ΕΚΤΙΜΗΣΗ ΡΥΘΜΟΥ ΤΕΚΤΟΝΙΚΗΣ ΑΝΥΨΩΣΗΣ ΜΕ ΤΗΝ ΠΟΣΟΤΙΚΟΠΟΙΗΣΗ ΜΟΡΦΟΜΕΤΡΙΚΩΝ ΔΕΙΚΤΩΝ

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Περίληψη

Η σύνδεση μεταξύ τεκτονικών διεργασιών και επιφανειακής διάβρωσης μπορεί να οδηγήσει στην εξαγωγή ποσοτικής πληροφορίας, ως προς τον ρυθμό ανύψωσης ενός ρηξιτεμάχους, με βάση τη σημερινή μορφολογία. Για το σκοπό αυτό έχουν αναπτυχθεί θεωρίες που συνδέουν τη διαφορική ανύψωση ρηξιτεμαχών με τη μορφή των ποτάμιων συστημάτων που τα διαρέουν και τα διαβρώνουν. Η δυνατότητα χρησιμοποίησης ψηφιακών μοντέλων αναγλύφου με υψηλή χωρική ανάλυση για τον ακριβή υπολογισμό μιας σειράς από μορφομετρικές παραμέτρους, αποτελεί ένα ισχυρό εργαλείο για την οριοθέτηση νεοτεκτονικών δομών με μεγάλη λεπτομέρεια καθώς και τον σχετικό ρυθμό ανύψωσής των.

Η περιοχή των νοτιο-ανατολικών ακτών του Κορινθιακού Κόλπου κρίθηκε ως ιδανική για την εφαρμογή αυτών των μεθοδολογιών λόγω της στοιχειοθετημένης (με κλασσικές μεθόδους) ανύψωσης που παρουσιάζουν. Έγινε συνδυασμός των μορφοτεκτονικών παραμέτρων που προέκυψαν με τους ρυθμούς τεκτονικής ανύψωσης που έχουν υπολογιστεί από προηγούμενες έρευνες και υπολογίστηκε ο μέσος συντελεστής διάβρωσης. Η κατάλληλη επεξεργασία των παραπάνω στοιχείων έδειξε ότι υπάρχει πολύ καλή συμφωνία μεταξύ των μορφοτεκτονικών παραμέτρων και των ανωμαλιών του υδρογραφικού δικτύου οφειλομένων σε τεκτονικά αίτια (ενεργά ρήγματα και ρηξιγενείς ζώνες, περιστροφή ρηξιτεμαχών), ενώ έντονες διαφοροποιήσεις σε τιμές των μορφοτεκτονικών παραμέτρων και σε συνδυασμό με παρατηρήσεις υπαίθρου αναδεικνύουν μη χαρτογραφημένες τεκτονικές δομές, οι οποίες είναι λιγότερο ή περισσότερο σημαντικές στη θεωρία για την τεκτονική εξέλιξη της περιοχής.

ESTIMATION OF TECTONIC UPLIFT RATE USING QUANTIFIED MORPHOMETRIC INDICES

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Abstract

The linkage between tectonism and erosion may lead to the extraction of quantitative information on the uplift rate of a fault block, based on the current relief. For this purpose different methodologies have been developed,relating the differential block uplift with the eroding pattern of the stream channels. High resolution DEMs are used for the calculation of several morphometric parameters providing a powerful tool for the exact delimitation of neotectonic structures and potentially the estimation of the uplift rate. The transition from the published theory to the accurate estimation of these geomorphometric indices is a complicated series of procedures based on calculations between arrays of pixels and visualize the results on a GIS platform. Some of the final images produced for this paper were not reliable for further interpretation because of the objective difficulty of expressing all the landforms with a table of numbers.

The south eastern coastal area of the Gulf of Corinth seems to be an ideal case for applying these kinds of methodologies due to already known -with conventional dating methods- uplift rates. The combination of the calculated morphotectonic parameters with the tectonic uplift rates derived by previous studies led to the calculation of the average coefficient erosion. The interpretation of these results showed very good relevance between the variance of the values of every morphometric index and the irregularities of the river network caused mainly by tectonism (active faults, block tilting). Strong variations of the index values combined with field data reveal tectonic structures that are not mapped yet and have their own importance on the theory of the Corinth rift tectonic evolution.

Λέξεις κλειδιά: ποτάμια διάβρωση, νεοτεκτονική, Κορινθιακός Κόλπος, τεκτονική γεωμορφολογία.

Key words: fluvial erosion, neotectonics, Gulf of Corinth, tectonic geomorphology.

1. Introduction

It is generally accepted that steep landscapes are associated with regions of rapid rock uplift even if some exceptions do also exist. The fluvial network consistently maintains its connection to tectonic forcing, and therefore contains potentially useful information about variations in rock uplift rates across the landscape. A number of studies have laid the groundwork for extracting this information, by exploring the theoretical response of channels to variations in rock uplift rate, and by analyzing fluvial profiles in field settings where the tectonics have been independently determined ((Whipple & Tucker, 1999), (Whipple & Tucker, 2002), (Kirby & Whipple, 2001)).

The methodologies discussed in this paper are used for the extraction of as much as possible tectonic information from the landscape by interpreting high spatial resolution digital elevation models (DEMs). The discussion focuses on the use of DEMs, which are inexpensive, easily obtained and can be used to extract much of this kind of information quickly and easily prior to field work. We summarize the basic theory published in previous researches giving an idea of research needs which must be met before we can have a reliable quantitative tool for neotectonic procedures in conjunction with quantified tectonic information derived from stream profile interpretation. However, some uncertainty remains as to what can and cannot be learned from an analysis of river profiles, as a standard method for extracting tectonic information from these data does not exist.

2. Methodology

The data used for this paper come from the digitizing of the 20m contours on topographic maps of 1:50.000 scale. A 25m DEM was produced and used for generating channel longitudinal profiles. The drainage network was extracted after using the DEM for generating a direction array and calculating the flow accumulation. Correctly produced high detailed DEMs are the simplest and most accurate method of generating data sets used in these kinds of morphometric analyses (Snyder et al., 2000) as they provide continuous data that can be used in various mathematic calculations and can be visualized in several ways in a GIS platform where they can be combined with other kinds of data (Vassilakis, 2006).

For an extended analysis of the study area we followed methods developed by Snyder et al. (2000) and Kirby et al. (2003). A group of built-in functions in ARC/INFO were used to create flow accumulation arrays and delineate drainage basins, a suite of MATLAB scripts to extract and analyze stream profile data from these basins, and an ArcMap interface for color-coding the steepness index value changes along the streams in a GIS. While pits and data holes in a DEM usually need to be filled to create flow direction and flow accumulation arrays for basin delineation, profile data should be extracted from the raw DEM matrix to ensure that no data are lost or created at this early stage in the processing. In practice, any suite of computer scripts which can follow a path of pixels downstream while recording elevation, cumulative stream wise distance, and contributing drainage area data is sufficient for collecting long profile data from a DEM.

A series of eight sub parallel basins were included in the analysis as most of their drainage network is dominated by bedrock erosion. Their main channel longitudinal profiles were analyzed and compared as they flow almost parallel to each other trending SW-NE. The methodology was applied on 828 channel heads which they are tributaries of the main streams in these basins but also in the catchments between them (Fig. 1). Linear regression of the logarithms of local channel gradient (S) and drainage area (A) data was used to find values for the concavity index (θ) and the steepness index (ks) using the following equation,

$$S = k_s A^{-\theta} \qquad (1)$$

The exponent, θ (the concavity index), and coefficient, ks (the steepness index), can be measured directly by regression of slope and area data. The next steps in the methodology is examining the slope-area data and make decisions about the number of distinct channel segments and the appropriate regression limits for each segment. The concavity index (θ) is generally found to be between 0.3 and 0.6 ((Flint, 1974); (Willgoose et al., 1990); (Tarboton et al., 1991); (Moglen & Bras, 1995); (Slingerland et al., 1998)), but values to 1.1 have been measured in some channels (Sklar & Dietrich, 1998). According to analyses by Whipple (2004), low concavities (<0.4) are associated either with short, steep drainages importantly influenced by debris flows (Brocklehurst & Whipple, 2002) or with downstream increases in either incision rate or rock strength, commonly associated with knickpoints ((Kirby & Whipple, 2001); (Kirby et al., 2003)). Moderate concavities (0.4−0.7) are associated with actively uplifting bedrock channels in homogeneous substrates experiencing uniform (or close to uniform) rock uplift. High concavities (0.7−1.0) are associated with downstream decreases in rock uplift rate or rock strength; downstream transitions to fully alluvial conditions and disequilibrium conditions resulting from a temporal decline in rock uplift rate.

Many channels can be adequately modeled with only a single segment, using unique values of ks and θ (Fig. 2). Others may contain multiple segments, reflecting spatial or temporal variations in rock uplift rate, climatic factors, or the mass strength of rock exposed along the profile (Fig. 2). In either case, linear regressions on slope-area data are typically conducted in two ways for each segment to allow inter-comparison among different profiles in the basin. In the first of the two regressions, segments of slope-area data with distinct steepness and/or concavity indices are identified, and are fit with ks and θ as free parameters using equation (1) as the regression model. In the second regression, individual segments of slope-area data are fit using a "reference" concavity, θref, to determine normalized steepness indices, ksn. A reference concavity is required for the interpretation of steepness values because ks and θ as determined by regression analysis are, of course, strongly correlated (Eq. 1). In practice, θref is usually taken as the regional mean of observed θ values in "undisturbed" channel segments (i.e., those exhibiting no known knick points, uplift rate gradients, or changes in rock strength along stream), and can be estimated from a plot superimposing all of the data from a catchment.

The coefficient ks is similar in principle -but more general- to the stream-gradient index (SL) developed by Hack (1973) and described in many quantitative tectonic geomorphology studies (Burbank & Anderson, 2001). The steepness index can be also expressed as the fraction of rock uplift rate (U) relative to base level and the coefficient of erosion (K) over the power of 1/n (Eq. 2), where n is the slope exponent. The later exponent is related to the concavity index that is expressed as in the equation 3, based on the erosion rule, where m is the area exponent.

$$k_s = (U/K)^{1/n} \qquad (2)$$

$$\theta = m/n \qquad (3)$$

The relationships implied by these equations are valid if the climatic and uplift conditions are constant, and both the parameters U and K are uniform along the stream profile. In the active areas these kinds of analyses can show anomalies related to active covered neotectonic structures.

The map view distribution of calculated steepness indices for all the tributaries in the study area can be another extremely useful tool for delineating tectonic boundaries (Kirby et al., 2003); (Wobus et al., 2006). Across the areas characterized with sudden change of ks values and where no serious climate or rock strength variations are observed, the tectonic settings seem to be the cause for a discrete break in rock uplift rates. In general, we expect channels with high steepness indices to characterize the high uplift zone, while those with lower steepness indices should characterize the low uplift zone (Snyder et al., 2000).

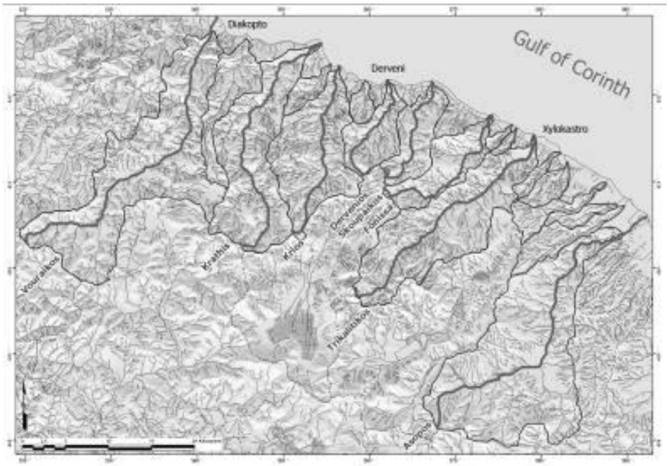

Figure 1. The drainage network of northeastern Peloponnesus is superimposed on a shaded relief extracted from the high resolution DEM. The eight basins that the methodology was applied are highlighted and the thicker lines represent the main streams.

3. Geological setting

The Corinth Rift is considered to be the most active neotectonic feature within the Eastern Mediterranean. It strikes WNW-ESE and it is 100 km long and 40 km wide, separating the continental Greece to the north from Peloponnesus to the south (Armijo et al., 1996) (Doutsos & Piper, 1990). North-dipping normal faults are the dominant tectonic features of the rift, forming a half-graben and producing N-S extension (Doutsos & Piper, 1990). The activity of the faults on the southern margin of the rift has migrated northward through time, with the footwall of active faults uplifted and backtilted (Sorel, 2000). GPS data indicate that extension rates increase from less than 5 mm/yr in the easternmost Gulf of Corinth to 10-15 mm/yr in the western Gulf (Clarke et al., 1998).

During the Late Pliocene the Corinth Rift had twice the width of the modern Gulf of Corinth. Synrift sediments that have recently been exposed in the uplifted southern part of the Corinth Rift, consist of Late Pliocene fluvial and lacustrine sands, silts and conglomerates. These are observed near the southern margin of the rift, passing upwards to Quaternary marls and Gilbert-fan delta conglomerates, whilst Late Pleistocene marine terraces are formed in a narrow zone along the north Peloponnesus coastline (Ori, 1989).

Uplift rates that have been calculated from the Late Pleistocene marine terraces decrease towards the eastern and the western part of the rift. The higher uplift rates were calculated in the central part of the basin that is between Aigio and Xylokastro and are about 1.0-1.28 mm/yr (Armijo et al., 1996), (McNeil & Collier, 2004). The lowest uplift rates are observed eastwards and estimated about 0.3 mm/yr near the city of Corinth and the Perachora peninsula (Collier et al., 1992), (Collier & Jones, 2003). Moderate uplift rates, about 0.7 mm/yr, were calculated towards the western end of the rift, near Psathopyrgos (Houghton et al., 2003).

4. Stream profile analysis

The key in this kind of methodologies is the level of detail and quality of the used digital data. Once a reliable and high detail DEM has been obtained, a variety of methods is appropriate for extracting the required stream profile parameters. After the first few manipulations of the grid layers, slope-area data are being extracted and smoothed from each tributary in a basin. In many cases it is also useful to superimpose all of the profile data from a catchment on a single plot. The resulting diagrams aid in determination of the upper and lower bounds on steepness values in the catchments, segregation of populations with distinct steepness values, and determination of an appropriate reference concavity, as discussed above (Snyder et al., 2000). With these composite plots, the analysis can be extended from individual tributaries to the regional scale.

We applied this methodology on the north eastern part of Peloponnesus and more specifically on eight hydrologic basins having their mouths at the southern coast of the Gulf of Corinth (Sabot & Maroukian, 1978) (Fig.1). The reference concavity index was determined at a value of 0.34, showing that theoretically the incision rate increases downstream; this was also verified during field work. The steepness index analysis showed that along the main streams the k_s values are often quite high (Fig. 2). At certain segments the values rise gradually, reaching a peak value and then dropping suddenly downstream. These points are related to large normal faults trending E-W, often perpendicular to the main streams. The higher values are observed at the footwalls and the low values at the hanging walls of the faults, which keep rising until the stream reaches the next fault towards north after which the rates drop again. This gradual increase of the steepness index downstream could be related to the increase of the incision rate caused by the southward tilting of the fault blocks at the north coast of Peloponnesus.

The observed variation of steepness index values due to the lithological changes is often gradual without sudden drops. The streams Trikalitikos, Krios and Dervenios have segments showing variations of this kind without any significant fault lines intersecting their valleys. Quite high ks rates are observed along most of the Trikalitikos stream (south of Riza) and the peak values have been calculated upstream in a formed gorge where the alpine basement is being eroded (Zelilidis, 2000). The high rates shown downstream could be credited to a reestablishment of the river flow on its way to the Gulf of Corinth. The same observation could be made also for Asopos river, where high ks rates are represented at the north of Nemea. The high incision is caused by the reestablishment of the river flow because of the uplift of the coastal area after the late Pleistocene period, as this is proved by the dating of marine terraces.

In general, after studying the drainage network of the area the eight basins were divided in three categories according to the calculated concavity index (θ) and the normalized steepness index (k_{sn}) (Fig. 2):

In the first bin, the rivers Vouraikos, Krathis, Skoupeikos and Fonissa are included, showing intermediate concavities $0.39<\theta<0.53$ and steepness rates of $17<k_{sn}<21$.

The next bin contains the rivers Krios, Dervenios and Trikalitikos that are showing lower concavities $0.22<\theta<0.26$ but the steepness rates are not very much different from the previous category ($17<k_{sn}<25$).

Asopos river cannot fit with the rest of the streams, as the highest concavity index is observed here, $\theta=0.49$, along with the lowest rate of $k_{sn}=11.8$. This can be related to the fact that it is not a bedrock channel without any significant lithologic changes, especially as far as the rock strength concerns, with no active faulting affecting its homogenous uplifting basin.

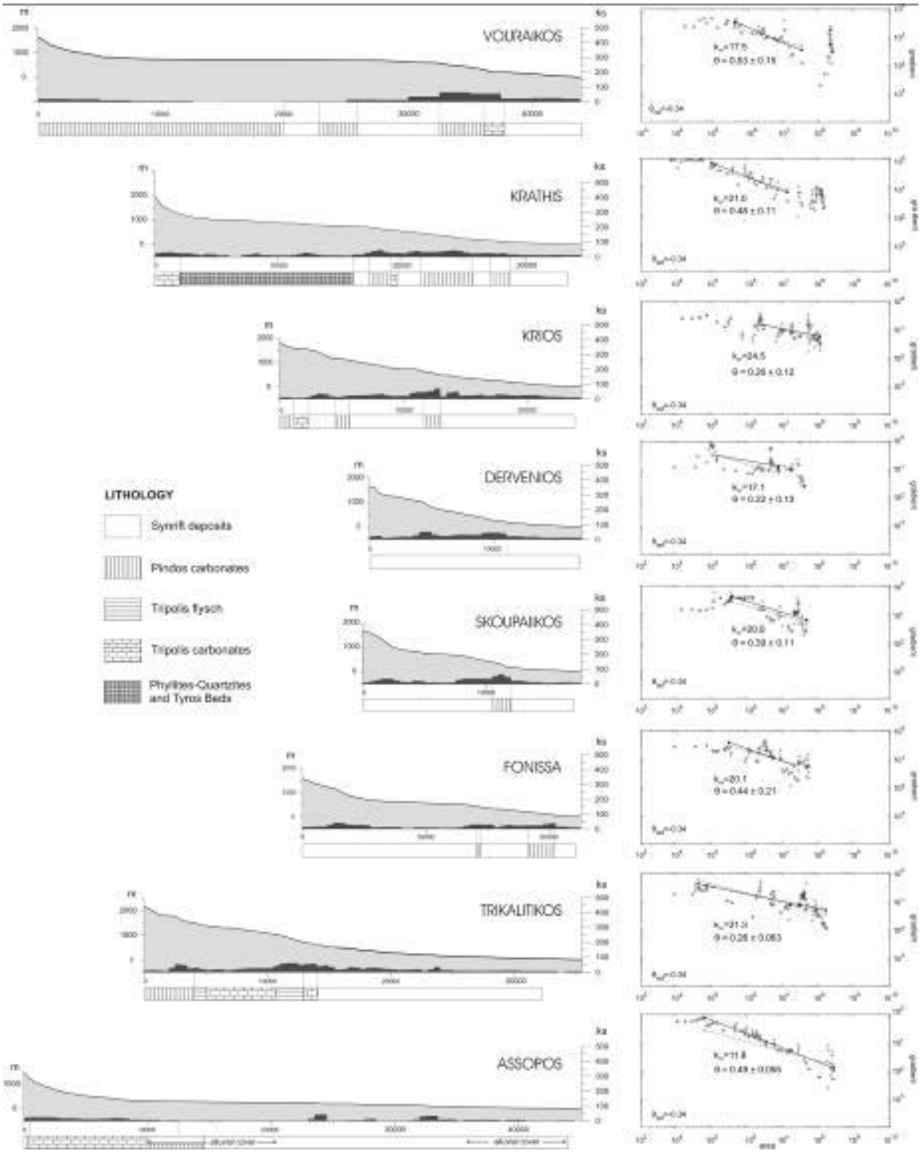

Figure 2. The profiles of the eight main streams that where studied and the lithology changes in combination to the calculated k_s index distribution along them. For every basin there is a slope/area graph, to the right, showing the θ and k_{sn} estimation for reference concavity θ=0.34.

We argue that the absence of high concavities or even negative rates of θ, is due to no significant decrease of tectonic uplift of the north Peloponnessus coast relatively to the upstream areas, in combination to the narrow deltaic fan deposits at the river mouths.

Excluding Asopos river, the normalized steepness rates for all the remaining basins are $17<k_{sn}<25$. The difference between Asopos basin and the westernmost area is interpreted as the dramatic change of the tectonic uplift. This is in agreement with the estimated uplift rates by dating the late Pleistocene terraces along the north Peloponnessus coastline, as at the western area between Xilokastro and Diakofto the uplift rate is of the order of 1.0-1.3 mm/yr, in contradiction to the Asopos mouth area, to the east, where the uplift rate is estimated no more than 0.3 mm/yr (Armijo et al., 1996), (Collier et al., 1992), (McNeil & Collier, 2004).

4. Discussion

The southeastern coast of the Gulf of Corinth was picked as an ideal region for extracting detailed morphometric parameters by using high resolution DEM and combining them with mapped neotectonic structures and tectonic uplift rates that are already published. The interpretation of all the data and the extracted information showed that there is a good agreement between the distributions of the morphometric parameters and the irregularities of the drainage network caused by tectonism (active faults, block tilting).

It is also clear that the area is not absolutely homogenous. There is a big difference between the uplift rates that have been estimated at specific points of sampling. With the use of morphometric methodologies one can expand the uplift rates on larger blocks, especially when these blocks contain large parts of drainage basins. It seems that the basin of Asopos is a similar case, as there is no active faulting intersecting this basin. The low steepness index values that were calculated for the Asopos basin, by using the described methodology, happen to be in very good relation with the estimated low uplift rates. There is also a very good relation of the pattern of the steepness index distribution at the western part of the study area with the much higher uplift rates. The highest morphometric rates are also connected to the active fault zones trending E-W. It seems that there is a structure trending almost N-S, differentiating the western basins from the Asopos basin to the east. This might be either a buried fault zone that is not exposed yet or even a discontinuity of the same orientation where the uplift rate is different from both sides. In any case all the data interpretations show that something is still happening at that area that might be investigated in the near future.

Utilizing the methodologies outlined above, we have enough clues to discuss a series of issues coming out from river profile data interpretation and the tectonic information that can be extracted from the landscape. However the least this method provides is a relatively accurate definition of patterns of rock uplift with a high degree of spatial resolution. A complete study should include correlations with detailed variations in rock uplift and exhumation rates as determined from marine terraces, thermochronologic data, and cosmogenic data; however, there is insufficient data available at present to calibrate and uniquely test river incision models.

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