CHAPTER THREE

Nature and Aims of Geomorphological Mapping

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1. INTRODUCTION

Geomorphological maps are amongst the best tools for understanding the physical context of the Earth's surface. They provide a full objective description of landforms (*morphography*) identified with specific names and depicted with their correct shape or, where not allowed by the map scale, by appropriate symbols. Geomorphological maps should include

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information on the spatial properties (dimensions, slope, curvature, relief) of landforms (*morphometry*); their origin and evolution in relation to endogenous/exogenous genetic agents and processes (*morphogenesis*), also considering the effects of bedrock lithology/structure control; their relative or absolute age (*morphochronology*); their activity status and rate of genetic processes (*morphodynamics*) and the type of bedrock and near-surface deposits.

These data, collected at different scales in relation to the purposes of an investigation, from systematic field survey and the interpretation of aerial photographs and/or satellite imagery, are commonly reported on topographic sheets or on enlarged remotely sensed images (ortho-photomaps, ortho-photoplans, photo-mosaics and so on) in order to highlight their spatial distribution and mutual relationships.

Since the first published geomorphological map (Passarge, 1914), the importance of these documents has increased progressively, as testified to by the large number of scientific programmes of systematic survey and mapping promoted in different countries, even at a national level (Klimaszewski, 1956; Macar et al., 1961; Galon, 1962; Pecsi, 1963; Savigear, 1965; Tricart, 1965, 1972; Verstappen, 1970; Maarleveld et al., 1974; Barsch and Liedtke, 1980; Ten Cate, 1983; Barsch et al., 1987; Evans, 1990; Brancaccio et al., 1994; Buza, 1997; Kneisel et al., 1998; Wakamatsu et al., 2002; Baker, 2009; Gustavsson and Kolstrup, 2009).

Today, geomorphological mapping is present as a preliminary investigation method in practically all land management projects and geological risk assessment and zoning. Moreover, geomorphological baseline data are increasingly required by other sectors of environmental research such as land ecology, forestry and soil science (Tricart, 1969; Cooke and Doornkamp, 1974; Panizza, 1978; Guida et al., 1996; Brunsden, 2003).

The following sections are dedicated to 'traditional' symbol-oriented geomorphological maps distinguished in terms of purpose and scale. After a short description of the modern tools available for the acquisition, storage and display of geomorphic data, the efforts currently performed by geomorphologists in the transition process from traditional symbol-based mapping systems to full-coverage, multiscale, object-oriented geomorphological models will be discussed. The last part of the chapter will present the geographical information system (GIS)-based, object-oriented method of geomorphological mapping presently applied to landslide hazard assessment at Salerno University (Italy).

2. TYPES OF GEOMORPHOLOGICAL MAPS

Two main categories may be distinguished among geomorphological maps: *basic geomorphological maps* and *derivative geomorphological maps* (Dramis and Bisci, 1998).

Basic geomorphological maps (*analytical maps*; Verstappen, 1977) are produced by simple graphic transfer of data directly collected from field survey or aerial-photograph interpretation (Verstappen and van Zuidam, 1968; Klimaszewski, 1982; van Zuidam, 1985), from geological maps, soil maps, vegetation maps, land use maps and so on. A typical aspect of these maps is the ability to make interpretations not necessarily previewed by the practitioner.

Basic geomorphological maps may be made following two different perspectives: the first is concerned with the evolution of the landscape over geological timescales (*morpho-evolution maps*); the second takes into consideration the typology, and activity status, of geomorphological processes affecting the investigation area (*morphodynamic maps*).

Morpho-evolution maps represent Earth surface evolution in relation to endogenous agents (such as large-scale crustal vertical movements, surface tectonics and volcanism) and exogenous processes connected with past to modern climates, and, for more recent times, human activities. These maps are produced at scales that are not too large, in order to allow a general view of fairly large geomorphological features (such as planation surfaces, alluvial and marine terraces and fault scarps) that can be recognised more easily over a relatively wide area, even after being modified by subsequent geomorphological processes or tectonics.

Morphodynamic maps consider phenomena connected with present surface geodynamics including the effects of human activities. They are made at a more detailed scale, thus representing, with the necessary accuracy, all the landforms and near-surface deposits related to geomorphological processes affecting the investigated area. In this type of map, a detailed representation of bedrock lithology (possibly classified according to the mechanical behaviour of outcropping formations) and structural setting is important. According to the survey project purpose, some additional information could be provided concerning ‘non-geomorphological’ aspects such as paleoseismology, volcanic activity, soils, surface water, groundwater, vegetation cover and land use (*synthetic maps*; Verstappen, 1977).

From the analysis of morphodynamic maps it is possible to outline the overall framework of the recent/present morphogenesis of the investigated area as well as to formulate reasonable predictions of the future behaviour of recognised surface phenomena, also assessing scenarios of first-generation geomorphological events in previously unaffected areas. Therefore, regardless of their significant scientific value, morphodynamic maps may assume a primary role in land management projects (urbanisation, road construction, pipelines, parks and so on) and in projects aiming to mitigate geological risks.

Derivative geomorphological maps are obtained through selection, generalisation and reuse of data reported in basic maps with the purpose of zoning the spatial/temporal distribution of significant geomorphological processes such as landsliding, floods, co-seismic surface deformations, volcanic eruptions and tsunamis (*pragmatic geomorphological maps*; Verstappen, 1977; Ten Cate, 1990). Derivative maps are more easily readable than the original basic maps and may also be used by non-specialists, including engineers, land planners and decision-makers. A typical example is that of geomorphological stability maps (Panizza, 1973).

Geomorphological hazard maps are derivative maps that describe the 'nature of risk-causing surface phenomena, and their magnitude and frequency of occurrence' (Petley, 1998). They can be based either on the knowledge of an expert geomorphologist or on the application of statistical/deterministic models.

Computer-assisted procedures, mostly based on the analysis of geological—geomorphological, meteo-climatic and land use parameters, may be used to assess the susceptibility of land (i.e. the probability that a geomorphological event of given typology and magnitude may occur in a given area) to the occurrence (expanded, reactivated or newly generated) of potentially dangerous processes (Dikau, 1990; Parise, 2001; Cardinali et al., 2002; van Westen et al., 2008; Leoni et al., 2009). If the recurrence time interval of events triggering surface processes (extreme rainfall, high magnitude earthquakes) is considered, it is possible to assess, for the study area, different levels of geomorphological hazard (i.e. the probability that a geomorphological event of a given typology and magnitude may occur in a given area over a given time interval). Notwithstanding unavoidable assessment uncertainties and mistakes, hazard maps derived from large-scale geomorphological maps may be particularly useful (Petley, 1998).

3. GEOMORPHOLOGICAL MAP SCALE

Scale is one of main issues in geomorphological mapping. The spatial scales of geomorphological features span over a large range, from 10^7 km^2 (continents, ocean basins) to 10^{-8} km^2 (glacial striations, ripples) (Tricart, 1965). Moreover, the persistence time ranges from 10^8 years (for the largest features) to less than 10^2 years (for the smallest ones) in relation to their size (Table 3.1) as described by the following general equation (Baker, 1986):

$$S = aT^b$$

where S is the size of the feature, T is its duration time, a is constant indicating the intensity factor of the related geomorphic process (i.e.

Table 3.1 Spatial/Temporal Order of Magnitude of Earth Surface Features

Order	km^2	Corresponding Earth Surface Features	Approximate Persistence (years)
1	10^7	Continents, ocean basins	10^8–10^9
2	10^6	Shields	10^8
3	10^4	Medium-scale tectonic units (sedimentary basins, mountain massifs, domes)	10^7–10^8
4	10^2	Smaller tectonic units (fault blocks, volcanoes, sedimentary sub-basins)	10^7
5	10^2–10	Large-scale erosional/depositional units (deltas, major valleys, piedmonts)	10^6
6	10–10^{-2}	Medium-scale erosional/depositional units (floodplains, alluvial fans, moraines, smaller valleys)	10^5–10^6
7	10^{-2}	Small-scale erosional/depositional units (ridges, terraces, sand dunes)	10^4–10^5
8	10^{-4}	Larger geomorphic process units (hillslopes, sections of stream channels)	10^3
9	10^{-6}	Medium-scale geomorphic process units (pools and riffles, river bars, solution pits)	10^2
10	10^{-8}	Microscale geomorphic process units (fluvial and aeolian ripples, glacial striations)	

Source: Modified from Baker (1986).

rapidity of expenditure energy per unit area) and *b* is a scaling factor (equal to about 1.0).

Taking into account the timescale of geomorphological phenomena, Baker (1986) considers three main categories:

1. *macroscale*, over which major phases of erosion/deposition occur, controlled by regional warping, mountain building and crustal plate movement,
2. *mesoscale*, which treats major changes in landforms and landscapes over hundreds to thousands of years involving a complex interplay between tectonic and climatic controls on geomorphological processes (e.g. growth/recession of glaciers, aggradation/degradation of river bed and progradation/recession of shorelines),
3. *microscale*, over which the major variables of tectonism and climate are assumed to be constant (processes that characterise sand dunes, glaciers, rivers or beaches reflecting only the short-term events that dictate local flow physics).

Considering that genetic mechanisms, persistence times and, more generally, the nature of the geomorphological features change with changing landform dimensions (Schumm and Lichty, 1965; Cullingford, 1980; Brunsden, 1993, Evans, 2003, Slaymaker et al., 2009), it follows that maps with significantly different scales cannot address the same geomorphological contexts unless they have different objectives. Therefore, the choice of the map scale is strongly constrained by the project targets (Brunsden et al., 1975; Baker, 1986).

According to the level of cartographic detail, geomorphological maps were classified by Demek and Embleton (1978) into three groups:

- *large-scale geomorphological maps* (map scale >1:100,000),
- *medium-scale geomorphological maps* (map scale from 1:100,000 to 1:1,000,000),
- *small-scale geomorphological maps* (map scale <1:1,000,000).

However, considering the previous definition of geomorphological maps, it seems more appropriate to apply the scheme proposed by Dramis and Bisci (1998) (Table 3.2):

- *large-scale geomorphological maps* (map scale >1:25,000),
- *medium-scale geomorphological maps* (map scale from 1:25,000 to 1:250,000),
- *small-scale geomorphological maps* (map scale <1:250,000).

Table 3.2 Map Scale Classes, Ranges and Mappable Lengths

Scale	Scale Range	Maximum/Minimum Mappable Lengths (40 cm/2 mm on the map) (km)
Small	<1:1,000,000	>400/>2
	1:1,000,000–1:500,000	400/2–200/1
	1:500,000–1:250,000	200/1–100/0.5
Medium	1:250,000–1:100,000	100/0.5–40/0.2
	1:100,000–1:50,000	40/0.2–20/0.1
	1:50,000–1:25,000	20/0.1–10/0.05
Large	1:25,000–1:10,000	10/0.05–0.4/0.02
	1:10,000–1:5000	0.4/0.02–0.2/0.01
	>1:5000	<0.01

3.1 Large-Scale Geomorphological Maps

Large-scale geomorphological maps are made with enough detail to allow the correct representation of morphographic, morphometric, morphogenetic, morphochronologic and morphodynamic features of most landforms recognisable on slopes, valley floors, plains, coasts and so on.

Adequate information should be given on the main stratigraphic—sedimentologic characteristics and thickness of landform-related near-surface deposits, as well as on the outcropping bedrock lithology (possibly classified on the basis of lithotechnical characteristics) and structural setting (layering, foliations, faults, joints and so on).

To better understand the genesis of landforms and evaluate their possible future trends, the map contents should be enriched with data concerning surface/groundwater, vegetation cover, land use and so on.

The production of large-scale geomorphological maps is essentially based on systematic field survey. The interpretation of remotely sensed imagery (aerial photographs, satellite imagery) should only be used as a supporting tool during different project stages:

- to set up a preliminary geomorphological framework of the investigation area,
- to check the correct cartographic design of the surveyed field features,
- to perform the final revision of the field-based geomorphological map.

Where possible, in order to allow the easy and rapid transfer of field data, it is advisable to use aerial photographs with a scale close to that of the base topographic map sheet. Field observations should also be supported by laboratory analyses (sedimentological, paleontological, palinological, chronological) as well as by computer-assisted topographic analyses developed using digital elevation models (DEMs).

Field work should also include a detailed survey of bedrock lithology, possibly classified according to the main lithotechnical characteristics of the outcropping formations (Tricart, 1965; Panizza, 1972; Peña Monné, 1997; Dramis and Bisci, 1998). Data should also be collected on bedrock stratigraphy and structure (layering attitude, faults, jointing), as well as on the nature and thickness of near-surface deposits and weathering horizons, especially in the case of process-oriented (morphodynamic) maps (Evans, 1990; Dramis and Bisci, 1998).

Even if data concerning bedrock geology can be taken from pre-existing large-scale geological maps, it is best practice to inspect rock outcrops during the survey campaign (if necessary, with the help of an expert geologist). The same process should occur for near-surface deposits whose characteristics (lithology, texture, fabric, thickness, water content) play an important role in landscape evolution.

The analysis of the lithological composition of clasts may also be useful (Bridgland, 1986; Jones, 2000; McClanegan et al., 2001; Wanders et al., 2004):

- to reconstruct the extension and boundaries of ancient fluvial basins prior to the formation of contemporary systems,
- to quantify the individual contribution to moraine construction by glacial tongues originating from lithologically different valleys,
- to understand if debris deposits are fed by the upper slope or have been transported long distances.

Clast fabric may provide information on transportation/deposition mechanisms and transporting fluid direction. Particularly important in this context are the orientation of clast long axis (commonly perpendicular to flow lines in river channels) and clast imbrication, the best indicator of flow direction (Yagishita, 1989; Nichols, 2009).

The chronological reference of landforms is essentially based on the age of related deposits as provided by dating with different relative and absolute methods (^{14}C, Uranium series, ^{39}Ar/^{40}Ar, ^{40}K/^{40}Ar, ^{210}Pb, OSL – optically stimulated luminescence, TL – thermoluminescence and so on) of material included therein (Lowe and Walker, 1997). Some specific methods (cosmogenics, dendrochronology, lichenometry, weathering level) also allow the dating of surfaces (Darlymple, 1991; Winchester and Harrison, 2000;

Watchman and Twidale, 2002; Gosse, 2007). In any case, independently from the existence of absolute dates, both landforms and near-surface deposits should be placed within a temporal succession (on the base of their reciprocal spatial relationships). Indirect information regarding the landform/deposit age and paleoenvironmental genetic conditions may be obtained by paleomagnetic or thermo-chronological data.

In the case of morpho-evolution maps, it is convenient to organise near-surface deposits not in contact among each other according to morphostratigraphic sequences (North American Commission on Stratigraphic Nomenclature, 1983).

The activity status of surface features may be deduced by field observations (e.g. detailed stratigraphic observations, archaeological investigations, characteristics of vegetation cover, lichenometry) supported by the comparison of multitemporal aerial photographs and/or high-definition satellite images and the analysis of archive data (local history, periodicals, newspapers, minutes of governmental meetings, notarial acts, maps, paintings, photographs, scientific papers and reports and so on) (Dramis and Bisci, 1998). Significant data can be obtained from the examination of cracks and other disturbances affecting buildings (Coltorti et al., 1986). For more recent events, interviews with residents may provide useful information.

A possible field classification of landforms, in terms of activity, may consider three main categories (Dramis and Bisci, 1998):

1. *Active landforms* — landforms visibly evolving under the action of their genetic agents and related geomorphic processes,
2. *Quiescent landforms* — active landforms characterised by discontinuous, step-like evolution mapped in a dormant stage,
3. *Inactive landforms* — landforms produced in a geomorphological context definitely different from the present one and evolving under the action of agents (different from the genetic ones) that generally tend to destroy or bury them.

At scales above 1:5000, geomorphological maps are particularly suitable for outlining a detailed framework of the spatial—temporal evolution of landforms (and related deposits) such as shorelines, river beds, landslides and weathering features (Sauro, 1977; Fenti et al., 1979; Seijmonsbergen and van Westen, 1990; Faccini et al., 2008). Mapping activities may also include geophysical investigations, exploration boreholes, field/laboratory geotechnical data (regarding near-surface deposits and outcropping bedrock) and instrumental monitoring of landform activity status. Also information on surface/groundwaters may be included to better understand the morphodynamics of the investigated area. These cartographic documents, called *engineering geomorphological maps* (Griffiths and Marsh, 1986; Fookes, 1997; Griffiths, 2001), can play a significant role in land management activities such as stability analysis in built-up areas, preliminary investigations for engineering works, waste disposal areas and seismic microzoning.

3.2 Medium-Scale Geomorphological Maps

Medium-scale geomorphological maps provide a representation of large landscape units (volcanic hills, fault slopes, tectonic basins, mesas, cuestas, inselbergs, planation surfaces, alluvial/coastal terraces, alluvial plains, glacial valleys, dune fields and so on) which can be reproduced in full, or at least for a large part of their extension, thus allowing the depiction of mutual relationships and morphochronologic sequences.

Smaller landforms, such as those present on slopes and valley floors, are grouped together or reproduced by means of not-to-scale symbols. Also the subdivisions of landforms, near-surface deposits and genetic processes should be necessarily more generalised than in large-scale maps. As an example, slope processes connected with gravity (landslides, soil creep) and running water slope processes (slope wash, gullying) may be grouped in the single category of denudation processes. At smaller scales, it is more appropriate to use comprehensive terms such as fluvio-denudational slope and fluvial-depositional plain.

As far as bedrock geology is concerned, the relevant data are normally extracted from pre-existing cartographic documents. In some cases, bedrock geology is represented together with landforms as geological—geomorphological units (e.g. fluvio-denudational slope on limestones and planation surface on sandstone).

Where not derived by the generalisation of large-scale maps, medium-scale geomorphological maps are essentially produced by concurrent aerial-photograph interpretation and field work. Field observations are usually restricted to sample areas or representative transects with the aim of collecting interpretative keys from remote sensing analysis.

3.3 Small-Scale Geomorphological Maps

Small-scale maps can be classified into three groups:

1. Maps produced by a number of ‘desk studies’ such as the generalisation of previous larger scale maps, extrapolation of known situations

from comparable areas and bibliography data (e.g. the IGU Geomorphological Map of Europe on the scale of 1:2,500,000 by Bashenina et al., 1968, 1971),

2. Maps directly derived from satellite imagery interpretation (e.g. the 1:15,000,000 scale geomorphological map of the world directly constructed from space imagery by Bashenina and Talôskaya, 1981; the 1:1,000,000 scale map of Argentine Pampa by Canoba, 1982; the landforms map of part of New South Wales, Australia, by Pain, 1985),
3. Derivative maps, simply obtained by generalisation of larger scale geomorphological maps.

Small-scale geomorphological maps represent the structural framework of the land surface and the long-term geomorphological history of major depositional and erosional units, volcanic hills and effusive rocks and morphotectonic mega- and macro-structures. They are used in education to ‘show the complex integration of the natural environment’ (Embleton, 1985) as well as in land management at the country level, providing a ‘first approach’ land classification particularly useful for wide regions.

4. NEW TOOLS IN GEOMORPHOLOGICAL MAPPING

The recent advances in satellite technology and the ability of modern personal computers to manage large volumes of digital data have introduced radical changes in geomorphological mapping, providing a positive solution to some ‘classical’ problems of the ‘traditional’ cartographic approach.

Particularly relevant in this context is the role of the *global positioning system* (GPS), *satellite imagery data*, high-definition *DEMs* and *GIS*. Oguchi et al. (2011) provided a more detailed description of data sources, whereas Smith (2011) details manual mapping and Seijmonsbergen et al. (2011) detail automated and semi-automated mapping techniques.

4.1 Global Positioning System

The GPS can provide accurate measurements of the latitude, longitude and elevation of a survey/sampling point by means of geometric trilateration (a method for determining the intersections of three sphere surfaces given their centres and radii) of a constellation of geostationary satellites

(Leick, 1995). For this reason, GPS has become more and more widespread among field geomorphologists (Cornelius et al., 2006), particularly for active processes (Coe et al., 2003). Voženílek (2000) compared GPS-aided geomorphological mapping and conventional surveying techniques, highlighting the utility of the tool in terms of accuracy and data management.

4.2 Satellite Imagery

Data collected by satellite sensors, mostly in a digital form, offer the opportunity of observing the landscape at a regional scale (some even stereoscopically), permit identification of features not perceptible on site or on larger scales as well as landscape changes at regular intervals of time (Campbell, 1987; Drury, 1990; Smith and Pain, 2009). Satellite imagery cannot be substituted in full for those collected by field work and aerial-photograph analysis, however the use of high-resolution satellite imagery (up to 0.5 m with GeoEye-1) may provide valuable support to the geomorphologic interpretation of the landscape, especially in constructing medium/small-scale maps (Ulaby and McNaughton, 1975; Townshend, 1981; Hayden, 1986; Bocco et al., 2001; Etzelmüller et al., 2001; Rao, 2002).

Multispectral sensors (panchromatic, colour, and near infrared, short wave infrared and mid infrared bands), thermal radiation scanners and active microwave sensors (side-looking airborne radar or synthetic aperture radar) may provide detailed information on land surface features, highlighting small elevation differences and ground irregularities even in cloudy regions. Radar data can also provide information on land surface properties such as slope and dielectric behaviour of outcropping materials.

4.3 Digital Elevation Models

DEMs, that is digital imagery in which each matrix point has a value corresponding to its altitude above sea level, can be derived by digitising elevation data from topographic maps or, directly, from stereo imagery, interferometric synthetic aperture radar or light detection and ranging (LiDAR) (Dikau, 1989, 1992; Oguchi, et al., 2011). These models provide a 3D representation of the investigation area allowing observations from different viewpoints and with different vertical scales. These may also be rendered by draping over the DEM aerial photographs, topographical maps, geological maps and geomorphological maps (Teeuw, 2007; Aringoli et al., 2008). Moreover, morphometric data, such as slope gradients and breaks, slope aspect, altimetric belts, surface roughness or grain, as well as parameters concerning hydrographic networks can be automatically extracted from DEMs.

The availability of detailed DEMs allows analysis of landscape morphology and related processes in terms of topographic morphometry or *geomorphometry* (Wilson and Gallant, 2000; Hengl et al., 2008). This investigation method, in particular, provides a significant contribution to tectonic geomorphology, whose principal goal is to extract information regarding the rates and patterns of active deformation from landscape topography (Montgomery and Brandon, 2002). In this context, the study of bedrock channels plays an important role, especially in understanding the relationship between relief, elevation and denudation rates (Howard et al., 1994; Whipple et al., 1999). Indeed, the long profiles of bedrock rivers may yield valuable information about the distribution of recent deformation within the underlying region (Merritts and Vincent, 1989; Burbank et al., 1996; Lavé and Avouac, 2001; Montgomery and Brandon, 2002).

4.4 Geographical Information System

GIS packages are reference tools for the collection, storage, analysis and cartographic display of geospatial data (Burrough, 2000; Krönert et al., 2001), including topographic base data. Input land surface elements from geomorphological mapping may be selected and distributed into different georeferenced *layers*, which can be superposed and compared, enabling advanced spatial data analyses such as map overlay, adjacency, connectivity and containment to be performed. A GIS built on geomorphological data, criteria and rules is termed a *geomorphological information system* (GmIS) (Meijerink, 1988; Létal, 2005).

Although ‘traditional’ cartographic documents are ‘*static maps*’ (that is not modifiable after their printing), those produced by means of GmIS may be considered ‘*dynamic maps*’, whose printouts are simple reproductions taken at a given update stage (Eklundh, 2001). Moreover, a GmIS allows the simple and rapid processing of thematic layers and production of numerical analyses. Further advantages include the automatic extraction of data from topographical maps, such as calculating slope gradient and aspect, changing map scale, projections and coordinate systems (Bonham-Carter, 1994; Longley et al., 2001), joining two or more adjacent maps without loss of design quality or selecting geomorphological features from the database to produce special purpose maps. This last feature provides a positive solution to the 'classical' problem of geomorphological maps in fully representing, in a readable form, all the requested aspects of the land surface (Gustavsson, 2005). However, there remain graphic limitations in the reproduction of classical readable *general purpose* geomorphological maps, covering the whole scientific remit of land surface features.

In a GmIS database, land surface features can be stored on map layers as pixels (*raster data*) or points, open lines or polygons (*vector data*) which may be combined with *attribute data*, describing their characteristics (see Smith, 2011). These latter can be divided into *spatial data* (feature location, topology and geometry), *temporal data* (feature age or time of data collection) and *thematic data* (feature type).

In more detail, the GmIS structure should include the following data organised according to a cross-validation scheme with informative levels verifying each other (*congruence control*):

- *Vector data* representing land features (geomorphological database *sensu stricto*),
- *Raster data* representing images (output data from pixel/object-oriented analysis),
- *Triangulated irregular networks* (TINs) representing land surface by means of irregularly distributed nodes and lines with three-dimensional coordinates (x, y and z) that are arranged in a network of triangles (physical model of the investigated area),
- *Addresses and locators* defining geographical positions (depository of surveyed data).

Moreover, a GmIS database should include information about surface and sub-surface properties such as stratigraphy and lithology.

GmIS data can also be stored as objects and groups of objects, not separated into layers but gathered into hierarchically arranged classes. This latter approach reflects more accurately the 'real world' even if it has the disadvantage of time-consuming problems (Heywood et al., 2002).

Some limitations in application of input data may result from their accuracy and reliability (as an example, the data extracted from geological maps, such as layering or lithological boundaries, are sometimes uncertain, inhomogeneous and imprecise, combining original field mistakes with map drawing mistakes). Therefore, it would be necessary to review the survey methods, substituting generic descriptions with GPS-located numerical data and ordering field-surveyed land features in a pre-processed model based on remotely sensed data. The conceptual validity of the model should be verified by definition and cross-validation of numerical parameters obtained from pixel/object-oriented analysis. The field data should be recorded on bespoke forms (paper based) or transferred to a laptop and directly processed using mobile GIS software (e.g. ArcPad from ESRI, TerraSync from Trimble and Mobile GIS from Tensing).

5. PROBLEMS AND EFFORTS IN CURRENT GEOMORPHOLOGICAL MAPPING

As discussed earlier, a geomorphological map should contain substantial information regarding landform genesis, chronology and dynamics as well as near-surface and outcropping bedrock. However, this goal has proved hard to achieve (Gustavsson, 2005; Gustavsson et al., 2006). In fact, the huge amount of data to be mapped and the need to keep maps sufficiently readable has forced geomorphologists from different countries to adopt legends which, under the influence of local environmental conditions and academic schools, do not consider sufficiently, or even ignore, some of these fundamental landscape aspects (Gilewska, 1967; Demek et al., 1972; Demek and Embleton, 1978; Salomé et al., 1982; Gustavsson, 2005). For example, bedrock lithology is not present in Polish maps (Klimaszewski, 1982), whereas different outcropping rocks represent the fundamental landform units in French and Italian geomorphological maps (Joly and Tricart, 1970; Tricart, 1972; Panizza, 1988; Brancaccio et al., 1994; Dramis and Bisci, 1998); geometrically homogeneous land sectors divided by discontinuity lines are used as basic landform units in the British and Alpine Geomorphology Research Group (AGRG) legends (Savigear, 1965; Cooke and Doornkamp, 1974; Brunsden et al., 1975; De Graaff et al., 1987; Rose and Smith, 2008); in contrast, ITC legends (Verstappen and Van Zuidam, 1968; Verstappen, 1970, 1977; van Zuidam, 1982) show slope form as contour lines whereas the base map units generally are large genetically homogeneous areas. Some legends are extremely complicated and difficult to read (Barsch and Liedtke, 1980; Barsch et al., 1987; Kneisel et al., 1998), whereas others are extremely simple with limited information (Kienholz, 1978).

Summarising, the ‘traditional’ symbol-based mapping systems adopted in different countries, sometimes for national projects, are not comparable with each other and unable to provide a complete representation of landscape complexity (features and evolution processes) at the different scales and are therefore insufficient to fulfil all the scientific and practical needs of society (Klimaszewski, 1982, 1990; Barsch et al., 1987; Ten Cate, 1990; Gustavsson et al., 2006).

On the other hand, multiscale mapping models, coherently managed with a GIS (Mark and Smith, 2004) and easily readable and applicable to multidisciplinary landscape studies at the regional level, are increasingly required by land administrators and decision-makers in different sectors of land management (such as geo-hazard zoning for risk mitigation, land conservation, inventory of geo-sites, soil mapping, hydrology, landscape ecology, environmental engineering, forestry and agronomy).

To fulfil these requirements, geomorphological maps should represent, as precisely as possible, the spatial properties of landforms, reducing the use of symbols in favour of correctly bounded geometric elements (*full-coverage mapping*). In this regard, the extremely wide range of landform sizes implies the need for new mapping models, able to represent correctly the same area at different scales.

These models should:

- increase typology, quality, quantity and combinations of manageable and representable geomorphological data. In particular, the information associated with each 'object' should be flexible enough to allow the representation of all related attributes (e.g. the terrace edge of Figure 3.2, besides being a linear entity, is also part of the polygon which defines the terrace itself and the underlying river bed),
- interact with the analysis and data representation of other disciplinary sectors at different scales,
- conform with *spatial data transfer standard* (SDTS) in order to promote and facilitate the transfer of digital spatial data between dissimilar computer systems (Goodchild et al., 1999).

A positive response to these requirements is provided by the use of GIS-based mapping models rooted on the following principles:

- *Exhaustivity and mutual exclusivity*: All the geomorphological objects should be recognised, delimited by discrete or indeterminate boundaries according to the *fuzzy—set theory* (Borrough, 1996) and classified in only one distinct class (Fisher et al., 2000, 2004, 2007; MacMillan et al., 2000b; Arrel et al., 2007) or in fuzzy non-exclusive geomorphic types (Zhu, 1999; Borrough et al., 2000, 2001),

- *Understandability and applicability*: Terminology, classification schemes and procedures should be easily understandable and applicable,
- *Repeatability and independence*: The obtained products (in particular the object limits) should be reproducible and independent from any operator decision, possibly by automatic landform recognition,
- *Hierarchical multiscalar congruence*: The mapping process should cover adequately and congruently, areas with different geomorphological characters at scales of different detail,
- *Operational flexibility and structural coherence*: The GIS structure should be modifiable by the inclusion of further data and goals without implementing new classification schemes.

Problems and efforts in current geomorphological mapping may be synthesised in the following basic points: data interoperability, hierarchical data structure and full-coverage object-oriented data management.

5.1 Interoperability

In geomorphology, as in other earth sciences, specified land objects and their structural/functional interrelations 'have to be seen as a mental model, simplifying real world conditions' (Dikau et al., 1991). Therefore, the semantic rules supporting a GIS-based geomorphological mapping system can be defined as relationships between computer representations and the corresponding 'real world' features within a certain context (Bishr, 1998). Moreover, GIS-based mapping operators should be able to interact among them even if working at different sites and with different computer systems.

A possible way to achieve this state of interoperability may be provided by the development of a definitive and authoritative ontological nomenclature of the geospatial domain, grounded on the idea that a knowledge base can be defined through the development of a set of unique, domain-specific concepts for objects and processes describing geospatial information. In the 'concept space', a set of such concepts exists as an interlinked network of nodes between and within domains. Based on existing equivalency between concepts and category meanings, each node in the 'category space' can be linked to its corresponding node in the 'concept space' (Ng, 1998). By explicitly defining these links, a formal ontological data structure can be created.

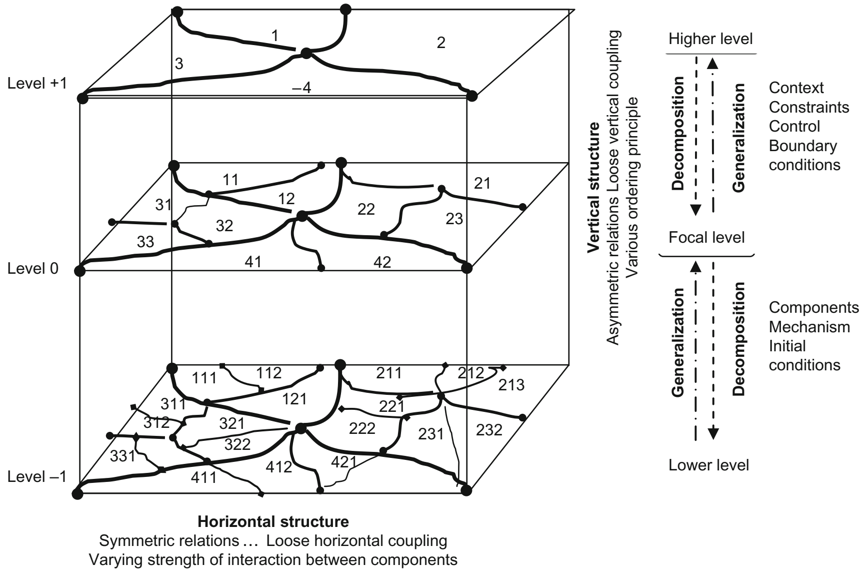

Figure 3.1 Illustration of hierarchical ordering/coding and horizontal/vertical relationship between the focal (initial) level and the higher/lower levels. In the focal to higher level transition, a set of generalisation algorithms allows the adaptation of time-spatial context, number and typology of control factors and boundary conditions. In the focal versus L-level transition, a set of decomposition algorithms are involved to extract basic components and mechanisms, modifying the previous initial conditions. *Modified from Wu (1999).*

5.2 Hierarchical Taxonomy and Multiscale Geomorphological Mapping

The problem of multiscale geomorphological mapping may be approached in the following manner: (1) the *principles of allometry* (Bull, 1975), that is the space–time relationships of landforms, including the energy rate involved in the genetic process and their persistence time (Huxley, 1972; Church, 1996; Small, 1996) and (2) the *hierarchy theory*, a set of principles to order structurally complex multilevel systems (Figure 3.1), with symmetrical, horizontal and asymmetrical upwards/downwards relationships (Koestler, 1967; Webster, 1977; O'Neil et al., 1986; Haigh, 1987; Seelbach et al., 1997; Wu, 1999; Krönert et al., 2001; Pereira, 2002).

A noteworthy aspect is the integration of 'traditional' symbol-based geomorphological legends with the hierarchically ordered land classification systems, largely applied in different sectors of the environmental sciences (Linton, 1951; Christian, 1958; MEXE, 1965; Christian and

Stewart, 1968; Ollier, 1977; Howard and Mitchell, 1980; Bailey, 1987; Speight, 1990; Dikau et al., 1991; Bisci and Dramis, 1992; Guida et al., 1996; Wielemaker et al., 2001; Pain and Kilgour 2003; McKenzie et al., 2005; Blasi et al., 2007; Pain et al., 2007; Paron et al., 2007). Through this approach, the land surface can be viewed as a mosaic of geomorphic objects that, by increasing observation detail, can be decomposed into smaller and smaller ones and vice versa. In this ordering system, called a *nested sequence*, each hierarchy level 'includes the cumulative effects of lower levels in addition to some new considerations (called emergent properties in the technical literature)' (Slaymaker et al., 2009).

5.3 Full-Coverage Object-Oriented Mapping

Full-coverage object-oriented mapping may be performed by expert judgement-based intercomparison between 'traditional' field mapping and pixel or object-oriented grid analysis for automatic landform recognition (Heil, 1980; Franklin, 1987; Molenaar, 1989; Hughes, 1991; Graff and Usery, 1993; Fels and Matson, 1996; Schmidt and Hewitt, 2004). The second procedure is based on *grid segmentation* techniques, allowing the partitioning of DEMs or remotely sensed imagery into non-overlapping regions (segments) representative of geomorphic entities (Baatz and Schäpe, 2000; MacMillan et al., 2000b; Blaschke and Strobl, 2001; Schiewe et al., 2001; Blaschke, 2003; Burnett and Blaschke, 2003; Drăguţ and Blaschke, 2006; Anders et al., 2009). With this technique, the geomorphic entities are designed with 'non-subjective' and repeatable boundaries better achieving quantitative landscape analysis and environmental design.

Two image objects are considered similar when they are near to each other in a certain 'feature space'; the semantic links between image objects are established on principles of object-oriented programming. An object is constituted by certain sub-objects; sub-objects are elements of super-objects. Sub-objects inherit certain characteristics from their respective super-objects and vice versa (Blaschke and Strobl, 2001). The decomposition of land features into smaller units, characterised by distinctive mechanisms, magnitude and evolution rates, may provide a positive contribution to a deeper understanding of their evolutionary trends, also in view of assessing related risk levels and setting up appropriate remedial measures.

Object-oriented geomorphological mapping is increasingly used in the automatic or semi-automatic definition of landforms, with particular reference to those connected with slope and fluvial processes. The capacity of overcoming the 'three-dimensional' limitations related to symbol-oriented methods and grid-based analysis (boundary/segment representation of geomorphic entities) will induce widespread diffusion of this system in the future. However, the transition to the full use of object-oriented geomorphological mapping will be not simple or immediate. In fact, before reaching the goal of a reliable automatic recognition of landforms from remote sensing imagery, the 'traditional' symbol-oriented mapping system will continue to be used at least as the first operative step of the object-oriented methodology.

6. EXPERIENCES OF GIS-BASED, OBJECT-ORIENTED MULTISCALE GEOMORPHOLOGICAL MAPPING

A new GIS-based, full-coverage, object-oriented geomorphological mapping system has been applied in Italy, in several national and regional projects on engineering geomorphology, landscape ecology and hydrology (Cascini et al., 2005; Rossi et al., 2006; Blasi et al., 2007). These activities constitute the 'core sector' of a GmIS at the Department of Civil Engineering and Great Risks interuniversity Consortium, Salerno University (Italy).

Intercomparison between 'traditional' mapping ('expert judgement-based') and automatic landform recognition allows a 'non-subjective' and repeatable delineation of the geomorphic entities in order to better pursue quantitative landscape analyses and environmental design. The hierarchical taxonomy shown in Table 3.3 is a modified version of the scheme applied in these projects (Guida et al., 1996, 2009 Cascini et al., 2005; Blasi et al., 2007; De Pippo et al., 2007). The informatic structure of the different taxonomic levels is organised in terms of 'nested topologic entities' (closed polygons, open lines and punctual symbols) supported by an attribute list. Moving upward towards smaller scales, polygons may change to lines or symbols. Moving downwards, symbols may change to lines or polygons, lines may change to polygons, whereas polygons may be decomposed into smaller features (Figure 3.2). In cartography this is termed a scale-dependent renderer.

Levels 1 (*physiographic domain*), 2 (*physiographic region*) and 3 (*physiographic province*) correspond to morphologically distinctive surface features significant at the continental, subcontinental and regional levels

Table 3.3 The Salerno University Hierarchical Multiscale Taxonomy

Level	Scale Range	Land Features Taxonomy	Corresponding Land Units in Other Classification Schemes	Persistence Time
1	<1:1,000,000	Physiographic domain	Physiographic domain (MacMillan et al., 2000a) Land region *p.p.* (Crofts, 1991) Land system *p.p.* (Linton, 1951)	10^8–10^9 years
2	1:1,000,000 1:500,000	Physiographic region	Physiographic region (MacMillan et al., 2000a) Land region *p.p.* (Crofts, 1991) Land system *p.p.* (Linton, 1951) Geotectonic region (Blasi et al., 2007)	10^8 years
3	1:500,000 1:250,000	Physiographic province	Physiographic province (MacMillan et al., 2000a) Land region (Crofts, 1991) Land system *p.p.* (Linton, 1951) Morphotectonic province (Guida et al., 1996; Blasi et al., 2007)	10^7–10^8 years
4	1:250,000 1:100,000	Landform system	Physiographic system *p.p.* (MacMillan et al., 2000a) Land region (Linton, 1951) Morphological system *p.p.* (Guida et al., 1996; Blasi et al., 2007)	10^7 years
5	1:100,000 1:50,000	Landform sub-system	Land system *p.p.* (Linton, 1951) Land system (Crofts, 1991) Morphological system *p.p.* (Guida et al., 1996; Blasi et al., 2007)	10^6 years
6	1:50,000 1:25,000	Landform pattern	Landform type *p.p.* (MacMillan et al., 2000a) Land facet (Crofts, 1991) Facet (Linton, 1951) Morphological unit (Guida et al., 1996; Blasi et al., 2007)	10^5–10^6 years
7	1:25,000 1:10,000	Landform complex	Landform type *p.p.* (MacMillan et al., 2000a) Land facet *p.p.* (Crofts, 1991) Facet *p.p.* (Linton, 1951)	10^4–10^5 years

(*continued*)

Table 3.3 (continued)

Level	Scale Range	Land Features Taxonomy	Corresponding Land Units in Other Classification Schemes	Persistence Time
8	1:10,000 1:5000	Landform unit	Landform element *p.p.* (MacMillan et al., 2000a) Land site *p.p.* (Crofts, 1991) Site *p.p.* (Linton, 1951)	10^3–10^2 years
9	>1:5000	Landform element	Landform element *p.p.* (MacMillan et al., 2000a) Land site *p.p.* (Crofts, 1991) Site *p.p.* (Linton, 1951)	10^2 years or less

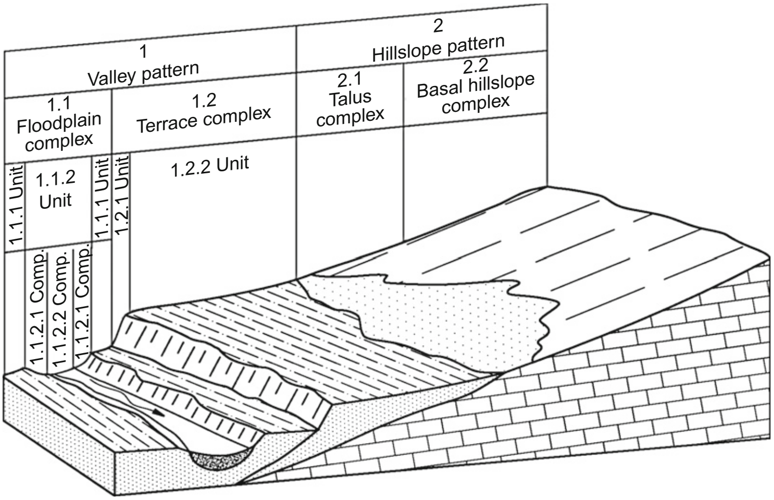

Figure 3.2 Nested hierarchic sequence of landforms.

(respectively), such as great mountain chains, sedimentary basins and forelands. The identification/delineation criteria of surface features are related to the physiographic expressions of long- to mid-term orogenetic/epeirogenetic activity over wide areas, primarily acquired from remotely sensed imagery and coarse resolution DEMs (~500 m × 500 m). The related maps are adequate to illustrate inter-regional/regional landscape features (Blasi et al., 2007), atmospheric circulation and neotectonics.

Level 4 (*morphological system*) includes prominent landscape components such as plateaus, valleys, plains and coastal belts. Their identification/delineation criteria imply the definition of coarse topo-position, polygenetic and polyphase consistency, acquired by automatic landform recognition from satellite imagery and coarse resolution DEMs (~100 m × 100 m). Additional data from previous studies and selected field surveys may be required. The resulting maps may be used for sub-regional landscape analysis (Guida et al., 1996; Blasi et al., 2007), environmental planning and hydro-geomorphology studies.

Level 5 (*morphological sub-system*) includes mid-size landscape components such as small ridges, hillslopes, large valley floors, piedmonts and moraine amphitheatres. The identification/delineation criteria imply the definition of detailed landform topo-position, morphometrics and morphogenetic consistency, acquired by automatic landform recognition from mid-resolution DEMs (~25 m × 25 m), and aerial-photograph interpretation with supplementary field work. The resulting maps may be used in local landscape analysis (Guida et al., 1996; Blasi et al., 2007), environmental planning and detailed hydro-geomorphology studies.

Level 6 (*morphological pattern*) includes large compound landforms (e.g. alluvial terraces, glacial cirques, coastal cliffs, talus belts). The identification/delineation criteria imply the definition of landform detailed topo-position, morphometrics and morphogenetic consistency, acquired by automatic landform recognition from mid- to mid-fine resolution DEMs (~25 m × 25 m to ~10 m × 10 m), aerial-photograph interpretation and field work. The resulting maps may be used in detailed landscape analysis (Guida et al., 1996; Blasi et al., 2007), local environmental planning and detailed hydro-geomorphology studies.

Levels 7–9 are essentially based on detailed field survey. The identification/delineation criteria imply the definition of landform detailed topo-position, morphometrics and morphogenetic consistency, acquired by automatic landform recognition from fine DEMs (~10 m × 10 m to ~5 m × 5 m), and the interpretation of large-scale aerial photographs. The resulting maps are commonly used as preliminary tools for programming further *in situ* investigations (Guida et al., 1996; Blasi et al., 2007). Level 7 (*landform complex*) includes mid-size landform produced by single or multiple geomorphic processes (e.g. large river channels, coastal arcs, large compound landslides).

Level 8 (*landform unit*) includes small landforms formed by single or multiple geomorphic processes (e.g. alluvial terrace scarp, moraine arcs and mid-size landslides) or landform components (e.g. terrace scarp slide, alluvial fan channel, coastal cliff notch, landslide scar and landslide accumulation zone). Level 9 (*landform element*) includes non-decomposable landforms with reference to the project purposes. Mapping at this level typically includes special investigation methods such as geotechnical tests, geophysical soundings, boreholes, laboratory tests and instrumental monitoring.

Level 8 usually represents the starting (focal) point for the production of lower level maps by nested landform composition. However, the focal scale level may change substantially in relation to the mapping project purposes.

The Salerno University mapping procedure (Guida et al., 2009) includes the following steps (Figure 3.3):

1. Production of a 'traditional' field-surveyed, symbol-based geomorphological map, normally at scales ranging between 1:5000 and 1:25,000, in relation to the mapping project purpose, focusing on morphography, morphometry and morphogenesis. The data source is a detailed field survey supported by aerial-photograph interpretation (1a); the legend is a symbol-oriented list of significant relief features (1b); the result is a 'traditional' field-surveyed, symbol-based geomorphological map (1c). The geological aspects of bedrock and near-surface deposits as well as other geomorphological/environmental relevant aspects of land units (such as dominant process and age) are digitally recorded as attributes and transferred into the database,
2. Aerial-photograph interpretation (2a), at a scale close to that of the survey base toposheet, to produce a full-coverage geomorphological map (2c) from expert judgement. At this stage, the geomorphological features are delimited and coded in a nested structure with boundary lines at different reliability levels (2b),
3. Primitive topological transformation (3a) of the mapped units supported by attribute list (3b),
4. Construction of an object-oriented, GIS-based geomorphological map,
5. DEM-based geomorphometrical analysis (5a), automatic multiscale landform recognition (5b) and object-oriented remotely sensed imagery processing (5c) (Baatz and Schäpe, 2000; Baatz et al., 2002; Arko and Stein, 2005; Minàr and Evans, 2008; Schneevoigt et al., 2008).

The main topics of the Salerno University geomorphological mapping model are presented in the annexes A and B. Annexe A illustrates the transition steps from a traditional symbol-oriented geomorphological map

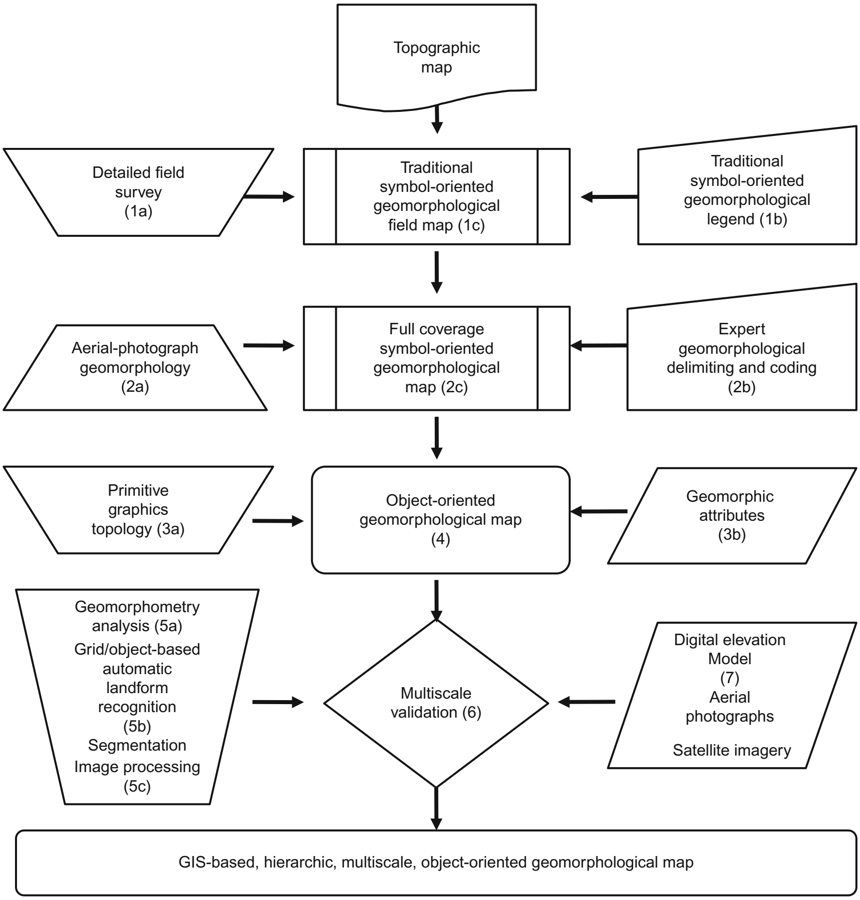

Figure 3.3 Flow diagram of the Salerno University geomorphological mapping system. The progressive numbers indicate the sequence of steps and sub-steps; the trapezoidic shapes indicate the field, laboratory and analytical data inputs; the rhomboid shapes indicate the graphical or code tools used to transfer inputs into preliminary (1c), intermediate (2c) and final (4) geomorphological map; the rhombus indicates the decision about the acceptance of the map into the GmIS.

to a full-coverage, object-oriented geomorphological map (landslide hazard map of Roveta Valley, Abruzzi, Italy). In Annexe B, the Salerno University GmIS (UNISA_GmIS) and the generalisation process from the 1:5000 (focal level) object-oriented geomorphological map of the Fisciano Campus area to 1:25,000 and 1:100,000 scales are presented. Annexe C shows some examples of 'traditional' symbol-oriented geomorphological maps.

7. CONCLUDING REMARKS

Over the last few decades, traditional symbol-oriented geomorphological mapping methods have been widely used for land management, especially in the field of geo-hazard evaluation and risk mitigation. However, these methods are not able to meet the current scientific and technical requirements of land management. In fact, despite major improvements introduced by new investigation tools and GIS-based procedures, symbol-oriented legends are unable to provide a suitable representation of the landscape complexity for a multipurpose, multidisciplinary and multiscalar approach to land management.

A proper representation of landscape complexity can be obtained through the characterisation of the spatial properties of landforms based on hierarchically arranged geometric elements (geomorphological objects), translatable from larger to smaller scales and vice versa by generalisation/decomposition. In this context, the GIS-based, object-oriented mapping system applied at the Salerno University may be considered as a milestone in a 'road map' towards a shared 'cartographic language', which preserves the previous experiences and provides, at the same time, appropriate support for present-day environmental projects.

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