

Conceptualization and Implementation of A Tectonic Geomorphology Study for Geothermal Exploration in the Great Basin, U.S.A.

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ABSTRACT

Characterization of tectonic extension and extensional faulting in the Great Basin, U.S.A. has been identified as a priority for geothermal exploration. Geomorphometry can be used to characterize extension rates through the quantification of tectonically induced landforms. A number of geomorphometry-based studies, within the context of tectonic geomorphology, have shown the usefulness of this type of analysis in characterizing tectonic extension, although generally at a regional scale. This paper discusses the conceptualization and implementation of geomorphometric methodologies, as applied to three classes of tectonically induced landforms, to develop local indices of uplift and extension. This is being accomplished with custom GIS embedded morphometric algorithms applied to measurements taken from remotely sensed imagery. Metrics produced from this analysis will be further assessed for ancillary morphologic controlling factors, such as lithology, climate, and time, using multivariate analysis. It is anticipated that the methodologies resulting from this work will be applicable across the entire Great Basin.

Introduction

In a meeting of geothermal investigators, industry, and DOE personnel, regarding geothermal research in Dixie Valley, Nevada (Dixie Valley Geothermal Workshop: Desert Research Institute, University of Nevada, Reno, June 12 & 13, 2002), several key topics surfaced as priorities, one of which was the characterization of extension and extensional faulting as related to hydrothermal convection systems in The Great Basin, U.S.A., and how this information might be applied to new geothermal exploration targets. Uplift and the relative lowering of base level is the principal control in the geomorphic evolution of fault-bounded mountain ranges and related landforms in extensional provinces. Numerous studies have utilized geomorphometric techniques to characterize

tectonic geomorphology, although generally at a regional scale (e.g. Azor et al, 2002; Miliareisis, 2001; Lou, 2000; Stokes and Mather, 2000; Hurtrez et al., 1999; and Formento-Trigilio et al., 1998). However, little geomorphometric work has been done at the local scale or for relating past extensional patterns and their relationships to geothermal systems in The Great Basin.

This paper addresses the conceptualization and implementation of a new research program using geomorphometric techniques, as applied to tectonically influenced landforms on a local scale, to facilitate landform metrics calculations that can be used to characterize extension over time. This includes the development of computer algorithms to automate metric calculations, which run in a GIS environment, and testing multivariate analysis to help separate and characterize major ancillary morphologic controlling factors, such as lithology, climate, and time. Extensional indices result that can be applied as extensional comparators over the entire Great Basin in a timely and cost effective manner as a geothermal exploration tool.

Conceptualization

This section lays the theoretical foundation upon which the logic for this study and algorithm development is based. The research considers three categories of tectonically induced landforms from which information on rates of extension can be extracted. These include (1) alluvial fans and stream gradients, (2) mountain ranges (hypsometry), and (3) faceted spurs.

Alluvial Fans & Stream Gradients

As alluvial fans and stream gradients are genetically related, they have been included in a single class. Alluvial fan morphology is controlled by tectonic setting and activity, lithology, climate, time, drainage basin area, feeder channel slope, source rock fracture density, basin relief, and stream flow volume and velocity. The tectonic control allows the morphometric analyses of alluvial fans to be used in the quantification of relative tectonic activity (Bull, 1977). The following formula, suggested by Bull (1964), is used to determine the fan to source basin area relationship:

$$A_f = cA_d^n \quad (1)$$

Where A_f represents the area of the fan, A_d the area of the drainage basin, c the area of a fan with a drainage area of one square mile, and n the slope of a regression line calculated using values of A_f and A_d for a given area. Hooke (1968) concludes that the value of c varies from bolson to bolson as a function of lithologic characteristics and tectonic history, with these factors representing primary intrabolsen variables. If equation 1 is applied in localized intrabolsen areas, lithologic effects can be factored making the value of c more useful in describing the effects of local tectonics, including the estimation relative rates of extension. A stream gradient index, discussed by Hack 1973; Keller and Pinter, 2002, and Azor et al., 2002 as:

$$I_{sg} = (\Delta H / \Delta L_r) L_{tc} \quad (2)$$

where H is the change in elevation along a channel reach, L_r is the length of the channel reach, and L_{tc} is the total channel length from reach midpoint to the upstream to the divide, can be used to help characterize lithologic differences (resistive v. less resistive) along a channel. The use of the latter index, along with mapped lithology in a GIS overlay, can provide an effective tool to facilitate an understanding of the effects of lithology on alluvial fan development.

Alluvial fan slope metrics can be used to create geomorphometric indices. Hooke (1968) describes fan slope as being controlled by discharge volume, discharge velocity, bed shear stress, lithology, and drainage-basin slope. Under static seismic and consistent climatic conditions alluvial fans develop steady-state equilibrium and drainage basins develop a state of dynamic equilibrium. Over time, the fan slope develops roughly proportional to the feeder channel gradient (Denny, 1965; Hooke, 1968). In seismically active areas both fans and drainage basins trend toward dynamic metastable equilibrium where earthquakes, causing surface fault rupture, create thresholds of change affecting their morphology. Base level is lowered—graded streams and stream segments can change to a state of degradation. According to Bull (1964), one of the effects of uplift on an alluvial system is an increase in sedimentation rates that results in the steepening of the fanhead. This also creates a concave-up section in longitudinal profile at the contact of the toe of the steeper new fan and the old fan surface. Sediments on fans in tectonically active areas tend to deposit at the fan head and also spread out laterally through multiple channels. Through time and seismic quiescence a reversal takes place as the fan becomes entrenched and distal fan deposition becomes predominant. An overall gentle concave-up longitudinal profile also forms. Considering the above factors, several metrics of alluvial fans can be postulated including:

1. Fan width to length ratios;
2. Fan slope to feeder-channel slope ratios;
3. Slope of post-uplift fan segment to pre-uplift fan segment ratios;
4. Geometry of fan longitudinal profiles.

Hypsometric Indices

Relief is primarily controlled by tectonics and erosion. In rapidly extending areas, which are conducive to the development of structurally-controlled deeply-circulating hydrothermal convection systems, relief can increase in relation to areas that have undergone less extension. Several morphometric indices, including the elevation-relief ratio (Wood and Snell, 1960), the hypsometric integral (Strahler, 1952), and the ZR ratio, which is described by Formento-Trigilio and Pazzaglia (1998) as a “rapid relief morphometric calculation of topography”, have been applied and found to be useful in the quantitative description of relative uplift. Pike and Wilson (1971) discuss mathematical similarities between the hypsometric integral and elevation-relief ratio suggesting that the results are identical, with the latter being less computationally intensive. Therefore, the hypsometric integral needs not be further considered.

The elevation relief ratio is defined as:

$$E = \overline{X}_e - Min_e / Max_e - Min_e \quad (3)$$

where \overline{X}_e is the mean elevation, Min_e is the elevation minimum, and Max_e is the elevation maximum.

The conceptually similar ZR ratio found by first determining the local mean elevation, which is calculated as:

$$\overline{Z} = \sum_n Z_r / n \quad (4)$$

where $\sum_n \overline{Z}_r$ is the sum of elevation values within a radius r and n is the number of elevation values with a circle of radius r .

Next, the local mean relief is calculated as:

$$\overline{R} = (Z_{max} - Z_{min})_r \quad (5)$$

The ZR ratio is calculated as:

$$ZR = \overline{Z} / \overline{R} \quad (6)$$

This study used only the ZR ratio as it was specifically designed for application with digital elevation models (DEMs) and as the use of more than a single index is not warranted due to the apparent similarity in the indices.

Faceted Spur Metrics

Little work has been done relating the use of faceted spur morphometrics as indicators of uplift. Faceted spurs are found on fault-bounded range-fronts and are potentially useful for analysis of degradational processes and relative vertical tectonic movement (Dohrenwend, 1987). Faceted spur formation and morphology are a function of the rate of vertical fault displacement and erosion. On a tectonically active range-front these roughly triangular shaped features would have relatively smooth faces, sharp apices, and slopes that are steep in relation to faceted spurs in areas that have stabilized. Therefore, the following metrics of faceted spurs will contain information related to uplift and extension, and erosion rates:

1. Slope;
2. Surface roughness;
3. Geometry of the apex.

Multivariate Analysis

Bull and McFadden (1977) warn that, although tectonism is generally the dominant feature in range-front landform morphology, it is only one of several factors involved in landscape evolution and that morphometric quantification may not be an indicator of sensitive temporal relationships. Different and variable physical processes influence landform metrics. These processes are not always obvious in the metrics. However, each process involved in the landform's evolution is tacitly encompassed within morphometric descriptions. Multivariate statistical methods may help unravel the tacit variables.

Remote Sensing and GIS

High spatial resolution remotely sensed imagery can be used to identify and map landforms. This data is inexpensive per unit area and gives the analyst a clear view of landforms; therefore, large areas can be covered in a cost-effective manner. A GIS system can be used to (1) visualize the imagery, (2) take measurements, (3) calculate metrics, and (4) archive data.

Implementation

Our primary objective is directed toward development of geomorphometric indices that describe relative uplift, from which relative extension through time is inferred. The current goal is the development of geomorphometric algorithms, integrated in a GIS interface, to facilitate the automated calculations of metrics in a cost and temporally effective manner. The GIS is also used for visualization of high spatial resolution satellite imagery draped over DEMs. This (1) allows landforms to be identified and measurements to be taken; (2) automation of data input into the geomorphometric algorithms; and (3) output of the results to a standardized database within the GIS.

It is believed that a multivariate data set will allow better characterization of the several controlling factors influencing each metric and, therefore, facilitate more accurate characterization of tectonic control and extension. Furthermore, it is probable and anticipated that that some metrics will be highly correlated and contain no additional useful information. These metrics will be disregarded after correlation analysis.

The following metrics are considered:

1. ZR ratio;
2. c of $A_f = cA_d^n$;
3. Fan length to width ratio;
4. Alluvial Fan slope to feeder channel slope ratio;
5. Slope of post-uplift fan segment to pre-uplift fan segment ratio;
6. Changes in concavity/convexity in fan longitudinal profiles;

7. Angular magnitudes along fan longitudinal profiles;
8. Stream-gradients;
9. Faceted spur apex geometry;
10. Faceted spur surface roughness;
11. Faceted spur slope.

Methodological Development and Current Status

Initial work has begun in Dixie Valley, Nevada. Work to date has focused on alluvial fan and drainage basin metrics. As algorithms and the number of necessary metrics are refined, they will be applied in other areas of The Great Basin.

IRS 5m spatial resolution panchromatic satellite data has been merged with 28.5m Landsat Thematic Mapper multispectral data effectively creating a 5m spatial resolution false color composite image from which geomorphic features can be mapped. At this stage of methodology development it is believed that the 5m data is adequate and possibly superior for the objectives. The use of higher spatial resolution data is problematic as some landforms, such as large fans, cannot be viewed on the computer screen in their entirety at full resolution. When using data with lower spatial resolution, some geomorphic features are hard to identify.

The first major hurdle in landform metrics mapping was related to the fact that no tool was available in any of the tested GIS applications that (1) generated a graphic of a feature profile and (2) output the XYZ data into a digital file. It was found that conventional GIS and digital image analysis software would allow linear profiles to be created graphically, but data output either did not exist or it was incomplete. This problem was solved by using a script found at ESRI's website (www.esri.com). The script, EZ Profiler 8.2™, developed by Min-Lang Huang (National Cheng Kung University, Disaster Prevention & Research Center, Tainan, Taiwan, R.O.C.), facilitates taking measurements from which data are saved to an ArcGIS™ shapefile (Figures 1 & 2). Areas are calculated from standard ArcGIS™ polygon geometry.

The shapefile, created using EZ Profiler 8.2™, is then imported into an ArcGIS™ geodatabase. The geodatabase contains all GIS information and is a standalone file in a Microsoft Access™ database format. Geomorphometric algorithms, in the new GIS tool set being created in this study, then access the geodatabase, make calculations, create new fields, and populate them with metrics.

Future Work

The metrics defined above are being incorporated into a comprehensive GIS database for Dixie Valley, Nevada. This will be followed by other areas within The Great Basin. These metrics, although very useful in their own right in describing relative uplift and extension, hold information about the controlling factors that influenced their values. It is planned that fuzzy-c-means classification (FCM; Bezdek, 1981) will be tested, after the Dixie Valley database is completed, to attempt separation and characterization of the various tacit controlling factors in the metrics.

FCM is an unsupervised classification method in that no *a priori* model is assumed and no training data set is required. FCM is an exploratory data analysis method, where the objectives are to find patterns, correlations, and relationships in the data itself,

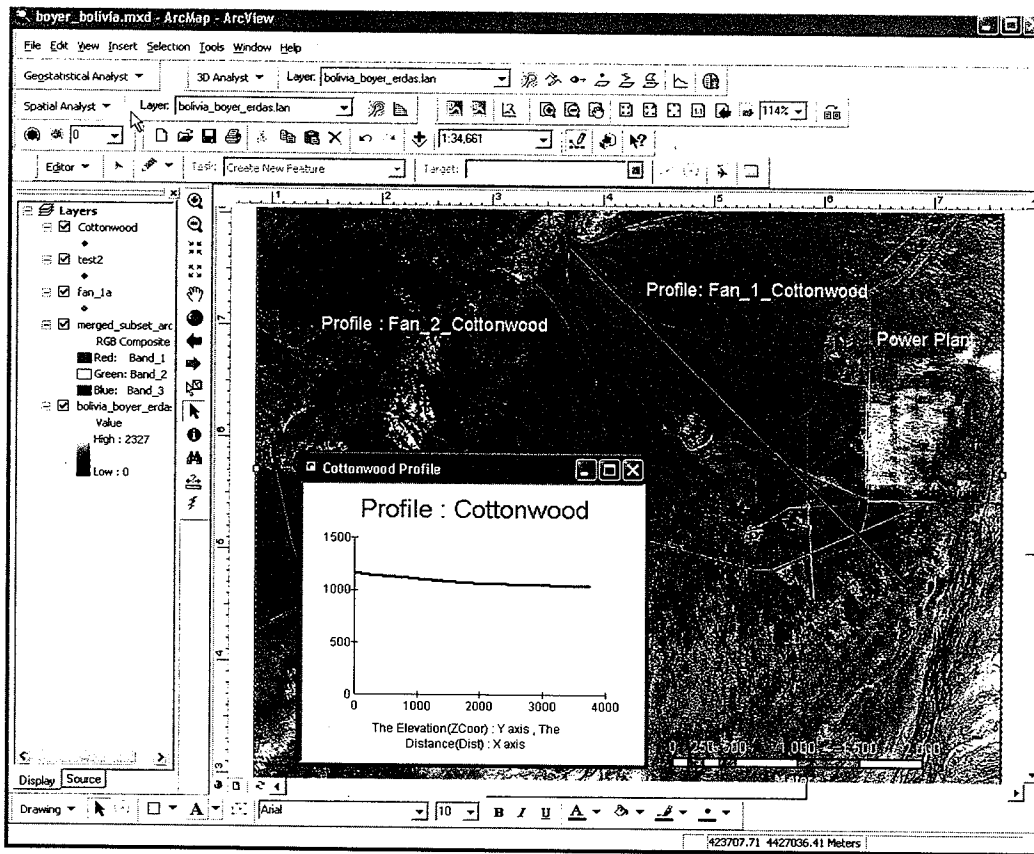


Figure 1. Fan profile Transects created with EZ Profiler 8.2™ are shown graphically as well as saved to a table. The background image in the ArcGIS interface is merged 5 m IRS panchromatic and 28.5 m TM multispectral data which are overlaying DEM data. The longitudinal profile is taken from Cottonwood Fan, Dixie Valley, Nevada.

FID	Shape	Id	XCoor	YCoor	ZCoor	Dist
0	Point ZM	0	424760.415093	4424927.57212	1164.590656	0
1	Point ZM	0	424790.415093	4424898.39179	1160.632773	41.850825
2	Point ZM	0	424820.415093	4424869.21146	1158.549290	83.701650
3	Point ZM	0	424850.415093	4424840.03114	1156.699536	125.552474
4	Point ZM	0	424880.415093	4424810.85081	1153.869224	167.403299
5	Point ZM	0	424910.415093	4424781.67048	1150.761110	209.254124
6	Point ZM	0	424940.415093	4424752.49015	1146.933732	251.104949
7	Point ZM	0	424970.415093	4424723.30983	1145.642499	292.955773
8	Point ZM	0	425000.415093	4424694.1295	1144.359247	334.806598
9	Point ZM	0	425030.415093	4424664.94917	1142.603416	376.657423
10	Point ZM	0	425060.415093	4424635.76884	1140.472626	418.508248
11	Point ZM	0	425090.415093	4424606.58851	1137.592065	460.359073
12	Point ZM	0	425120.415093	4424577.40819	1134.752555	502.209897
13	Point ZM	0	425150.415093	4424548.22786	1133.899086	544.060722
14	Point ZM	0	425180.415093	4424519.04753	1132.372269	585.911547
15	Point ZM	0	425210.415093	4424489.8672	1129.810644	627.762372
16	Point ZM	0	425240.415093	4424460.68687	1127.428512	669.613196
17	Point ZM	0	425270.415093	4424431.50655	1125.721301	711.464021
18	Point ZM	0	425300.415093	4424402.32622	1123.188542	753.314846
19	Point ZM	0	425330.415093	4424373.14589	1121.424360	795.165671
20	Point ZM	0	425360.415093	4424343.96556	1119.819497	837.016496
21	Point ZM	0	425390.415093	4424314.78524	1118.298502	878.867320
22	Point ZM	0	425420.415093	4424285.60491	1115.630302	920.718145
23	Point ZM	0	425450.415093	4424256.42458	1113.533650	962.568970
24	Point ZM	0	425480.415093	4424227.24425	1111.168608	1004.419795

Figure 2. Shape file data set created with EZ Profiler 8.2™. This contains all necessary information for input into the fan metric algorithms.

with few assumptions or hypotheses (Tukey, 1977). Such an approach is important in an early phase of research, because absolute assumptions cannot be made regarding the structure of the data set or the identity of the controlling factors. FCM is a multivariate method that takes advantage of all input variables simultaneously. Unlike Principal Components Analysis, no matrix inversion is involved, so it is more robust than PCA-based methods. FCM also has the desirable feature that it does not assume “hard” clusters. That is, while some samples may be classified as having membership in a distinct cluster, other samples may have degrees of membership in multiple clusters. These degrees of membership are expressed in the cluster membership matrix. Although this application is experimental, it is very likely that this technique will give us insight into the variable factors involved in the evolution of the landforms used in the generation of indices.

Conclusions

Past work clearly defines the usefulness of geomorphometric techniques in tectonic studies. However, most of these studies were regional. Applied in local areas throughout The Great Basin, metrics derived from tectonically induced landforms will likely provide an excellent set of data to allow comparisons of relative extension rates throughout the area. Five meter spatial-resolution colored satellite images appear to be optimal for mapping the landform features in a GIS environment. Metrics can then be calculated rapidly using the new tools being developed in this study. It is also likely that the multivariate approach taken in this study will help unravel the several controlling factors that influence landform development in extensional provinces.

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