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Scale-dependent Geomorphometric Analysis for Glacier Mapping at Nanga Parbat: GRASS GIS Approach.

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1 Introduction

Mountain environments are the result of complex interactions involving climate, tectonic and surface processes. Unfortunately, scientists do not understand a variety of processes and feedback mechanisms that control the geodynamics of topographic evolution, and dictate the nature of environmental change, and resource related issues. Thus the analysis of topography is essential for studying the role of surface processes in topographic evolution.

Numerous scientists have tried to utilize morphometric parameters to automate geomorphological mapping at different scales [23, 25]. While physically-based models have produced promising results [16, 18], they do not consider the hierarchical organization of the topography. Many of the issues fall in the category of formalizing the concept of homogeneous terrain units at a variety of scales.

Current software cannot automatically extract meaningful terrain units or objects from a DEM. There have been attempts to extract homogeneous units such as valley bottoms, ridges, pits and saddles [1, 26, 45], and higher-order geomorphologic features such as landform types [40, 41]. Various methods, however, are not appropriate for extracting complex terrain features such as slope facets, river terraces, or the active extent of a modern-day glacial valley.

Unfortunately, hierarchy theory is generally described with no formal mathematical guidelines or rules established to define the organizational structure [31]. Issues include defining the concept of homogeneous terrain properties [22, 23], defining the various scale ranges that determine the number of levels in the hierarchy [38], solving the problem of indeterminate boundaries, addressing topological relations, and identifying and using appropriate geometric and contextual attributes to characterize terrain objects [23, 25].

The basic problem represents the transformation of theory and concepts into mathematics and models that effectively transform continuous fields of morphometric properties into real entities that can be observed on the landscape.The overall objective of this research is to develop an object-oriented approach at modeling the topography to determine if hierarchy theory and terrain objects can be used to accurately map alpine glaciers at Nanga Parbat in northern Pakistan.

Specific research objectives were too: 1. Determine the significance of first- and second-order derivatives of the elevation field. 2. Examine the inherent statistical properties of terrain objects to determine if geometry and contextual relationships can be used to characterize landforms. 3. Determine if a simple hierarchical model can be used to map alpine glaciers at Nanga Parbat.

The research presented here is a selection of the most critical and key ideas from my Master's thesis, for more in depth information please see and refer to [37]. Here the problem is not presented in full details and special focus is given to the role of GRASS (Geographic Resources Analysis Support System) GNU/GPL GIS in the research.

2 Literature Review

Scientists have been interested in the western Himalaya because of its extreme topography, complex tectonics and active geological processes. The massif of Nanga Parbat has been recognized as unusual in terms of extreme relief and modern surficial denudation rates [28, 6, 10, 11]. [10], [12], and [11] have identified the dominant surface processes and have estimated the magnitude of fluvial denudation rates, valley incision rates, and alpine basin denudation rates. These works, and others have demonstrated that surface processes are highly active at Nanga Parbat, and that denudational unloading of the massif is possible given the magnitude of denudation, and an active sediment transfer cascade into the Indus River. The first GIScience approaches to studying the Nanga Parbat massif was reported by [34]. Preliminary geomorphometric analysis of a high resolution DEM included hypsometric, swath profile, and altitude and slope analysis of the massif. Perhaps the most important findings regarding Nanga Parbat are related to relief production and system dynamics. [33] first noticed the hierarchical organization of Nanga Parbat topography with distinctive "V" and "U" shaped valleys associated with active river incision and glaciation, respectively.

Numerous spatial theories, including hierarchy theory, have been developed along similar lines of thinking in geomorphology, geoecology, and landscape ecology [30, 22, 23, 25, 13, 14], as Earth scientists have observed the hierarchical nature and scale dependencies of landscapes and numerous phenomena. [30] discussed the use of morphometric parameters in applied landscape-ecological research. From a certain point of view, these hierarchical levels can be related to the concepts of scale and microrelief and mesorelief as described by [39]. [39] proposed that scale can be addressed as orders of relief, such that features and landforms exist at scales representative of picorelief, nanorelief, microrelief, mesorelief, and macrorelief, up to megarelief. [22] argued that the current status of the geomorphological system dictates the organization of the topography. He presented the theory of *elementary landforms* as morphometrically, morphogenetically and morphodynamically homogeneous basic terrain elements.

Most of the research on terrain characterization and classification has dealt with the problems of deriving drainage networks and delineating drainage basins from DEMs. Extraction of drainage networks and basins is now considered a mature technology with a well developed literature [7, 2, 1]. [44] extracted hills and valleys from a contour map. [5] used satellite imagery and a DEM to delineate alluvial fans. [42] utilized a differential gradient method to subdivide a DEM surface into concave, convex, and flat regions. [41] developed an algorithm for mapping land components by using slope angle and slope aspect information. The character of the work of [39] is very interesting and exhibits a strong theoretical and methodological framework as a basis for mapping. An approach quite different from every other presented here was taken by [17]. The authors used the RST interpolation function for delineation of convex and concave terrain features.

Collectively, this work demonstrates the partial success in computer-based geomorphological mapping. However, accurate results have only been obtained for well defined geomorphological landforms, such as basins, or stream networks.

3 Study Area

The Nanga Parbat massif at 8125 m altitude is the ninth highest mountain in the world, and an area of rapid erosional unroofing [8, 9, 27, 29]. Research of glacial denudation [43], denudation of small alpine basins [12], and valley incision processes [11] revealed that rapid and localized, but still short-term and episodic differential denudation at Nanga Parbat appears to be responsible for the extreme relief. [6] and [32] conducted the first significant geomorphometric analysis of Nanga Parbat using a DEM with 3 arcseconds (∼90 m) grid spacing. More recent geomorphometric analysis of Nanga Parbat massif was conducted by [34, 33, 35] and [37].

The geomorphometric analysis presented by [33, 35] for Nanga Parbat was limited by the spatial extent of the DEM (Figure 1). In the research of [35] special attention was given to hypsometric analysis of basins at Nanga Parbat (Figure 2). The results are presented in Table 1. The study showed that Nanga Parbat basins can be divided into three groups, based on their dominate surface processes and unique topography [35]. Open Source GRASS GIS was used for the DEM preprocessing, and to extract watershed boundaries. Specifically, two version of GRASS were used. Binary version of GRASS 4.3 for IRIX^{TM} operating system (due to the SG3D visualization tool support), and compiled GRASS 5.0 beta release (due to support of floating point rasters). Hardware equipment was represented by the state-of-the-art SGI ORIGIN^{TM} 2400 server, powered by 24 CPUs at 300 MHz, and 6 GB of memory, with an sufficient storage capacity around 200 GB. Also several SGI O_2^{TM} workstations were used for Nanga Parbat project. Even `r.watershed` module is well tested, processing such an extremely high relief and reasonable large dataset (raster of 3386 x 3551 cells with 20m resolution) required special approach. It has to be noted that it is not possible to extract all basins at once, since they are all of different size. That is why "moving `d.zoom`" approach was used to pick up individual basins. It means that `d.zoom` module was used for each basin to select the area including just the watershed. Then, after adjusting the "minimal size" of the basin to be generated, the individual watershed was extracted. When extracting all 22 glacial basins, `r.patch` module was used to generate final map layer.

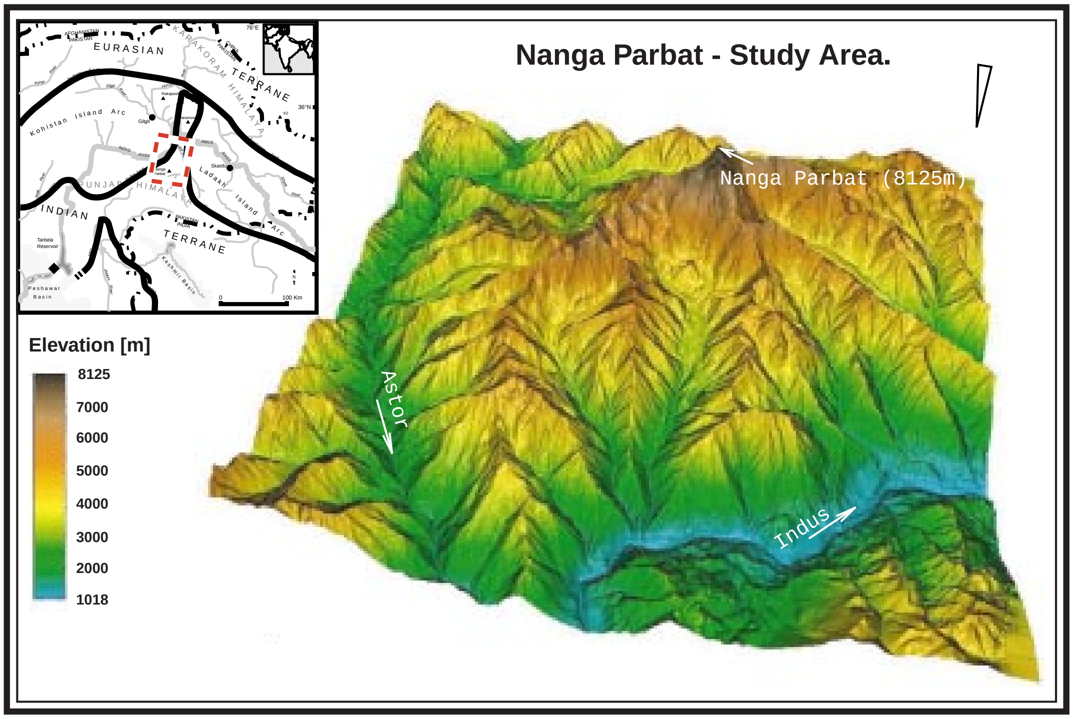

Figure 1: Digital elevation model of the Nanga Parbat study area generated by GRASS GNU/GPL GIS. Original SPOT DEM was preprocessed to achieve desirable smoothness (`s.surf.rst` module was used with the following parameters φ=20, and B_a=5) A color scheme represents altitude variation. SG3D visualization tool was used to generate 3D model.

Table 1: Nanga Parbat watershed statistics (from [35]).

Id.	**Watershed**	**Planimetric area** $[km^2]$	**Surface area** $[km^2]$	**Min. elevation** $[m]$	**Max. elevation** $[m]$	**Relief** $[m]$	**Perimeter** $[m]$	**Hyps. integral**
1	Mushkin	32.554	38.690	1590	4825	3235	28708.33	0.463
2	Mammocha	28.580	36.089	1978	5293	3315	26870.46	0.540
3	Doian	13.670	15.851	1547	4278	2731	17880.90	0.529
4	Shaigiri	11.334	16.762	3869	7428	3559	18256.89	0.425
5	Gamma	15.260	19.016	4013	6769	2756	19803.90	0.416
6	Lichar	36.787	47.721	1146	5110	3964	31567.45	0.573
7	Alpha	10.196	13.149	3940	6887	2947	16253.12	0.358
8	Diamir	109.537	145.554	2503	8126	5623	56641.83	0.427
9	Patro	79.374	103.588	1061	6552	5491	52033.06	0.492
10	Raikot	174.111	220.651	1125	7845	6720	77110.97	0.465
11	Buldar	118.990	150.610	1122	6825	5703	57199.04	0.519
12	Sachen	57.779	71.598	2127	6395	4268	45578.00	0.425
13	Sm. Lotang	11.912	14.240	2788	5271	2483	18002.26	0.528
14	Lotang	30.738	37.583	2784	5762	2978	29520.21	0.425
15	Bazhin	20.399	31.096	3632	8117	4485	24953.51	0.386
16	Tap	7.871	11.790	3719	7756	4037	13738.72	0.385
17	Gurikot	28.291	33.881	2591	5065	2474	30328.85	0.540
18	Mazeno	84.892	102.874	2504	6536	4032	51249.85	0.488
19	Jalipur	48.806	62.920	1071	5192	4121	40783.80	0.597
20	Chongra -Chungphar	54.860	72.252	2918	7072	4154	35889.57	0.377
21	Bulan	11.186	14.207	2187	4898	2711	20160.66	0.548
22	Beta	5.808	7.749	4065	6958	2893	13639.49	0.365

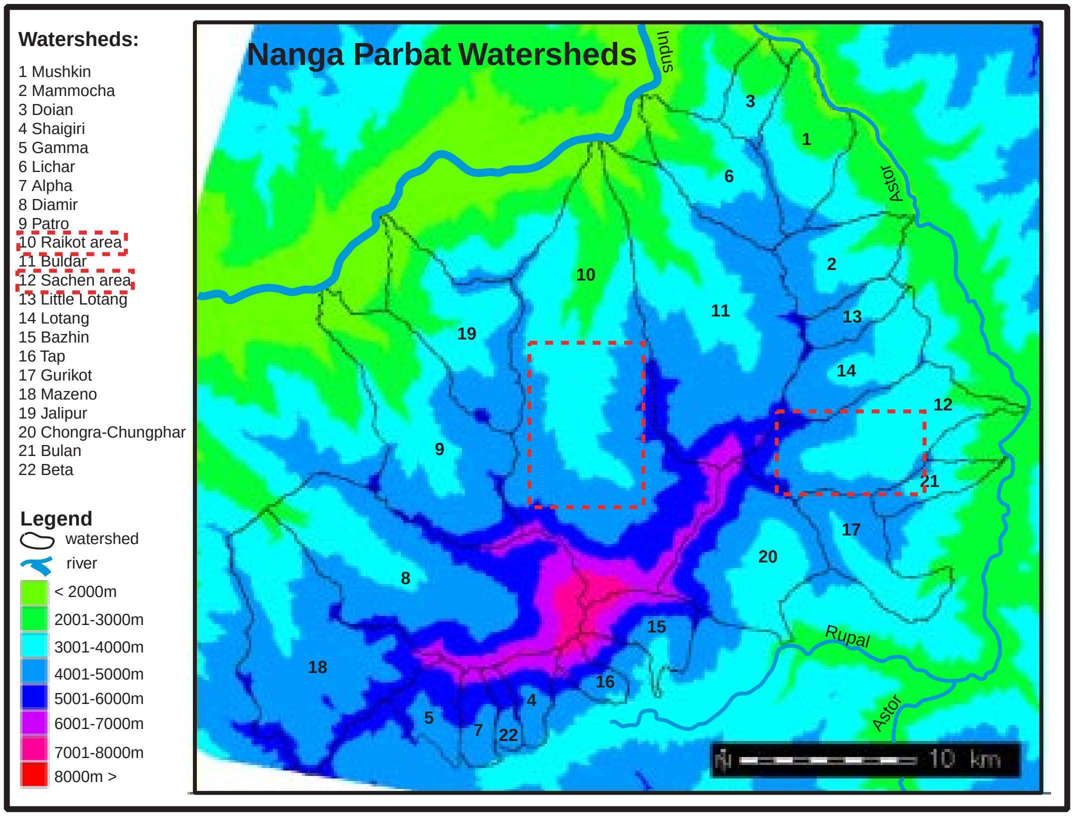

Figure 2: Nanga Parbat watersheds. Twenty two watersheds were identified and delineated in GRASS using `r.watershed` module. Final map was generated by patching individual basins together using `r.patch` module. (from [35]).

Table 2: Univariate statistics for Sachen study area.

Morphometric parameter	Minimum value	Maximum value	Range	Arithmetic mean
Sachen study area.				
Elevation (Z)[m]	3162.8	5758.4	2595.6	4040.5
Slope angle (β_T) [°]	0.1	67.0	67	26.7

```
GRASS:  r.patch -z input=sub1,sub2,sub3...sub22 output=nanga.basins
```

GRASS was also used to compute basic morphometric characteristics for newly extracted watershed. Specifically, the combination of `r.stats` and `bash` shell script was used. It has to be noted that GRASS performed well at individual basins extraction, however certain experience with `r.watershed` is required, and only one basin terminus had to be delineated manually with the support of satellite image and the DEM.

In this research only Sachen Glacier (Figure 2) mapping, and modeling results are presented, however two distinct area sites (including Raikot Glacier) were studied in [37], and Raikot glacier results only are presented at [36]. Sachen site was chosen to cover the spatial extent of alpine glacier below the equilibrium line. Basic univariate statistics for Sachen glacier are presented at Table 2.

Sachen glacier (Figure 2) is oriented in a W-E direction and covers the upper part of the Sachen valley. The study area for Sachen basin is 5260 m long and 4380 m wide. Lateral moraines can be identified on both sides, but the one at the south part of the glacier is less interrupted and more solid in character. Slope angles vary over the glacier surface within the range of $\sim$0.1° to 11°, and the upper part of the basin, varies between $\sim$3440-4000 m in altitude.

4 Methodology

In this research, a methodological framework has been developed to test the efficacy of using a DEM and terrain objects for geomorphological mapping (Figure 3). The steps are initially presented, and then described in depth as follows:

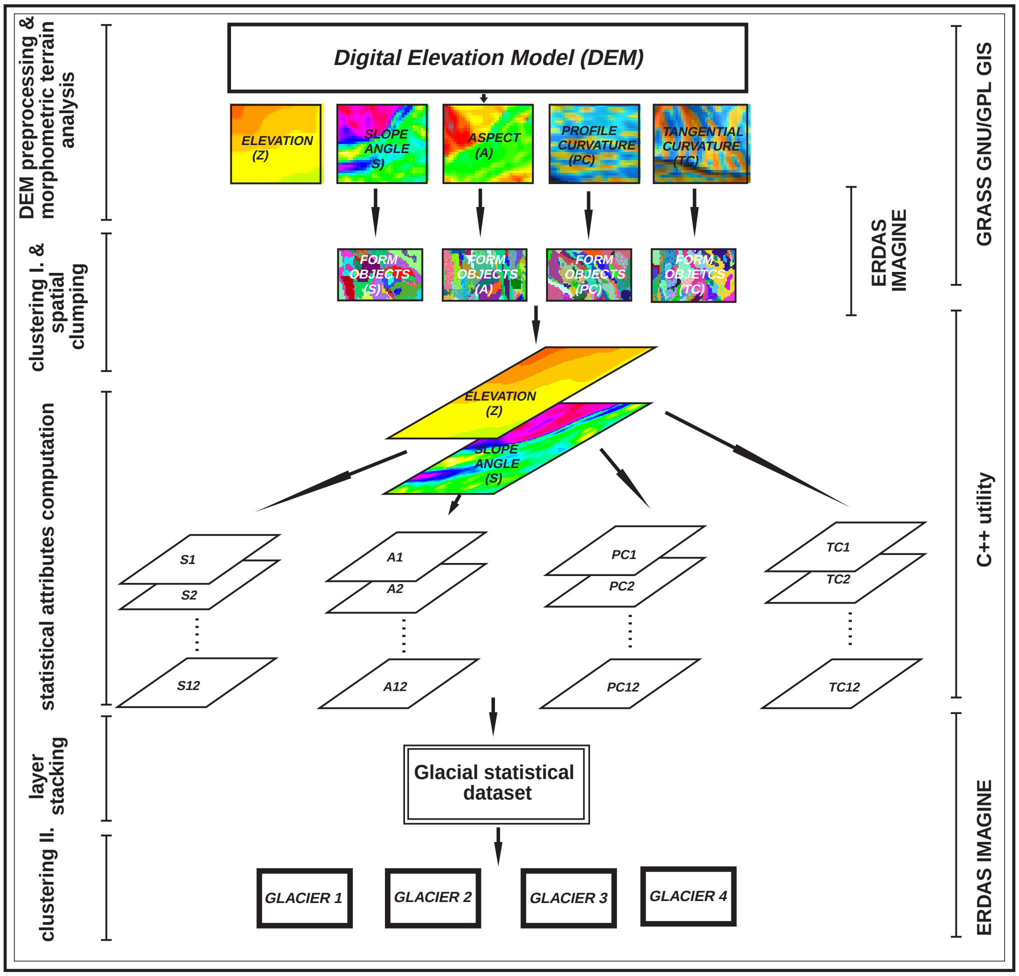

Figure 3: Methodological design of the project showing individual research procedures with related software environments.

1. **Data preprocessing.** A high quality DEM is required for geomorphological mapping. Commonly, high-frequency variation must be suppressed, as it can be related to errors resulting from the use of various DEM generation methods.

2. **Morphometric terrain analysis.** The DEM is then used to produce continuous fields of the morphometric parameters of the topography. These include first- and second-order derivatives of the elevation field such as slope angle (β_T), slope aspect (ϕ_T), profile curvature (ω_p) and tangential curvature (ω_t).

3. **Terrain-form objects (TFO).** TFOs must be identified and delineated as a starting point to define the topographic structure. The identification of elemental TFOs will be based upon the use of four morphometric parameters (β_T, ϕ_T, ω_p, ω_t) independently. For each morphometric parameter, TFOs will be identified on the basis of one-dimensional statistical separability. An unsupervised classification approach using the ISODATA algorithm (included at ERDAS IMAGINE^{TM} software package) was used to accomplish this.

4. **Spatial clumping and individualization of TFOs.** A spatial analysis procedure, called clumping, was used to uniquely identify the number of spatially continuous TFOs over the landscape.

5. **TFO spatial analysis.** The delineation of TFOs using spatial clumping was needed so that the inherent geometric properties of a TFO could be calculated. Contextual relationships were not taken into consideration. Object-oriented software was developed to calculate a variety of object attributes that were evaluated as the basic data for aggregation of TFO into landform objects.

6. **Landform objects (LOs).** To test the efficacy of hierarchy theory for landform mapping, a simple two-level hierarchy was chosen by which TFOs would be aggregated to generate LOs. The TFO attributes were stacked to generate a topographic dataset for generating LOs. An unsupervised classification approach using the ISODATA algorithm was used to accomplish this. Results were compared to field data and satellite imagery to see if this simple model of the topography could be used to map alpine glaciers.

A DEM generated from previous research conducted by [34] was used as a foundation dataset for this research. The DEM has a measurement resolution of 20 m and a vertical accuracy of $\pm 8-12$ m. It was generated from two SPOT panchromatic stereo-pairs using the autocorrelation technique. Its original quality is very good for locational accuracy and precision, although it does exhibit high-frequency artifacts. Given the nature of this research, a new DEM had to be generated so that undulations in the elevation field are associated with relief and landforms. In addition, high-frequency noise would dramatically affect the magnitude of first- and second-order derivatives needed for topographic characterization.

The objective of DEM preprocessing was to produce a better quality DEM that did not exhibit a high-frequency variance component, but enhanced the lower-frequency information content. To accomplish this, random sampling of the original DEM was used to extract site data which was used in a spatial interpolation procedure called "regularized spline with tension" to generate a new DEM [15].

```
GRASS:  r.random input=nangadem nsites=25 sites_output=spot.sites25
```

The sample locations represent a 25 % sample of the original DEM. This sample size was based upon a previous study that determined that this percentage produced acceptable results. The number of data points was sufficient to cover critical terrain features and was spatially sparse enough to enable a spatial interpolation algorithm to produce a smooth function between sampled points.

This function, together with several improvements, such as a segmentation algorithm for large datasets, was implemented into GRASS - GNU/GPL GIS. The value of the φ parameter for this research was determined empirically by performing numerous interpolations at test sites at Nanga Parbat.

As part of a test procedure, the RST function was used to compute elevation Z , and slope angle β_T at a test site located in Sachen basin (Figure 4). Based on initial sensitivity testing, the following values of tension (φ), and smoothing (B_a) were used: $\varphi = 20$, $B_a = 5$. The φ and B_a parameters are important parameters which control the interpolation process. The RST function smoothed the terrain enough to decrease undesirable variation, but preserved important terrain features, such as lateral moraines.

```
GRASS:  s.surf.rst sites=spot.sites25 smoothing=5 tension=20 \
elev=NZ aspect=NA slope=NS pcurv=NPC tcurv=NTC
```

This procedure produced a 20 m DEM for the Nanga Parbat region (Figure 1). The new DEM was compared to the original using summary statistics and spatial profiles (Figure 5). Visual inspection and quantitative analysis confirmed that the new DEM was appropriate for further analysis. Spatial profiles showed that the DEM preserved important terrain features, while decreasing the high-frequency noise.

Morphometric terrain analysis was conducted to characterize the properties of the topography. The computation of four parameters is mathematically defined. Surface geometry can be analyzed efficiently when the surface is interpolated with a bivariate function $z = f(x, y)$, that is continuous up to second-order derivatives, and when parameters characterizing surface geometry are expressed via derivatives of this function. Before deriving mathematical expressions for these parameters using the basic principles of differential geometry, the following simplifying notations are introduced:

$$f_x = \frac{\partial z}{\partial x}, \qquad f_y = \frac{\partial z}{\partial y}, \qquad f_{xx} = \frac{\partial^2 z}{\partial x^2}, \qquad f_{yy} = \frac{\partial^2 z}{\partial y^2}, \qquad f_{xy} = \frac{\partial^2 z}{\partial x \partial y}, \tag{1}$$

and

$$p = f_x^2 + f_y^2, \qquad q = p + 1. \tag{2}$$

Slope Angle and Gradient.

The slope angle at point A, can be defined as an angle between the contact plane to a point on the

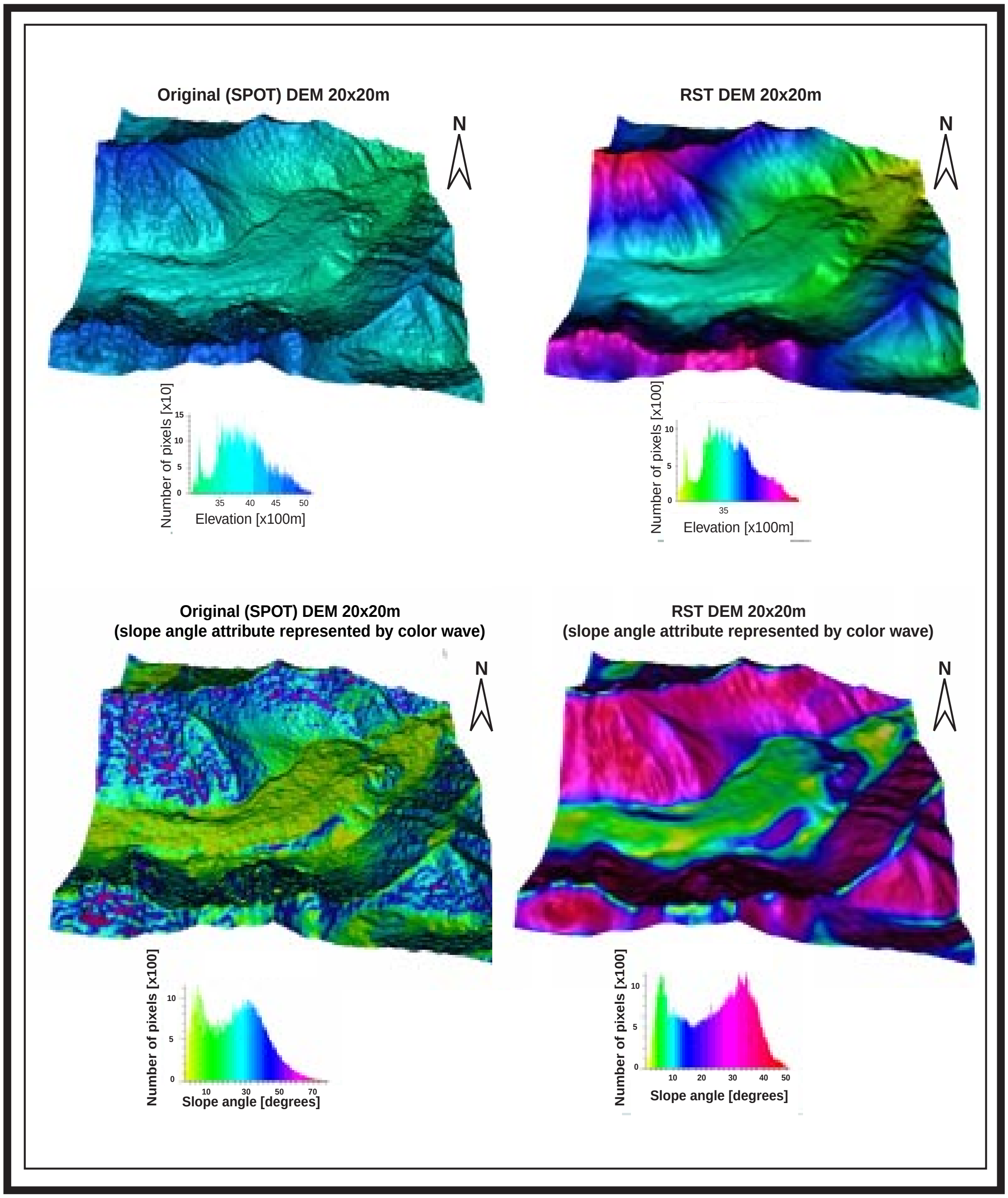

Figure 4: Comparison of elevation (upper part) and slope angle (lower part) based upon the original SPOT DEM and RST interpolated DEM of the Sachen Glacier area.

topography and a horizontal plane with respect to the geoid. It can be mathematically defined as follows:

$$\beta_T = \arctan \sqrt{p}. \tag{3}$$

Slope Aspect of the Terrain

The slope aspect of the terrain is an important morphometric parameter that defines the cardinal direction of the slope and controls numerous physical processes. It is mathematically defined as follows:

$$\phi_T = \arctan \frac{f_y}{f_x}. \tag{4}$$

Profile Curvature

Gravitational flowlines are imaginary lines on the topography that connect points oriented in the direction of maximum slope. Other than valley streams, ridge lines, singular summits, and depressions, where more than one flowline can exist, every point on the topography can only have one flowline. The curvature of the flowline in the normal direction to Earth's surface was presented by [19, 20] and can be represented as:

$$\omega_p = -\frac{f_{xx}f_x^2 + 2f_{xy}f_x f_y + f_{yy}f_y^2}{p\sqrt{q^3}}, \quad (5)$$

where profile curvature represents the local change in slope angle over the projected plane, in the direction of the flowline. From a sediment flux perspective, the velocity of sediment transport depends upon the slope angle (more precisely upon the magnitude of *gradient*), and ω_p influences acceleration or deceleration of the matter flux along the flowline [23].

Tangential Curvature.
Another morphometric property of the topography is the tangential curvature of the relief in the direction of tangent to contours. It can be expressed by the following equation [19, 20]:

$$\omega_t = -\frac{f_{xx}f_y^2 - 2f_{xy}f_x f_y + f_{yy}f_x^2}{p\sqrt{q}}. \quad (6)$$

Tangential curvature represents local changes in the direction of the contour which are related to the gravitational flux. A $\omega_t < 0.0$ indicates concavity, such that deposition is more likely to occur. Conversely, $\omega_t > 0.0$ indicates convexity, such that erosion is more likely to occur, all other factors being equal.

Terrain-Form Objects.
The first objective for characterizing the organization of mountain topography is to identify TFOs based upon the concept of homogeneous morphometric properties. There is a paucity of research that defines how this issue should be addressed, although [38] and [24] indicate that slope facets could be used, Because it is necessary to represent discrete objects, and there are numerous approaches that can be used to create TFOs, a simple approach was used.

An unsupervised classification approach and the ISODATA clustering algorithm was used to define the spatial extent of TFOs on the landscape. This approach is ideal for identifying homogeneous TFOs because it is based upon the variance structure of the data submitted to the algorithm, and it iteratively adapts to the variance structure, as defined by statistical separability in n-dimensional space. For each morphometric parameter, eight cluster classes were produced. A convergence coefficient of

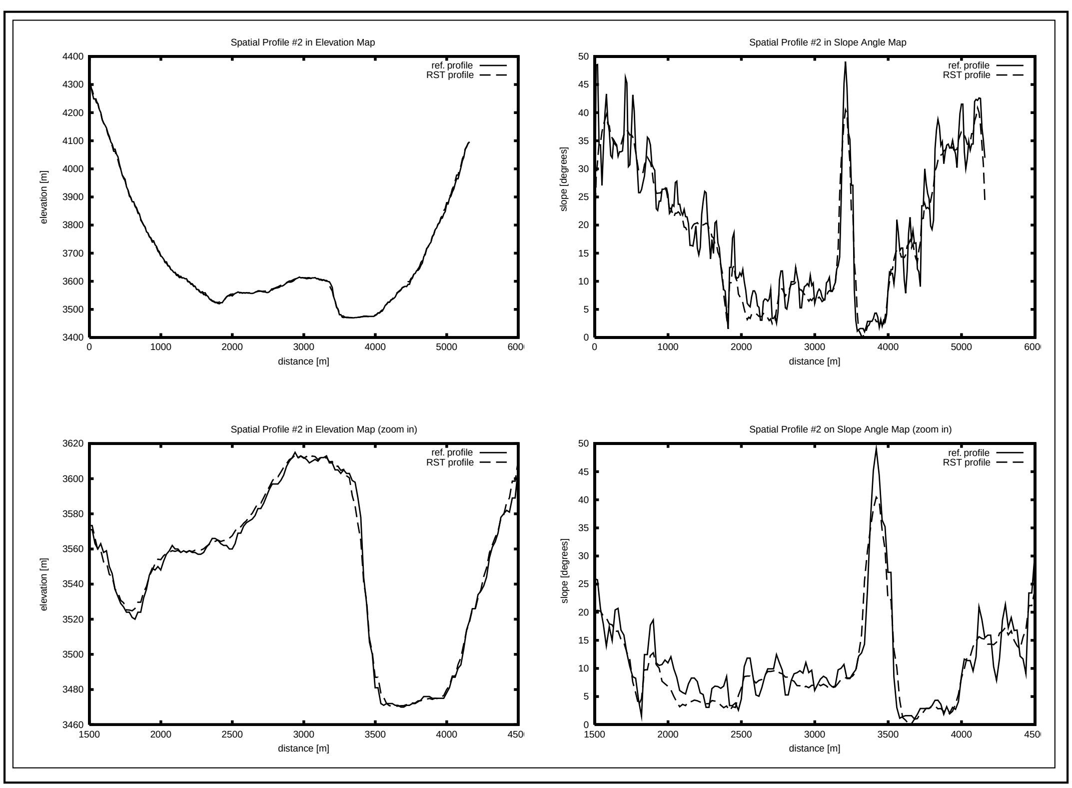

Figure 5: Spatial profile results for Sachen Glacier test site. The location of the profile is presented at Figure 7.

Table 3: Terrain-form object attributes. These attributes were calculated using TFO maps and the DEM, and slope angle map.

a_1 - Planimetric area [m^2]	a_2 - Surface area [m^2]
a_3 - Minimum altitude [m]	a_4 - Minimum slope angle [°]
a_5 - Maximum altitude [m]	a_6 - Maximum slope angle [°]
a_7 - Mean altitude [m]	a_8 - Mean slope angle [°]
a_9 - $\sqrt{\sigma}$ of altitude [m]	a_{10} - $\sqrt{\sigma}$ of slope angle [°]
a_{11} - Relief [m]	a_{12} - Range of slope angle [°]

1.0 was used. This approach to producing TFOs is significant, as the spatial distribution of TFOs is defined based upon the inherent variance in the morphometric properties that have been submitted to the algorithm. The algorithm automatically partitions the variance structure and prevents an analyst from defining artificial ranges of morphometric properties which have no physical meaning.

This resulted in a classification map for each morphometric parameter. Further spatial analysis was required to identify individual TFOs on the basis of local spatial continuity.

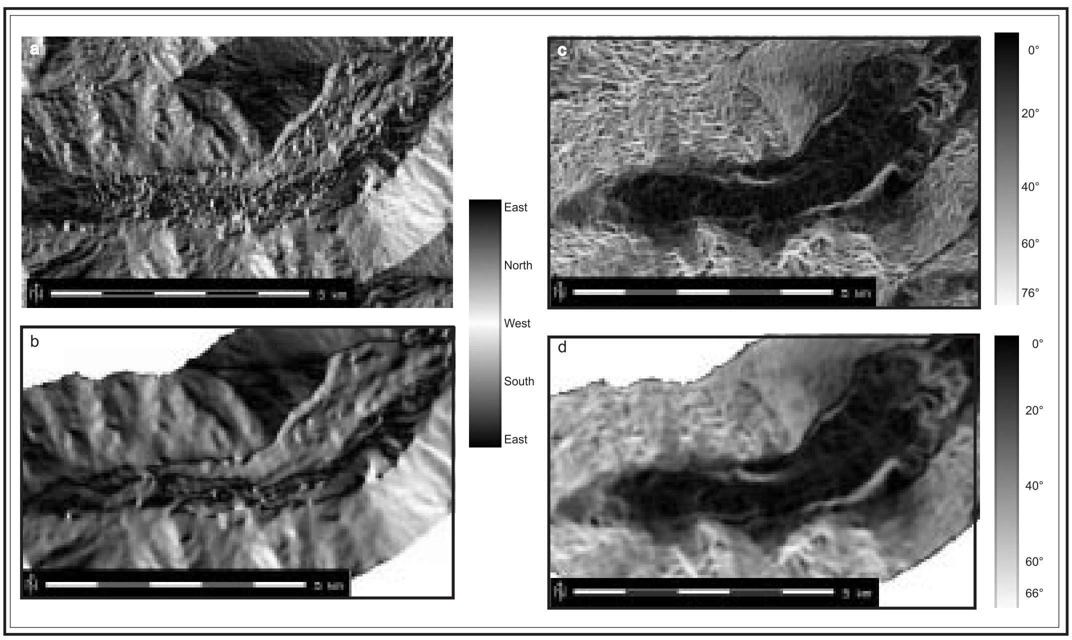

Figure 6: Comparison of SPOT and RST morphometric fields represented by (a) SPOT slope aspect, (b) RST slope aspect, (c) SPOT slope angle, and (d) RST slope angle at Sachen Glacier.

Spatial Clumping.

Spatial clumping was used to identify TFOs on the basis of local spatial continuity. The classification maps were submitted to a clumping algorithm that identified the total number of TFOs over the landscape. This procedure was done for each classification map so that individual TFOs were produced for the four morphometric parameters.

An object-oriented spatial analysis approach at mathematical characterization of these objects was then implemented, to calculate the inherent attributes of each TFO. It is important to note that there is a plethora of possible geometric and contextual properties that can be computed for each TFO. A simple approach was taken to examine basic geometry, relief and slope characteristics. These attributes were generated by spatially stratifying the elevation and slope fields using the TFO maps. This spatial analysis procedure resulted in 12 attributes that could be used for aggregation. The list of attributes is presented at Table 3. These attributes were chosen to determine if basic geometric attributes could be used for aggregation of TFOs into landform objects at the next hierarchical level.

Landform Objects.

TFO attributes were examined in image form to determine which would be most valuable for subsequent analysis. Many of the attributes differentiated alpine glacier surfaces from the surrounding topography. The attributes chosen from various TFO maps for mapping the Sachen Glacier are as follows: from slope angle TFOs: a_8, from slope aspect TFOs: a_8, and from profile curvature TFOs: a_8. TFO attributes based upon ω_t were excluded, as they did not visually differentiate glacier characteristics from the surrounding landscape characteristics.

The next step was to determine how TFOs would be aggregated to produce LOs at the next level in the hierarchy. A simple, two-level hierarchy was used, as the measurement scale of the DEM did not enable a reasonable representation of landform features such as seracs, ice cliffs and other small scale features (i.e., landform features represent a level between TFOs and LOs). An unsupervised classification procedure and the ISODATA clustering algorithm were used to produce LOs. Before cluster analysis was performed, the TFO attributes were scaled to a similar range so that the classification results would not be biased.

5 Results

The original SPOT DEM exhibited a variety of problems which included high-frequency spatial variance, artificial undulations, and terrain-landform artifacts. Consequently, it was essential to generate a new high-quality DEM which could be used for geomorphometric analysis. Spatial profiles across the Sachen Basin and Glacier presented at [37] confirm that the high-frequency variation has been significantly removed (Figure 5). The results indicated that the RST interpolation procedure did not remove relief associated with features such as lateral moraines, alpine glaciers and high-altitude glacier erosion surfaces.

The slope angle maps, and slope aspect maps (Figure 6) were visually compared. These results indicate that the new RST interpolation procedure can produce reliable elevation and morphometric fields that can be used for geomorphological mapping.

Upon confirmation of the RST interpolation results, new elevation and morphometric fields were produced for Sachen study area. The profile curvature highlighted the convexity associated with ridge-tops and lateral moraines (Figure 7). The tangential curvature distribution did a remarkable job of highlighting the crests of ridges and alpine-basin (Figure 7).

These results indicate that manual interpretation and mapping of glaciers based upon this morphometric information is feasible. Finding an automated mapping solution, however, that combines morphological information, represents a unique challenge.

Terrain-Form Objects

The main objective of TFO generation was to identify the elemental topographic structure associated with landforms. This was achieved by identifying statistically separable classes of slope, slope aspect, profile curvature, and tangential curvature.

Classification results indicated that eight classes met the spatial size requirement, although separability results indicated that some of the classes were not statistically separable. When the size of the TFO was taken into consideration, however, achieving better separability came at the risk of producing TFOs that extend over a large area (i.e., smaller number of cluster classes). A selection of eight classes was a compromise that addressed the two criteria.

The spatial distribution of slope-angle TFOs revealed an interesting pattern.(Figure 8). Glaciers surfaces are represented by relatively large objects which exhibit a homogeneous spatial pattern. Conversely, most other TFOs are small in size and collectively exhibit complex spatial patterns. Other portions of the landscape exhibit a very different pattern based upon their size, shape and contextual relationships.

It is plausible that the process of glaciation, and rapid changes in the topography of glacier surfaces, which are governed by dynamic deformation and ice flow, produces relatively homogeneous slope TFOs. Conversely, highly resistant granitic and metamorphic rocks in other portions of the valley, and polygenetic slope-forming processes, dictate greater variability in the size, shape and contextual relationships of TFOs. This same pattern, although reversed, occurs for slope-aspect TFOs (Figure 8).

The spatial pattern of profile- and tangential-curvature TFOs clearly revealed that the curvature pattern of the glacier surface is very different than the surrounding landscape. Generally, profile-curvature TFOs over the glacier surface exhibited a directional shape that was perpendicular to the profile direction of both glaciers (Figure 8). Results for tangential curvature (Figure 8) indicated that unique spatial patterns of tangential-curvature TFOs exist for the glacier surfaces. Although it would be difficult to map glaciers using this information, it is clear that the size, shape and context of these curvature TFOs clearly differentiate alpine glaciers surfaces from the surrounding topography.

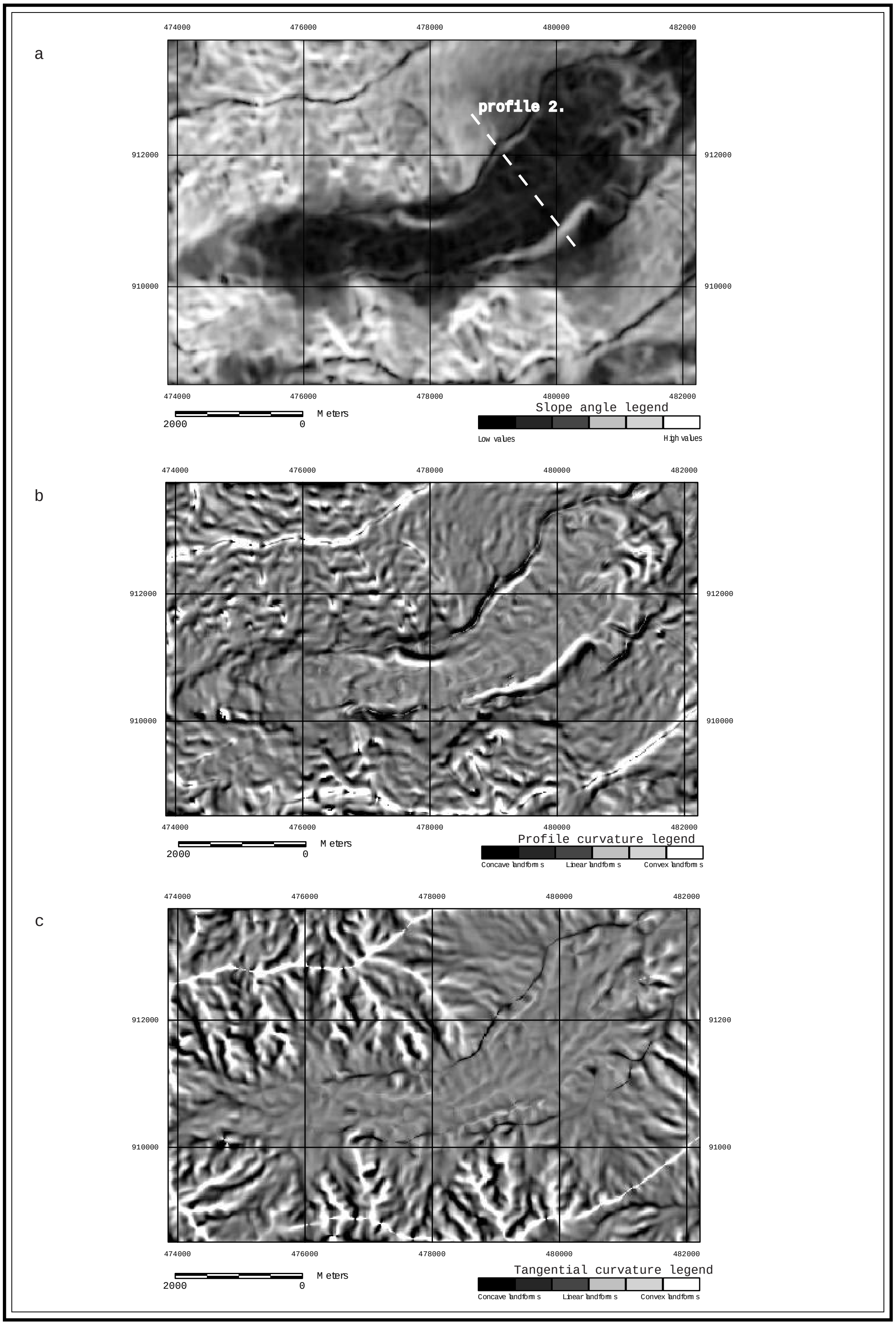

Figure 7: Detailed maps of morphometric fields of (a) slope angle, (b) profile curvature, (c) tangential curvature at Sachen Glacier. Profile analysis of *profile 2.* located at Sachen slope angle map (a), is presented at Figure 5.

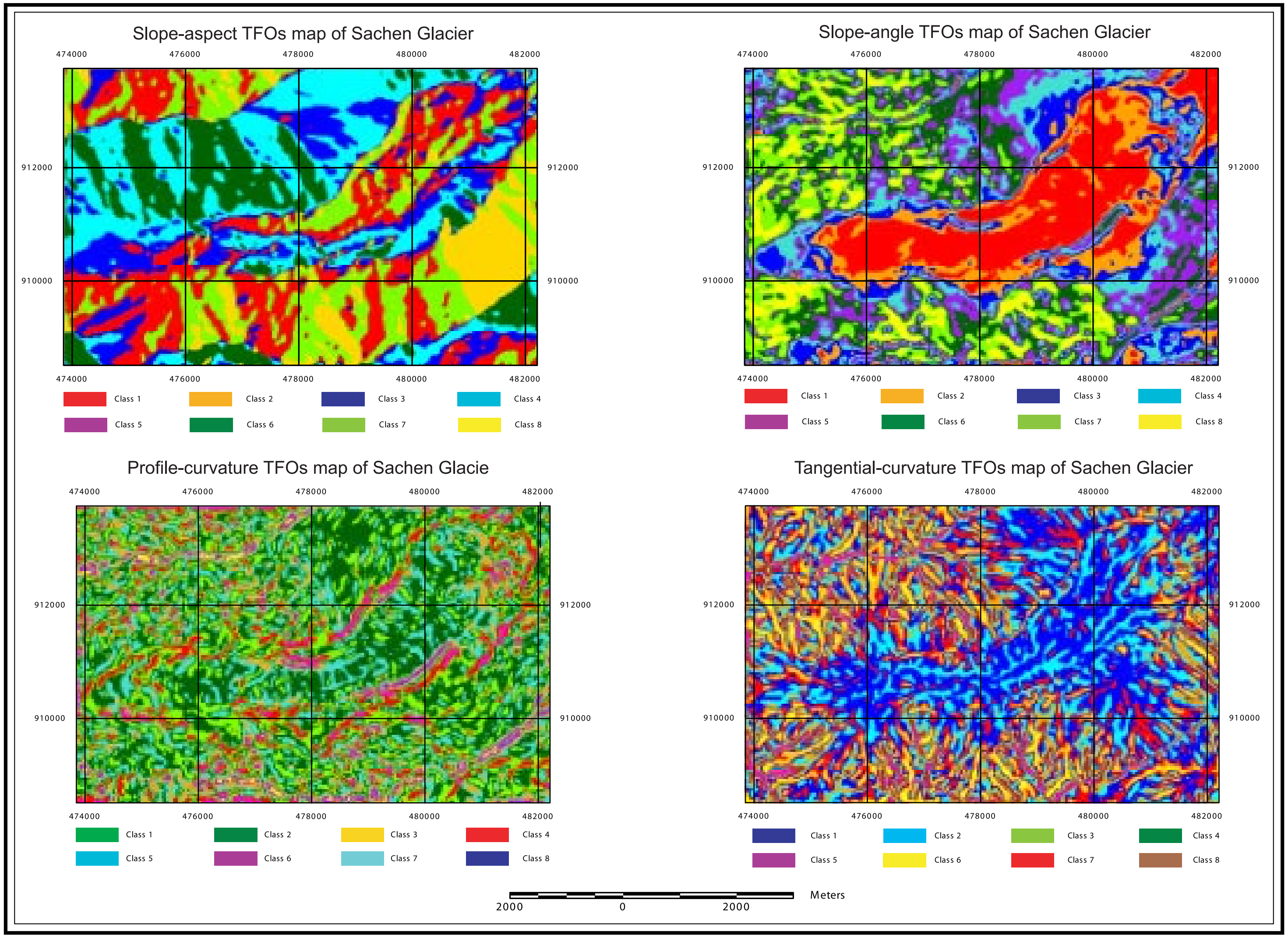

Figure 8: Terrain Forms Objects (TFOs) of Sachen Glacier.TFOs based on slope aspect, slope angle, profile curvature, and tangential curvature.

Attributes of Terrain-Form Objects
The distribution of each TFO served as a spatial constraint for the calculation of TFO attributes. Twelve statistical attributes were computed for each TFO. TFO attributes were then assigned to corresponding pixels to generate TFO attribute images, that were visually examined. The objective was to identify attributes that could be used to differentiate glacier topography from non-glacier topography.

The slope TFO attribute images are presented in Figure 9. Many of the attributes did not accurately differentiate the glacier surface from other portions of the landscape. In particular, the minimum, maximum, and mean slope-angle attributes however did the best job. Similarly, the slope-aspect TFO attribute images were evaluated (Figure 10). Some altitude measures delineated the Sachen Glacier, but could not be used to delineate the lower portion of the glacier. The mean slope attribute did the best job. The profile-curvature TFO attributes images for Sachen Glacier can be seen in Figure 11. Area metrics produced patterns of homogeneous curvature that delineated the Sachen Glacier from the surrounding landscape. The mean slope angle also delineated the Sachen Glacier very well. Similarly, the tangential-curvature TFO attributes exhibited highly variable patterns that were not diagnostic of the Sachen Glacier (Figure 12). The minimum slope angle produced the most homogeneous results, although the boundaries of the glacier were not identifiable.

These results indicate that of the twelve statistical attributes examined, slope attributes were the most useful for differentiating glacier surfaces from other portions of the landscape. It is plausible that these attributes may have value when computed from more complex TFOs that represent the integration of two or more morphometric properties (e.g., slope facets).

Landform Objects
To identify LOs, the statistical attributes of TFOs were used in cluster analysis. The methodology assumes that individual cluster classes represent unique landforms. In an ideal situation, the generation of two classes should divide the landscape into two groupings - glacier surface and non-glacier surface. Results for the Sachen Glacier clearly indicate that the statistical attributes do not permit diagnostic differentiation, using statistical separability as a means of defining the next hierarchical level (Figure 13). They demonstrate that slope attributes can be used to accurately delineate the Sachen Glacier when slope, slope aspect, and profile curvature information is taken into consideration. Collectively, these results indicate that diagnostic mapping is not possible using this simplistic hierarchical model. Landform features are complex, and results indicated that more attributes would have to be taken into consideration. The results of various phases in the analysis, however, indicate that there is significant potential for diagnostic mapping. Hundreds of other TFO attributes can be computed and evaluated, and numerous methodologies regarding classification and spatial aggregation, offer new opportunities for accurately characterizing the topography and identifying hierarchical levels.

6 Discussion

Addressing the problems of hierarchy theory and scale-dependent geomorphological mapping in complex mountain environments is a notoriously difficult endeavor. The literature on these topics is essentially theoretical, although simplistic attempts to solve the mapping problem using morphometric parameters and hierarchy theory have been proposed (e.g., [39, 44, 42, 24, 23, 5]).

Definition of Terrain-Form Objects
It is clear from the visualization of the morphometric properties of the topography, that they contain important information on the topographic structure of the landscape. The concept of identifying homogeneous terrain properties has been proposed as an approach that can be utilized to identify elemental terrain-form objects [23]. Other researchers have indicated that this concept might not necessarily produce adequate results, and that other approaches need to be investigated [31]. Although the later may be true for terrain objects of larger size that do not exhibit homogeneous attributes, and that homogeneity should not be the only basis for spatial aggregation of lower-order objects into higher-order objects. In fact, the TFOs in this study were highly correlated to landform features and landforms. Slope-angle and slope-aspect TFOs accurately delineated the boundaries of alpine glaciers, although curvature objects did not appear to accurately correspond glacier's surface.

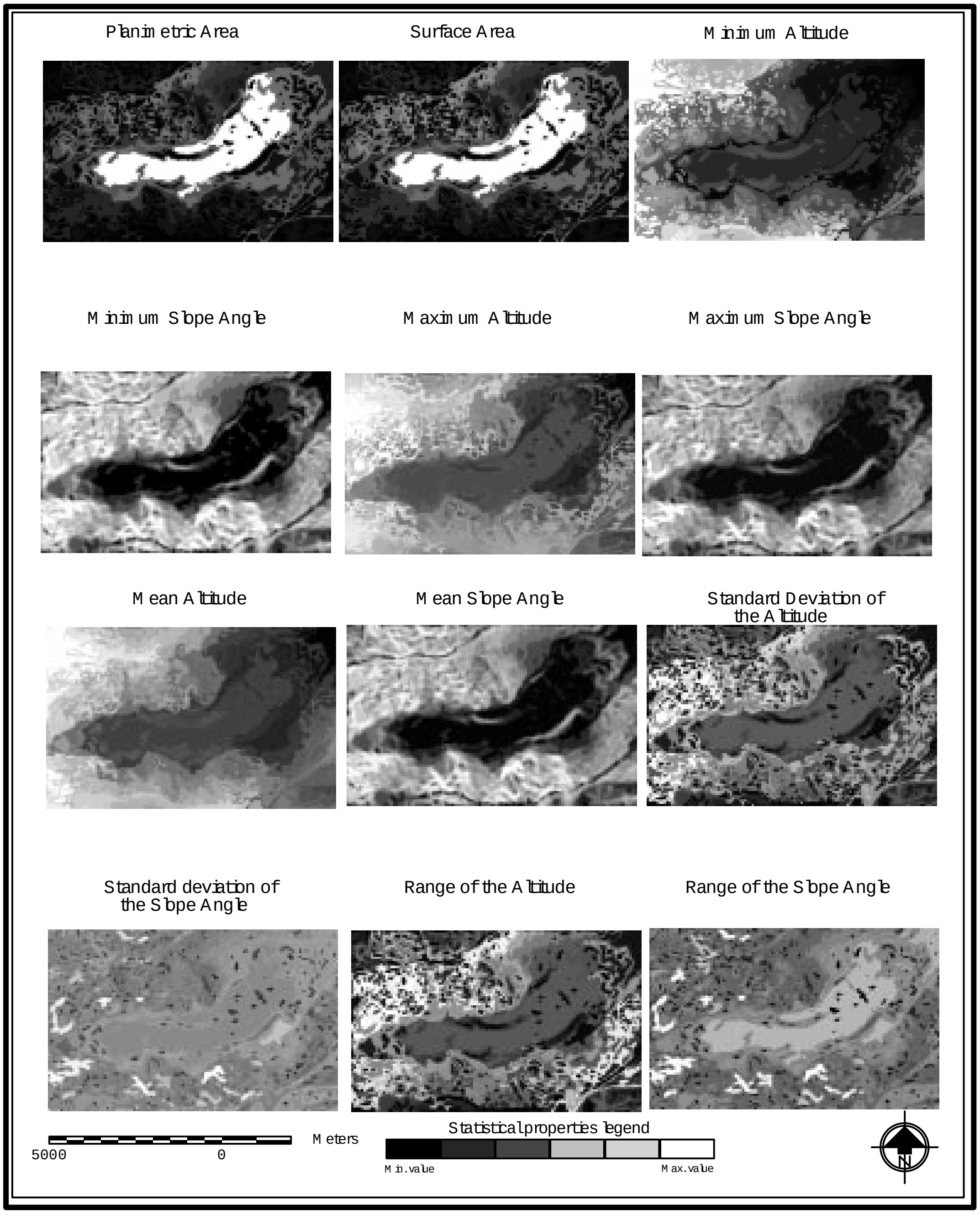

Figure 9: Statistical attributes of slope-angle TFOs for the Sachen Glacier.

These results suggest that the accuracy of identifying elemental terrain-form objects is not associated with the concept of homogeneity, but is related to the issue of defining the topology of morphometric parameters that can be used to define complex homogeneous TFOs. [39] indicated that slope facets, a combination of slope aspect and slope, can be used as a fundamental TFO. [31], and [21, 23] indicated that curvature is very important, and suggested that a typology of TFOs should be based upon this property. Moreover, numerous morphometric parameters can be integrated together and clustered to form TFOs of new quality. This approach is technically easy to perform within the *R* statistical package [3, 4]. However the issue of scale has to be taken into consideration, as there are specific meaningful morphometric properties tied to each cartographic and geographic scale [25]. A promising approach is the generation of slope facets [39, 41]. This TFO represents the combination of slope angle and slope aspect.

Collectively, the results indicate that elementary topographic-form elements that initially define the organization of the topography, can be defined in variety of ways. Additional research into establishing a topological model is required, although the role of individual morphometric parameters

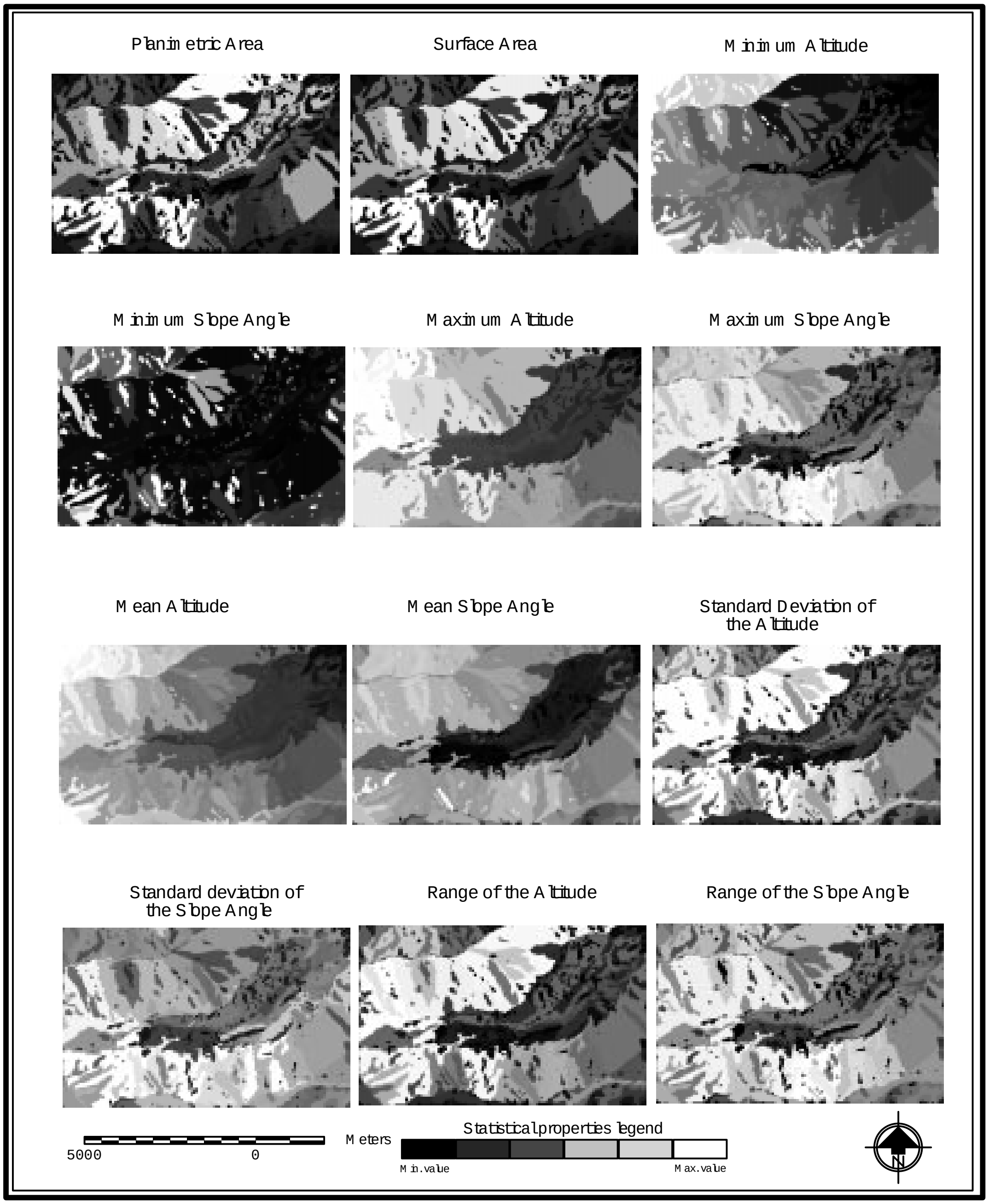

Figure 10: Statistical attributes of slope-aspect TFOs for the Sachen Glacier.

needs to be assessed before diagnostic TFOs can be formally defined and generated.

Attributes of Terrain-Form Objects

Visual examination of TFO attributes, revealed that they could not be used to uniquely delineate and differentiate glacier surfaces from non-glacier surfaces. The results, however, clearly indicated that attributes such as slope angle did characterize the influence of glaciation at high altitudes to some degree. These results do not rule out the possibility that these attributes can be valuable if more complex TFOs are generated based upon a typology of morphometric properties. The differences in shape, frequency, and direction were evident in the slope-angle, slope-aspect, profile-curvature, and tangential-curvature TFO maps. Even though the TFOs were generated using a simplistic approach, the results clearly indicate that TFO shape should be considered, as it could have been used to identify glaciers surfaces.

The need for additional geometric and contextual information becomes most important when attempting to characterize the hierarchical organization of the topography, and when examining the

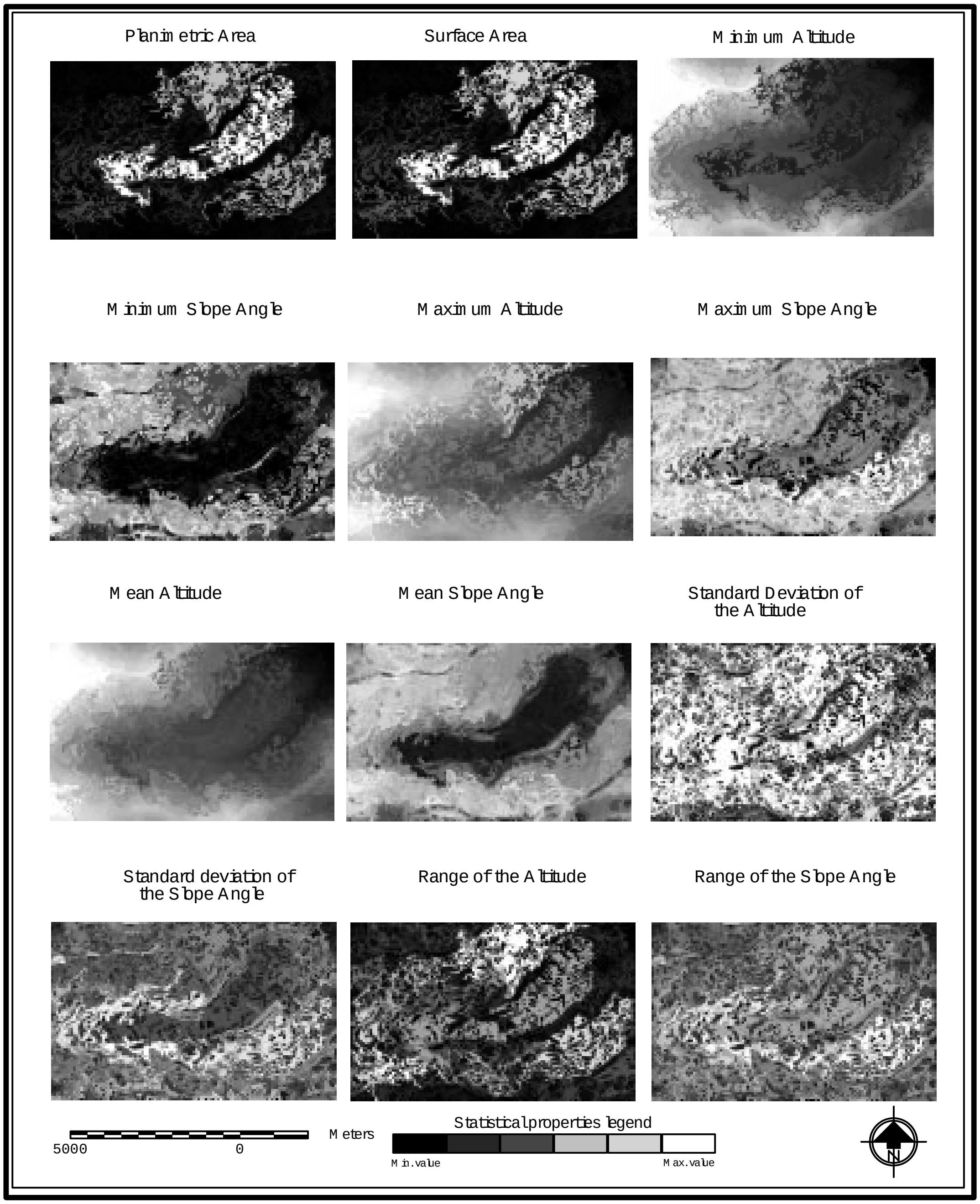

Figure 11: Statistical attributes of profile-curvature TFOs for the Sachen Glacier.

patterns that emerge when viewing TFO maps and TFO-attribute maps. Contextual information such as distance, direction, and spatial topology, are critical attributes that describe the topographic complexity of TFOs and TFO-attribute patterns. Initial and promising results were presented by [25].

Higher-Order Objects

The approach used in this research involves the concept of homogeneous TFO attributes. Cluster analysis was used to create higher-order landform objects based upon similarities in the selected TFO attributes. Theoretically, this approach may work, if the correct attributes are used and they are diagnostic of specific landforms. In practice this approach did not work, as the attributes are not diagnostic of process or landforms. Furthermore, this approach represents a simplistic characterization of the hierarchical organization of the topography, such that single or multiple hierarchical levels may exist between TFOs and LOs, and were not represented.

From a geomorphological perspective, this simplistic model could have been substantially improved by modeling landform features, thereby increasing the number of hierarchical levels. Geo-

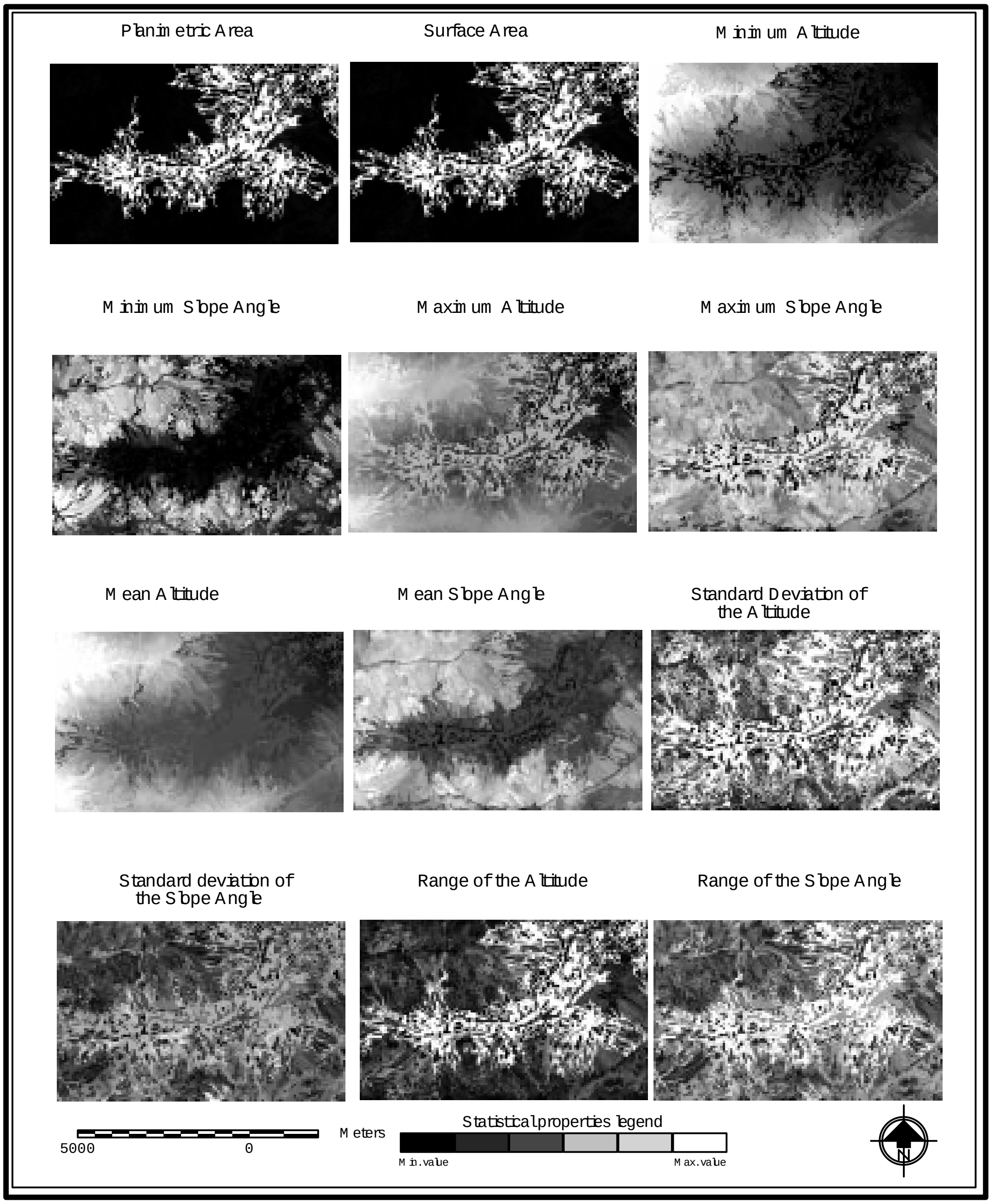

Figure 12: Statistical attributes of tangential-curvature TFOs for the Sachen Glacier.

metric and contextual information may be well suited for establishing criteria for the classification or spatial aggregation of TFOs to produce landform-feature objects. Simple landform taxonomy could then be used as the rules for spatial aggregation and the generation of LOs. An important research question will be to determine whether contextual information can be used in a diagnostic fashion for generation of higher-order features.

7 Summary and Conclusions

Morphometric terrain analysis using high resolution DEM was used to study Sachen Glacier at Nanga Parbat to determine if there are unique morphometric patterns which differentiate the glacier from surrounding landforms. Simple two-level hierarchical model was evaluated, and tested to determine if it is adequate for automatic glacier mapping. Morphometric analysis proved to be useful in delineating geomorphological landforms, and it has shown its potential in scale dependent study of process-form relationship.

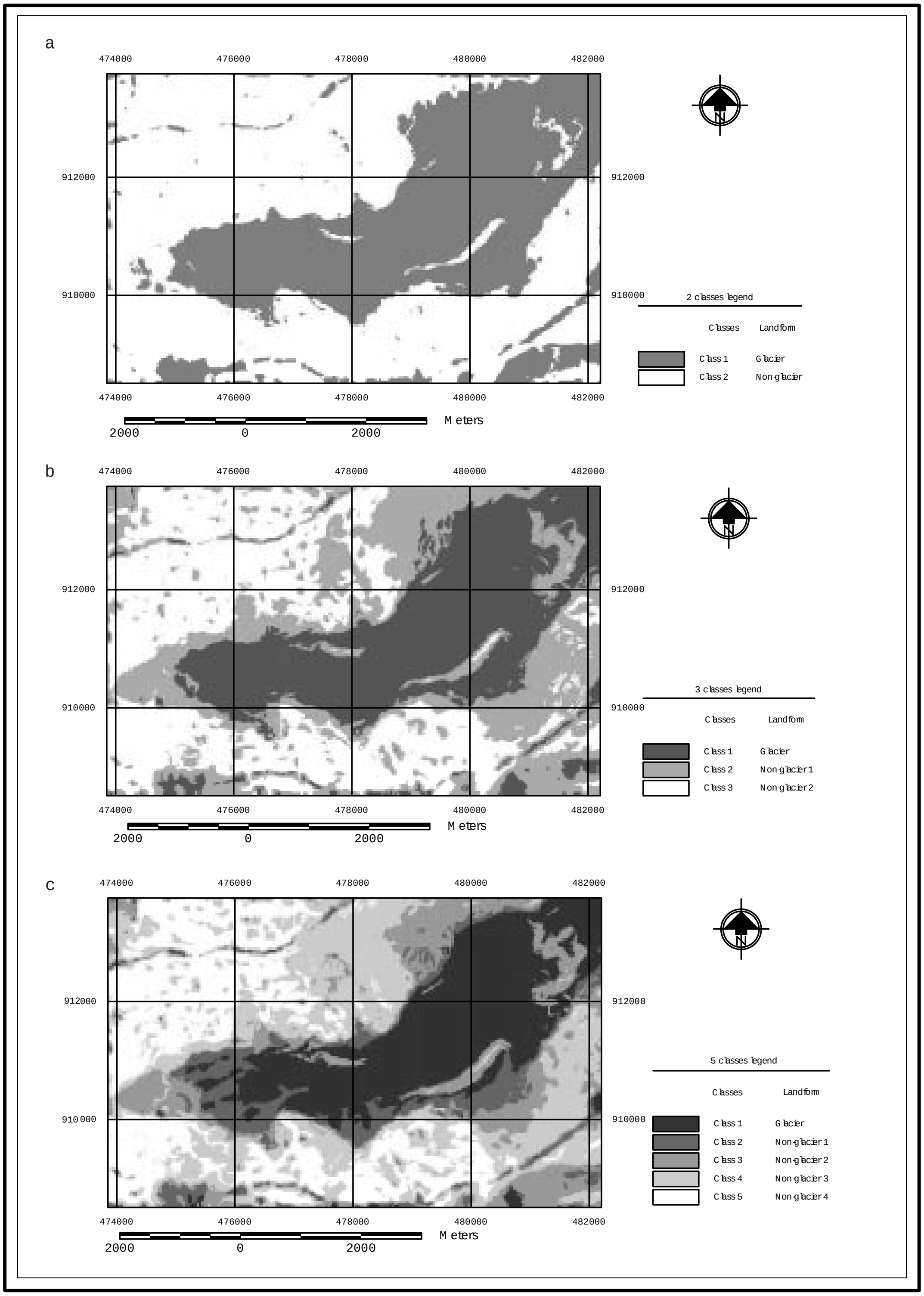

Figure 13: Final glacier – non-glacier landscape classification at Sachen glacier.

Two-level hierarchical model appeared to be inadequate to map such complex and dynamic landforms as glacier definitely are. Morphometric approach, with its potential do generate unique morphometric attributes for different scales, showed to be promising. Consequently, the research disclosed the need for contextual and topological parameters evaluation, as they can be the key in TFOs aggregation into hierarchically higher real-landscape topographic forms. Also precise mathematical definition of hierarchy theory is strongly needed.

GRASS GIS performed well in morphometric terrain analysis, and handling large dataset. It has to be noted, that in the connection with *R* statistical environment it offers almost unlimited research techniques which are required to address the issue of scale dependent morphometric analysis presented in this research.

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