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Small-scale and Multi-scale Relief Mapping

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Summary

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The aim of this chapter is to provide an overview of recent developments in the fields of small-scale and multi-scale relief mapping. Hypsometric tinting, relief shading, continuous color shading, plan oblique relief and other techniques are widely used for maps covering large territories at small scales. The main difference between these techniques and large-scale terrain cartography is that the representations become highly abstract at the observational scale and thus require a high level of generalization. At very small scales, the terrain is stylized to convey distinctive geographic and morphological features. The positional accuracy of valleys and mountain chains becomes less important, and terrain features are depicted as abstracted symbols at the smallest scales.

Thus, two main topics are of interest in this chapter: the automation of representation techniques and the generalization of digital elevation models. We focus on both small-scale and multi-scale mapping, which are interrelated because related generalization techniques are specific to the representation techniques. The following sections first discuss general requirements for digital terrain generalization at small scales, then discuss terrain visualization with (a) traditional relief shading and plan oblique relief, (b) continuous color shading and (c) hypsometric tinting.

Keywords: relief shading, hypsometric tints, terrain generalization, small-scale and multi-scale mapping

1 Small-scale mountain cartography: relief features and data sources

According to Zarutskaya (1958) small-scale relief representations should be geographically credible and retain the most distinctive features of large landforms. At small scales, relief forms are extensively exaggerated and contours are deliberately shifted and stylized to portray typical morphological features, while positional accuracy becomes less important (Guilbert et al. 2014). Imhof (1982) singles out scales smaller than 1:100,000. He mentions that terrain generalization at these scales is required over the entire map area and not only in particular places. As Imhof states, tones and contrasts in small-scale shaded relief are dependent primarily on elevations and differences in elevation, and no longer on the angle of slope. Stylized symbols for formations gradually replace individual features as the scale becomes smaller (Imhof 1982).

Considering these principles, Samsonov (2011) identified three main features of multi-scale hypsometric mapping, which deals with interactive relief maps that have changeable levels of detail:

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1) Every map scale should represent relief forms of a corresponding size and hierarchical level. There should be a focus on the visualization of prominent terrain features and structure lines.
2) At scales smaller than 1:100,000, intensive generalization should be applied to maintain most characteristic forms of the earth's surface.
3) While changing map scale, representation parameters such as contour intervals, hypsometric colors, and relief shading character should transition gradually.

In automated production environments, small-scale relief mapping requires high-quality generalized digital elevation models (DEMs). The production and availability of terrain models during the last decade stimulated the development of specific digital generalization methods. While models such as WorldDEM, ASTER GDEM and SRTM have spatial resolutions suitable for large-to-middle-scale cartography, there are global models such as GTOPO30, ETOPO1, ETOPO2, ETOPO5, GEBCO, and more recently the GMTED2010 dataset with spatial resolutions varying from approximately 250 meters to 5 km. Table 1 summarizes the resolution of these terrain models.

Unfortunately, a suitable resolution does not automatically lead to an appropriately generalized terrain representation. At small scales, morphologically important terrain features are often smoothed and the digital representations often do not successfully portray the characteristic shapes of landforms. Thus, specialized procedures for small-scale DEM generalization are essential.

2 Traditional relief shading and plan oblique relief

The first work in automated digital relief shading was conducted by Yoeli (1965). Many improvements have been proposed since Yoeli's initial work, such as enhanced illumination models (Horn 1982, Kennelly & Stewart 2006) or local adjustments and aerial perspective (Brassel 1974, Jenny 2001). Until recently, little attention has been dedicated to the automation of small-scale relief shading. Several algorithms have been developed for preserving and emphasizing the most distinctive features in small-scale relief shading, including work by Böhm (2000), Prechtel (2000) and Patterson (2001).

For very small scales, Leonowicz et al. (2010) developed an original algorithm based on surface curvature. The algorithm is specifically intended for relief shading. The main goal of the proposed technique is to reveal ridges and valleys (defined by areas of high negative and positive curvature), then exaggerate these areas by appropriate filtering (high and low quartile moving window filters), and finally to combine the resulting images using terrain slope as weight function. Mountainous and flat areas are treated with different parameters, prioritizing ridges in mountain areas and valleys in flatter areas. The resulting image (see Fig. 1c) represents the main features of the topography more vividly than the terrain model processed by simple low-pass filtering (see Fig. 1b), while the visual complexity compared to the source DEM (see Fig. 1a) is greatly reduced.

Tab. 1: Resolution of current global digital elevation models

#	DEM	Degree resolution	Planar resolution, m (approx.)	Year of initial release	Producer	Ocean covered
1	**WorldDEM**	0.4″	12	2014	Airbus Defence & Space	No
2	**ASTER GDEM**	1″	30	2009 (v.1), 2011 (v.2)	NASA, METI	No
3	**SRTM**	1″, 3″	30, 90	2000	NASA	No
4	**GMTED2010**	7″, 15″, 30″	250, 500, 1000	2010	USGS	No
5	**GEBCO**	30″, 1′	1000, 2000	2003 (1′), 2008 (30″)	GEBCO	Yes
6	**GTOPO30**	30″	1000	1996	USGS	No
7	**ETOPO1**	1′	2000	2008	NASA	Yes
8	**ETOPO2**	2′	4000	2001 (v.1), 2006 (v.2)	NASA	Yes
9	**ETOPO5**	5′	10000	1988	NASA	Yes

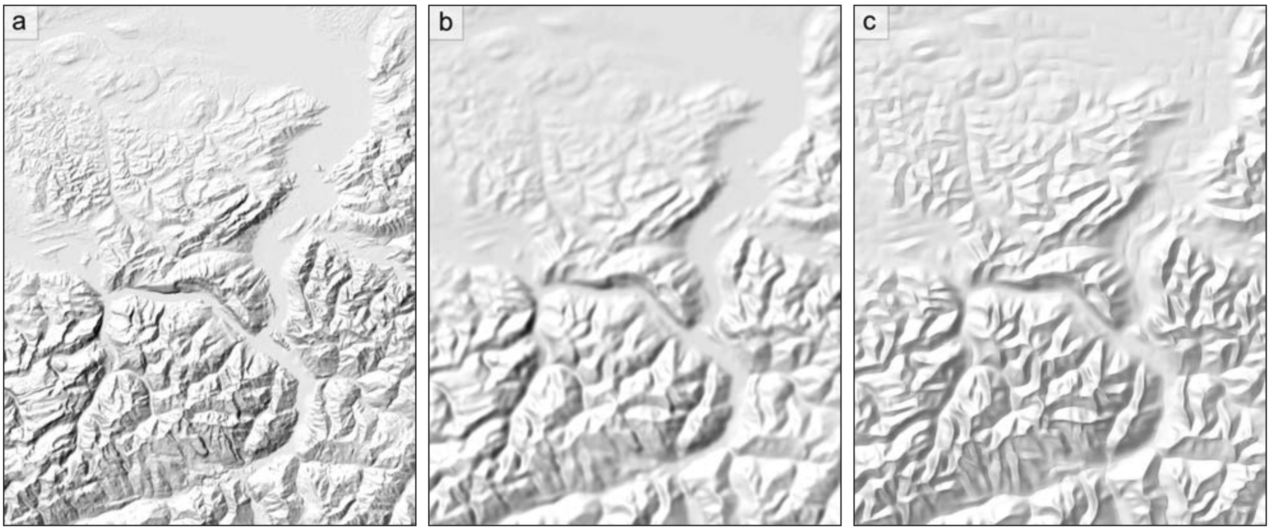

Fig. 1: Automatic generalization for small scale relief shading by Leonowicz et al. (2010): (a) Source SRTM DEM, (b) filtered SRTM DEM, (c) DEM filtered by the new technique.

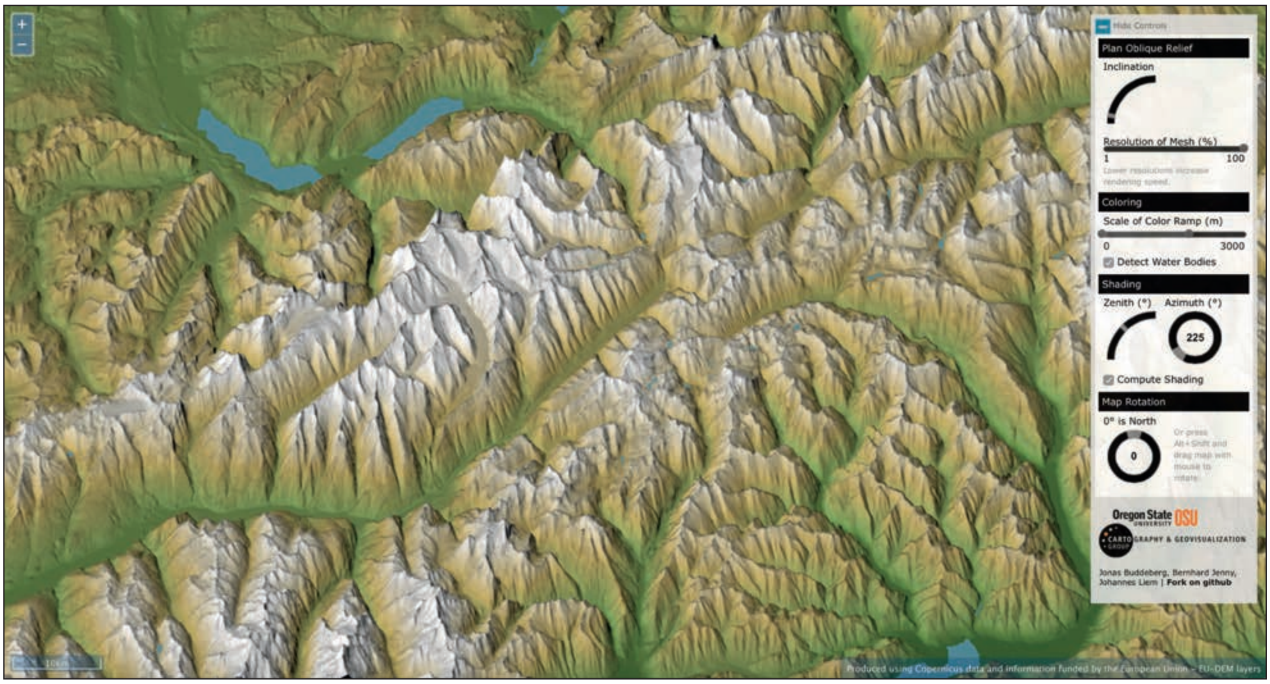

Fig. 2: Interactive plan oblique relief by Buddeberg et al. (2014) applied to the "Plan Oblique Europe" web map.

An alternative way to enhance small-scale terrain shading is the use of the plan oblique relief technique, initially introduced to digital cartography by Patterson (2004a) and developed further by Jenny & Patterson (2007). The purpose of this method is to project the terrain surface to a map plane using inclined parallel rays instead of vertical rays, which are used in standard relief shading. A lower inclination angle produces a stronger perspective effect. This technique is effective in both large- and small scale-mapping (Patterson 2013). An interactive web-based application demonstrating this technique has been developed with WebGL by Buddeberg (Buddeberg et al. 2014, Jenny et al. 2015) (see Fig. 2).

Relief shading can be further enhanced by using topographic openness (Yokohama et al. 2002) or the sky view factor (Zakšek et al. 2011). Topographic openness expresses the degree of enclosure of a location, and is applied to visualize topographic character. It is an angular measure of local occlusion. Concave surfaces have positive openness and convex surfaces have negative openness. The related sky view factor reflects the percentage of the sky that is visible from each point. Koshel et al. (2012) applied both techniques to small-scale representations of bathymetric relief. They demonstrated that the two methods produce visually different results, with topographic openness generating a more detailed visualization. An example image covering the bottom of the White Sea near the European North of Russia is shown in Figure 3.

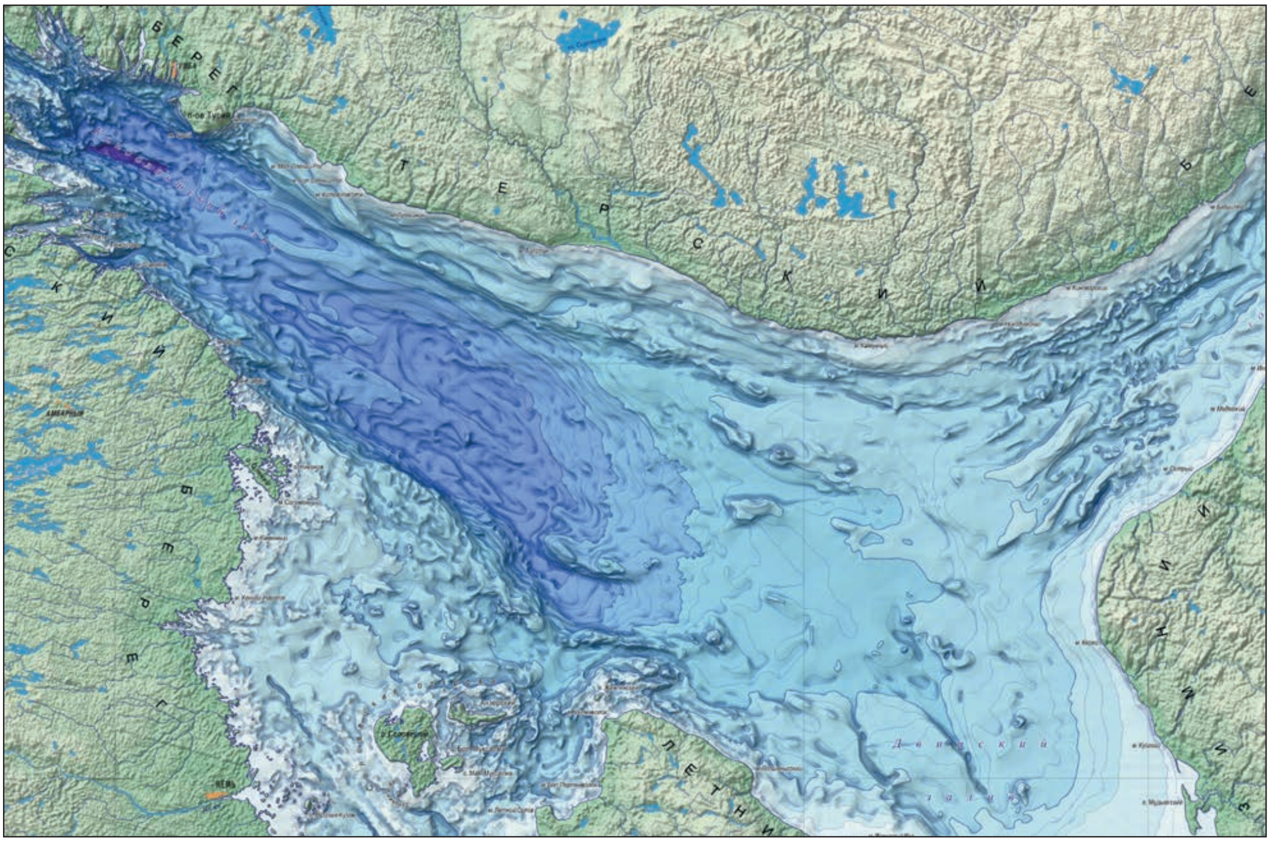

Fig. 3: Small-scale image of White Sea relief visualized by a combination of bathymetric colors and topographic openness (KOSHEL et al. 2012). Reprinted with the permission from the authors.

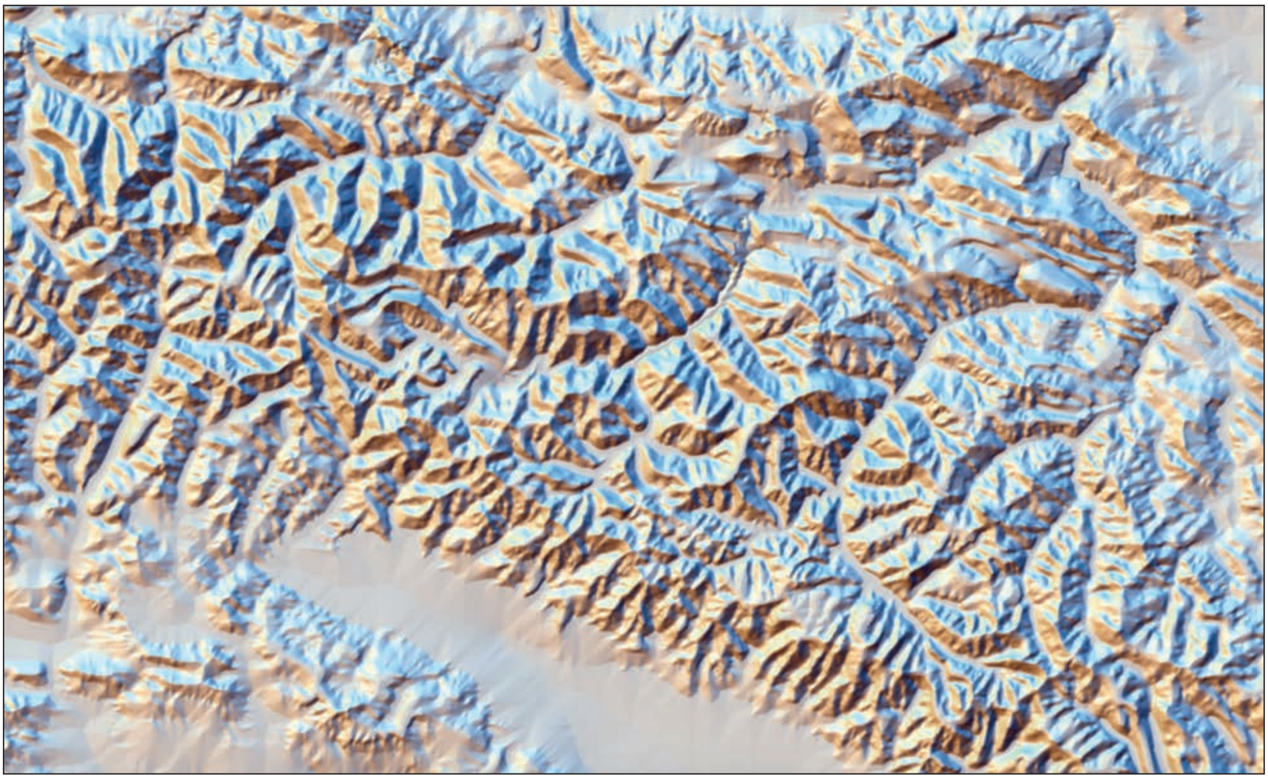

Fig. 4: Multicolor relief shading by KOSHEL (2004). Three light sources of constant intensity are used (red — 165° azimuth, green — 135°, blue — 105°). Reprinted with permission from the author.

3 Continuous color shading

Several visualization approaches for continuous color shading have been developed. The general model of these approaches can be expressed as:

$$color = f(Z, \boldsymbol{I}, \boldsymbol{V})$$

where Z is elevation, $\boldsymbol{I}$ is the vector of illumination intensities from possibly multiple sources and $\boldsymbol{V}$ is the vector of other factors influencing terrain color on a map at a particular point.

The color relief shading algorithm developed by Koshel (2004) allows the use of three light sources for to create a picturesque landscape at sunset. In this technique, each color channel of the output image (R, G, and B) is associated with a corresponding light source with its own zenith, azimuth, and luminosity. According to the general formula, Koshel computes $color = f(\boldsymbol{I})$, where $\boldsymbol{I} = \{I_R, I_G, I_B\}$. An example of a resulting image is provided in Figure 4.

Another approach to color relief shading inspired by the Swiss school of cartography was developed by Jenny & Hurni (2006). They used a two-dimensional color look-up table in which the X-axis is used for illumination and the Y-axis is used for elevation. This table allowed for continuously changing the color as a function of aspect and elevation (see Fig. 5). The color look-up table is interpolated from control points defined by the user. According to the general model, Jenny & Hurni's approach is $color = f(Z, I)$, where I is a gray value between 0 and 255 and is taken from a grayscale shading. A similar technique with aspect-variant luminosity was introduced by Kennelly & Kimerling (2004).

Another closely related technique for small-scale mapping is cross-blended hypsometric tinting, introduced by Patterson (2004b) and developed further by Patterson & Jenny (2011, 2014). The purpose of this representation technique is to locally change the elevation color gradient according to natural environmental conditions. The model of this approach is $color = f(Z, V)$, where V is the type of environment. Patterson & Jenny (2011) differentiated four major environments: warm humid, cold humid, arid, and polar. They developed color scales for these four environments (see Fig. 6 left). Four color images are blended using masks, which allows for combining several color scales and creating gradual transitions between them. The final image shows cross-blended hypsometric tints combined with traditional shaded relief (see Fig. 6 right).

No one technique uses the full potential of all three shading variables. The research field is open for the future development of more complex color shading techniques that exploit elevation, illumination, and other factors simultaneously.

4 Hypsometric tinting

Hypsometric tinting is a traditional cartographic relief representation technique. Classic guidelines for the generalization of small-scale contours for hypsometric tinting were covered in detail in monographs by Horn (1945), Zarutskaya (1958), and Imhof (1982). The main goal of small-scale hypsometric tinting is to emphasize major landforms and remove unnecessary details, while keeping the contour lines as close to their original positions as possible. Terrain features are processed as entities, which means that they are either removed or retained, but not shortened or otherwise diminished in size. However, this is not a strict limitation, as small-scale terrain generalization requires exaggerating the size of terrain features, which inevitably leads to contraction of neighboring features.

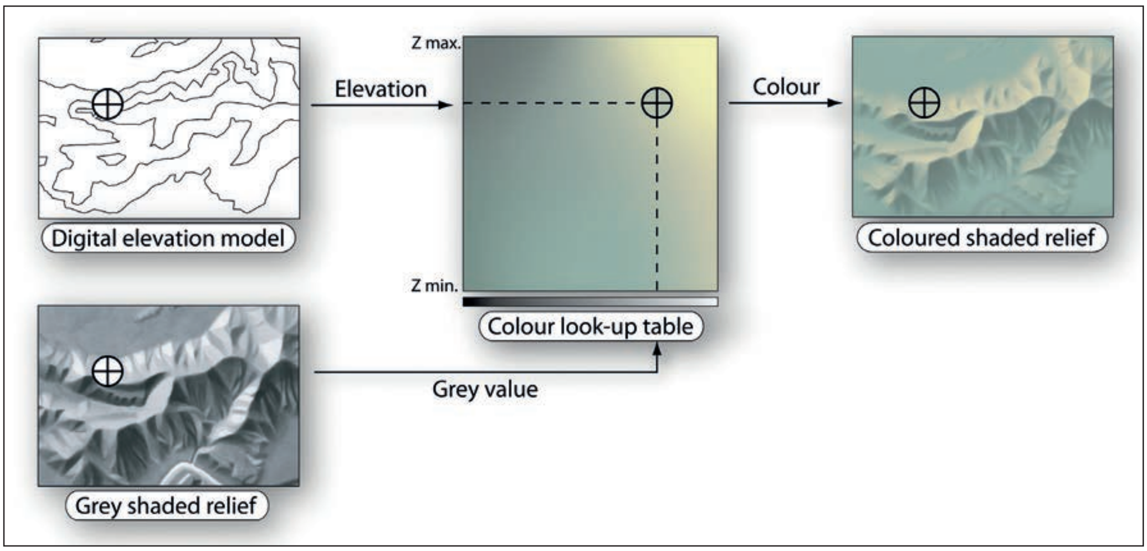

Fig. 5: Tinting a grayscale shaded relief with Swiss-style color shading (Jenny & Hurni 2006). A color is extracted from the look-up table based on the original grey value and the elevation extracted from a terrain model.

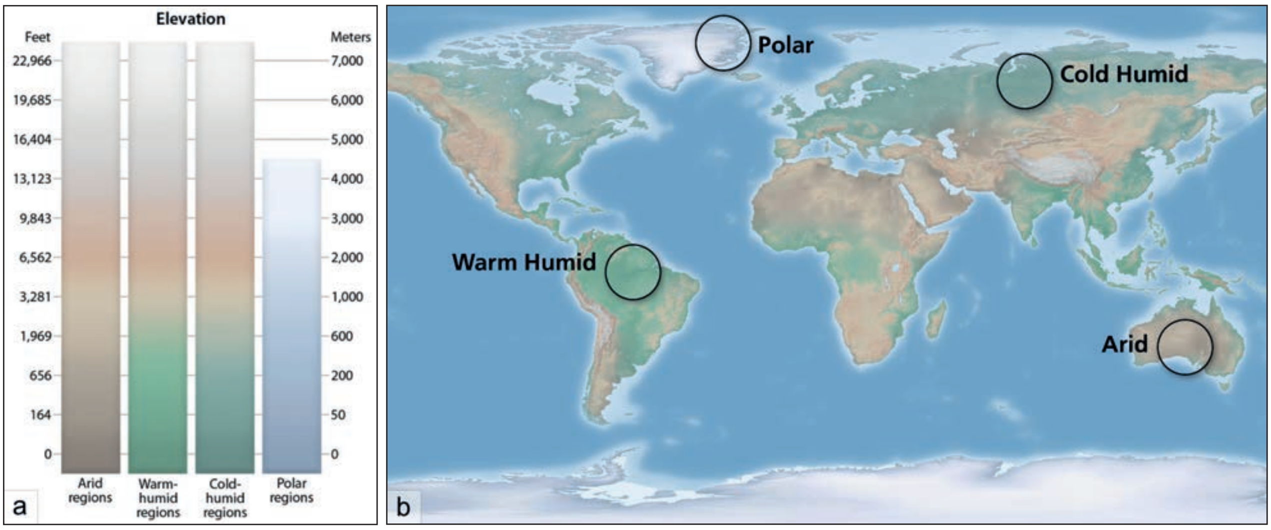

Fig. 6: Cross blended hypsometric tints by PATTERSON & JENNY (2011): (a) Left — four color scales for different natural environments. (b) Right— resulting image.

There are two approaches to the generation of small-scale contour lines. The first is to generalize the contours themselves. An analysis of contour generalization methods reveals that such methods are more difficult to implement than indirect methods based on DEM generalization, because of the necessity of considering topological relationships between lines (ZHANG et al. 2007), the complexity of structure line derivation (AI 2007), and difficulties when contour intervals should be different (PELED et al. 1989).

Another approach is to first generalize the underlying terrain model and then apply hypsometric tints. During the recent decade, several algorithms have been developed that allow for object-oriented approaches. Among those are works by JORDAN (2007), AI & LI (2010), LEONOWICZ et al. (2009), and SAMSONOV (2011). All of them exploit the idea of correspondence between negative landforms and stream networks. Each stream is associated with its valley, which can be removed, retained, or even exaggerated during the generalization process. JORDAN (2007) used Strahler stream ordering and then removed low-order valleys by triangulating watershed borders. This led to the removal of negative terrain features. AI & LI (2010) used a similar methodology. They divided a process into three stages: stream network generalization using Strahler stream ordering, the extension of large valleys, and smoothing the surface within the areas of removed valleys. Both works were not concerned with small-scale relief representation.

A more specific method of terrain generalization for small-scale hypsometric tinting was pioneered by LEONOWICZ et al. (2009). In the first stage, a stream network derived from the original terrain model was generalized using a procedure based on flow accumulation values. As opposed to selection by stream order, this approach allowed for including stream length as a criterion and thus the preservation of valley lengths. The source terrain model was processed using upper and lower quartile filters, which resulted in two intermediate models: one with exaggerated (widened) valleys and another with exaggerated ridges. A final terrain model was obtained by a weighted combination of these intermediate models. Buffers around the

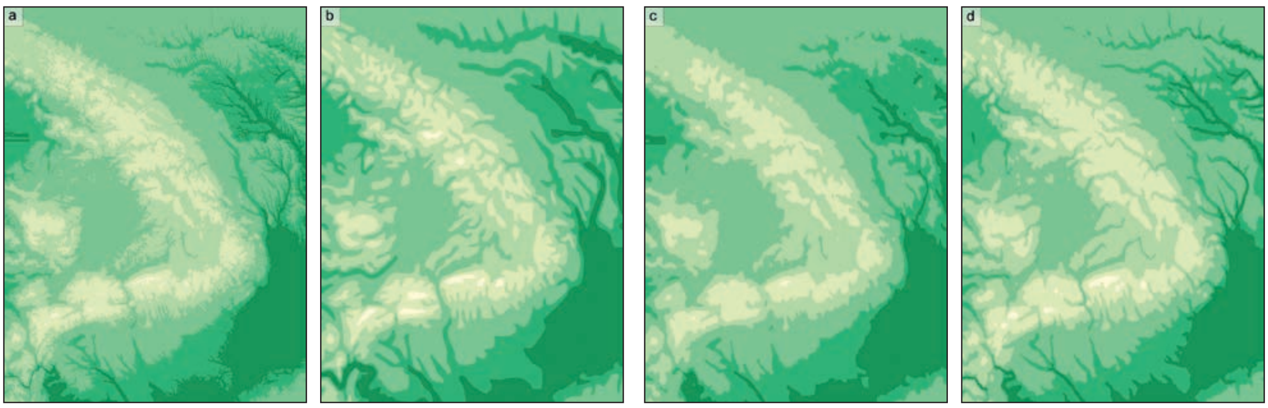

Fig. 7: Hypsometric tints generalization by LEONOWICZ et al. (2009): (a) — original GTOPO30 DEM. (b) — manual generalization reference. (c) – generalization by median filter (filter size: 5×5 cells, applied 10 times). (d) – generalization by combination of upper and lower quartile filters.

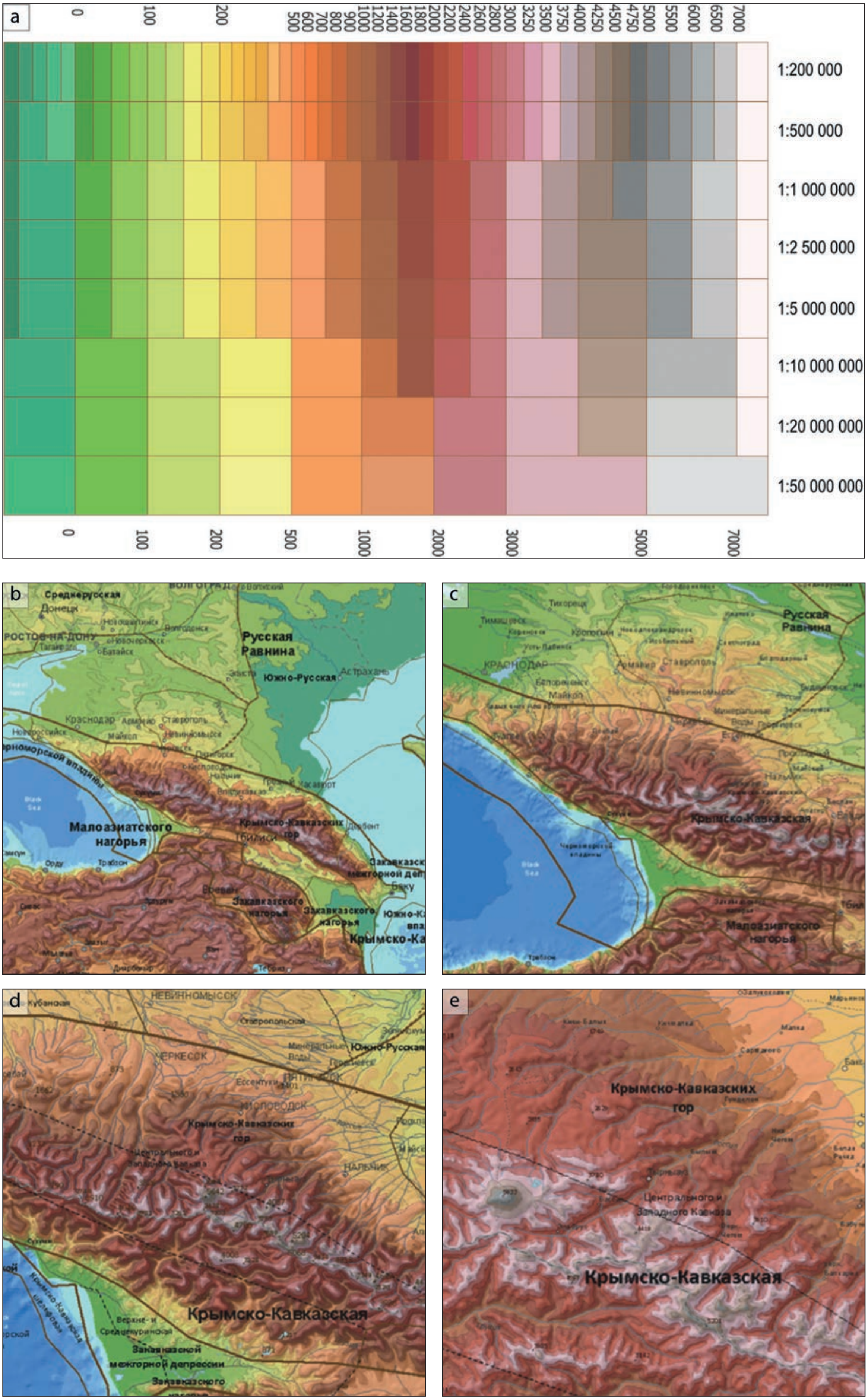

Fig. 8: (a) Multi-level color hypsometric scale, (b)–(e) example levels of detail for 1:10M, 1:5M, 1:2.5M and 1:M scales from multiscale hypsometric map of Russia (Samsonov & Khaliullina 2014).

generalized streams were used to construct surface of weights for combining the two models. The resulting hypsometric rendering provided satisfactory results and contained only the most important terrain features. However, the results were not as visually pleasant and consistent as a manually generalized reference map (see Fig. 7).

Guided by the demands of modern map users, SAMSONOV (2011) developed a methodology for generating multi-scale hypsometric maps that are suitable for rendering in web-based and mobile zoomable environments. The major focus of his work was the development of complex color scales that can support the gradual refinement of hypsometric levels when a user zooms in from continental to local scale. Initially, a simple color scale intended for visualization in scales smaller than 1:1,000,000 was developed (SAMSONOV 2011). Recently, a more sophisticated color scale was presented by SAMSONOV & KHALIULLINA (2014) for a multi-scale hypsometric map of Russia and contiguous territories, that includes eight scale levels from 1:200,000 to 1:50,000,000 (see Fig. 8). The vertical elevation range was subdivided into several zones, and for each zone a unique color gradient was developed. However, this is a time-consuming manual task that needs to be automated in the future.

The methodology by SAMSONOV & KHALIULLINA (2014) was based on previous works, which were enhanced and combined into one workflow. Negative terrain features were identified by stream generalization algorithms as suggested by LEONOWICZ et al. (2009). However, the removal of the features was not based on filtering, but rather on TIN-based processing. This approach was inspired by a technique by JORDAN (2007), which was enhanced by including two levels of watersheds. Low and high quartile filtering was replaced by minimum and maximum filtering and applied at a post-processing stage to locally enlarge valleys and watersheds. The resulting workflow allowed for the production of high-quality digital elevation models for small-scale mapping. The resulting map was published as a web-based ArcGIS.com educational service. This service additionally provides information about selected geomorphological regions and interactive elevation profiles (see Fig. 9).

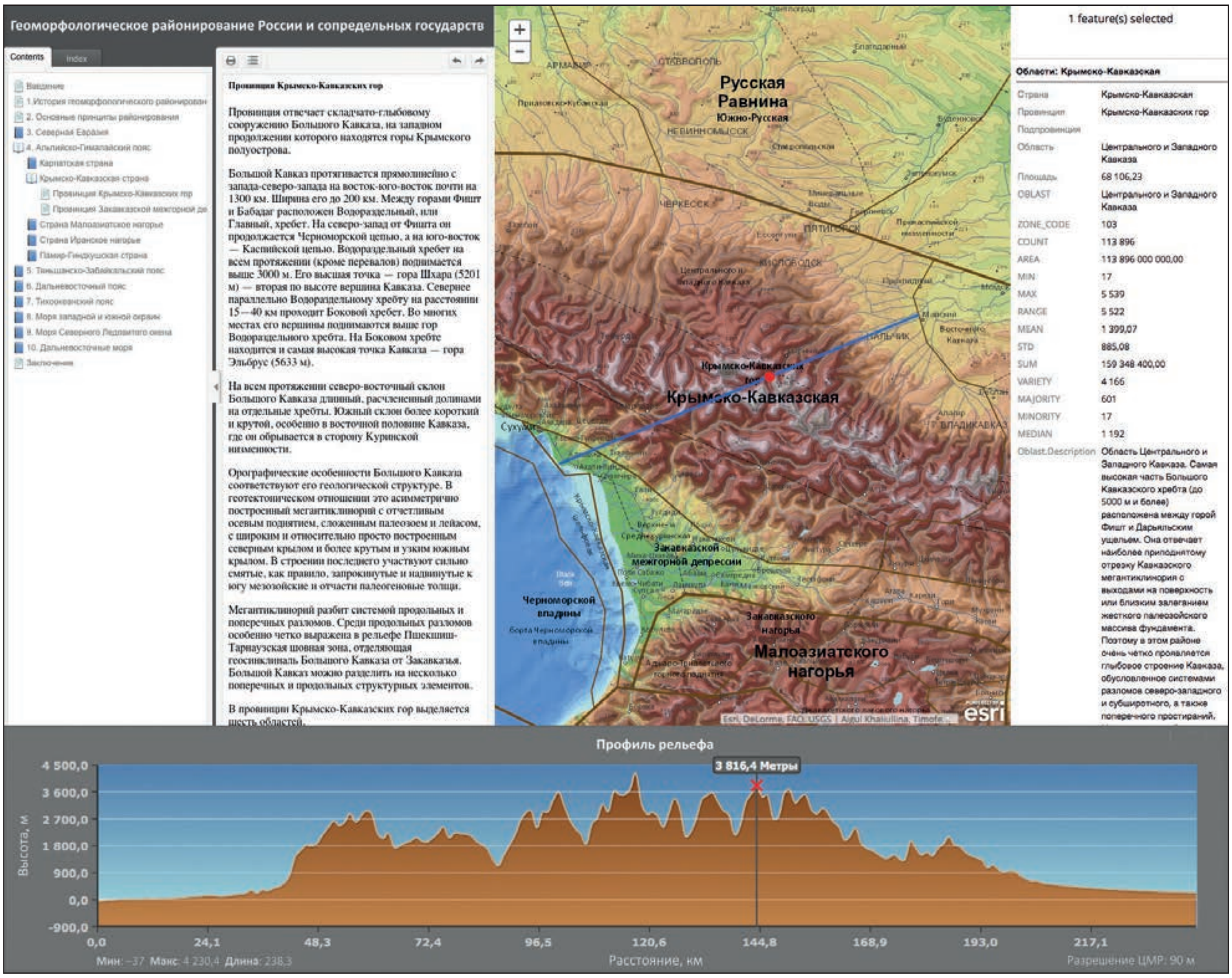

Fig. 9: Web-based educational service containing a multiscale hypsometric map of Russia, information about geomorphological regions and profiling functionality (SAMSONOV & KHALIULLINA 2014).

5 Conclusion

During the last decade, a significant amount of innovative research in the field of small-scale relief mapping has been conducted. Nearly all approaches to cartographic relief representation have been automated and enhanced, including traditional relief shading and its modifications, continuous color shading, and hypsometric tints. The availability of high-quality terrain models incited the development of specialized algorithms for terrain generalization, which are generally based on the skeleton of terrain structural lines (streams and watersheds). Finally, a multi-scale hypsometric mapping concept emerged that brings cartographic relief representations to web mapping and mobile applications.

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