Mean-curvature watersheds: A simple method for segmentation of a digital elevation model into terrain units

Bård Romstad[a,b,c] and Bernd Etzelmüller[a,c]

[a] Department of Geosciences, University of Oslo, PO Box 1047 Blindern, N-0316 OSLO, Norway
[b] CICERO Center for Climate and Environmental Research, PO Box 1129 Blindern, 0318 OSLO, Norway
[c] International Centre for Geohazards (ICG), PO Box 3930 Ullevaal Stadion, N-0806 OSLO, Norway

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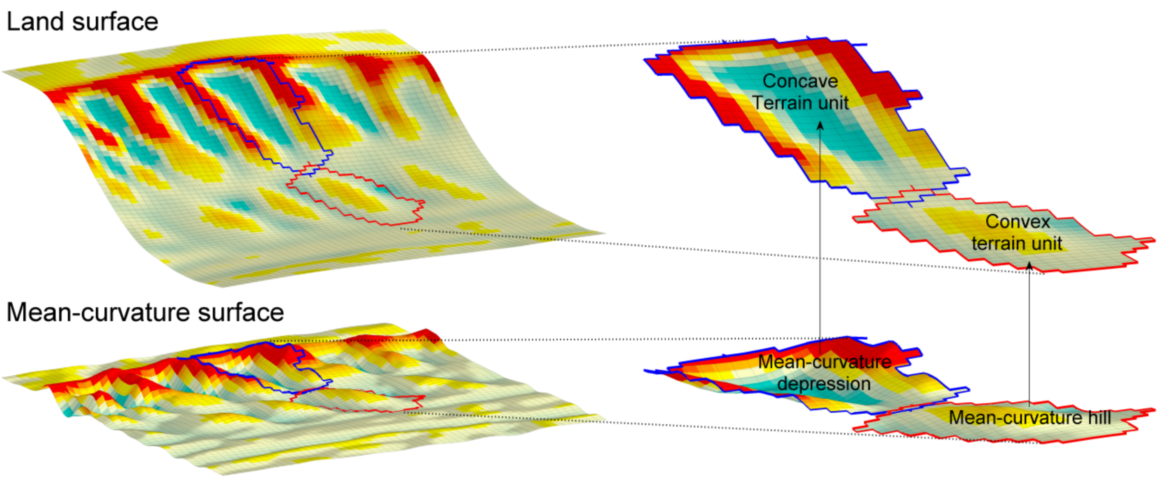
Graphical Abstract



Abstract

Terrain segmentation is the process of subdividing a continuous terrain surface into discrete terrain units. If the resulting units represent meaningful geomorphic objects the approach may facilitate studies of not only landforms and land forming processes, but also the interaction among surface form, soil, vegetation, hydrology and topoclimatic regimes. Commonly used methods for terrain segmentation fail to produce terrain units with a potentially large, but cyclic variation in topographic attributes, such as uniformly curved areas bounded by topographic break-lines, although this topographic characterisation is common for a number of landforms. This paper describes a new method for terrain segmentation using mean-curvature (MEC) watersheds. The method produces objects that contain a cycle of MEC values. Thus the topographic variation within each object may be large, but due to the cyclic nature of the MEC variation a geometric simplicity is ensured. In a case study we show how the resulting terrain units correspond well with a number of landforms and surface types observed in the field, and conclude that the method can be expected to be of great value for a number of applications within geomorphology and related disciplines.

1. Introduction and background

Geomorphometry is the science of quantitative land-surface analysis and we have seen this type of analysis used in a large number of geo-related applications, especially within geomorphology, geology, hydrology, soil science, vegetation science, climatology and meteorology (Hengl and Reuter, 2009). Common for all applications is that they are based on topographic attributes calculated from a gridded digital elevation model (DEM). Topographic attributes are traditionally calculated on a cell by cell basis, adapting a field-based view of the land-surface (Moore et al., 1991; Wilson and Gallant, 2000). One fundamental problem is the difficulty of identifying topographic attributes that describe patterns of landforms or landform systems (MacMillan et al., 2004). This is ultimately due to the lack of context in the calculation of topographic attributes. Most attributes are locally derived and more or less scale specific in the sense that they vary with the size of the filter used for their calculation. Shary et al. (2002) has pointed out that the problem can be addressed to some extent by the use of regionally derived attributes such as upslope catchment area or the topographic wetness index. Other authors have suggested a multi-scale approach (Wood, 1996; Gallant and Dowling, 2003; Schmidt and Andrew, 2005) where topographic attributes calculated at multiple scales are combined. In both cases the issue of context is addressed within the field based paradigm and attributes are still calculated on a cell by cell basis. A different approach has been to segment the continuous terrain into discrete objects. The idea is by no means a new one and reviews of different methods can be found in e.g. MacMillan et al. (2004), Minár and Evans (2008) or MacMillan and Shary (2009). The concept is to redefine the basic spatial unit from a single grid cell to a group of adjacent cells, a *terrain unit*, which is assumed to represent a meaningful spatial entity. The process can generally be referred to as *terrain segmentation* (Strobl, 2008). It can be a powerful approach as it allows the calculation of contextual information such as the geometry and statistical properties of individual objects as well as object topology. The strength of the approach, however, relies completely on the ability of the segmentation algorithm to provide terrain units that represent meaningful geomorphic objects.

Methods that have been successfully used for terrain segmentation can roughly be divided into two main groups: Edge-based and region-based methods. The most effective edge-based methods have focused on defining hydrological objects: channels, divides and the hillslopes that occupy the area between them (e.g. Band, 1986; Carrara et al., 1991; Band et al., 2000; MacMillan et al., 2000). The hillslopes can be taken to represent explicit physical units of the surface defined by their hydrological connectivity. The explicit link between each unit and different hydrological domains on the surface is a very favourable property of these methods, and they also reflect the observation that drainage patterns are helpful in revealing and defining landforms (MacMillan et al., 2004). A weakness with these methods is that they have been less successful in identifying two or more parts of a hillslope separated by shifts in slope gradient, as they are still hydrologically connected (MacMillan and Shary, 2009). Significant topographic break-lines, or surface discontinuities, are only considered when they coincide with the hydrological objects and the geometry of the resulting hillslopes may therefore often be non-uniform, especially along the direction of slope. Rowbotham and Dudycha (1998) addressed this issue by further dividing hillslopes into slope facets using edges extracted from minima and maxima of plan and profile curvature surfaces, but they found it difficult to establish well-connected networks from these edges without manual editing.

Among the region-based methods the trend has been to adopt region-growing methods from digital image analysis that construct regions (objects) by iteratively merging adjacent regions with similar topographic characteristics until some halting criterion is met (Friedrich, 1998; Romstad, 2001; Drăguţ and Blaschke, 2006; van Asselen and Seijmonsbergen, 2006;

Etzelmüller et al., 2007). The halting criterion effectively controls the scale of the resulting objects and is usually defined as the maximum heterogeneity allowed within individual objects. By using topographic attributes such as slope gradient, slope direction and curvature as input variables, one can expect the resulting terrain units to be morphologically homogeneous and consistent with e.g. Speight's (1974) landform elements or form facets as defined by Dikau (1989). Objects are defined by their internal properties, rather than via the boundaries that separate them. Still, object boundaries tend to respect topographic break-lines as these are areas with a large topographic variation that disagree with the homogeneity criterion. There is, however, an obvious conflict in trying to maximise the internal homogeneity of a set of topographic attributes of different orders (e.g. both first and second derivatives of a surface). As an example, areas with a homogeneous, non-zero curvature will necessarily have a non-homogeneous slope. Thus the segmentation result can generally not be expected to include terrain units with a uniformly curved surface. Another problem with region-growing algorithms is that they are often unstable in the sense that segmentation results may vary widely with only little change to the underlying data sets (Strobl, 2008). Simple region-growing algorithms are also very sensitive to the magnitude of topographic variation in an area. This means that algorithms will typically lead to over-segmentation in rough and steep terrain or under-segmentation in gentle areas. More advanced algorithms address this by including measures of region size, shape, and uniformity in the homogeneity criterion (Baatz and Schäpe, 2000; Benz et al., 2004). Thus the algorithm can be tuned to produce terrain units that better fit the characteristics of objects of interest.

To summarise it seems evident that the hillslopes resulting from methods based on hydrological flow have a rather clear topographic definition, each hillslope capture the extent of one full cycle of topographic variation from crest to channel. It is a deterministic method where the size and shape of each unit is mainly determined by the *frequency* of topographic variation while the *magnitude* of topographic variation is irrelevant. As long as the hydrological connectivity is preserved, there is no constraint on the internal geometry of the hillslope. Thus topographic break-lines may very well exist within a unit. Region-growing methods create terrain units which are homogeneous in topographic attribute and consequentially object boundaries also tend to respect topographic discontinuities. But the commonly used methods are stochastic and, unlike the hillslopes, a clear topographic definition of the units is generally lacking and must be inferred from subsequent analysis. Region-growing methods may also not be appropriate when relevant terrain units are characterized by a uniform, but large variation in topographic attribute.

In this paper we describe a method for terrain segmentation that was first suggested by the current authors at the Geomorphometry2009 conference (Romstad and Etzelmuller, 2009). Here terrain units are defined by watersheds in the mean-curvature image. A similar method was introduced by Mangan and Whitaker (1999) for partitioning of 3D surface meshes within computer graphics, but to the authors knowledge such a methodology has not so far been applied on DEMs for the purpose of terrain segmentation. We explore the properties of mean-curvature watersheds through some theoretical examples before we suggest a detailed methodology. The appropriateness and potential applications of the method is illustrated in a case study where the objects resulting from the terrain segmentation is compared to mapped landforms and surface types.

2. Curvature watersheds

Surface curvature is a topographic attribute that describes the convexity/concavity of a terrain surface. Curvature calculation is based on second derivatives; the rate of change of a first derivative such as slope gradient or slope direction (aspect), usually in a particular direction (Gallant and Wilson, 2000). The two curvature measures most frequently used are the profile and the plan curvature. The profile curvature (*PRC*) describe the rate of change of slope along a flow line and can be related to acceleration/deceleration of gravitational flow, while the plan curvature (*PLC*) describe the rate of change of aspect and is associated with flow convergence/divergence (Moore et al., 1991; Gallant and Wilson, 2000). Since *PLC* can take extremely large values where the gradient is small, a better measure for topographic convergence is the tangential curvature (*TAC*), which is the curvature in an inclined plane perpendicular to the direction of flow and the surface (Gallant and Wilson, 2000; Shary et al., 2002).

Mean curvature (*MEC*) is defined as the average curvature of any two mutually perpendicular normal sections at a given point on a surface (Shary, 1995; Shary et al., 2002). Olaya (2009) states that *MEC* "describes mean-concave and mean-convex terrains, which makes it especially interesting for geomorphologic studies". It is commonly agreed upon that the sign of curvature is positive for a convex shape and thus positive values of *MEC* are associated with areas of relative deflection while negative values indicate relative accumulation (Olaya, 2009). Shary et al. (2002) categorizes *MEC* as a field invariant morphometric variable as it is independent of the direction of gravity (or any other vector field). The implication of this is that the *MEC* values calculated for all points on a given surface does not change if the surface is tilted. It was shown by Shary (1995) that *MEC* equals half the sum of *PRC* + *TAC*. This indicates that while *MEC* is independent of the direction of gravity it can still be related to the two accumulation mechanisms of gravitational flow, and Shary (2006) refers to a number of studies where *MEC* was successfully used to describe properties of soil moisture, erosion processes and landforms.

Transitions between adjacent landforms are often accompanied by topographic break-lines, i.e. a surface discontinuity such as a break in slope gradient or slope direction. A break in slope gradient is usually associated with a change in the dominant surface process and may also be linked to lithological, pedological and vegetation characteristics. Consequently such break-lines often indicate the boundary between adjacent geomorphological units on a map (Giles, 1998). Similarly breaks of slope direction often define the boundary between local catchments, which may be linked to changes in hydrological conditions. These two types of break-lines will implicate significant shifts in either of the two accumulation mechanisms and therefore a corresponding signal should be found in the *MEC* image. Because the magnitude of curvature values is highly dependent of the underlying relief the signal from a topographic break-line is best defined as a local extreme in the *MEC* image. These extremes coincide with the network of channels and drainage divides in the *MEC* image and can be extracted using the same methods as the ones used for extracting hydrological objects from a DEM. A significant difference between an *MEC* image and a DEM is that closed depressions in the latter are usually considered as artefacts and removed. In an *MEC* image, however, closed depressions may be interpreted as terrain unit where the accumulative property of the surface is at a maximum at a point somewhere in its interior and is continuously decreasing towards its minimum along the boundary.

Within digital image analysis, watershed segmentation refers to a method for extracting regions, or objects, from grey-level images (Sonka et al., 1998). Regions are constructed around local minima in the image and efficient and accurate algorithms have been developed that builds regions by simulating a gradual "flooding" of the image. Watershed boundaries are formed where the "water spills over" between two neighbouring basins (e.g. Vincent and Soille, 1991). It is thus a region-based segmentation method, but contrary to other region-based methods the homogeneity criterion is not a statistical measure, but the hydrological connectivity between image pixels and seeds that are positioned at all local minima. When a watershed segmentation algorithm is applied to an *MEC* image each resulting region will consist of a full cycle of *MEC* values. The region will be formed around a depression in the image and its full extent is defined by the "drainage divide" between neighbouring basins. For this reason we may refer to these regions as *MEC depressions*. Because the region boundaries are found along local maxima of curvature we should expect them to coincide with convex topographic break-lines. By calculating watersheds from the inverted *MEC* image we obtain another set of regions which we may refer to as *MEC hills*. These are formed around local maxima in the original *MEC* image and the region boundaries can here be expected to include all concave topographic break-lines.

Fig. 1 shows four idealised terrain profiles, the *MEC* values along these profiles, and the extent of curvature watersheds. The terrain profiles basically describe landforms with different rotations, but otherwise identical geometry (closed/open depression/eminence). Since the mean curvature is field invariant the signal is also identical for all profiles, but the sign changes between depressions and eminences. A similar situation on a full surface is illustrated in Fig. 2. In all four cases it is evident that the apparent landform can be successfully delineated by watersheds from either the original or the inverted *MEC* values. This is important because this type of topographic configuration is common for a number of specific landforms (e.g. dunes, cirques, moraine ridges, drumlins and pingos). It also implies that the use of *MEC* watersheds may offer a solution to the previously unresolved issue of quantitatively identifying open depressions (Shary, 2006; MacMillan and Shary, 2009).

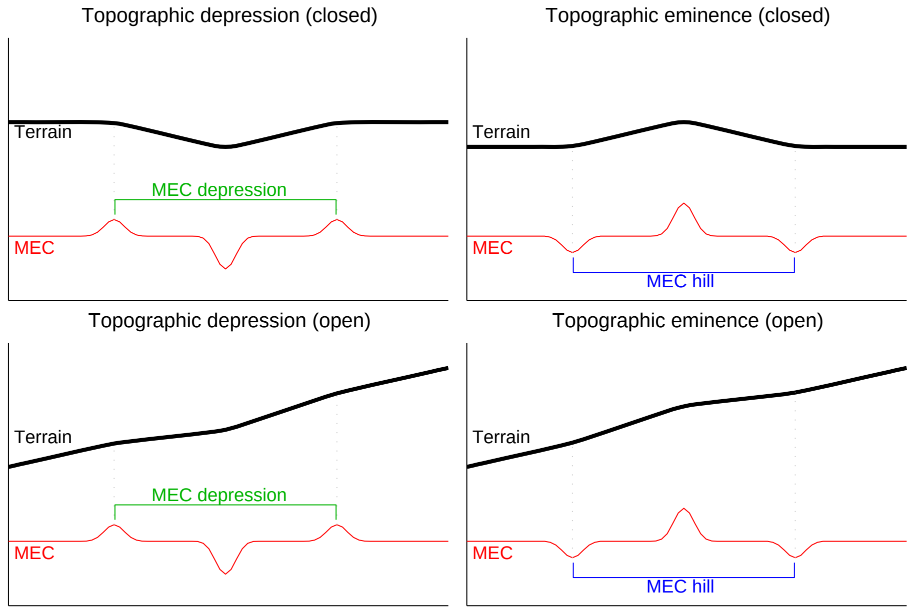


Fig. 1. Terrain profiles over topographic depressions and eminences, corresponding *MEC* values and the curvature watershed that delineates the landform. The apparent landforms are basically different rotations of the same surface geometry. Because *MEC* is field invariant the signal is identical (except for sign changes) for all four cases.

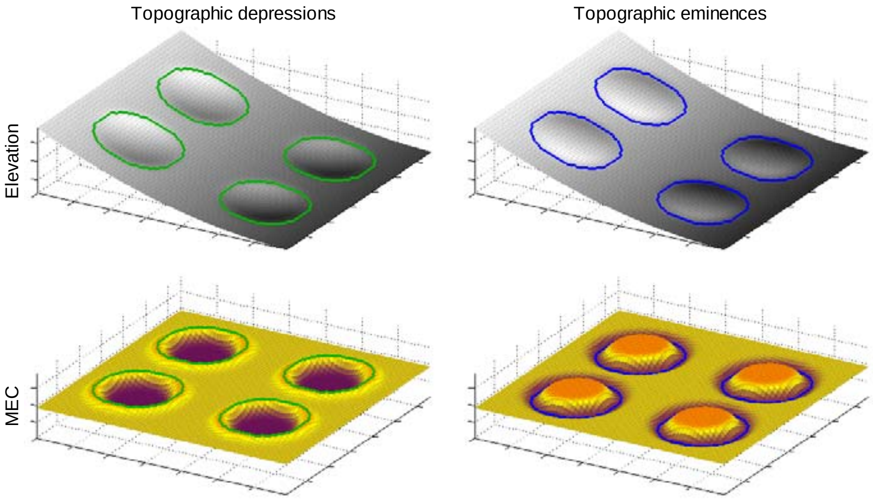


Fig. 2. Synthetic terrain surface with depressions and eminences, corresponding *MEC* images, and the watersheds that delineate the landforms.

In Fig. 3 we see *MEC* watersheds calculated on an idealised hillslope profile. While all topographic break-lines along the profile are represented by a boundary from either of the two sets of watersheds, it is clear that not all watershed boundaries do represent significant topographic break-lines. In areas with successively accelerating terrain the significant signals in *MEC* are exclusively positive. Thus it is only the boundaries of *MEC* depressions that represent topographic break-lines here (D1 to D3 in the figure). This does not mean that the *MEC* hills in the same area are irrelevant, in the current example they do in deed represent actual topographic eminences, but they are not confined by significant break-lines. In successively decelerating terrain the situation is opposite and it is the *MEC* hills that are confined by topographic break-lines (H4, H5 and H7) while depressions are unconfined. The objects in the transition zone between accelerating and decelerating slopes are only partly confined by topographic break-lines, but here the *intersection* between *MEC* depressions and hills will generate fully confined objects ($H3 \cap D4$, $H6 \cap D6$, $H6 \cap D7$ and $H8 \cap D8$). If we assume that transitions between adjacent landforms, surface types or soil types observed in the field are accompanied by topographic break-lines we should also expect their boundaries to coincide with an *MEC* watershed boundary, but typically the boundaries of *MEC* depressions are less likely to be significant in successively decelerating/converging terrain (e.g. valleys) while the boundaries of *MEC* hills are less likely to be significant in successively accelerating/diverging areas (e.g. convex plateaus or ridge tops). We can also observe that the well confined objects along the hillslope profile in Fig. 3 are in good agreement with classification schemes such as the morphological types of landform elements (Speight, 1990), the landform elements in a hillslope system (Pennock et al., 1987) or the nine unit landsurface model (Conacher and Dalrymple, 1977). To illustrate this we have suggested an interpretation of these objects according to Conacher and Dalrymple's model.

It is worth noting that since *MEC* in Fig. 3 is calculated along a single hillslope profile, it only reflects the relative acceleration/deceleration of gravitational flow and is thus equivalent to *PRC*. Fig. 4 shows a full hillslope with *MEC* watersheds overlaid. Here *MEC* values reflect both accumulation mechanisms of gravitational flow and the interpretation of the objects becomes more complex. A relatively consistent catenary sequence can still be inferred from the vertical boundaries that separate the different decelerating/accelerating sections of the hillslope, but in addition lateral boundaries divide the hillslope into different overlapping convergent and divergent parts.

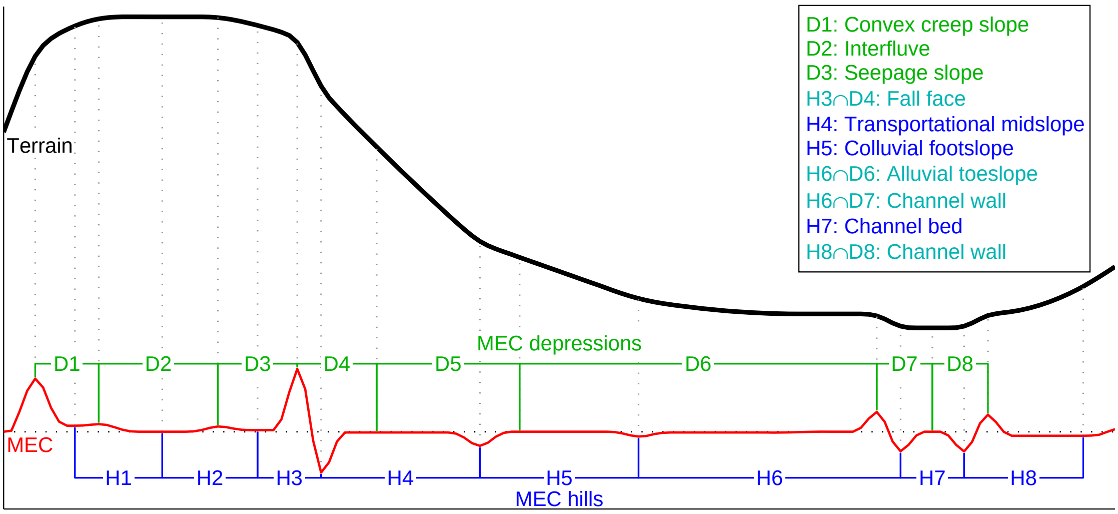


Fig. 3. An idealised hillslope profile, the corresponding *MEC* values and the two overlapping sets of *MEC* watersheds. The legend suggests an interpretation of the watersheds according to the *nine unit landsurface model* by Conacher and Dalrymple (1977)

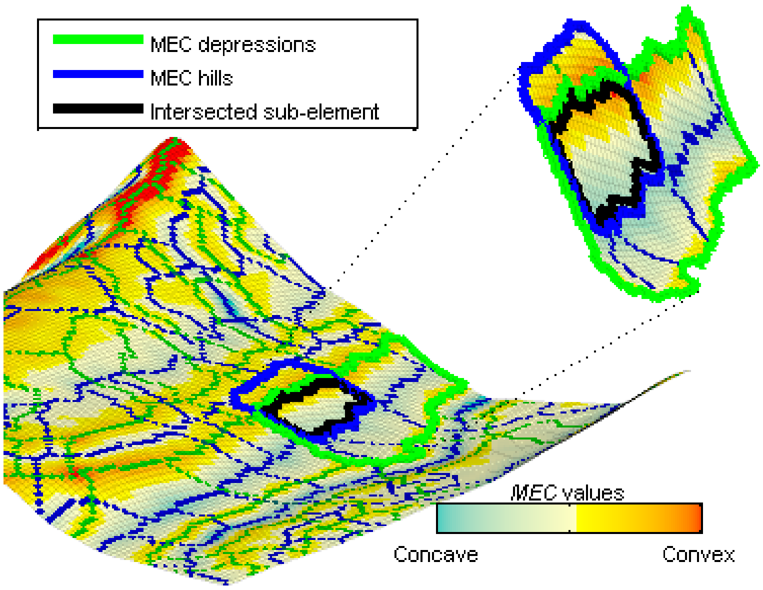


Fig. 4. *MEC* watersheds calculated for a real terrain surface. Lateral boundaries divide the hillslope into different convergent/divergent parts while the vertical boundaries separate between the different decelerating/accelerating sections. Inset, detail of a convex *MEC* hill (shoulder), a concave *MEC* depression (footslope) and the sub-element resulting from their intersection.

From the examples above it becomes clear that an *MEC* depression can be an actual concavity in the terrain (topographic depression), but it can also be a planar or convex area bounded by convex break-lines (e.g. section of a successively accelerating slope or a plateau). Vice versa an *MEC* hill may be an actual convexity (eminence) or it may be a planar or concave area bounded by concave break-lines (e.g. section of a successively decelerating slope, a valley bottom or a channel bed). Objects may be fully confined, partly confined or unconfined by topographic break-lines. All types of objects describe a terrain unit with a relatively simple and uniform geometry, but while fully confined objects may be well suited for delineation of specific landforms or surface types, unconfined objects are better interpreted as vague objects representing different mean-concave or mean-convex domains of the terrain surface.

MEC watersheds also allow for the introduction of what Shary et al. (2002) refer to as "regional and field-invariant morphometric variables". Properties of *MEC* watersheds such as their size or shape are obviously regional, and they can also be considered field invariant as *MEC* is independent of any vector field. They are not scale-free, however, because the *MEC* itself is a local variable which is highly scale dependent. Thus the scale of the resulting regions will ultimately depend on the resolution of the DEM and the size of the local operator used in *MEC* calculation.

3. Method

A brief outline of the method can be summarised with the following five steps, all of which will be described in more detail below:

1. Smoothing of the original DEM
2. Calculation of mean curvature (*MEC*)
3. Filling shallow minima in both the *MEC* image and the inverted *MEC* image
4. Thresholding the *MEC* images at a minimum value
5. Applying a watershed algorithm to both *MEC* images

The above procedure was implemented in Matlab version 7.6 using standard functions from the Image Processing Toolbox. Our implementation takes a gridded DEM as input, together with three adjustable parameters: the degree of DEM smoothing, the minimum watershed depth, and the lower threshold for *MEC* values. The output was two separate segmentation results: *MEC* depressions and *MEC* hills.

Surface curvature is very sensitive to noise in the elevation data and grid based calculation of curvature may also exhibit bias along the cardinal and diagonal directions (Shary et al., 2002). In order to minimise these effects the DEM can be smoothed with a low pass filter prior to curvature calculation. In our implementation the filter used for DEM smoothing was defined as an input parameter, because 1) the degree of smoothing necessary for sufficient removal of noise will be dependent on the quality of the DEM, and 2) smoothing of the DEM implies terrain generalisation by reducing the high frequency component of the topographic variation. Thus the smoothing parameter can be actively used to adjust the scale of the resulting units.

MEC was calculated for each cell on the smoothed DEM with the method described by Young (1978) and Evans (1979). An inverted *MEC* image was calculated by multiplying *MEC* with −1. All further processing was applied to each of these two images independently.

The images may have minor fluctuations in *MEC* values that represent insignificant changes in the surface geometry. In order to resolve this, local depressions with a shallow depth (shallow minima) should be suppressed (filled) prior to segmentation. The filling of shallow minima was achieved with the *imhmin* function in Matlab's Image Processing Toolbox. The function identifies all depressions (pits) in the image and fills them up to a specified depth. Filling shallow minima will not alter the position of any watershed boundary, but it will result in a boundary collapse, after a "dam breach", at the lowest point along the boundary of a shallow watershed. The shallow minima threshold depth therefore effectively defines the minimum magnitude of *MEC* cycles to be captured by the segmentation algorithm and can also be used to adjust the scale of the segmentation result. Again the appropriate threshold value will be dependent on the quality of the input data, but also by the degree of smoothing applied to the DEM, as the smoothing will alter the magnitude of *MEC* values. The minimum watershed depth was therefore defined as an input parameter which could be adjusted accordingly.

In addition we defined an absolute lower threshold of *MEC* values. All variation in the *MEC* images below this threshold value was removed. This was motivated by the assumption that the absolute effect of random errors and grid artefacts on the calculated *MEC* values is much greater in strongly curved areas. In addition it can be argued that for many applications even relatively large fluctuations in strongly curved areas may be of less importance because they usually do not imply a significant change in the accumulation mechanisms of gravitational flow. The application of a minimum threshold value on the *MEC* images ensures that contiguous areas with an *MEC* value below the threshold will belong to the same object. Since the threshold is applied only to the negative values, convex break lines remain unaffected in the *MEC* depressions result, while for *MEC* hills the concave break lines are not affected. The threshold value was defined as an input parameter, but in our analysis we consistently used a value of two times the standard deviation in the *MEC* image. Fig. 5 shows the combined effect of removing shallow minima and applying an absolute lower threshold to *MEC* values and we observe how low magnitude fluctuations and fluctuations below the minimum curvature threshold are ignored in the final segmentation result.

For the actual watershed segmentation we used the *watershed* function of the Matlab Image Processing Toolbox. The function uses an algorithm for grey scale images published by Meyer (1994) and is only briefly described here.

1. First a set of markers, or seeds, are positioned at all local minima in the image. Each marker is given a unique label.
2. The neighbouring pixels of each marked area are inserted into a priority queue with a priority level corresponding to the grey level of the pixel (lowest grey level value, or *MEC* value in our case, is first in the queue).
3. The pixel with the highest priority level is extracted from the priority queue. If all the neighbours of the extracted pixel that have already been labelled have the same label, then the extracted pixel is labelled with their label. All non-labelled neighbours that are not yet in the priority queue are added to the queue.
4. Redo step 3 until the priority queue is empty.

The result is a labelled image identifying each of the watersheds/regions in the input matrix. All non-labelled pixels represent watershed boundaries. The algorithm was applied to both the *MEC* image and the inverted *MEC* image. Our final output was thus two labelled images, one identifying the *MEC* depressions and the other the *MEC* hills.

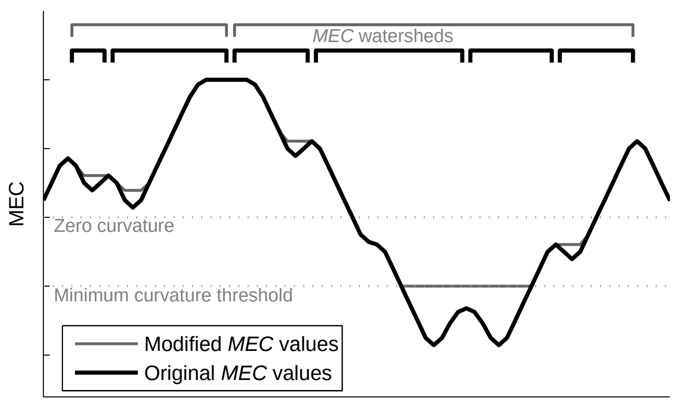


Fig. 5. A profile along a hypothetical *MEC* image illustrating the effect of suppressing shallow minima and setting a minimum value threshold. The thick black lines represent the original *MEC* values and watersheds while the thinner grey line represents the modified *MEC* values and corresponding watersheds.

4. Results and discussion

4.1 Test area and parameter settings

The terrain segmentation was tested on a DEM with a spatial resolution of 20 m from an area around Adventdalen, at 16°10'E and 78°9'N on Spitsbergen, Svalbard (Fig. 6). This area is characterized by horizontal or slightly dipping Mesozoic sedimentary sediments, incised by both fluvial and glacial valleys with steep slopes (Major et al., 2000). Permafrost is continuous (Humlum et al., 2003) and local glacierization dominates at present. The area comprises an ensemble of glacial and periglacial landforms and sediments, dominated by gravitational processes along the slopes (talus, debris flows, and solifluction) and sorting processes (patterned ground) on valley bottoms and higher plateaus (Tolgensbakk et al., 2000). In order to investigate the potential of *MEC* watersheds for geomorphological applications the segmentation result was compared to a geomorphological and Quaternary geology map at a scale of 1:100 000, published by The Norwegian Polar Institute (Tolgensbakk et al., 2000).

Fig. 6 shows the objects resulting from an *MEC* watershed segmentation of the study area overlaid on the geomorphological map. *MEC* depressions and hills are shown separately in the figure for easier comparison between individual objects and features in the geomorphological map. The optimal parameter settings for the segmentation procedure depend on the quality of the DEM and its resolution relative to the scale of terrain units relevant to the application at hand, but as explained in Section 3 a slight degree of both DEM smoothing and shallow minima suppression are required in order to reduce the effects of errors, noise and artefacts from the terrain representation. DEM smoothing is a local operation which reduces the high frequency component of the topographic variation, while shallow minima suppression is a regional operation that removes low magnitude variation. Thus they have different effects on the segmentation results. This is illustrated in Fig. 7, which shows three different segmentation results for the area indicated by the grey box in Fig. 6. All three segmentation results have approximately the same number of objects, but they are produced by using different combinations of parameter settings. In the left panel only slight smoothing is applied to the DEM while the minimum watershed depth set to a relatively large value. The resulting MEC watersheds have jagged boundaries and object size varies greatly with topographic relief. This is expected as this configuration of parameters has minimal effects on high-frequency information in the DEM and generalisation is mainly due to shallow minima suppression. The magnitude of *MEC* variation tends to increase with increasing relief and therefore stronger generalisation occurs in low relief areas. In the middle panel a more moderate degree of smoothing is applied to the DEM while the minimum watershed depth is adjusted downwards accordingly (these are the same parameter settings as used for Fig. 6). We have thus balanced an increased generalisation in the high-frequency domain by less removal of low-frequency information. The result is smoother object boundaries, more generalisation (i.e. larger objects) in high relief areas and less generalisation in areas with gentle relief. In the right panel of Fig. 7 *MEC* watersheds are calculated from a strongly smoothed DEM, and minimum watershed depth is set to a relatively small value. Consequently generalisation mainly occurs due to removal of high-frequency information in the DEM. The effect is an even more uniform distribution of object size in all areas, but the large degree of DEM smoothing obviously involves loss of topographic detail. Surface discontinuities are by definition local features degrade with an increasing degree of DEM smoothing. In areas with abrupt changes of elevation strong DEM smoothing may also cause a slight shift in the horizontal position of extreme *MEC* values away from the actual position of the surface discontinuity.

Setting the degree of smoothing, or the minimum watershed depth, beyond the extreme values used in Fig. 7 was judged inappropriate for our case study. For the terrain segmentation displayed in Fig. 6 we used the moderate setting for both the smoothing filter (a 9×9 Gaussian with σ = 2.0) and the minimum watershed depth (0.1 std of MEC values ≈ 0.6° 100 m^{-1}) resulting in an average object size of about 8 ha and the discussion below is based on this segmentation result.

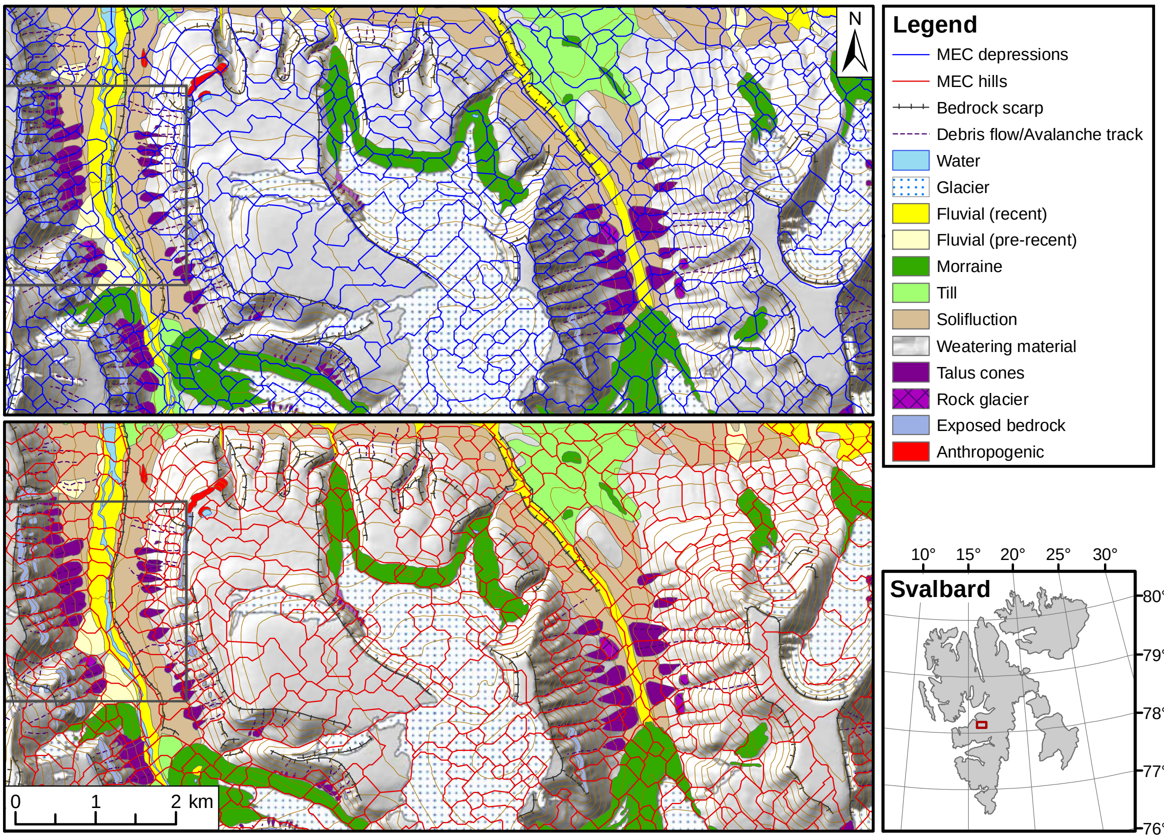


Fig. 6. Geomorphological map over the study area overlaid with *MEC* depressions (top panel) and hills (bottom panel). The grey box in the western part of the study area indicates the extent of Fig. 7.

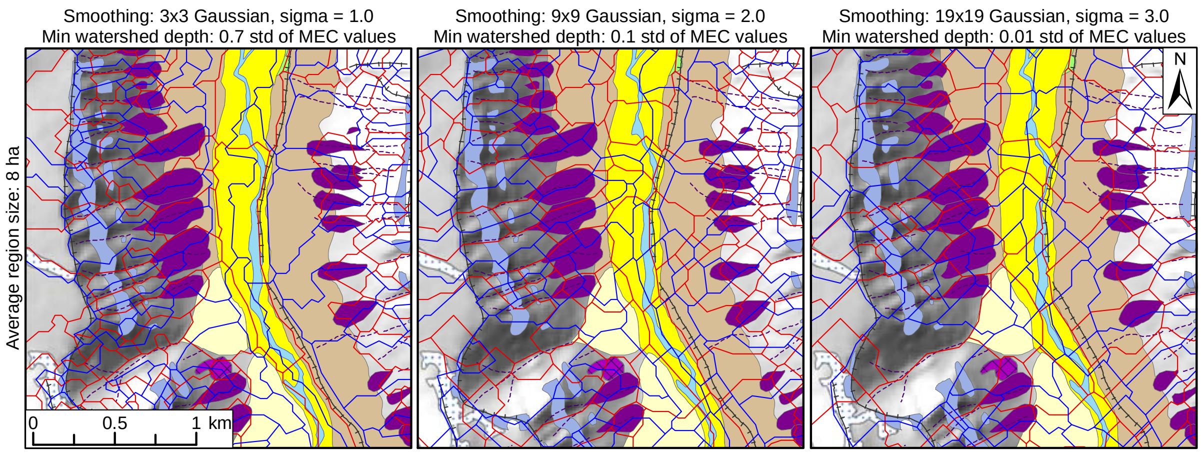


Fig. 7. The effect of different parameter settings on the segmentation result. In the left panel only a slight DEM smoothing is applied while minimum watershed depth is set to a relatively high value. In the middle panel a moderate setting for both the smoothing filter and the minimum watershed depth is used, while in the right panel strong DEM smoothing is applied while minimum watershed depth is set to a very low value.

4.3 *MEC* depressions

MEC depressions are shown in the top panel of Fig. 6 and we observe that practically all major scarps, crests and edges in the map are accompanied by boundaries of *MEC* depressions. This is expected as these features coincide with convex topographic break-lines. Another obvious pattern is that individual *MEC* depressions matches a number of the large chutes and canyons incised in the steep slopes. In the upper slopes individual objects also outline open depressions formed around debris flow/avalanche tracks, many of which are found directly above talus aprons. These objects are more or less fully confined by surface discontinuities. *MEC* depressions are also formed around headwalls, but here each landform (e.g. escarpment or cirque headwall) is usually represented by a sequence of adjacent objects. Each object is confined by surface discontinuities along the upper scarp and sometimes also in the lateral directions, while their lower boundaries are mostly unconfined. The narrow valley bottom in the eastern valley forms a channel which is well represented by a series of adjacent *MEC* depressions. Also these objects are only partly confined, but here mainly in the lateral directions (towards the valley sides). None of the above-mentioned landforms is explicitly identified as objects in the validation map, but they are still noticeable features in the landscape and many of them are implicitly defined via linear features such as bedrock scarps. They are landforms characterized by a truly concave geometry, typically formed by erosion and net material loss, and they can be assumed to serve as source areas for material that is removed through gravitational, fluvial or glacial action.

The objects occupying the high plateau in the eastern part of Fig. 6 represent another type of *MEC* depressions. Also these are well confined in at least one direction, but they are not truly concave objects, but rather characterized by a planar or even slightly convex geometry. As discussed in Section 2, these types of objects are expected in areas where concave topographic break-lines are lacking.

The remaining *MEC* depressions are objects with concave geometry, mainly in the along-slope direction (footslopes). A considerable share of these objects is confined by surface discontinuities in the vertical direction (their upper and/or lower boundary), representing a more or less well-defined footslope section of a hillslope profile. On footslopes with talus formation objects are also relatively well confined laterally and outline the "basin" between neighbouring talus. Still a number of the remaining *MEC* depressions are generally unconfined objects that merely describe a section of the terrain that is mean-concave, but with poorly defined boundaries.

4.4 *MEC* hills

In the lower panel of Fig. 6 we see the *MEC* hills overlaid on the same map. Simple convex landforms, such as talus aprons, rock glaciers and alluvial fans are in very good agreement with individual objects. This can be attributed to the well-defined signature these landforms create in the MEC image, both in terms of a distinct boundary and an otherwise uniform interior. Ice-cored moraine ridges are another type of convex landforms in the area. These are split up into several objects due to an undulating surface. Still, the boundary of each moraine is more or less continuously overlapped by the *MEC* hill boundaries. A number of the *MEC* hills are also formed around distinct convexities in the terrain, mainly scarps and ridgelines. While these objects are characterized by a strongly convex shape they are usually not very well confined in any direction, except for in the steep dissected slopes where there is a well-developed pattern of ridges and consequently also well-defined depressions in between them. In our study area convex topographic break-lines also form a much more consistent network than their concave counterparts do. This sometimes leads to the formation of *MEC* hill objects with a complex shape, formed around connected ridgelines that extend in several directions.

The downslope sequence of surface material types in the study area is typically weathering material at the upper slopes, colluvium and talus below steep and dissected slopes, solifluction material and sometimes patches of till in the lower slopes, and fluvial material in the valley bottoms. The transition from one surface material type to another usually coincides with a decelerating shift in slope gradient, resulting from and/or resulting in changes in surface process. In such a successively decelerating terrain we should expect *MEC* hill objects to be meaningful and our results also show that vertical MEC hill boundaries in these areas generally coincide very well with the boundaries between the different surface types in the validation map. This pattern is particularly evident along the lower slopes of the valley in the western part of the map in Fig. 6. The objects here are typically planar or slightly concave objects confined in the vertical direction by concave topographic break-lines, which mark the transition between the different surface material types.

4.2 General properties of *MEC* watersheds

Both *MEC* depressions and hills have a relatively even distribution of object size and they generally appear as simple objects, both in terms of their interior geometry and their shape. While the segmentation algorithm itself ensures a certain degree of simplicity for the internal geometry, the size and shape of the objects can be linked to the frequency of *MEC* variation in the study area. Obviously the size of the objects will decrease with increasing frequency, and objects will become elongated in areas where the frequency is anisotropic. An example of the latter can be seen in the dissected slopes or along well developed networks of channels or ridgelines.

MEC watersheds have many similarities with hillslopes constructed from hydrologically based segmentation methods: Both methods are deterministic and they detect cycles of topographic variation, rather than areas with homogeneous topographic properties. The size and shape of both hillslopes and *MEC* watersheds are thus solely determined by the frequency of variation at the resolution considered, while no constraint is put on the maximum magnitude of variation within objects. There is, however, often a strong relationship between these two quantities as topographic frequency tends to increase with increasing relief. We should therefore expect both methods to produce smaller objects in high relief areas compared to areas with low relief. Hillslope objects are defined by a hydrological network of channels and divides, constructed directly from the terrain surface. *MEC* watersheds, on the other hand, are defined by a pseudo-hydrological network constructed on a *curvature* surface. While the first network ignores topographic break-lines that do not disrupt the hydrological connectivity, all topographic break-lines are included in the latter network because surface discontinuities create local extremes in the *MEC* image. The network of channels and divides from the DEM and the *MEC* image will overlap along distinct channels or ridgelines where local extremes in the DEM are pronounced and thus represent topographic break-lines. The process relevance of channels and divides in the *hydrological network* is obvious also when they occur without any pronounced extreme value: While the network line itself may not be perceived as a distinct object here, it still serves as a boundary between areas that belong to different hydrological domains. In contrast, the process relevance of *MEC* watershed boundaries that occur in areas without any pronounced extreme in the *MEC* image is unclear. These boundaries separate areas that belong to different convex or concave surface domains, but they cannot be linked to any specific surface process.

4.5 Combining *MEC* depressions and hills

It is evident that the two sets of *MEC* watershed objects (depressions and hills) complement each other. *MEC* depressions are objects characterized by a general concave geometry and/or a strongly convex boundary, while *MEC* hills display the opposite properties. In terms of surface processes *MEC* depressions are well aligned with areas where erosional processes are dominant in shaping the terrain while *MEC* hills have stronger relevance for depositional landforms. For some applications it may be sufficient to use only one of the two sets of objects. As an example strongly concave *MEC* depressions in our study area indicated areas of erosion and net material loss. By calculating measures describing the slope and curvatures for each object we should be able to distinguish between objects representing canyons, escarpments, cirque headwalls and initiation zones for debris flows and avalanches. Likewise we should be able to predict areas of colluvial, alluvial, fluvial or glacial deposits using *MEC* hills and their attributes. Because the two overlapping sets of objects describe complementary properties of the terrain it may be a great potential in using them in combination. In a combined result both convex and concave topographic break-lines will be included. In addition each sub element can be described with a combination of its own attributes and the attributes of the *MEC* depression and *MEC* hill to which it belongs. This opens up for a powerful description of the terrain surface where each of the sub elements can be described in a wider topographic context. To use an example from our study area, sub-elements resulting from the intersection of steep and convergent *MEC* depressions and steep and divergent *MEC* hills indicate a dissected slope because such slopes have a pattern of alternating hollows and ridges. The calculation and potential application of such object-based topographic attributes is outside the scope of this study, but it is certainly a topic that should be investigated further.

Minár and Evans (2008) define *elementary forms* as the smallest and simplest type of relief units, which are indivisible at the resolution considered. Their recognition as fundamental units in a system for land surface segmentation is facilitated by their geometric simplicity (e.g. linear slope, curved slope or horizontal plain). They suggested that singular lines and points defined by local extremes, lines of inflection and other discontinuities could define the basis for the segmentation of such units. The sub-elements resulting from the combination of *MEC* depressions and *MEC* hills agrees well with this definition. Each sub-element will be geometrically simple and both convex and concave topographic break-lines are respected. Because all topographic break-lines are acknowledged as boundaries, uniform surface processes can be assumed within each element. Combined with the possibility of a rich topographic description, this suggests that these terrain units may have a large potential as spatial units in earth system modelling and analysis, e.g. mapping units for predictive modelling of landforms, erosional and depositional processes, slope stability, soil types or ground thermal regimes.

While both the theoretical analysis and the case study presented here indicate that the method could be appropriate for a number of applications, efforts should be made in order to assess how the method performs in other areas. Especially the effect of the underlying relief, the dominant surface processes, and the quality and resolution of the DEM on the segmentation result should be investigated. In this study we only considered watersheds calculated from the *MEC* image, but for a specific application watersheds calculated from other curvatures may be more relevant. An obvious example is the use of *PRC* watersheds for separating a hillslope into sections in a catenary sequence.

5. Conclusion

Watershed segmentation of mean curvature (*MEC*) images is a terrain segmentation method that is conceptually simple, makes use of relatively simple algorithms, and can be implemented in most GIS. The method is deterministic and combines some favourable properties of both edge-based and region-based terrain segmentation methods: topographic break-lines are generally respected as they tend to coincide with local extremes in curvature images, and geometric simplicity is ensured as each object can only include one single cycle of curvature values. While each individual *MEC* watershed may contain a large range of topographic variation, both in terms of elevation itself and its derivatives, any variation tends to be uniform and cyclic. The method thus acknowledges significant shifts in slope gradient within a single hillslope and it is also able to produce units that are characterized by a uniform, rather than homogeneous, topographic variation.

The scale of the terrain units produced by the segmentation method can be controlled to some extent by adjusting the degree of DEM smoothing and the minimum watershed depth in the *MEC* image, but because curvature is a local variable the possible range of scales is still limited by the resolution of the original DEM.

Two sets of terrain units can be produced: *MEC* depressions and *MEC* hills. The two sets are overlapping and describe different, but complementary properties of the topographic surface. Terrain units in each of the sets corresponded well with a number of landforms and surface types represented in a detailed geomorphological map. This suggests that each of the sets may have relevance for prediction of specific types of landforms or as mapping units in predictive models for certain surface processes.

A third set of terrain units can be constructed from the intersection of *MEC* depressions and hills. Here both convex and concave topographic break-lines will be included and thus uniform surface processes can be assumed within each unit. The units may be interpreted as elementary forms, simple and indivisible, and each of them can be described by a combination of their own attributes and the attributes of the *MEC* depression and *MEC* hill to which they belong. Thus a more comprehensive description of the topographic surface is possible where both the concave and convex properties of each sub-unit can be recognised. Due to the combination of uniform surface process, geometric simplicity and the possibility of a rich topographic description, this combined segmentation result can be expected to be relevant to a number of applications within geomorphology and related sciences.

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