Linking geomorphic systems theory and remote sensing

A conceptual approach to Alpine landform detection (Reintal, Bavarian Alps, Germany)

Nora Jennifer Schneevoigt, Zürich, Lothar Schrott, Salzburg

1 Introduction

Alpine regions are moving into the focus of scientific attention: chapter 13 of Agenda 21 is dedicated to mountains, 2002 was declared «International Year of the Mountain» and German Geographers' Day 2003 was entitled «Alpine World – Mountain World: Islands, Bridges, Borders». The sustainable preservation of alpine regions represents a global issue, because a tenth of the world's population lives in mountains, while a multiple indirectly depend on mountain resources. Geomorphologic activity in alpine regions is significantly greater than in its foreland. Therefore, mountain environments display quick changefulness in time and space (Caine 1974) and react very sensitively to global change (Kääb 2002).

As higher regions often cannot be observed from the ground, remote sensing (RS) applications lend themselves to the investigation of the alpine sediment cascade. While geomorphologic research often uses geographical information systems (GIS) coupled with RS data, only few genuine RS techniques are employed. Difficulties in the accurate designation of landforms add to the general intricacy of handling alpine data in RS. Yet object-oriented classification constitutes a new and promising approach to combine the advantages of GIS and RS. This study aims at illustrating the role of object-oriented RS as a tool in high mountain geomorphology within the context of systems approaches to alpine sediment fluxes and deposits.

2 Allocation of landforms in alpine regions

In order to detect landforms by RS, a compilation of their distinctive features is required. The better the knowledge of the target classes (Tab. 1), the greater the chances of differentiating between them in image data (Schneevoigt et al. 2006). Varying geomorphic process activities result in a patchwork make-up of landforms. Hence, activity status and processes involved are vital for their detection: texture and spectral characteristics of individual landforms can be very heterogeneous.

2.1 Target landforms

A landform is defined by its particular shape. However, strict delimitations of landforms rarely exist in landscape, as many forms show no clear boundaries (Fig. 1 and 2). Moreover, landforms often form part of other landforms – scale and given interest determine where a spectator would set a division. Depending on geographic situation, age, maturity and markedness of a landform, its geomorphometry also varies enormously (Rasemann et al. 2004). Besides, detection of landforms in RS data can be hindered by the fact that many landforms originate from interacting processes and display partially interfingered, complex assemblages (Fig. 2). Equifinality blurs underlying processes as well: different processes can render the same landform shapes, which however should bear different names according to the building process. For instance, a strict separation of avalanche from debris flow deposits is not always possible in situ (Fig. 1B) nor hence in a satellite scene.

This fuzziness of high-mountain terrain features (Kääb 2002) urges consideration of context for sound RS classifications: landforms result from spatially distributed and interlinked geomorphologic processes which are consecutively modelling landscape by filling and emptying different types of stores. Monocausal, linear process-form relations cannot be established because of interactions which vary spatially and temporally. Further investigation is still needed to fully understand landform development in high mountains (Becht et al. 2005; Jordan & Slaymaker 1991; Schrott et al. 2002). RS applications benefit from increased knowledge on target classes (Tab. 1), as more possibilities of feature analysis arise in classification hierarchies.

Deciphering sediment flow and storage is tricky since a focus on single events or forms ignores greater context (Fig. 2), whereas a large scale point of view cannot fully grasp complexity (Fig. 1B). A systemic approximation unites these antipodes: on the one hand, it facilitates the delimitation of single components by allowing the zooming in onto systemic details. On the other, its holistic approach places all components into subsystems and these into greater superordinate systems, thus restoring the entirety of landscape. Hence systems theory, paralleled by object-oriented RS, helps in overcoming the scale problematics in space. As the temporal aspect of RS is limited, the following section focuses on the micro time scale of the present.

crest regions	rockwalls	valley bottom	
cirques & hanging valleys	avalanche & debris flow tracks	avalanche & debris flow tracks	avalanche & debris flow deposits
less inclined bare rock	vegetation covered slopes	talus sheets & cones	rockfall partly/ fully overgrown
free faces	free faces	alluvial fans	rockfall deposits
snow & ice	loose sediments	floodplains	moraine deposits

Tab. 1: Target groups of Alpine landform classification
Zielklassen der alpinen Georeliefformen-Klassifikation
Classes cibles pour la classification des formes du relief alpin

2.2 Systemic approaches to alpine sediment fluxes and deposits

With the onset of process-orientated geomorphology, Strahler (1952) adapts the concept of open systems to geomorphology: in- and output of energy and matter characterise these flow systems striving for a steady state, i.e. an equilibrium of transfers in the system as a whole. Hack (1960) refers to dynamic relationships between process components: as soon as a system contains negative feedback loops, it shows a tendency towards establishing a dynamic equilibrium, as, for this reason, a capability of compensation is given. Landforms thus develop to a state of maturity that is in a continual state of destruction and reconstruction.

Chorley (1962) and Chorley & Kennedy (1971) further promote general systems theory, focussing on inner complexity: they perceive environment as a hierarchy of organised subsystems and mountainous regions as dynamic cascading systems. Although not all processes work in downslope direction, «sediment cascade» generally designates alpine material transport. It is defined as a structure in which the output of one subsystem forms the input of another (Fig. 3). Any movement is determined by regulators at the interfaces between processes and forms (Fig. 3), i.e. by the disposition, presence or absence of geomorphological variables (e.g. storage potential, slope). Internal thresholds of the individual variables interfere with external thresholds of other regulators in the same or surrounding subsystems, allowing for reaction intervals and different reaction patterns even in adjacent forms. This explains the complexity and nonlinearity of alpine systems, where high rates of energy transfer result in rapid sediment turnover (Caine 1974; Chorley & Kennedy 1971).

Despite its benefits, the systems approach initially did not gain general acceptance due to limited implementation. With more powerful computer systems in the 1990s, paradigms in geomorphology changed: with the increasing improvement of memory space, the systems approach regained vitality. Recent research on sediment transport systems increasingly simulates sediment cascades in (peri-)glacial environments (Ballantyne 2002; Becht et al. 2005; Otto & Dikau 2004; Rothenbühler 2006; Zemp et al. 2005).

2.3 The Alpine sediment cascade of the Reintal

The project Sediment Cascades in Alpine Geosystems (Sedimentkaskaden in alpinen Geosystemen - SEDAG) models qualitative and quantitative sediment turnover (Becht et al. 2005; Schmidt & Morche 2006; Schrott et al. 2002; Unbenannt 2002), including the identification of different storage types (Tab. 1) and their spatial patterns. RS hence represents a helpful tool, especially considering the higher, inaccessible parts of the valley (Fig. 1B; Schneevoigt et al. 2006). The conceptional Alpine sediment cascade (Fig. 3) by Schrott et al. (2002) is based on systems theory, synthesising Chorley & Kennedy's hierarchical cascading systems concept (1971) and Caine's alpine sediment transfer model (1974). It shows the spatial distribution of storage types in the Reintal (Fig. 1) in three subsystems cascading downslope via processes. Today, 79% of the sediment stores representing geomorphic process units in the Reintal valley bottom are inactive, overgrown (Fig. 1B, 2) and decoupled from the cascade.

As hardly any sediment leaves the subcatchment, the Reintal equals a nearly closed sediment system (Unbenannt 2002). An imbalance in favour of input prevents the onset of a steady state or dynamic equilibrium. It leads to quickly growing sediment stores, exemplified in high sedimentation rates of 18 to 27 mm a^{-1} (Schrott et al. 2002 and this issue). These stores form buffers which can trap material for centuries and millennia (Jordan &

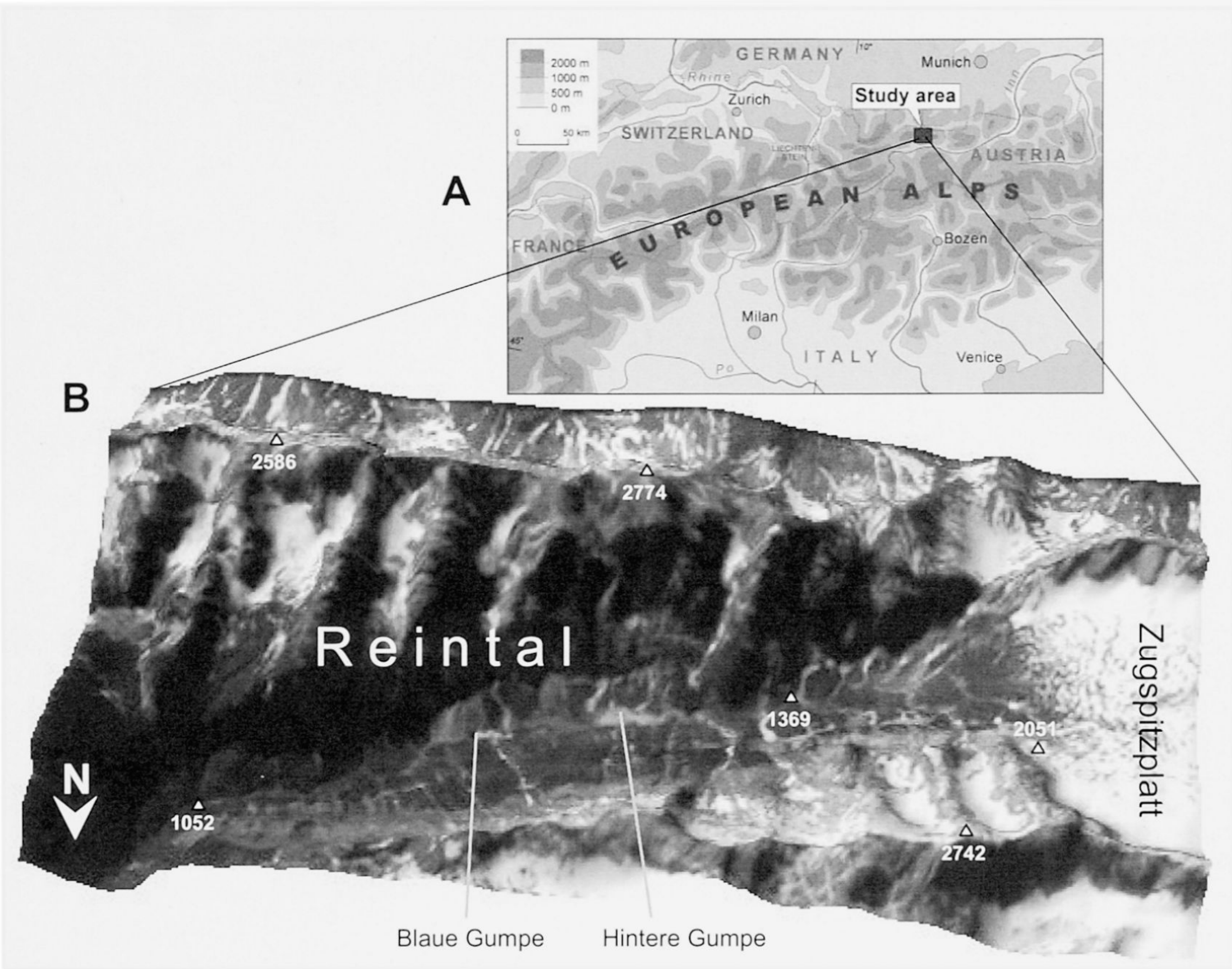

Fig. 1: A) Geographical location of the Reintal (Bavarian Alps, Germany). B) ASTER scene (29.5.2001) in RGB 3-1-2 draped over digital elevation model (DEM), view from north-north-west.
A) Geographische Lage des Reintals (Bayerische Alpen, Deutschland). B) ASTER-Szene (29.5.2001) in RGB 3-1-2 über ein digitales Höhenmodell (DHM) gelegt, Sicht aus Nord-Nord-West.
A) Situation géographique du Reintal (Alpes bavaroises, Allemagne). B) Scène ASTER (29.5.2001) en RGB 3-1-2 drapée sur un modèle numérique de terrain (MNT), vue du nord-nord-ouest.
Source: DEM generated by SEDAG partners, data: Bavarian Geodetic Survey; ASTER image provided by the ASTER science team

Slaymaker 1991), introducing major temporal variations into the system. The heterogeneity of alpine regions and recent climate change add to the difficulty of designing universally applicable schemes of sediment fluxes. Thus overall, quantitative models of sediment cascades fully describing landscape development are still lacking.

3 Optical RS in alpine geomorphology

For a better understanding of the complex material flow systems engendering landscape variability and natural hazards (Kääb et al. 2005), RS constitutes an adequate tool. It permits global, regular coverage of remote areas at a wide range of scales. However, extreme altitudinal differences within small horizontal intervals in alpine terrain may result in offsets of several pixels or hundreds of meters if scanned at disadvantageous angles. Illumination and shading vary enormously because of relief influences (Fig. 1B). Yet high mountain geomorphologists increasingly recognise the potential of RS (Bishop & Shroder 2004). The long-distance perspective facilitates pattern detection and monitoring of otherwise inaccessible landscape sections: remotely sensed imagery and digital elevation models (DEM) complement one another for geomorphological analyses based on applications from the RS community (Giles & Franklin 1998; Kääb 2002).

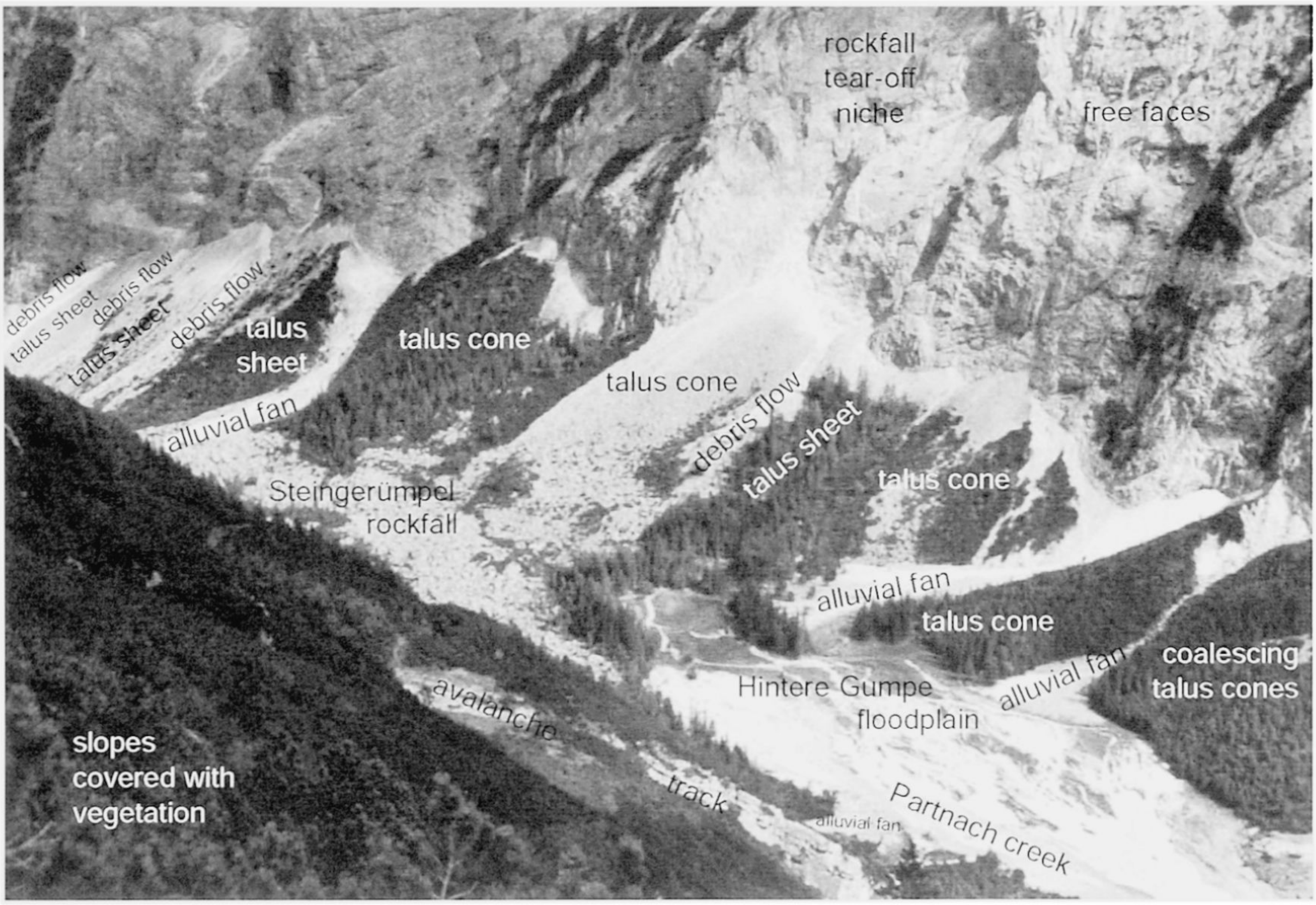

Fig. 2: Alpine landform assemblage around the Hintere Gumpe floodplain (Reintal, Bavarian Alps). Photo overlaid with labels of landforms, view facing south-east.
Vergesellschaftung von alpinen Georeliefformen um die Schwemmebene der Hinteren Gumpe (Reintal, Bayerische Alpen). Foto mit Bezeichnungen der Georeliefformen, Blick nach Süd-Ost.
Assemblage de formes du relief alpin autour de la plaine d'inondation appellée Hintere Gumpe (Reintal, Alpes bavaroises). Photo avec dénominations des formes du relief, vue en direction du sud-est.
Photo: L. Schrott 2001

3.1 GIS versus RS

Whereas GIS approaches to the analysation of RS data are manifold, studies employing RS methodology occur less frequently in high mountain geomorphology. GIS-based spatial analysis in the form of statistical arithmetics, neighbourhood relationships and clusters allows for a differentiation of patterns in landscape. While descriptive calculations per cell (e.g. slope, aspect, curvature) have been applied for two decades now, (semi-) empirical landscape modelling has only been operationalised in GIS environments of late (Bishop & Shroder 2004). Several studies confirm the potential of optical RS imagery and GIS for the assessment of geomorphic forms and processes (Etzelmüller et al. 2001; McDermid & Franklin 1994; Walsh et al. 1998).

Snow and ice monitoring represents the foremost research topic when it comes to genuine RS, as field measurements quickly reach their limits here. For more than two decades now, the full range of possibilities concerning optical satellite data on snow applications has been exploited (Bishop & Shroder 2004; Kääb et al. 2005; Paul 2000; Paul et al. 2002, 2004; Schaper 2000). For example, the Global Land Ice Measurements from Space (GLIMS) programme centres on the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor, scenes of which also form the basis of this study (Fig. 1). For climate monitoring, an inventory of global land-ice extension is thus being developed by a worldwide consortium combining RS and GIS (Kääb 2002).

Recent developments lead to a coalescence of GIS and RS: current object-oriented software unites RS

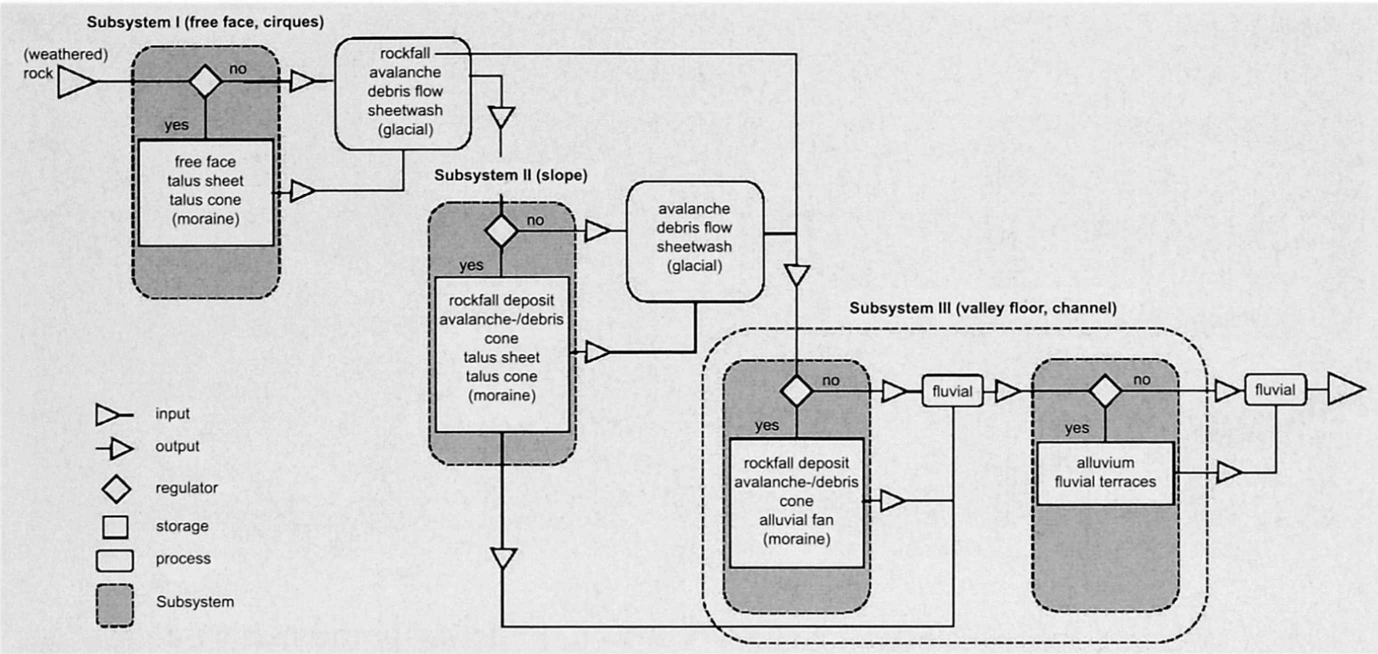

Fig. 3: Conceptual Alpine sediment cascade of the Reintal (Bavarian Alps, Germany)
Konzeptionelle alpine Sedimentkaskade des Reintals (Bayerische Alpen, Deutschland)
Modèle conceptuel de la cascade sédimentaire alpine du Reintal (Alpes bavaroises, Allemagne)
Source: SCHROTT et al. (2002)

applications with GIS statistics into one desktop environment. While pixel-oriented RS analyses the spectral characteristics of each pixel individually, object-oriented RS also considers the neighbourhood of a pixel. It assumes that adjacent pixels showing certain similarities belong to one group, so that the entire scene is divided into image segments (Fig. 4) before classifying it in a second, separate step (Fig. 5). This method produces more homogeneous results through spectral generalisation, thus smoothing out irregular pixel-dominated patterns and creating more realistic forms (BAATZ & SCHÄPE 2000; KOCH et al. 2003).

3.2 Segmenting images into objects

The idea of image segmentation arose in the 1970s, but like systems approach only became operational twenty years later with high-capacity computers. Segmentation techniques are used to deal with intensified in-class variability brought forth by increasing spectral and spatial image resolution (SCHIEWE & TUFTE 2002). The spectral properties of image objects are addressed by mean values, standard deviations and ratios of the incorporated pixels. Image objects also comprise geometric features, as image objects vary in shape and extent (Fig. 4). Neighbourhood relationships, sub- and superordinations, morphometric and class-related features can be analysed as well (BAATZ & SCHÄPE 2000; BENZ et al. 2004; BLASCHKE & HAY 2001). As object-based class descriptions hence reach far beyond spectral information, they are well suited for three-dimensional alpine applications, where spectral input alone does not suffice (GILES & FRANKLIN 1998; SCHNEEVOIGT et al. 2006).

The object-oriented software eCognition segments an image in a knowledge free way via region-growing, an automatized heuristic optimisation method assessing the potential increase of spectral heterogeneity in a weighed merge of two pixels or segments considered. Next to this colour criterion based on spectral information alone, shape parameters can be used to correct highly textured data which otherwise would produce frayed and distorted segments. This constitutes an advantage especially in high mountain data. Yet it must be applied carefully, as it implies an arbitrary divergence from the given spectral information based on pure arithmetics (BAATZ & SCHÄPE 2000).

From the colour and shape input, the region-growing algorithm produces image objects with a minimized average heterogeneity in any desired resolution or scale. However, vital information for all classes often cannot be displayed in one single resolution, while segmentation must be applied to an entire image with one scale parameter. Multiresolution segmentation allows a simultaneous depiction of several image levels segmented on different scales (BAATZ & SCHÄPE 2000; BENZ et al. 2004). For example, a small scale parameter

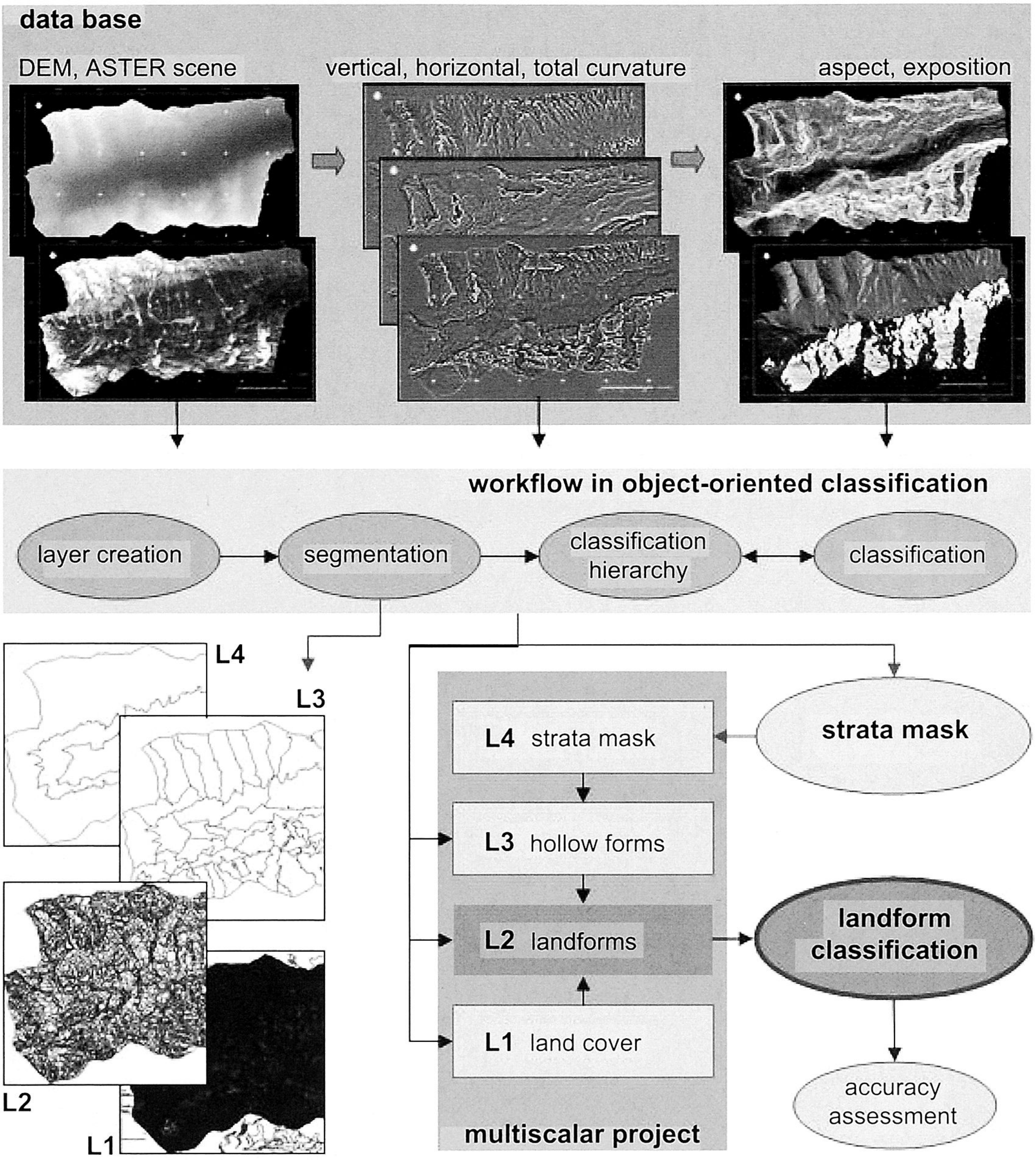

Fig. 4: Object-oriented classification. Top: input data for object-oriented analysis: ASTER satellite scene (15 m resolution resampled to 5 m), DEM (5 m resolution) and five DEM derivatives (5 m resolution). Bottom left: segmentation on four hierarchical levels L1 to L4.

Objektorientierte Klassifikation. Oben: Datengrundlage der objektorientierten Analyse: ASTER-Satellitenszene (15 m Auflösung), DHM (5 m Auflösung) und fünf DHM-Ableitungen (5 m Auflösung). Unten links: Segmentierung auf vier Hierarchie-Ebenen L1 bis L4.

Classification en fonction des objets. En haut: données récoltées pour la classification; scène de satellite ASTER (résolution de 15 m rééchantillonnée à 5 m), MNT (résolution de 5 m) et cinq dérivées du MNT (résolution de 5 m). En bas à gauche: segmentation sur quatre niveaux hiérarchiques L1 à L4.

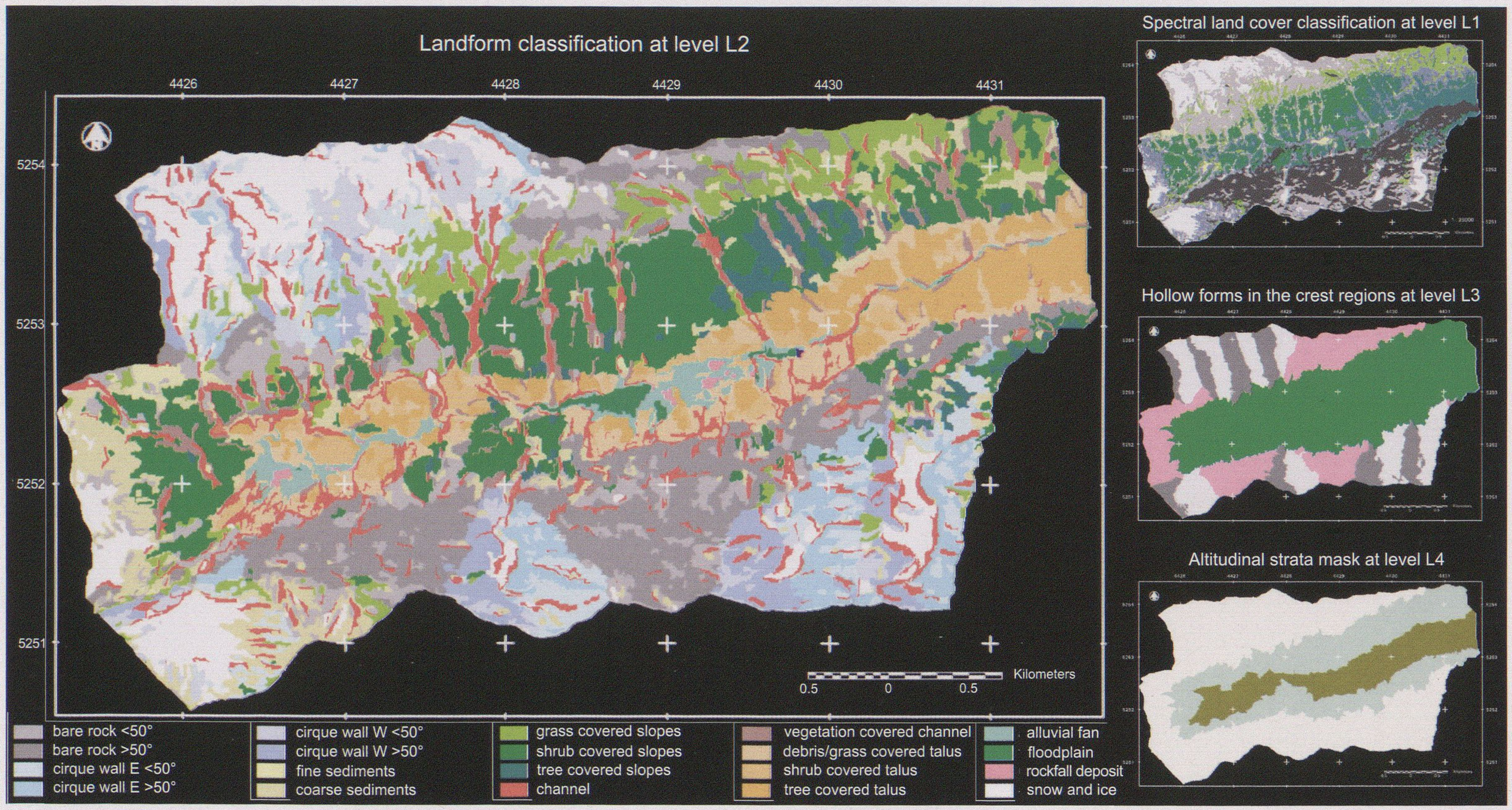

Fig. 5: Object-oriented classification results: spectral land cover classification at level L1, landform classification at level L2, hollow forms in the crest regions at level L3, altitudinal strata mask at level L4

Ergebnisse der objektorientierten Klassifikation: spektrale Oberflächen-Klassifikation auf Ebene L1, Georeliefformen-Klassifikation auf Ebene L2, Hohlformen der Gipfelregionen auf Ebene L3, Höhenstufen-Maske auf Ebene L4

Résultats de la classification: classification spectrale de la couverture terrestre au niveau L1, classification des formes du relief au niveau L2, dépressions dans la région des crêtes au niveau L3, masque des strates verticales au niveau L4 best conveys the heterogeneous Reintal ground surface, whereas the delineation of a mask encompassing three altitudinal subsystems (Fig. 3, 5) implies a very high scale parameter. The final classification should be executed on an intermediate level, not too detailed but showing also relatively small landforms.

This meets the demand for hierarchical and scale dependent RS classifications. Dikau (1994) states that the hierarchical organisation of topography has not yet been taken appropriately into account in studies on mountain geomorphology. Multiscalar approaches can correct this defect (Fig. 4).

3.3 Hierarchical landform classification at four levels in the Reintal

An ASTER satellite scene, a DEM (5 m resolution, generated in the ArcInfo spline algorithm Topogrid from data by the Bavarian Geodetic Survey) and its derivatives were assessed at four levels ranging from very small spectral units to the altitudinal strata mask (Fig. 4). The finest level, L1, was segmented based on spectral information only, while the coarsest layer, L4, represents a strata mask made in a separate object-oriented project. All segmented levels were then classified individually (Schneevoigt et al. 2006) with a knowledge base containing features immanent in a class itself and inherited ones passed on by parent classes in the classification hierarchy. Thus, working on multiscalar levels focussing on differently sized landform features mimics the systems approach, allowing for detailed and general views at once (Fig. 4).

The L1 classification renders ground land cover, level L3 eastern and western walls of cirques and hanging valleys, all of which leads to a sound L2 landform classification shown in Figure 5. The good fit of the results to ground truth is demonstrated in Schneevoigt et al. (2006). Detection limitations are reached with landforms such as moraine and rockfall deposits (which have been overprinted by more recent processes for centuries or millennia) and some complex alluvial fans. The majority of classes such as cirques, rockwalls, floodplains, fine and coarse sediments were well assessed, and some could even be differentiated more than previously expected, e.g. the vegetation covered slopes and talus cover, leading to twenty final thematic landform classes (Fig. 5).

4 Conclusions

RS applications with geometrically medium-resolved, multispectral image data allow the classification of Alpine landforms or geomorphic process units to a great extent, even when dealing with such small landscape units as on the valley bottom of the Reintal (Fig. 2). Thus, RS constitutes a valuable tool in the elaboration of the Alpine sediment cascade, particularly on account of its high detection capacity in otherwise inaccessible crest regions and rockwalls. Object-oriented classification rules should be transferable to other regions, as they depend less on reflection values, atmospheric conditions and arbitrarily selected training areas than pixel-based ones (Blaschke et al. 2002). Application of the approach to different study areas will show whether or not it prepares the ground for a semi-automatic landform classification scheme.

Acknowledgements
We thank the Remote Sensing Laboratories, University of Zurich (T. Kellenberger, K. Itten), the Center for Remote Sensing of Land Surfaces (S. Schiefer, M. Braun) and the Remote Sensing Research Group (H.-P. Thamm, G. Menz), both University of Bonn, for their cooperation. SEDAG has been funded by the German Research Foundation since 2000 (Schr 648/1-3). N.J. Schneevoigt was supported by the German National Scholarship Foundation, SEDAG and the International Fellowship Programme of the Gottlieb Daimler and Karl Benz Foundation.

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Summary: Linking geomorphic systems theory and remote sensing. A conceptual approach to Alpine landform detection (Reintal, Bavarian Alps, Germany)
Although the global importance of high mountains is increasingly being recognised, their geomorphic process system has not been completely understood as yet. While systems theory and geographical information systems (GIS) approaches have been long-serving in alpine geomorphology, the implementation of remote sensing (RS) tools is still rare. However, object-oriented image analysis lends itself to alpine applications, as it unites the benefits of RS and GIS. The systems approach and the object-oriented classification of an ASTER satellite scene with digital elevation information are parallelized in the Reintal (Bavarian Alps). In a hierarchical, multiscale data segmentation and classification, alpine landforms can be detected with high accuracy. Hence, RS techniques represent a valuable tool for high mountain geomorphology.

Zusammenfassung: Parallelen zwischen geomorphologischer Systemtheorie und Fernerkundung. Ein konzeptioneller Ansatz zur Erkennung alpiner Georeliefformen (Reintal, Bayerische Alpen, Deutschland)
Obwohl die globale Bedeutung von Hochgebirgen zunehmend erkannt wird, ist ihr geomorphologisches Prozesssystem noch nicht ganz entschlüsselt. Während die Hochgebirgsgeomorphologie Systemtheorien und Geographische Informationssysteme (GIS) seit langem verwendet, nutzt sie Fernerkundungswerkzeuge kaum. Dabei bietet sich objektorientierte Bildinterpretation für alpine Anwendungen an, da sie Vorteile von Fernerkundung und GIS vereint. Der systemtheoretische Ansatz und die objektorientierte Klassifikation einer ASTER-Satellitenszene mit digitalem Geländemodell werden am Beispiel des Reintals (Bayerische Alpen) parallelisiert. Durch hierarchische, multiskalige Segmentierung und Klassifikation können Reliefformen mit hoher Genauigkeit detektiert werden. Somit stellen Fernerkundungstechniken ein wertvolles Instrument für die Hochgebirgsgeomorphologie dar.

Résumé: Des liens entre la théorie systémique géomorphologique et la télédétection. Une approche conceptuelle appliquée à la détection des formes du relief alpin (Reintal, Alpes bavaroises, Allemagne)
Bien que l'importance globale des hautes montagnes soit de plus en plus reconnue, la systématique des processus géomorphologiques n'a pas encore été suffisamment étudiée. Alors que les approches se basant sur la théorie systémique et les Systèmes d'Information Géographique (SIG) ont été employées depuis longtemps en géomorphologie alpine, l'usage d'outils de télédétection est encore peu fréquent. Cependant, l'analyse d'images orientée-objet se prête aux applications alpines, puisqu'elle réunit les avantages de la télédétection et des SIG. Dans l'exemple du Reintal (Alpes bavaroises), l'approche systémique est utilisée parallèlement à une classification orientée-objet issue d'une vue satellitaire ASTER et de l'information numérique de terrain. Une segmentation et une classification hiérarchique multiscalaire permettent alors de classifier les formes du relief avec un haut degré d'exactitude. Les techniques de télédétection représentent donc un outil valable pour la recherche géomorphologique alpine.

Dipl.-Geogr. **Nora Jennifer Schneevoigt**, Remote Sensing Laboratories, Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland.
e-mail: nschnee@geo.unizh.ch
Prof. Dr. **Lothar Schrott**, Department of Geography and Geology, University of Salzburg, Hellbrunnerstrasse 34, A-5020 Salzburg, Austria.
e-mail: lothar.schrott@sbg.ac.at

Manuskripteingang/received/manuscrit entré le 30.1.2006
Annahme zum Druck/accepted for publication/accepté pour l'impression: 26.9.2006