Advanced methods for georelief segmentation

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Abstrakt. Segmentace georeliéfu je důležitou součástí GmIS (Geomorfologického informačního systému), který je vyvíjen ve spolupráci Katedry fyzické geografie a geoekologie, Fakulty přírodovědecké, Univerzity Komenského v Bratislavě, Katedry matematiky – oddělení geomatiky, Fakulty aplikovaných věd a Katedry geografie, Fakulty pedagogické, Západočeské univerzity v Plzni a dále Fakulty životního prostředí, Univerzity Jana Evangelisty Purkyně, Katedra informatiky a geoinformatiky.

Cílem tohoto příspěvku je představení pokročilé metody pro vymezování hranic elementárních forem georeliéfu, což jsou geometricky spojité plochy, které mají stejnou genezi a předpoklad pro stejný průběh geomorfologických procesů. Elementární forma je ohraničena liniemi nespojitosti, na kterých je tato geometrická, dynamická a genetická spojitost narušena.

Pro vymezování hranic elementárních forem georeliéfu byl vyvinut algoritmus založený na Cannyho hranovém detektoru. Tento algoritmus vyhledává nespojitosti v površích odvozených morfometrických charakteristik až do třetího řádu, které odpovídají hranicím jednotlivých elementárních forem. Pro odvození povrchů morfometrických charakteristik třetího řádu bylo nutné implementovat robustní metodu aproximace parciálních derivací třetího řádu pomocí metody vážených nejmenších čtverců. Pro vymezené segmenty hranic elementárních forem je automaticky ohodnocena kvalita vymezení, resp. geomorfologická významnost. Toto kvalitativní ohodnocení hran pomáhá z výsledku odfiltrovat nevýrazné hrany a hrany vzniklé chybou vyhodnocení.

Klíčová slova: elementární forma georeliéfu, vymezování, hranice elementární formy georeliéfu, GmIS, GIS, interpolace RST.

Abstract. Georelief segmentation is one of the most important parts of GmIS (Geomorphological information system), which is being developed in cooperation of Comenius University in Bratislava (Slovakia), University of West Bohemia in Pilsen and University of Jan Evangelista Purkyně (the Czech republic).

The aim of this paper is to introduce advanced methods for delimitation of elementary forms of georelief boundaries, which are geometrically continuous surfaces with the same genesis and preconditions for the same geomorphological processes. Elementary forms are delimitated by lines of discontinuity where is this geometrical, dynamical and genetical continuity broken.

The following steps of delimitation of elementary forms of georelief are unwind on the preciseness of delimitated borders of the elementary units of georelief.

For delimitation of elementary forms boundaries was developed an algorithm based on Canny edge detector. This algorithm searches for discontinuities in the layers of derived morphometrical characteristics up to the third order. These lines of discontinuities are identical to the boundaries of elementary forms. For the derivation of the layers of morphometrical characteristics was developed and implemented a robust method for approximation of partial derivatives of the third order based on the weighted least squares method. The boundaries segments are then rated along with their geomorphological importance and the quality of delimitation. This helps to filter less-important edges and interpolation artifacts.

Keywords: elementary form of georelief, delimitation, border of elementary form, GmIS, GIS, RST interpolation.

1 Elementary forms and their boundaries

In accordance with [2] we can define three axioms which create the theoretical background for the georelief segmentation.

- Elementary form of georelief may be considered as a continuous surface - geometrical field of altitudes.
- In the set scale it is possible to find discontinuities on the Earths surface - which may be considered to be the natural boundaries of geomorphologic objects.
- These discontinuities and other characteristics of the Earth surface are results of geomorphologic processes, which depend or are influenced by gravitation.

Specific structural elements of the field create the natural base for its segmentation. Such elements may be called singular lines and points. Here can we encounter for example extreme points and lines (peaks, pits, saddle points and ridges), inflex points and discontinuities of the altitude field and other derived fields. [1]

A form of georelief consists of segments, which are characterized by different types and levels of homogeneity. This may be in an ideal way expressed by the constant value of altitude or derived morphometrical characteristics. Discontinuity of these characteristics marks logical boundaries of the segments (elementary forms). Then we can define an ideal elementary form as element of the georelief with a constant value v altitude, or two or more well interpretable morphometrical characteristics bound by lines of discontinuity.

The representation of the whole Earths surface with the help of elements with constant value of selected morphometrical characteristic has a strict theoretical consequence by delimitation of elementary forms. In geometrically ideal case, boundary of two elementary forms defined by different values of morphometrical characteristic must be a line of discontinuity - a sudden discrete change of a value of some of the morphometrical characteristic (see Figure 1).

For automatic delimitation of the elementary forms boundaries, we have to search for the lines of discontinuity. We will use the following rule: point of discontinuity of derived surface of the first order (slope, aspect) matches the maximal value in the derived surface of second order (change of slope = curvature) and this matches the zero value in the derived surface of the third order (change of curvature).

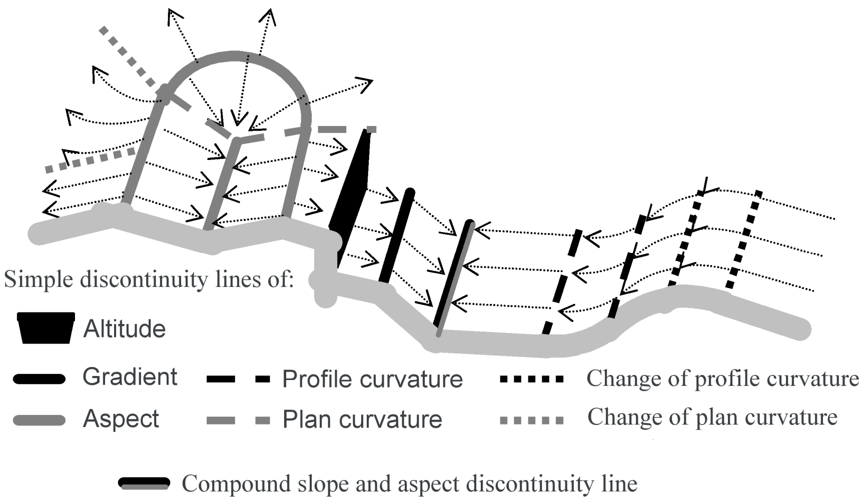

Figure 1 Lines of discontinuity [2]

2 Delimitation of elementary form boundaries

In [pacina 2007] were introduced various algorithms for automatic delimitation of elementary forms boundaries. These algorithms were further tested (see [3], [4]) and based on the results was as the most suitable algorithm for delimitation of elementary forms boundaries chosen the algorithm based on the Canny edge detector. For easy evaluation of the results were the algorithms applied only on the altitude field. Such delimitated lines accord to the ridge and valley lines (maximum = ridge, minimum = valley line).

This algorithm works on the following principle.

1. In the first step is on the input data applied Canny edge detector. This detector searches for edges corresponding to inflex points in the input data.
2. In the next step are in-between these inflex points searched local maxims and minims, which corresponds to lines of discontinuities.

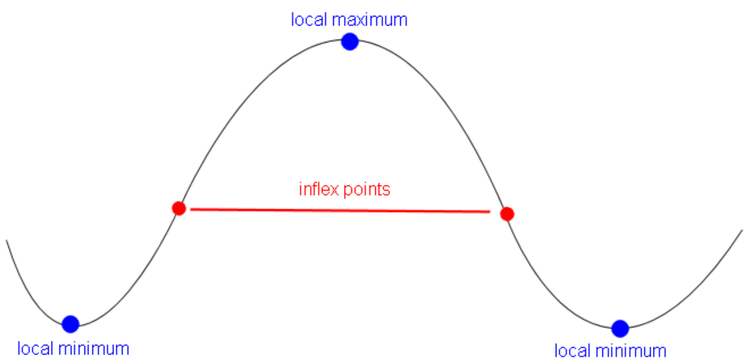

Figure 2 Principle of Canny based algorithm

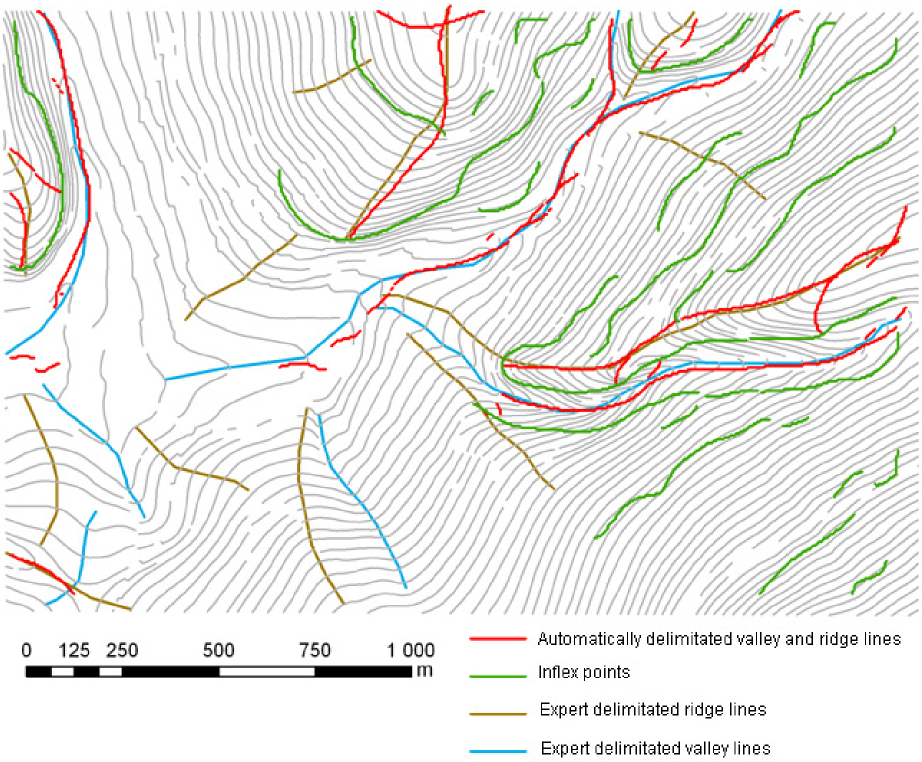

Figure 3 Lines of discontinuity delimitated in the field of altitudes

In (Pacina, 2008) were selected the following morphometrical characteristics of higher orders to be used for the delimitation of boundaries of elementary forms:

- g_t – gradient change in the direction of a contour line,
- a_g - orientation change in the direction of a fall line,
- A_{Nt} – orientation change in the direction of a contour line,
- a_{gn} - change of orientation change in the direction of a fall line,
- A_{Ntt} – change of orientation in the direction of a contour line.

3 Approximation of partial derivatives of the third order

In many software used for GIS analysis is implemented computation of the first and the second partial derivative. For computing surfaces of derived morphometrical parameters of the third order (in our case a_{gn} and A_{Ntt}), we need to approximate partial derivatives up to the third order. We will approximate the input data by a general polynomial of the third order (1):

$$z_{i,j}(x,y) = a_0 + a_1(x-x_i) + a_2(y-y_j) + a_3(x-x_i)^2 + a_4(y-y_j)^2 + a_5(x-x_i)(y-y_j) + a_6(x-x_i)^3 + a_7(y-y_j)^3 + a_8(x-x_i)^2(y-y_j) + a_9(x-x_i)(y-y_j)^2 \quad (1)$$

We will use the 5x5 neighborhood of actually computed point. Let us mark the coordinates of the centre of the 5x5 neighborhood in which we will approximate the derivatives (x_i, y_j). On figure 1 are shown the nods of the 5x5 neighborhood. Symbols *f* in each of the nods represents function values in the nod. Value *h* is distance between the nods.

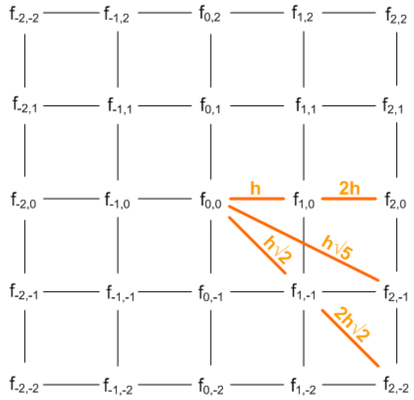

Figure 4 Nods of the 5x5 neighborhood

Estimation of derivatives

Let us estimate derivatives of the polynomial in the point (x_i, y_j). Then $z(x_i, y_j) = a_0$. Partial derivative of *z* by *x* will then be:

$$\frac{\partial z}{\partial x} = a_1 + 2a_3(x - x_i) + a_5(y - y_j) + 3a_6(x - x_i)^2 + 2a_8(x - x_i)(y - y_j) + a_9(y - y_j)^2 \quad (2)$$

From which results:

$$\left.\frac{\partial z}{\partial x}\right|_{(x_i, y_j)} = a_1 \quad (3)$$

And the other derivatives:

$$\left.\frac{\partial z}{\partial y}\right|_{(x_i, y_j)} = a_2, \left.\frac{\partial z^2}{\partial x^2}\right|_{(x_i, y_j)} = 2a_3, \left.\frac{\partial z^2}{\partial y^2}\right|_{(x_i, y_j)} = 2a_4, \left.\frac{\partial z^2}{\partial x \partial y}\right|_{(x_i, y_j)} = a_5,$$
$$\left.\frac{\partial z^3}{\partial x^3}\right|_{(x_i, y_j)} = 6a_6, \left.\frac{\partial z^3}{\partial y^3}\right|_{(x_i, y_j)} = 6a_7, \left.\frac{\partial z^3}{\partial x^2 \partial y}\right|_{(x_i, y_j)} = 2a_8, \left.\frac{\partial z^3}{\partial x \partial y^2}\right|_{(x_i, y_j)} = 2a_9. \quad (4)$$

Estimation of the derivatives coefficients

We interleave the polynomial (1) across 25 nods (5x5 neighborhood), but the polynomial (1) has got only 10 coefficients, so we use the least squares method. To encounter the higher influence of points closer to the center of approximate area, we will use the weighted least square method.

$$\sum_{k=-2}^{2} \sum_{l=-2}^{2} w_{ij}[f_{k,l} - z(x_i, y_j)]^2 \quad (5)$$

where $w_{i,j}$ is the weight of x_i,y_j point, $f_{k,l}$ is value in the nod and $z(x_i,y_j)$ is the function value of the polynomial (1) in the point (x_i,y_j).

For the right choice of the weight is important to take into account the influence of the surrounding nods, which should be decreasing with the increasing distance from the middle. For the computation was used the following weight:

$$w_{i,j} = \frac{2h\sqrt{2}}{\delta + h\sqrt{i^2 + j^2}}, \quad (6)$$

where $\delta \geq 0$ (for example 0.1), which influences the importance of the points further from the center.

The system of linear equations $\mathrm{Qa} = \mathrm{f}$ for computing the unknown coefficients $\mathbf{a}$ can be overestimated hence in general must not have any solution. We will then estimate the unknown coefficients $\mathbf{a}$ by the least square method[2].

The unknown coefficients $a_0, \ldots a_9$ of the polynomial (1) are given by

$$\mathrm{a} = \mathrm{B_w f}, \tag{7}$$

and $\mathrm{B_w}$ is computed by this formula

$$\mathrm{B_w} = inv(\mathrm{Q^T W^T W Q})\mathrm{Q^T W^T W}. \tag{8}$$

Size of matrix **Q** is 25×10, size of **a** is 10×1 (vector of unknown coefficients) and $\mathbf{f}$ is 25×1 (vector of the nods).

The computation made in this way is very fast. The matrix $\mathrm{B_w}$ is computed only once during the first computation. We do not have to compute all the coefficients of a, but only those we need for computation of the partial derivatives of desired order. The matrix $\mathrm{B_w}$ was computed analytically (with the help of symbolic computations in Matlab). This helped to avoid the rounding error during computation of matrix $\mathrm{B_w}$, which made the computation even more precise.

4 Delimitation of elementary form boundaries

The automatic delimitation of elementary forms boundaries should forego a data preprocessing to obtain the *trend surface*. Trend surface is a generalized digital elevation model, which keeps the main terrain characteristics[3].
Algorithm based on Canny edge detector was applied on the surfaces of selected morphometrical characteristics (g_t, a_g,, $\mathrm{A_{Nt}}$, $\mathrm{a_{gn}}$, A_{Ntt}). To describe the importance of the boundary or its geomorphologic importance are the segments of elementary form boundaries evaluated by two significant parameters: general sharpness and affinity (local specific sharpness).

The parameters work as follows:
General sharpness: the computation of this parameter uses two layers of derived morphometrical parameters – the actual and of lower order. The principle of the computation is based on the theory that a discontinuity if the selected field equals to local extreme in the field which is derived from it. In our case (see Figure 5) is the computation shown on the field of altitudes and on derived field of gradient. Inflex points in the field equals to local extremes in the field of gradient. The value of general sharpness for the actually computed point used the value of altitudes of neighboring inflex points, which correspond to neighboring local extremes in the field of gradient. Computation based on the same principle can be then applied to for any other morphometrical characteristic.

Affinity expresses how the boundary is approaching the geometrically ideal boundary (discontinuity). In the case of altitude field (most important discontinuity) is the value of affinity set by the value of slope of corresponding cells (90° slope = ideal discontinuity). The value of slope corresponds to the affinity of given boundary to ideal discontinuity of the field altitudes. This can be used for other morphometrical characteristics as well.

[2] For the whole derivation of the weighted least square method see [4].
[3] See more in [3], [4].

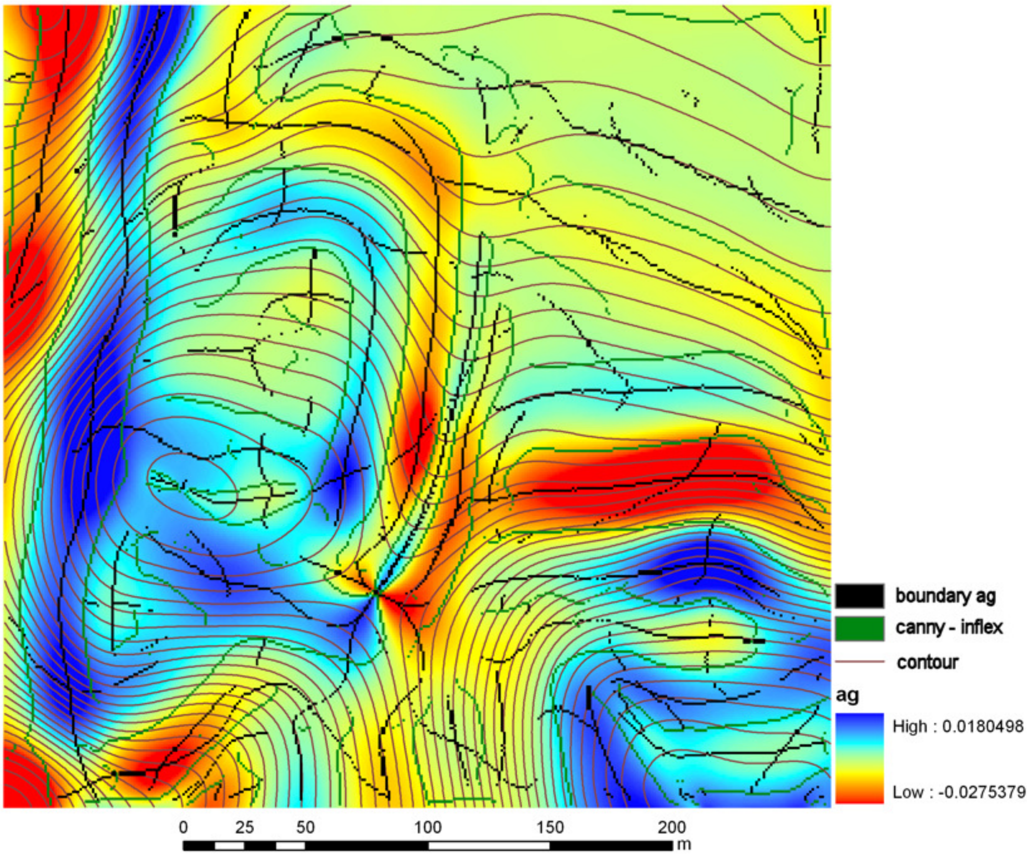

Figure 5 Delimitated discontinuity lines

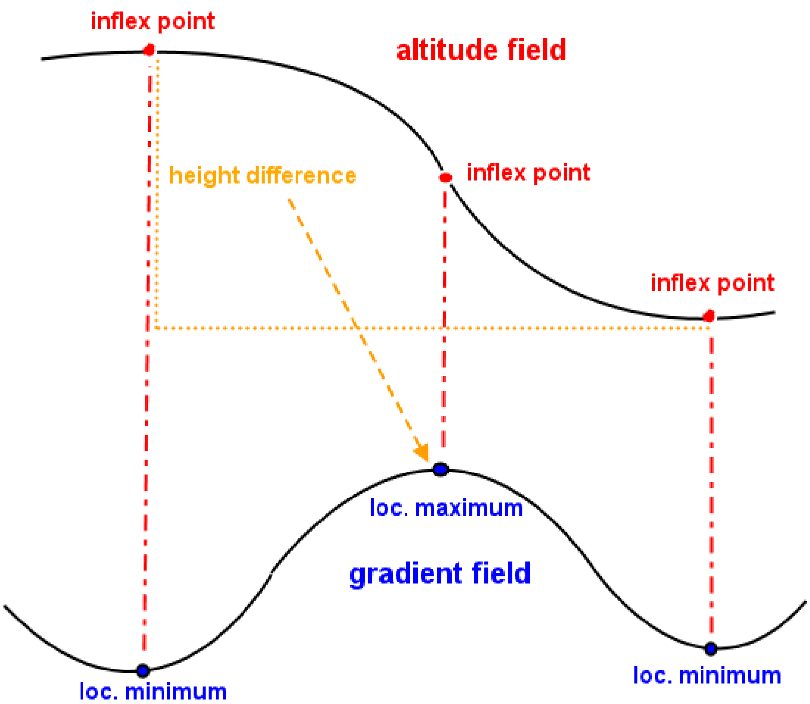

Figure 6 Principle of general sharpness characteristic

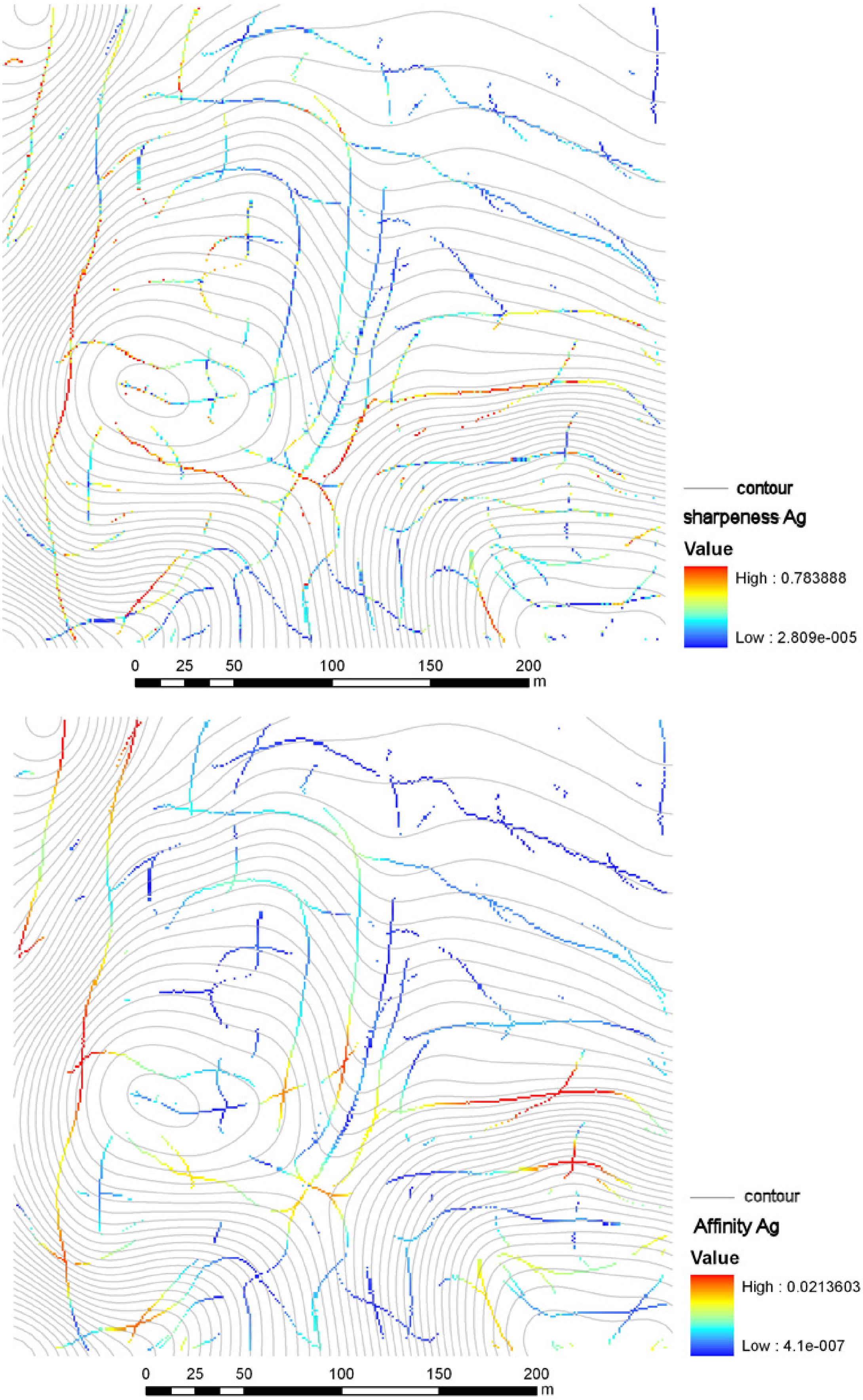

Figure 7 Importance of the delimitated boundaries

From the automatically delimitated boundary segments of *protoforms*[4] we need to delimitate their whole areas. Delimitation of the areas (surfaces) has not been automated yet, so the method of operator should be used. For the operator-based delimitation method were set the following rules:

- we follow the hierarchical order,
- by evaluating of each layer we follow the selection criteria:
  1. the value of affinity,
  2. the value of sharpness,
  3. continuity of the boundary,
  4. length of the boundary,
  5. spatial continuity (composition).
- if part of line is of lower quality, we consider it as complex,
- we set the limit distances between the boundaries,
- the surroundings of singular points is not used,
- surface delimitated by boundaries must have inner homogeneity.

With the help of expert-geomophologist were from the input data delimitated boundaries of protoforms along with the above described criteria. In the figure 8 we can compare the results of delimitated protoforms by the method described in this paper with results presented in work [2], where is the delimitation based on empirical knowladge. Segments of automatically delimitated boundaries led the expert to more detailed elementarization. Differences from the expert-delimitated boundaries are the errors, but the amount of input information led to a model with higher detail.

5 Conclusions

This article has shown a possible way for automatic georelief segmentation for the requirements of GmIS. Algorithm based on the *Canny* edge detector delimitates segments of forms boundaries with high preciseness. It searches for the inflex points in the input data and then finds the lines of discontinuities in-between them. The discontinuities are sought in field of morphometrical characteristics of higher orders. For derivation of these field with sufficient preciseness was in this article introduced a robust method for approximation of partial derivatives of the third order. The delimitated boundaries segments correspond with the boundaries of elementary forms of georelief and they are even more precise then geomorfologist delimited boundaries in paper [2]. The next task would be to automate the delimitation of areas of elementary forms by the above described delimitation rules.

[4] *Protoform* is a delimitated but unclassified elementary form

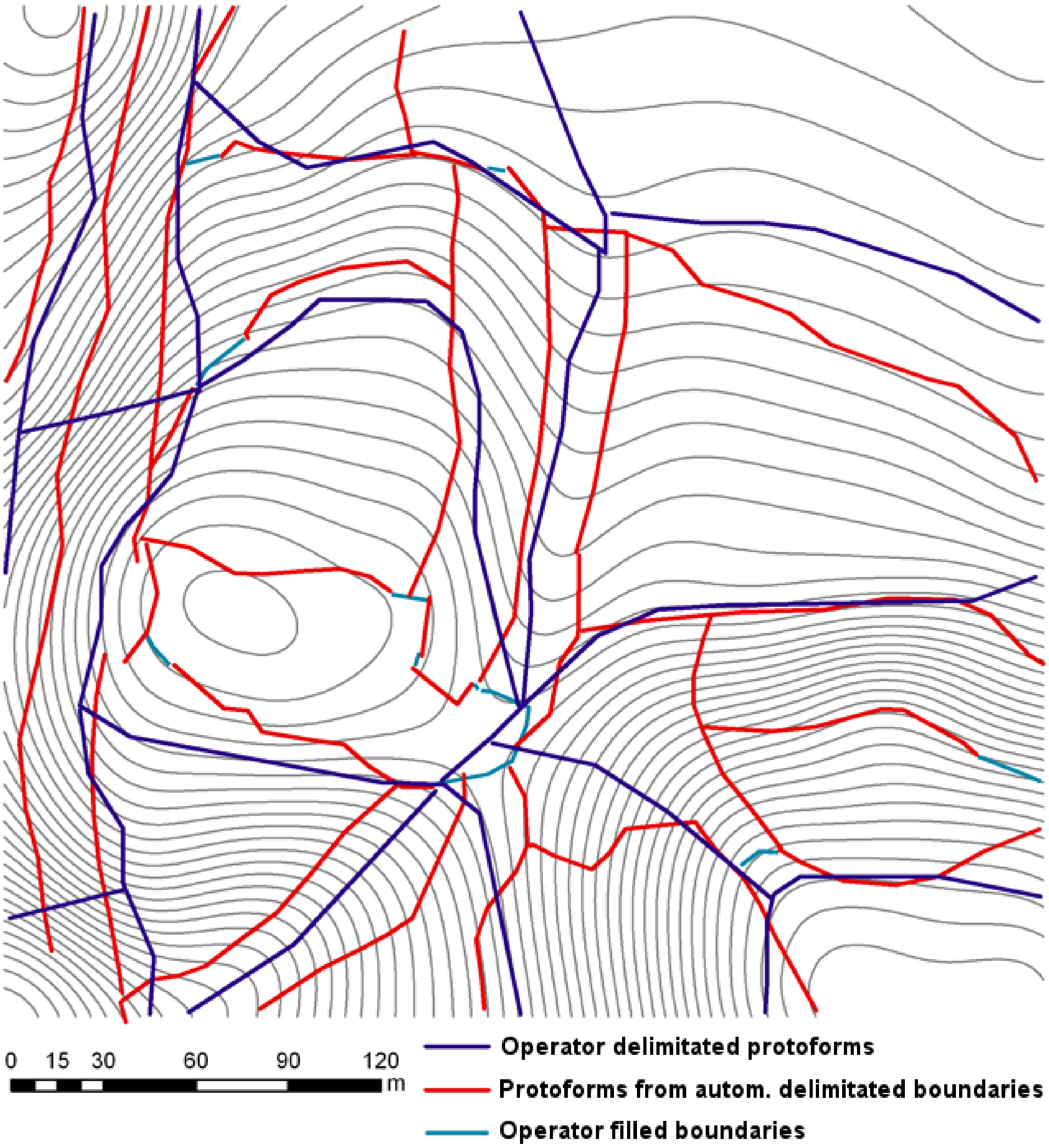

Figure 8 Delimitated protoforms

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