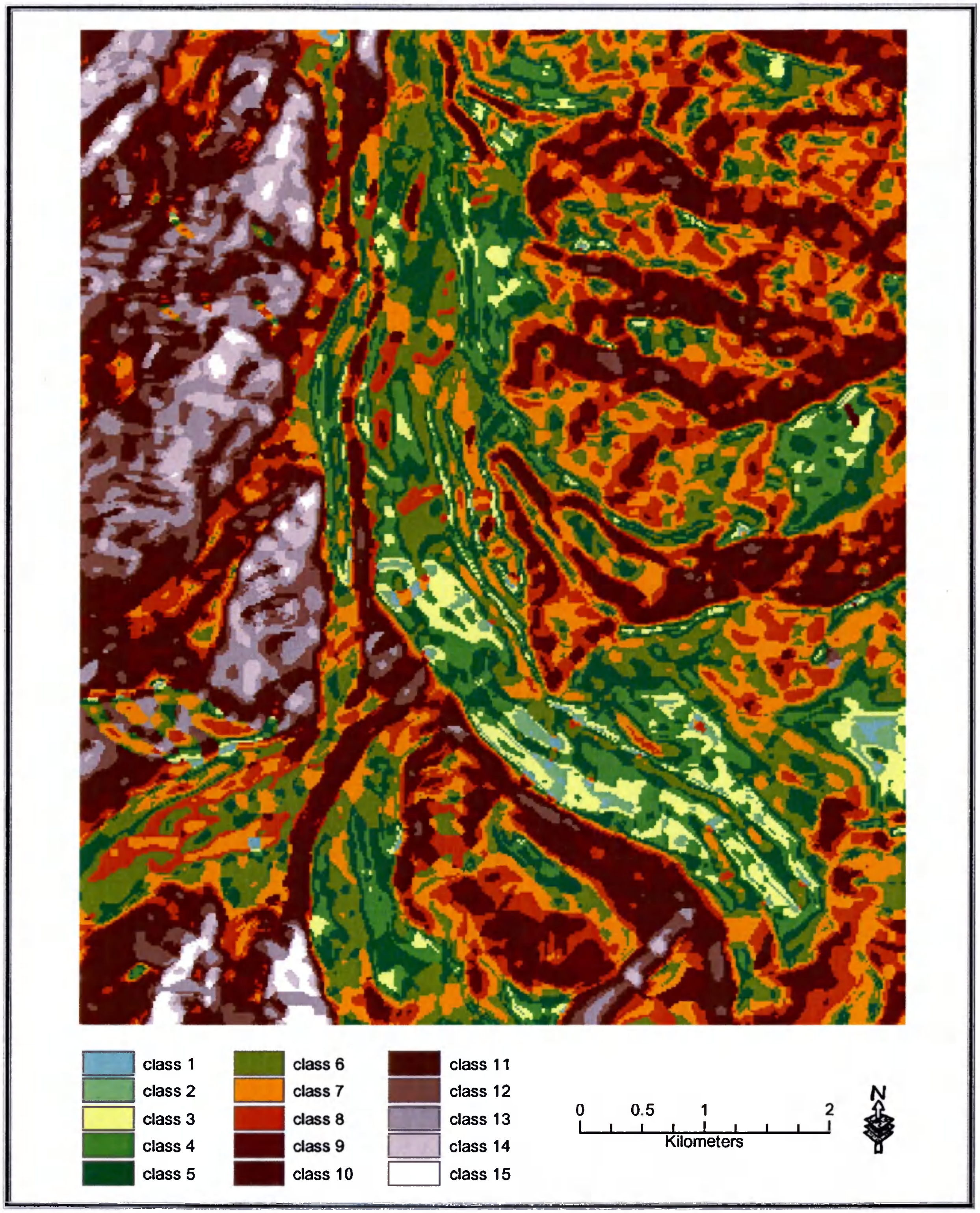


Figure 5.44: Slope-facets ETFOs map of Raikot Glacier.

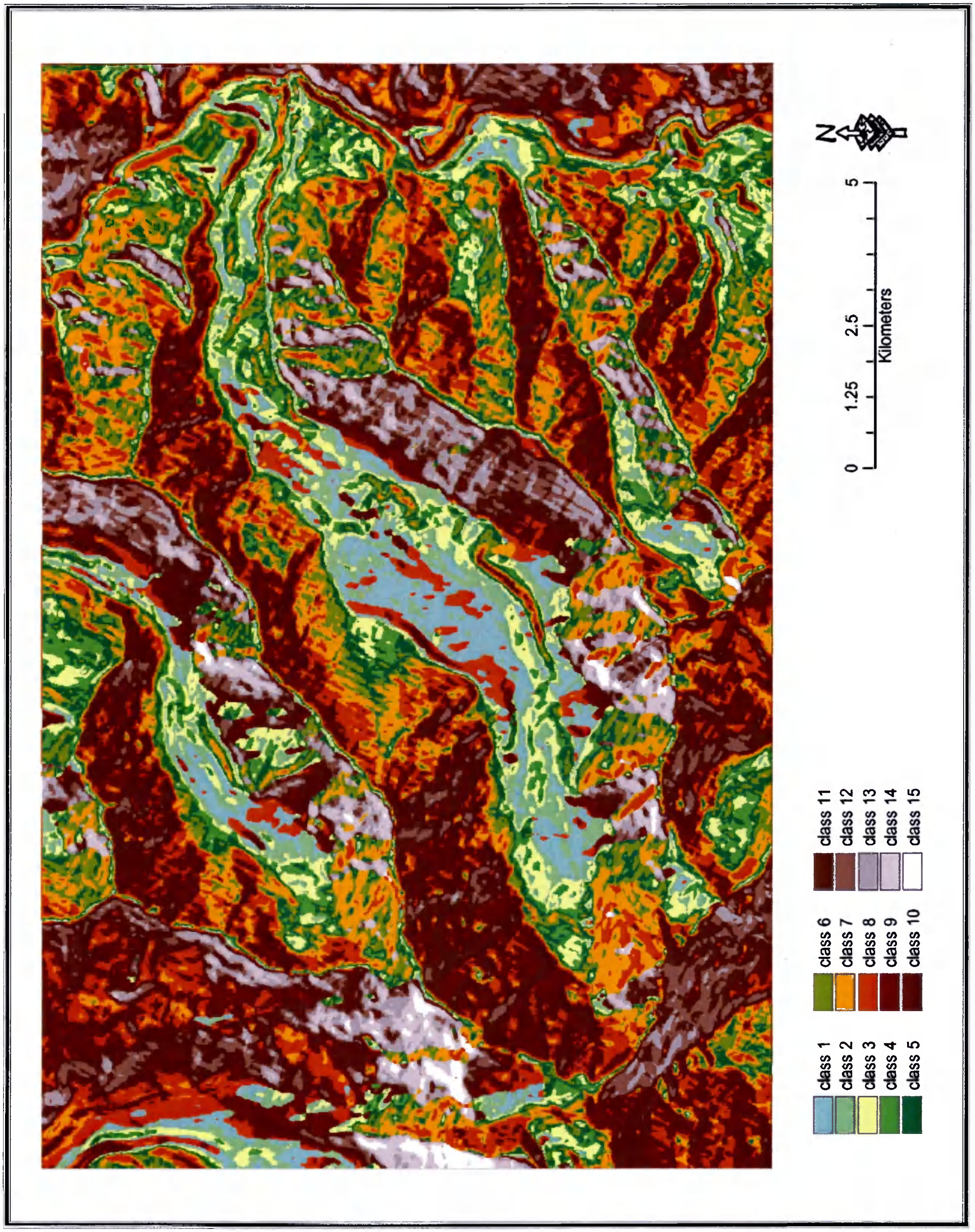


Figure 5.45: Slope-facets ETFOs map of Sachen Glacier.

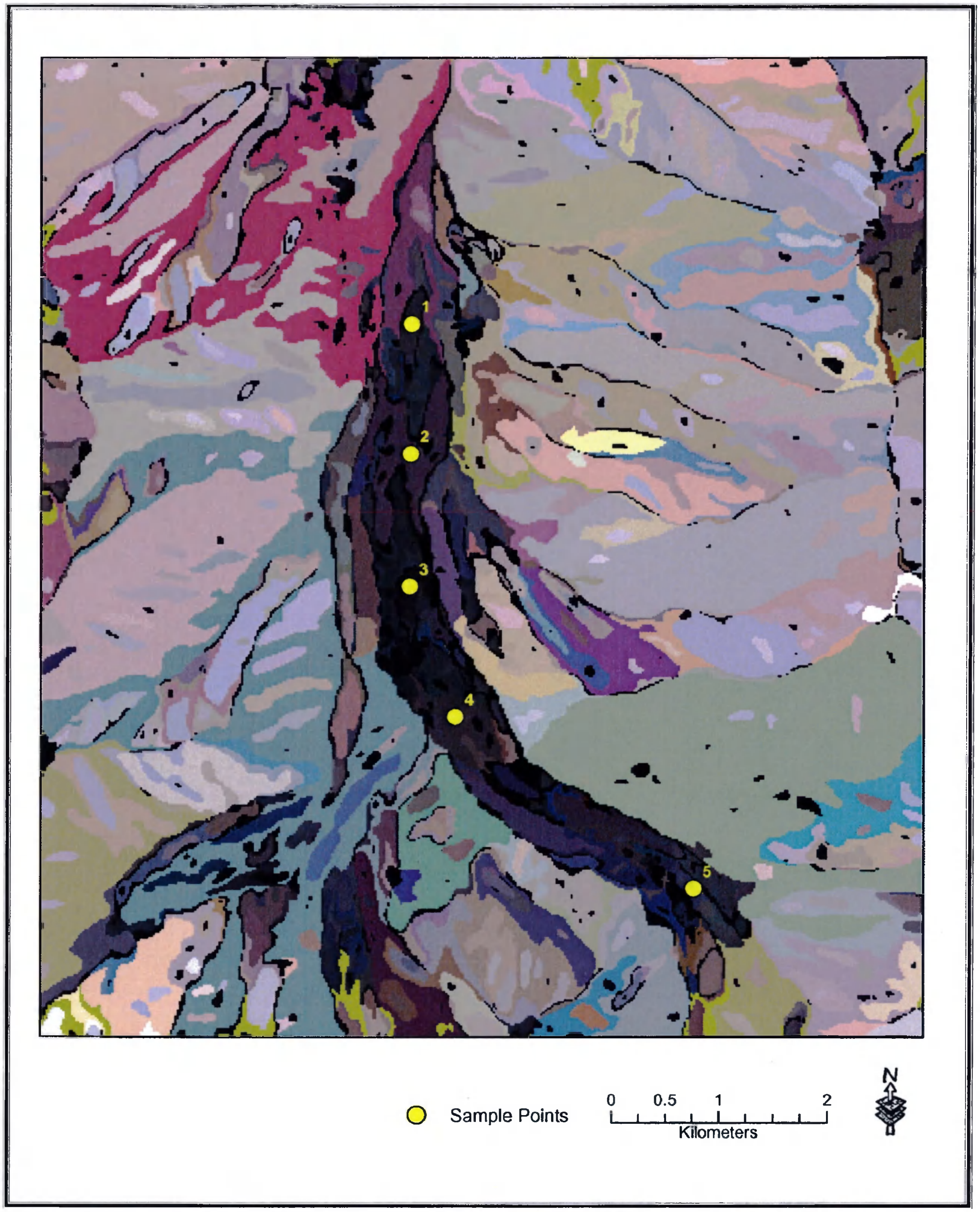


Figure 5.46: Map of toposequence objects at Raikot Glacier with profile points along the glacier (see figure 5.47 for resulting slope-angle curves of chosen profile points/slope-aspect objects).

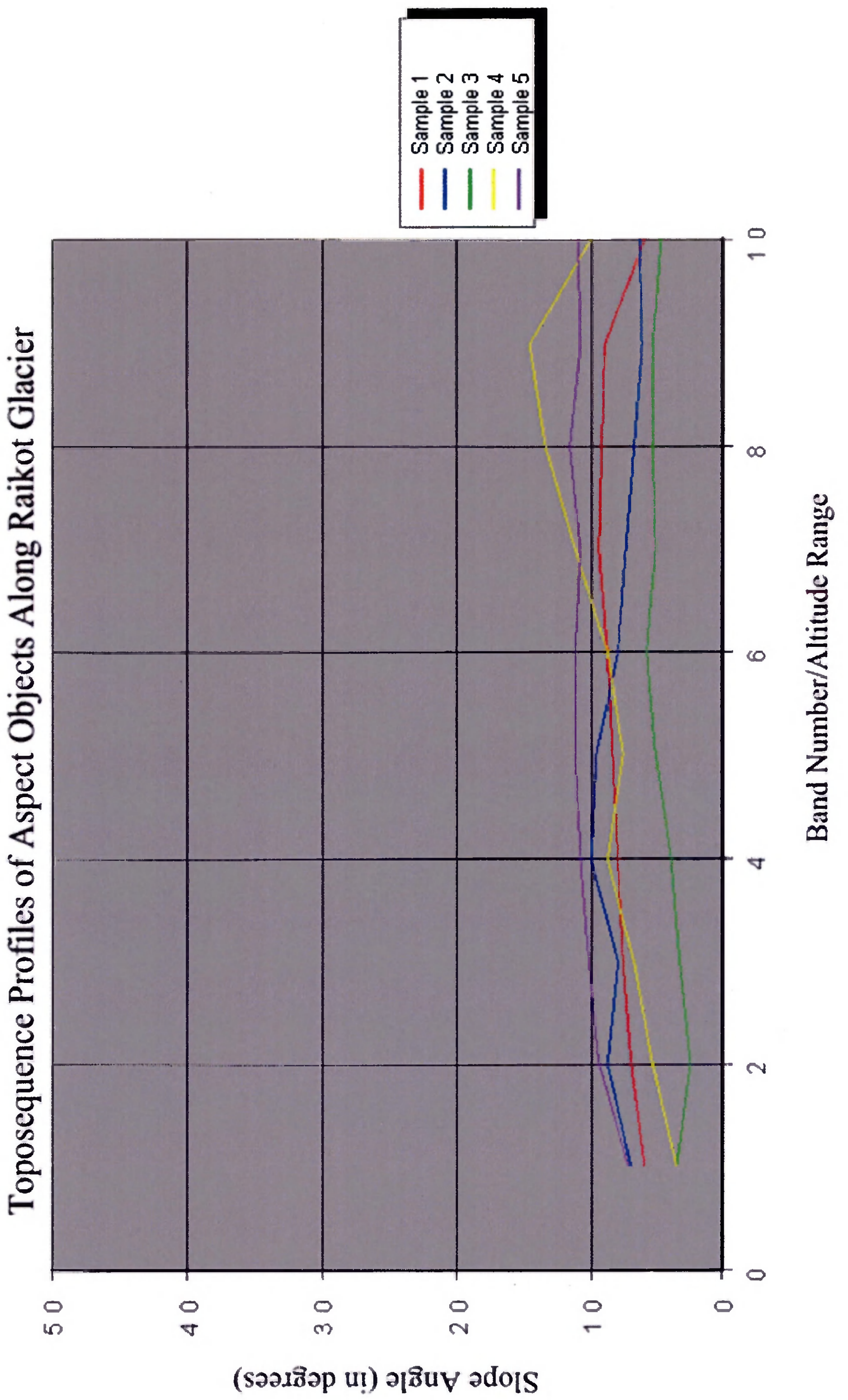


Figure 5.47: Toposequence profiles depicting slope-angles values of ten different altitude ranges within chosen slope-aspect objects along Raikot Glacier (see figure 5.46 for the location of slope-aspect objects or profile points).

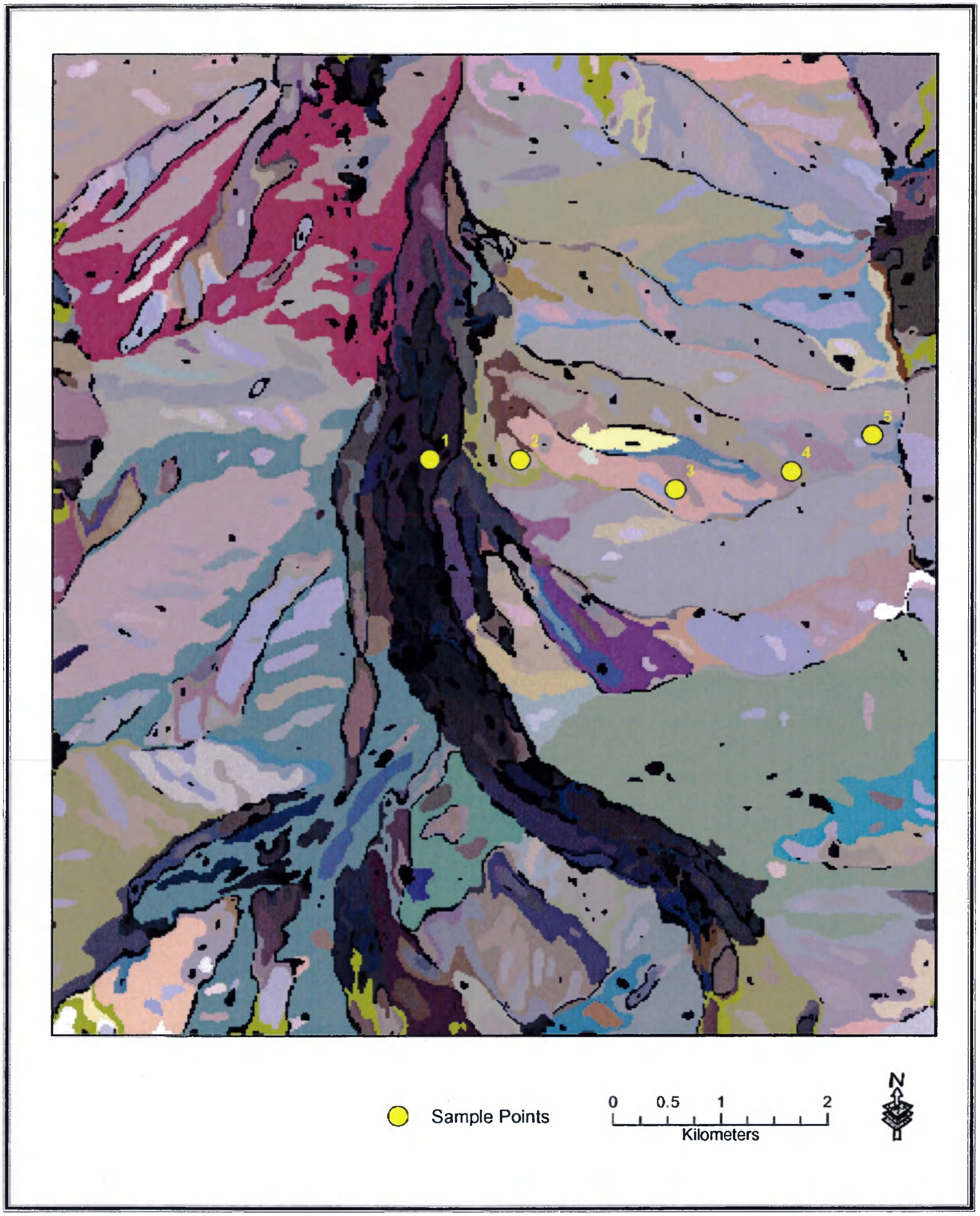


Figure 5.48: Map of toposequence objects at Raikot Glacier with profile points across the glacier (see figure 5.49 for resulting slope-angle curves of chosen profile points/slope-aspect objects).

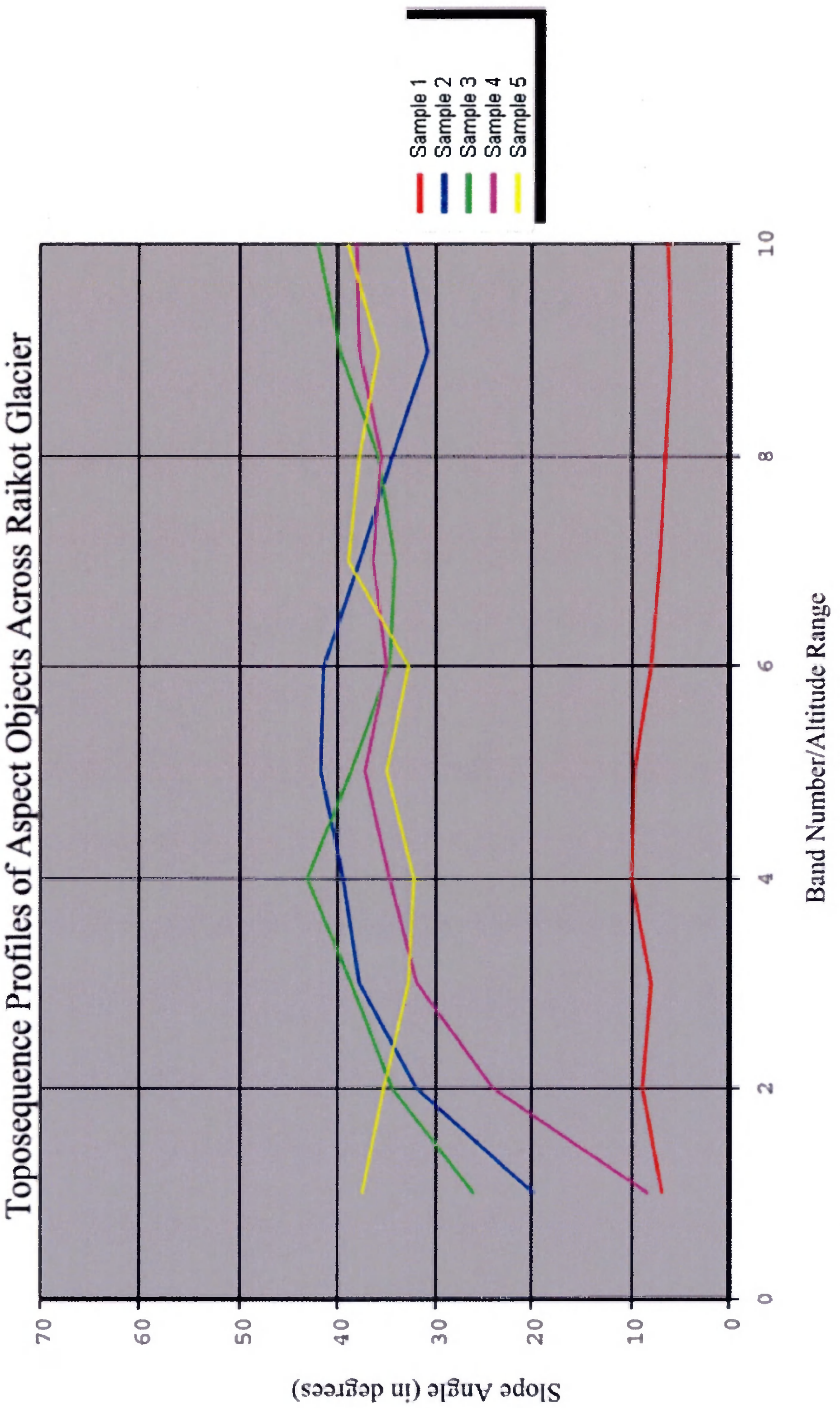


Figure 5.49: Toposequence profiles depicting slope-angles values of ten different altitude ranges within chosen slope-aspect objects across Raikot Glacier (see figure 5.48 for the location of slope-aspect objects or profile points).

Chapter 6

Discussion

Automated mapping of glacier surfaces is a very difficult endeavor. The effective utilization of hierarchy theory to characterize and map the complexity of glacier topography is also difficult because a model of a hierarchical system has not been formalized, and mathematical rules to characterize objects at different levels is poorly defined. The existing literature on the use of hierarchy theory is extremely theoretical (Baume, 1991; Hasse, 1969; Koestler, 1967; Mossimann, 1990), with little practical guidance. There have been some attempts to utilize morphometric fields and hierarchy theory in surface mapping (Bishop et al., 2001; Bonk, 2002; Dikau, 1992; Minár, 1995), however, there are still many issues to be addressed.

This research demonstrates that it is very difficult to account for the scale-dependent nature of topography. To address this, elemental form objects must be correctly identified and delineated. The issue of geomorphometric primitives is related to form objects, however, the concept of geomormorphic features versus form features/objects must be differentiated. Furthermore, the use of morphometric parameters is an issue related to generating primitives and elemental forms. Techniques to accomplish this as well as aggregation techniques to generate the next hierarchical level of objects needs to be developed and tested. Similarly, the concepts of homogeniety and heterogeniety must be better developed, as each may have a role in establishing the hierarchical nature of topography. Finally, the role of spatial and object-oriented analysis must be carefully considered as a means for accomplishing geomorphological mapping. These issues are addressed in the following sections.

6.1 Geomorphometry

Visual examination of the geomorphometric parameters revealed unique attributes associated with topographic structure, glacier surface characteristics, and surface processes (Bishop et al., 2001, 2003). Slope-related information is very important for mapping glaciers. In particular, the slope angle can be used for differentiating glacier surface from the surrounding topography, as glaciers in the western Himalaya exhibit relatively shallow slopes. In many instances, slope-angle can be used to delineate portions of the glacier, as steep slopes are found along the boundary of the glaciers.

Slope-aspect information is also very important as it defines one aspect of the topographic structure. Given that many glaciers flow in a perpendicular direction to valley walls, the boundaries of glaciers are sometimes oriented in opposite directions to the walls, making it possible to delineate the glacier in those locations. It is also clear that on some glaciers, the highly dynamic nature of glacier surface changes dictates high spatial variability in slope-aspect caused by rapid ice deformation. This is not the case on valley walls that exhibit more resistant rock surfaces.

The slope-curvature metrics, which have been explored by many (Gauss, 1827; Krcho, 1973; Mackay et al., 1992; Pike, 2002; Yokoyama et al., 2002) also provide valuable information about the topography and glaciers. Ridges and valleys can be accurately identified and the boundary of glaciers can be delineated, as the base of a glacier boundary is frequently concave. Profile- planimetric- and tangential curvatures characterize a different aspect of topographic curvature.

The openness metrics, introduced by Yokoyama et al. (2002), characterized the meso-scale curvature of the topography. When applied over glacierized basins, it highlighted the valley bottoms, which also correspond to glacier surfaces, as they are found in valley bottoms. Similarly, other features such as ablation valleys also get highlighted. Consequently, the metrics are not extremely valuable for uniquely identifying glacier surfaces. Visual examination of the results show that the openness metric with a radius of 100 m better highlights glacier boundaries than using a radius of 500 m. More research, however, needs to be conducted to determine how meso-scale curvature information can be fully exploited for glacier mapping.

Bishop et al. (2001) indicated that single topographic parameters cannot be used for diagnostic landform mapping because each morphometric parameter characterizes different aspects of the topography. When slope-angle, slope-aspect, planimetric, profile, and tangential curvature information are integrated via human interpretation, it is possible to delineate and map glaciers. Automating this process is difficult and the topographic information must be integrated in a systematic way. Research has not yet adequately addressed this issue. It can potentially be addressed, however, by formalizing various concepts and features related to topography. Some examples include topographic primitives, topographic structure, and toposequence information. Formalizing these concepts will require the fusion/integration of morphometric information.

Bishop et al. (2000b) also pointed out a non-linear slope-altitude relationship, where shallow slope angles were also found over broad flat valley floors and at high-altitude erosion surfaces. This demonstrates that the simple utility of the magnitude of morphometric parameter will not uniquely permit the classification of glaciers and other landforms. A systematic multi-parameter approach that is based on a scale-dependent model is required.

It is clear that morphometric parameters must be combined (Bishop et al., 2001). Object-oriented analysis offers the potential to address this and scale issues in landform mapping.

It also permits the generation and utility of addition information such as geometry and typology, that can be used to formalize important concepts such as slope-facet structure and toposequence information.

6.2 Elementary Terrain-Form Objects

Generating form-objects is the basis of formalizing the hierarchical nature of the topography. In order to do so, methods must be used to permit the identification of spatially homogeneous morphometric parameters. The work of Krcho (1973, 2001), Lastočkin (1987) and Minár (1995), examined the topic from a theoretical perspective. The method of cluster analysis was used in this research to generate primitive form-objects. The concept of morphometric homogeneity has been criticized by some information scientists and they indicate that this should not be the basis of aggregation of simple objects into high-order objects (Brändli, 1996). This point is valid if the results do not uniquely correspond to topographic structure or landform features. This was the case for most of the simple form objects that were generated, with the exception of slope-facet objects which do correspond to legitimate topographic structure. Furthermore, Bishop et al. (2001) found that the combination of curvature information can produce form objects that do correspond to geomorphic features, and there spatial combination can be used to identify and map glacier features such as moraines, ice-cliffs, and supraglacial lakes. Consequently, the concept of homogeneity is valid in the generation of slope-facets.

The utility of most of the form objects to characterize topographic structure and glacier features was extremely limited. This was due to utilizing one morphometric parameter and the clustering algorithm. The clustering algorithm enforces the homogeneity rule and works relatively effectively for the slope-aspect parameter, because it defines the directional structure of the topography. Curvature information needs to be integrated with slope-aspect objects so that breaks in the slope can further generate sub-objects that accurate define slope facets. In addition, slope-curvature objects are required that define planar, concave and convex slope objects. To accomplish this, methodological procedures other than cluster analysis are needed.

Dikau (1992) indicated the potential of slope-facets, and that they represent a fundamental form object. Visual examination of terrain slope-facets indicate that they can be used to delineate glacier boundaries. In addition, lateral moraines and ablation valleys are also characterized appropriately. More research involving the combination of slope information with slope-aspect to generate slope-facets is warranted.

Toposequence information was found to be valuable for glacier mapping. The results demonstrate that if accurate slope-facet object can be generated, the slope-angle altitude function can be used to differentiate slope-facets on- versus off- glacier in some instances. The relief within the slope facet could also be a useful object parameter. It would still be difficult, however, to differentiate valley bottom from glacier surface because both exhibit low slope. Other information such as the slope curvature-altitude function might permit differentiation. Another possibility is the hypsometric curve. This approach has significant potential, however, more research is still warranted.

Finally, the generation of elemental form objects that accurately characterize topographic structure permit the generation and utility of additional information such as shape and topology. For example, ice cliffs exhibit a unique shape that is entirely different from other glacier and landscape features. Similarly, elongated linear features such as moraines, and highly irregular shape such as rivers can be uniquely identified and mapped. Very little work on shape has been conducted, although the geometric attributes of landscape features is very important.

Similarly, spatial relationships and contextual information such as distance, direction, connectivity, and containment can be used to assist in mapping efforts. There is a paucity of research on this topic, as the problems of generating basic forms must be solved before applied research on object geometry and typology can be effectively conducted.

Given the conceptual and practical complexities associated with utilizing hierarchy theory to characterize topography, only a few studies have applied it for glacier mapping. A rigorous theoretical framework is required to guide research. As previously mentioned, any approach must utilize contextual and geometric information and topology to assist in problem solving. Topological properties, such as connectivity and adjacency in a hierarchical model could reveal important information on morphogenetics which could also be used as criterion for the spatial aggregation of form objects into higher-order objects and terrain features. Scientists do not currently know the value of hierarchy theory in characterizing topographic structure, or the number of hierarchical levels that glacier topography or mountain landscapes in general.

Several important questions still remain: 1) What type of form objects are needed to characterize topographic structure? 2) What object-attributes are necessary at different levels in the hierarchy? 3) What concept or method serves as the basis of aggregation at a particular hierarchical level? This research demonstrate that the use of hierarchy theory has tremendous potential in landform mapping. Simple form objects can accurately characterize some aspects of topographic structure and geomorphic features. The answers to the other questions are not clear at his point in time, but theoretical research has demonstrated the feasibility. With the advent of new data sources, high quality digital elevation models and more advanced geographic information technology, researchers can better assess the utility of hierarchy theory and object-oriented analysis for glacier and landform mapping.

Chapter 7

Conclusion

It is essential to understand climate forcing, as it partially controls environmental change and resource availability. It is widely known that alpine glaciers directly and indirectly respond to climate. Consequently, glacier assessment can provide valuable information on climate change. Assessing alpine glacier fluctuations in complex mountain environments poses unique logistic, political and technological challenges. Furthermore, we have much to learn about their complex interactions with the atmosphere, other surface processes and lithosphere that also dictate changing conditions. Glacier distributional change is perhaps one of the most basic forms of information that is needed to provide insight into climate warming and negative mass balance. Accurate geometric information, however, can be difficult to obtain, and glacier mapping poses unique challenges to the remote sensing and GIScience communities. Consequently, the objectives of this research were to explore the use of topographic information and object-oriented analysis for automated mapping of alpine glaciers.

The overall objective was to evaluate the utility of topographic information and spatial analysis for glacier mapping. Geomorphometric analyses were performed to generate first-and second- order morphometric parameters. These parameters were found useful in highlighting different characteristics of the topography, and do permit delineation and mapping of glaciers when utilized in mapping via human interpretation. Slope angle and curvature parameters were most useful in highlighting the boundaries of the Raikot and Sachen glaciers. The openness metrics, which characterize meso-scale curvature, were useful in highlighting valley bottoms. It follows therefore that the results of geomorphometric analyses support the overall hypothesis that unique attributes associated with scale-dependent hierarchical structures of mountain topography can be depicted by morphometry.

The first objective was to evaluate topographic parameters for generating elemental form-objects. It was found that individual morphometric parameter cannot be used to generate form-objects that are representative of topographic structure or landform features. The results do show however, that a combination of morphometric parameters is required to appropriately characterize the topography. Slope facets, which represent the combination of slope and slope-aspect information, can be utilized effectively to represent topographic structure and assist in differentiating glacier topography from other basin topography. Slope-facets do characterize glacier boundaries if they are accurately computed. The challenge is to utilize slope angle and slope-curvature information to highlight changes in the slope for a particular slope direction. The results indicate that other topographic primitives and form-objects must also be utilized for a more accurate characterization of glacier topography. Furthermore, the results clearly reveal the importance of geomorphometric analysis and that the topography can be represented using hierarchy theory. This also supports the hypothesis that a scale-dependent approach could work, although this was not specifically demonstrated, as multiple levels in the hierarchy are needed. Nevertheless, more robust geomorphometric techniques are needed to permit effective combination of morphometric fields.

The second objective was to evaluate the feasibility of topo-sequence information for characterizing glacier/non-glacier surfaces. Toposequence generated from object-oriented analysis demonstrate the usefulness of this approach. First, it should be noted that the generation of elemental form-objects defines a component of the topographic structure. Information for each component is then generated. This information can be land cover, topographic, geometric, and/or topological in nature. This greatly facilitates mapping, although, only topographic information was used in this study. Topo-sequence information, as used in this study, represented the slope-altitude function within slope-aspect objects. The results clearly indicated the value of object-oriented analysis for glacier mapping. In addition, the results support the hypothesis that toposequence information can effectively differentiate between glacier and non-glacier surfaces. The concept of topo-sequence needs to be further developed and used in object-oriented analysis.

The last objective was to demonstrate that an object-oriented approach to analysis could facilitate glacier mapping and topographic representation. The approach requires the transformation of a field into discrete objects that represent some aspect of the topography. Cluster analysis, utilized to accomplish the spatial-aggregation process is of little use once implemented in a spatial aggregation of elemental form-objects into higher-order objects and represents a critical research area. Theoretically, some elemental form-objects can be aggregated to represent and map some terrain/landform features. Classic examples include moraines and ice-cliffs that are part of a glacier. Slope facets were the only elemental form-object that reasonably characterized the topography. Furthermore, the hierarchical structure should be better formalized as specific forms and features may require different aggregation techniques. This work, and the work of Bonk (2002) clearly demonstrates that another approach needs to be developed and evaluated.

This research has extended the findings of Bonk (2002) and shown the value of object-oriented analysis. It is very critical, however, that new methods be utilized to combine geomorphometric parameters. Another significant issue is the production of highly accurate DEMs, which serve as the basis of mapping. Furthermore, the integration of land-cover information can be valuable. Finally, given that there are so many different geomorphometric parameters, an evaluation of their utility for landform mapping seems warranted.

Important information may result from shape analysis. Numerous features have unique shape characteristics such as ice -cliffs, moraines, and rivers. Numerous shape metrics exist and can be applied to elemental form-objects. The problem is the original classification that is required in order to obtain a good spatial representation of the form object. If the spatial distribution of the object can be identified, shape information can be used to automatically detect unique features. This can help in defining the hierarchical nature of the topography. In addition, shape may help to identify the process genetics that created a selected feature, as the shape of the topography or feature is the result of dominant and interacting processes, which operate over a range of spatial and temporal scales.

Advanced spatial-topological analysis offers the possibility of exploring the relationships among terrain features. Proper understanding of the contextual interrelationships may provide information about the self-organization properties of the topography. Software that permits the collective integration of the aforementioned information would greatly improve alpine glacier mapping capabilities. Until then, glacier mapping of debris-covered glaciers remains a difficult task. This research is a small step in that direction.

Appendix A

Appendix

Scale

Lam and Quattrochi (1992) give three connotations of scale in the Earth Sciences:

- *Cartographic scale or map scale* - denoted as a ratio, refers to the proportion or distance on a map to the corresponding distance on the ground (Cao and Lam, 1997).
- *Geographic scale* - the spatial extent of a study area; large scale $(1 : 10,000, 1 : 5000)$ covers a small area with more detail whereas small scale $(1 : 50,000, 1 : 100,000)$ covers a large area with less detail. It follows that geographic scale can be also called *extent* or *domain*, which is the area or volume over which observations are made.
- *Operational scale* - refers to the spatial extent of phenomena and processes; operational scale is 4D spatio-temporal scale.

Furthermore scale can be:

- *Measurement scale* - refers to the size of an area upon which the measurement of a property is based, e.g. the measurement scale associated with a DEM is the spatial resolution or grid resolution, which serves as the basis for characterizing the altitude field (Cao and Lam, 1997).

- *Hierarchical scale* - is based upon hierarchy theory, which characterizes landscape as the hierarchical organization of the topography. Thus, hierarchical scale refers to the size of the objects that present the hierarchical organization (Dikau, 1992).

Recently, other terms are used in relation to the scale problem and modeling at different scales. Most important of these are (cf. Bierkens et al., 2000):

- *Support* - is the largest volume or area for which the property of interest is considered homogeneous. The complete specification of the support includes the geometrical shape, size, and orientation of the volume. The support can be as small as a point or as large as the entire field. A change in any characteristic of the support defines a new regionalized variable. Changes in the regionalized variable resulting from alterations in the support can sometimes be related analytically.

- *Support unit* - refers to the sub-area or sub-volume with the same area or volume as the support.

- *Coverage* - the ratio of the sum of areas or volumes for which the average values are known.

- *Sample* - a subset of n support units taken from the population of N support units that make up an area whose properties have been observed. This implies that 'large scale' refers to large areas; 'small scale' refers to small areas, which is the inverse of what is meant by 'geographic scale' and 'cartographic scale'.

Hierarchy Theory

The components of hierarchy theory are:

- *Hierarchy spatial reasoning* - leads to a theory of hierarchical spatial reasoning (HSR) which is a method of spatial problem solving that uses hierarchy to infer spatial information and to draw conclusions (Car, 1997).

- *Nested hierarchy* - larger spatial scales and smaller temporal scales characterize lower levels; higher-level hierarchies are characterized by smaller spatial scales and low frequency behavior (Urban et al., 1987).

- *Elemental terrain form object* (ETFO) - represent a topographic entity that serves as the basic object from which other objects are defined. An elemental terrain form object is delimited on the basis of geomorphometric parameters such as slope, slope aspect, profile curvature, planimetric and tangential curvature. ETFO are homogeneous in one or several morphometric properties. These objects exist at a variety of scales, depending upon the complexity of the topography.

- *Terrain feature* - represents an aggregation of ETFO

- *Landform feature* - represents an entire landform, which has been defined based upon aggregation of terrain features and ETFO.

Other components of hierarchy theory are:

- *Part-whole* - an element on a higher level consists of one or more elements of the lower level. In the view of a part-whole relationship, a higher-level element is a whole and a lower level element is its part (Palmer, 1977). The role of whole and part changes from one level to another: an element being a part of another element at the higher level is a whole for elements of the lower level, and has properties assigned to both arts and wholes.

- *Janus-effect* - an element at a hierarchical level has two different faces, one looking toward wholes in a higher level and the other looking toward parts in a lower level. Koestler (1967) identified this property as a fundamental property of all types of hierarchy and called it the Janus-effect (after the Roman God Janus who had two faces). Further he defined the term holon to reinforce this two-faced characteristic of hierarchical systems. Holons generate emergent properties, which are not apparent from an analysis of the individual components, that is, the whole is greater than the sum of the parts.

- *Near decomposability* - is related to the nesting of systems within larger subsystems, and is based on the fact that interactions between various kinds of systems decrease in strength with distance (Simon, 1973). Such a system is likely to behave either as a single, nearly uniform system consisting of components that hang together rather strongly, or as a set of localized subsystems. A system of the latter kind is hierarchical in nature.

Other Terms

- *Georelief* - is considered as a solid but dynamic division line between atmosphere and hydrosphere as well as between lithosphere and pedosphere, and mostly biosphere. Its position presents the central part of a geographical sphere, where maximal exchange of energy, information and matter is located (Dzurovčin, 2000).

- *Geomorphologic agent* - refers to a material object, in which part of its total energy is used during geomorphologic process (e.g. air, water, in various states and forms with its kinetic, thermal, and chemical energy; rocks with their potential and kinetic energy; magma with its thermal and kinetic energy) (Minár, 1995).

- *Geomorphologic process* - is a process that directly induces changes in the continuance of the georelief. Process covers particular fluxes of matter, changes of matter-energetic interactions of georelief and the continuance of the relief as well (Minár, 1995).

- *Geomorphometry* or *Morphometry* - is numerical characterization of topographic forms (Schmidt and Dikau, 1999). Using the words of Rasemann et al. (2004), geomorphometry can be defined as the science of quantitative description and analysis of the geometric-topologic characteristics of the landscape. Within the framework of process-form relationships, geomorphometry deals with the recognition and quantification of landforms.

- *Morphometric parameters* - refers to first and second order derivatives (zx, zy, zxx, zxy, zyy) of the elevation field, such as slope angle, slope aspect, profile, tangential and planimetric curvature (Krcho, 2001).
- *DEM - Digital elevation model* or *DTM - Digital terrain model* - represents an altitude surface derived from altitude data using an interpolation algorithm (Rasemann et al., 2004).
- *GIS - Geographic Information Systems* - represent a computer-based tool to capture, manipulate, process, and display spatial or geo-referenced data. They contain both geometry data (coordinates and topological information) and attribute data, that is, information describing the properties of geometrical objects such as points, lines and areas (Fedra, 1993).

Glaciers

- *Valley glaciers* - glaciers that flow between confining rock walls (Sharp, 1988)
- *Ice sheets* - glaciers that bury the rocky landscape and flow unconfined by virtue of their great thickness (Sharp, 1988).
- *Terminus* or *Downglacier extremity* - is the line where losses by all causes equal the rate at which ice can be supplied by accumulation and forward motion.
- *Zone of accumulation* - is the zone where vectors of particle motion are downward into the ice mass as each year's snowfall adds a new surface layer to the glacier.
- *Zone of ablation* - represents the zone where vectors of particle motions point toward the ice surface, because a surface layer is annually removed, exposing progressively

deeper ice (figure A.1).

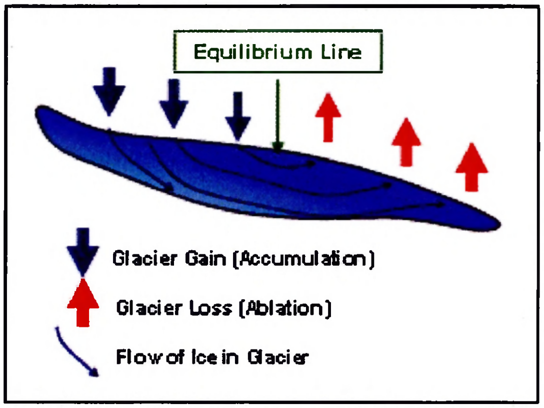


Figure A.1: Mass balance of valley glaciers.

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