Interpretation of tectonics from digital elevation data in the San Gabriel Mountains.
CA: Evaluation of Methods and data sources.

by
Katerina Dimitris Spyropoulou
B.A., Department of Geology
University of Athens (2001)

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Signature of
Author

Department of Earth, Atmospheric, and Planetary Sciences
May 21, 2003

Certified
by
Dara Entekhabi
Professor of Civil and Environmental Engineering
Thesis Advisor

Certified
by
Kelín X. Whipple
Associate Professor of Geology and Geochemistry
Thesis Advisor

Accepted
by
Ronald Prinn
Department Head
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ABSTRACT

The identifiable pattern of the qualitative geomorphologic parameters such as steepness and concavity values that derived from the slope-area analysis of 28 tributaries in the San Gabriel Mountains were used to estimate relative rock uplift rates. The results suggest that the eastern region of the San Gabriel Mountain is controlled by a high rock uplift rate while the western region is controlled by a low rock uplift rate. Furthermore, arrangement of the variations of the steepness and concavity values suggests the presence of an active fault zone between the western and the eastern region of the San Gabriel Mountains. This tectonic zone is responsible for the apparent differentiation in rock uplift rates between the two mountain regions. This conclusion is supported from previous knowledge that suggests faster exhumation and high erosion rates of the East San Gabriel (ESG) block
and slower exhumation and lower erosion rates of the Western San Gabriel (WSG) block (Spotila, J., Blythe, A., House, M., Niemi, N., Gregory, B., 2002). Moreover on the technological side of this project, plots of steepness or concavity values derived from analysis of SRTM (30 meter resolution), ASTER (30 meter resolution), USGS (30 meter resolution) and USGS (10 meter resolution) DEMs analysis suggest that USGS DEM-10 meters and SRTM DEM-30 meters are currently the most accurate methods to accurately quantify differential steepness and concavity values for the area of the San Gabriel Mountains in Southern California. Finally, the application of different smoothing options on the plots of slope-drainage area analysis of the tributaries of the San Gabriel Mountains suggests that a 600meter window size is the optimum size with more reliable information and better noise elimination.

1. INTRODUCTION

A principal goal of tectonic geomorphology is to extract information regarding rates and patterns of active deformation directly from landscape topography. Specifically rivers and their gradients are a dynamic recorder of the tectonic activity. In tectonically active regions, the bedrock channel network dictates critical relationships among relief, elevation and denudation rate (Howard, 19994; Howard et al., 1994; Whipple et al., 1999; Whipple et al., 2001, Whipple et al., 2002). Thus channel steepness analysis is a promising avenue for investigating tectonic uplift rates.
Digital Elevation models (DEMs) are an inexpensive and efficient data source that can provide important information for the analysis of topography, river channels and the distribution of displacements. USGS (United States Geological Survey) DEMs have been derived from 1: 24,000 scale USGS topographic maps. The shuttle radar topography mission (SRTM) acquired topographic data over 80% of Earth’s land mass. The ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite imaging system obtains detailed maps of earths land surface temperature, emissivity and elevation. The great availability of different digital landscape topographic data in areas where tectonic patterns are well known provides a promising approach to investigate the spatial distribution of tectonic displacement rates.

Although DEMs are useful tools for the analysis of the landforms, there are several factors that have to be confronted. For example, the ASTER DEM from the San Gabriel Mountains includes areas with clouds and their dark shadows which can create many areas with missing data. Sometimes it is also possible that the DEM reflect tree-top elevations rather than the ground surface. Moreover SRTM DEMs have areas with missing data, associated with usually steep slopes, buildings, and shadows can create. Noise is also one of the major problems that affect DEMs. Thus estimating parameters based on DEM analysis demands careful handling methods. Especially river channel analysis based on DEMs analysis requires cautious steps. Different smoothing options have been proposed but no systematic analysis of their merits has been published. Thus an evaluation of the methods that we use to extract quantitatively information from different digital topographic data sources is more than necessary.
The goal of this project is to develop a theory for comparing different digital elevation models on their abilities to accurately quantify differential concavity and steepness values through stream profile analysis of 28 tributaries, in regions of rapid erosion such as the San Gabriel Mountains in Southern California. The comparison will take place among four different sets of data:

- USGS DIGITAL ELEVATION MODEL (30 and 10 meters resolution)
- SRTM DIGITAL ELEVATION MODEL (30 meters resolution)
- ASTER DIGITAL ELEVATION MODEL (30 meters resolution)

Our research has dual objectives both technological and scientific. On the technology side we will examine different smoothing options in order to determine the optimum procedure that will extract the most reliable channel information with the better noise elimination. On the scientific side we will analyze how channel slope varies with drainage area and whether systematic variations in steepness and concavity values can be correlated with uplift rates. Finally we will compare our results with data on uplift rate patterns and we will highlight regions of tectonic activity that control topography in the San Gabriel Mountains.
1.1 Characteristics of Data Sources

1.1.1 USGS DEMs

United States Geological Survey (USGS) Digital Elevation Models (DEMs) of the San Gabriel Mountains were used as an initial source data for our stream profile analysis. USGS DEMs are produced from interpolation of the elevations from stereomodel digitized contours, which have been derived from 1: 24,000 scale USGS topographic maps. DEMs consist of a raster grid of equally spaced elevation values. The original source data in this research was 7.5-Minute DEMs with 10 and 30-meter square grid spacing. The average file size of a 30-meter DEM is approximately 1.1 megabytes and 9.9 megabytes for a 10 meter DEM. (U.S Department of the Interior U.S. Geological Survey, National Mapping Division, (August 1997), General, Standards for Digital Elevation, http://rockyweb.cr.usgs.gov/nmpstds/acrodocs/dem/1DEM0897.PDF).

The only measurable errors in the DEM exist as vertical errors that partly are ascribed to errors that are created through converting horizontal and vertical components of the source contour lines to gridded format (U.S Department of the Interior U.S. Geological Survey, National Mapping Division, (January 1998), Specifications, Standards for Digital Elevation Models http://rockyweb.cr.usgs.gov/nmpstds/acrodocs/dem/2DEM0198.PDF). Consequently, to measure the horizontal error within the DEM precisely, it is necessary to first confirm the shape of the feature to be measured and after that the horizontal position of that feature may be verified. Horizontal accuracy can be determined using constants known as grid posts that are located at precise mathematically defined horizontal positions.
Furthermore, the vertical root-mean-square error (RMSE) is used to describe the vertical accuracy of a DEM, including errors introduced during production of the data. The RMSE is defined as:

\[ \text{RMSE} = \sqrt{\frac{\sum (Z_i - Z_t)^2}{n}} \]

where \( Z_i \) = interpolated DEM elevation of a test point, \( Z_t \) = true elevation of a test point, \( n \) = number of test points.

The error of a DEM depends on the type of source data used. For 7.5-minute DEMs derived from a photogrammetric source, 90 percent have a vertical accuracy of 7-meter RMSE and 10 percent are in the 8- to 15-meter range. 7.5- and 15-minute DEMs derived from vector or DLG hypsographic and hydrographic source data have RMSE of one-half of a contour interval.

A number of factors can affect the accuracy of the final DEM product and produce topographic errors. The source data mostly include three types of errors: blunders, systematic errors and random errors (U.S Department of the Interior U.S. Geological Survey, National Mapping Division, (January 1998), Specifications, Standards for Digital Elevation Models http://rockyweb.cr.usgs.gov/nmpstds/acrodocs/dem/2DEM0198.PDF). Blunders are mistakes caused by misreading contours, transposing numeric values, invalid correlations, or incautious observations. In any case, errors caused by blunders must be removed prior to access in the data base. Systematic errors include vertical elevation shifts, either for the quadrangle as a whole or for individual local areas or profiles, non-existent features, such as, ridges, benches and inappropriate clarification of terrain.
surfaces caused by effects of trees, buildings, and shadows. Systematic errors can be significantly eliminated when the cause is known. Random errors which are those that remain after blunders and systematic errors have been removed, are of an entirely random nature and completely unpredictable.

1.1.2 SRTM DEMs

I also used a DEM produced by the Shuttle Radar Topography Mission (SRTM) Data Base. The shuttle radar topography mission (SRTM) is a cooperative effort between NASA, the US National Imagery and Mapping Agency, the Italian Space Agency (ASI), and the German Aerospace Center (DLR). Interferometric synthetic aperture radar (INSAR, C-Band ($\lambda=5.6$ cm), X-Band ($\lambda=3$ cm)) was used to acquire topographic data over 80% of Earth's land mass.

In radar interferometry, two radar images are taken from slightly different locations (Bampler, R., 1998, Synthetic Aperture Radar Interferometry, http://www.ifp.uni-stuttgart.de/publications/phowo99/bamler.pdf). The SRTM hardware required to acquire these images consists of one radar antenna in the shuttle payload bay and a second radar antenna attached to the end of a mast extended 195 feet (60 meters) out from the shuttle. The result is a high resolution image of the microwave reflectivity of the ground. Each SAR image pixel is represented by a multipart number. Its amplitude is a measure for microwave reflectivity and its phase reflects the distance (range $R$) of the respective ground resolution cell to the SAR antenna. The phase difference
(interferometric phase) $\Phi$ of two corresponding systems is related to the range difference (parallax) via:

$$\Phi = p \times \left\{ \frac{2\pi (R2-R1)}{\lambda} \right\}$$

R1 and R2 are different ranges for any ground point and where $p=2$ for repeat-pass (images are taken at different times possibly by the same radar) and $p=1$ for single pass (requires a dual channel radar system with a transmit/receive master antenna and a receive-only slave antenna) interferometry.

The SRTM digital elevation model used as an original source data in this research meets Interferometric Terrain Height Data (ITHD)-2 specifications: 30 meter x 30 meter spatial sampling with 16 meter absolute vertical height accuracy, 10 meter relative vertical height accuracy and 20 meter absolute horizontal circular accuracy.

The achieved accuracy with the INSAR method depends on the pixel size, the base to height relation, the contrast and slope of the area, but also the time interval between imaging both scenes. Particularly there are many phase and height errors that can influence the SRTM DEM accuracy.

**Errors in the baseline length** will produce a tilt of the DEM by the same angle which will give an overestimation of height and a non-linear distortion of the DEM.

**Atmospheric inhomogeneities** may cause spatially varying wave propagation delays. But for single-pass interferometry these wave delays cancel out because both antennas 'look' through the same atmospheric conditions due to the small interferometric baseline (Dupont 1996; Goldstein 1995; Hansen 1999; Massonet et. al. 1995).
Phase measurement noise results in random height errors. In single-pass interferometers phase noise is caused by thermal noise of the radar receivers. Repeat-pass receivers suffer more from phase noise measurements. The locations of the backscatterers between the two acquisitions in a resolution element sometimes change and the phase information deteriorates (Zebker and Villasenor 1992). Consequently the DEM accuracy reduces. That's why the generation of DEMs over water bodies is impossible by repeat-pass interferometry and that's why for the most preferable technique for a high precision DEM generation is a single-pass interferometer.

Finally one problem that occurs in SRTM DEMs is the presence of failed areas with no returned elevation (called radar shadows or gaps). Radar shadowing occurs when the radar beam is not able to illuminate the ground surface in the down range dimension, behind vertical features or slopes with steep sides. Since the radar beam does not illuminate the surface and no energy is available to be backscattered, shadowed regions will appear black on an image.

1.1.3 ASTER DEMs

Digital image data used also in this study has been obtained by the ASTER sensor. ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument on board TERRA-1, a satellite launched in December 1999 as part of NASAs Earth Observing System (EOS). ASTER is used to obtain detailed maps of land surface temperature, emissivity, reflectance and elevation and is a suite of three high-performance optical radiometers with 14 spectral channels that contribute valuable
scientific and operational data on the earth. It is designed to meet the mission requirements of operational users and scientific researchers in the visible and near infrared (VNIR), the short wavelength infrared (SWIR), and the thermal infrared (TIR).

Each ASTER image contains its own stereo pair provided in the form of a 3N (nadir) and a 3B (backwards) pair of images with 15 m spatial resolution (Harold R. Lang, JPL Roy Welch, “ATBD-AST-08 Algorithm theoretical basis document for aster digital elevation models standard product AST 14 version 3.0” revised 5 February 1999, University of Georgia). Extracting digital elevation data from a pair of ASTER images from the same field position converts these two bands into a pair of partially epipolar images which have a pixel displacement in the satellite flight direction proportional to the pixel elevation. Afterwards a cross-correlation method is used to transform this displacement into elevation values. The difference in observation time between two pictures is as small as 55 seconds, and this means that the earth surface is observed twice almost at the same time and no significant change in pictures due to optical conditions and atmospheric fluctuations, allowing us to expect a high-precision picture correlation. Finally an Absolute ASTER DEM can be created with ground control points (GCPs). Alternatively a relative DEM can also be generated without ground control points.

DEM have an absolute horizontal and vertical accuracy of up to 7 meters with appropriate GCPs and up to 10 meters without GCPs. A simple geometry-based photogrammetric rule that is applicable to assessment of ASTER DEM accuracy is:

\[ \Delta h = \frac{H \Delta p}{B} \]

(Welch, 1989)
where H/B is the inverse of the B/H (base/height) ratio (in the case of ASTER 1.0/0.6 or 1.7), and Δp is the difference in parallax (xy displacement) of a point in the two images forming the stereo pair. Assuming Δp correlation errors in the range of 0.5 to 1.0 pixels (7-15 m), Δh errors (RMSEz) would be in the ±12 m to ±26 m range.

The quality and accuracy of a DEM produced from optical satellite imagery is dependent on a number of factors such as the radiometric quality of the images, the ground cover within the area of interest, the temporal difference between the acquisition of the imagery and the accuracy of the ground control used to reference the imagery.

Another problem concerning the ASTER DEM accuracy is vegetation. There are cases where small bushes or trees are concentrated along river channels. So it is possible that the measurable signal concerning the topography comes from those objects (bushes, trees) and does not reflect the ground surface topography. Clouds are also a major problem because they and their shadows affect the correlation analysis (AsterDTM main page, http://www.creaso.com/english/12_swvis/13_envi/AsterDTM/asterdtmfaq.htm). Sometimes there are no clouds or cloud shadows at a certain location in the 3N image, but they are in the 3B image. Such a phenomenon will destroy the correlation, and will create an area of low accuracy DEM values. Generally an ASTER DEM can be produced from an image with clouds. However the clouds and their dark shadows on the image will be shown as a “void area” or a “no data” area on the DEM. Both thick and high wispy clouds will cause void areas in a DEM and will also cause data near the clouds to be inaccurate. This is a particular problem with the ASTER scenes from the San Gabriel Mountains, and it creates many areas with missing data.
1.2 Stream Profile Analysis

1.2.1 Theory

During the past fifty six years, numerous studies regarding river geometry have been based on a well-known relationship that relates local slope and drainage area in a wide range of tectonic, lithologic and climatic settings (e.g., Montgomery, 2001; Snyder, 2000; Whipple and Tucker, 1999; Tucker and Bras, 1998, Howard and Kerby, 1983; Flint, 1974). The relationship is expressed as follows:

\[ S = k_s A^{-\theta} \]  

(1)

where \( S \) is the local channel slope, \( A \) is the upstream drainage area, \( k_s \) is a coefficient called steepness index and \( \theta \) is a scaling exponent known as concavity index.

Using any river incision model for fluvial erosion, theoretical results yield a form of equation (1) in which the steepness coefficient \( k_s \) is positively correlated with the rock uplift, \( U \) (e.g., Whipple and Tucker, 2002). Channel steepness index is known (Snyder et.al. 2000) to be a function of rock uplift rate (\( U \)) when lithology and climate are uniform within the drainage basin. Moreover if rock uplift rate \( U \), is constant along a river, the channel concavity index, \( \theta \), typically varies in a narrow range between 0.4 and 0.7 (e.g., Tucker and Whipple, 2002). However if \( U \) systematically changes along a river, the zone of distributed uplift may be characterized by a change in concavity. Thus, high concavity profiles are expected in settings were rock uplift rates increase upstream while low concavities are expected were rock uplift rates decrease (Kirby and Whipple, 2001).
However interpretations of the steepness index, $k_s$, is complicated by the fact that $k_s$ and $\theta$ as determined by regression analysis are strongly correlated. This compilation is readily by-passed by calculating a “normalized” steepness index, $k_{sn}$, for a reference concavity, $\theta_{ref}$:

$$K_{sn} = A_{cent} (\theta_{ref} - \theta)$$

$$A_{cent} = 10^{(\log A_{max} + \log A_{min})/2}$$

where $k_s$ and $\theta$ are determined by regression and $A_{min}$ and $A_{max}$ bound the segment of the profile analyzed.

Furthermore the log-transform of equation (1) predicts a linear relationship between log $S$ (Slope) and log $A$ (drainage Area). Plots of log $S$ vs. log $A$ (Figure 1.2.1_1) extracted from natural river longitudinal profiles should exhibit an increase in the y-intercept ($k_s$) with an increase in rock uplift rates (due to the above theoretical predictions). Thus slope-area analysis of channel profiles can be a promising approach to extract information about tectonic uplift rates.

At present, there are many limitations that influence our ability to quantitatively estimate rock uplift rates from an analysis of fluvial channel profiles. A number of factors influence the quantitative relationship between the parameters of our model and the existing steepness and concavity indexes respectively. For example, one limitation that plays an important role to this relationship is climate. Obviously it is rather difficult to distinguish precisely how precipitation affects the channel profiles along a mountain front since precipitation is not uniform over the long geologic period during which this channel
evolved. Moreover channel widths may adjust to changes in uplift rate (e.g., Montgomery 2002), complicating the relationship between $U$ and $k_s$. Additionally, the response of bed morphology to increased rates of rock uplift is also not well known. To date, many scientists (e.g., Whipple and Tucker, 1999, Sklar Dietrich 2001) have tried to understand the controls on bed morphology and its relationships with tectonics, topography, and climate. From all the above, it is obvious that confident extraction of quantitative information from river profiles needs improvement and requires systematic testing of river incision models. However slope-area analysis of channel profiles can be a powerful qualitative tool for understanding fluvial incision processes and quantifying deformational patterns in space and time.

Thus by using DEM analysis from different data sources of high resolution topographic data, we will try to qualitatively extract information on the channel gradients in the area of San Gabriel Mountains consequently we will infer the distribution of the active tectonic processes. So our research includes slope-area plots for 28 river channels of the San Gabriel Mountains and furthermore the calculation of steepness and concavity index respectively (Figures 1.3_3, 1.3_4). Besides by understanding how channel slope varies with drainage area and how the above indexes ($k_s, \theta$) can be correlated with uplift rates ($U$), we will be able to define tectonic signals that control our field area. Finally we will compare our results with previous knowledge of the area of the San Gabriel Mountains that will allow us to highlight regions of characteristic tectonic activity that control topography in the area.
1.3 Application to the San Gabriel Mountain

The San Gabriel Mountains (SGM) are located on the eastern portion of Los Angeles County separating the Los Angeles basin from the Mojave Desert. The range is composed of a two mountain regions: the western and the eastern region. The eastern region attains elevations of over 3000 meters while the western region attains elevations of over 1500 meters. The SGM have a steep, abrupt range front on the south and a gentle ramp on the north. Slopes are steep throughout the entire eastern half, but much less so on the westward side (Figure 1.3_1). The major tributaries of the San Gabriel Mountains for the western region are: Big Tujunga, Little Tujunga, Alder Creek, Aliso, and Pacoima Creek, for the central region: Bear Creek and San Gabriel River, and for the eastern region: Vincent Gulch, Cattle, Fish and Pomona, Cruhs.

The lithological composition of SGM Range contains Proterozoic rocks including gneiss, amphibolite, and anorthosite–gabbro-syenite complex (e.g Ehlig, 1975, 1981; Barth et al., 1995), several large granitic bodies of at least two distinct generations, one Triassic in age and one late Cretaceous (e.g Barth, 1990; Barth and May, 1992), which intruded at mid-crustal levels. There are also felsic dikes and plutons emplaced at relatively shallow depths during late Oligocene and middle Miocene time (e.g. Miller & Morton, 1977; May & Walker, 1989). These rocks are cross-cut by a mafic dike swarm of probable middle Miocene age (Ehlig, 1981; Hazelton & Nourse).

Faults are one of the major factors that influence relief in the SGM. The SGM are cut by a great density of faults that reduce the average size of intact rock bodies. Geodetic, seismic and geomorphic evidence indicate that the Sierra Madre and the
Cucamonga fault are active, reverse-slip faults and are thought to flatten beneath the mountain range at depths of greater than 12 – 15 km (Hadley and Kanamori, 1976; Yeats, 1981; Webb and Kanamori, 1985; Ryberg and Fuis, 1998). The San Gabriel Fault zone separates blocks that have different thermal histories and erosion rates (Blythe et al., 2000), although an eastward increase in slip rate along the Sierra Madre fault zone may also be the reason for the intense erosion on the eastern region of SGM.

Due to previous research (Spotila, J., Blythe, A., House, M., Niemi, N., Gregory, B., 2002), existing geologic and limited thermochronometric data were used to create maps of average long term erosion rates in the SGM (Figure 1.3_2). Thermochronometric apatite fission tracks and (U-Th)/He data constrains long term exhumation rates. Based on these results the spatially averaged erosion rate over the past 6 Myr on the SGM is 0.35 mm/yr. and the average depth of erosion is 2.1 km, creating a sediment volume of 4620 km³. Furthermore, the whole region is distinguished by four fault-bounded blocks which experienced significant differences in exhumation history. Within these four blocks the Permian-Triassic granite and metamorphic rocks in the Mountain Baldy (MB) and Sierra Madre blocks in the east region have young apatite fission-track ages (Figure 1.3_1), indicating rapid exhumation rates while the Precambrian granite and anorthosite in western San Gabriel blocks (WSG) in the west region have older fission-track ages indicating slower exhumation rates.

Finally previous knowledge (e.g., Spotila, J., Blythe A., 2002) also for the SGMs indicates that most erodible lithologies correspond to high rates of erosion, while resistant lithologies generally correspond to lower rates of erosion. For example, there is a high erosion rate on schist and low erosion rate on quartzite. This conclusion is not rigorous
because San Gabriel Mountain Range is characterized by a great density of faults, different deformation history factors that can control erosion processes. However, several rock units are probably very erodible or chemically unstable such as the mica-rich Pelona schist. This is the reason why the San Gabriel River has exploited the weak Pelona schist to form a rugged canyon below neighboring peaks capped by more resistant cretaceous granodiorite (e.g. Mt. Baden Powell; Ehlig, 1981).

Due to the previous knowledge it is clear that there is evidence that suggests that erosion patterns control the geomorphic evolution of the SGM. Furthermore the evidence indicates that these patterns of erosion are influenced by the distribution of active structures and bedrock erodibility. We also know that the distribution of climate is not uniform. The systematic precipitation along the southern rangefronts, lead us to expect differences between the river channel profiles on the southern front and the rest of the range where precipitation is less.

From all the above it is obvious that the SGM is an ideal area for our study. Testing our results (how channel slope varies with drainage area and how steepness and concavity indexes can be correlated with uplift rates) on an area of known erosion and tectonic patterns provides a template to explore the relationship that controls tectonics and topography in the San Gabriel Mountains. Furthermore, the availability of four different digital landscape topographic data (USGS-10m, USGS-30m, ASTER-30m and SRTM-30m, DEMs) provides an excellent opportunity to evaluate the relative source and to test and refine DEM data handling methods.
2. SOURCE DATA ANALYSIS (DIGITAL ELEVATION MODELS)

2.2 Data Handling Methods

2.2.1 DEM Preparation

The first step in our analysis was to merge a set of grids (one for each USGS quadrangle), to create the initial DEM of the area of SGM. The mosaic process (Arc Info command) was used for merging the grids and generating the initial DEM. As a result of this composition there were several factors that had to be confronted in order to improve the accuracy of our initial DEM. One factor was the failed areas with no returned elevation (gaps). Another important factor was the areas where water cannot flow out and generate a direction array (pits). To eliminate the influence of those two factors the procedure that was adopted is described below. At this point we have to mention that those problems occurred mostly for the SRTM and ASTER DEMs.

Our first task was to eliminate the gaps. In order to fill the missing data of these gaps, interpolation methods were used. Gaps of up to three rows (or columns) of “no data” cells (the length of the gap is unrelated) they were filled with the mean cell value of the four by four (4 x 4) square leaving the valid existing data unchanged. If the gap was wider than 3 cells, the size of the window size might have been conservatively increased. So, for the SRTM DEM we used three different window sizes to fill the initially small holes. The first interpolated SRTM DEM was interpolated using a six by six (6 x 6) focal window, the second using a nine by nine (9 x 9) and the final using a twelve by twelve
Similarly the final interpolated ASTER DEM was achieved using a thirty by thirty (30 x 30) window size (Figure 2.2.1_2). Figure 2.2.1_2 demonstrates the ASTER DEM presented more and wider gaps (red spots on the figure) than the SRTM DEM. It is also important to mention that interpolated DEMs sometimes may significantly affect the results of a particular analysis. For example if we have to extract information from an area that has been filled with an interpolated value the information for that specific area is not reliable and should be ignored. In our analysis this possibility is minimal since we extracted the river profiles from areas with no gaps (Figure 2.2.1_2). Moreover, even if there were gaps in the river channels, then we could eliminate the analysis of the specific channel or ignore the segment of the river profile that corresponds to that gap. Before we start analyzing our results it is important to clarify that the stream profile analysis of our research is based on the initial DEMs and not those generated after the interpolation. The interpolated data only used to calculate drainage paths and drainage area values for each pixel. At last, in order to create our drainage network using again Arc Info commands, we filled the pits, and the flow accumulation grid was created. The original DEM and not the filled DEM was used in the analysis.

Finally one of the major problems that affect DEMs accuracy is noise, frequently producing scattered slope points that may limit our ability to estimate reliable information for the channel steepness and concavity indices. One way to improve the level of noise is to try to understand the correlation of noise with the channel slope and the pixel size. Therefore our research was focused on investigating the optimum window size of a moving average filter with the better noise elimination and the most reliable channel information.
2.2.2 Methods and Results

The objective of our analysis is the determination by linear regression of model steepness (ks) and concavity (θ) coefficients from plots of log S vs logA for 28 tributaries of the SGM. Two software tools were used for those calculations. First, Arc View for picking the river profile (either from the mouth or the divide of the river) and second Matlab V6.5 was used in order to extract channel steepness and concavity. Two different Matlab scripts were used. With the first script, channel slope and concavity were sampled without smoothing options and by extracting data using contour-crossings of the channel profile based on the original contour interval (i.e. 12.192m for USGS DEMs). This script was used only for the analysis of the USGS 10 meter DEM. Moreover the log-bin averaged slopes from the unsmoothed data were plotted for comparing the unsmoothed data with that produced using different smoothing options. With the second script, channel slope and concavity were sampled using variable smoothing options (i.e. 200m, 600m, 1000m, window of a moving average filter) sub-sampling profiles at a constant vertical spacing (~10-20 meters). For both scripts a reference concavity of 0.45 was used, to allow direct comparisons of steepness coefficients between model runs.

We first present six log slope vs log area profiles from specific tributaries (West 2= Alder Creek, Center 2= Bear Creek and East= Cattle) that were derived from the stream profile analysis of the USGS DEM-10m. On each plot we present the results of the first script (no smoothing data) and the log-bin averaged slopes from the unsmoothed data with the three different moving average window sizes 200-meters, 600-meters and 1000-meters respectively (Figures 2.2.1_3, 2.2.1_4, 2.2.1_5).
With reference to the same river profile, as the window size becomes larger the noise becomes less. Of course that does not mean that this less noisy data is any more accurate. Analytically, by using the 200m window size, the distribution of slope points for specific segments (i.e for drainage area $A = 10^8-10^9$ for west 2 tributary) of the river profile seems to have wide dispersion that limits our ability to define accurately steepness and concavity indexes. As we move to the 600m window size, for the same segment, there is a small convergence of the points down slope. Finally using the 1000 meters window size for the same segment, again produces a small downwards shift of the scatter slope points with associated less dispersion than the one that we had for 600meters window size. Since both the 600meters and 1000meters window sizes produce good images, the goal of this research is to determine which is more reliable.

There are instances this can be done very easily. For example, knickpoints within a channel are plotted in positions where there is usually a small slope break apparent on the slope-area plots. Testing those positions with different windows size it can be seen that using 1000 meters window size the expected knickpoint disappears and the slope appears as a straight line. In contrast, using a window size of 600 meters window size the slope break is still observable. In order to examine our suspicion that 600m window size is an optimum size with the better noise elimination and the more reliable channel information we tested six tributaries of the east part of the SGM and we present plots of steepness and concavity indexes of the same segment of the tributary respectively, using as an initial source data USGS DEM-10m, USGS DEM-30m, ASTER DEM-30m and SRTM DEM-30m, vs. the window size (Figure 2.2.1_6, 2.2.1_7).
It is obvious that the steepness coefficient values (Table 2.2.1_1) of the examined tributaries, with the exception of tributary EAST1, appear to have a better fit with a 600m window size. In contrast, the plots of the concavity coefficient values of the examined tributaries do not present any systematic arrangement that allow us to confirm that 600m window size is the optimum size with the most reliable information. One limitation that might affect our results is that we used steepness and concavity values produced from a randomly chosen segment of the tributary and not from the one with the best slope point distribution. Another limitation is that steepness and concavity values were determined by linear regression analysis which means that possible different regressions for the same segment of the tributary might have given different values. Thus another purpose of our investigation was to examine the correlation of noise with the regression line of our data.

Thus we present the plots between slope and drainage area that include the theoretical steepness and concavity values that derived from the regression analysis of our DEMs and the model steepness and concavity values that derived after adding random noise to the theoretical values of our regression analysis. Figure 2.2.1_8 demonstrates two sets of plots. The left column presents plots of slope vs. log of the drainage area that derived from adding random error to the theoretical values of slope. The right column presents plots of slope vs. log-drainage area that derived from adding the log of the random error to the theoretical values of slope. It is obvious that for different values for steepness indexes (50, 100 and 150 respectively) and the same values of the concavity index (0.3) is a good fit of the regression line for both the true and the noisy data. Especially there is a better fit between the true and the noisy data concerning the plots that derived from adding the log of the random error appear to have a much
better fit than those that derived from adding the random error. Analytically using a steepness value of 150 and a theta value of 0.3, the noisy data that includes the random error, had a 1.4% divergence from the initial steepness and concavity values. In contrast the noisy data that includes the log of the random error had a 1.09% divergence from the initial steepness and concavity values. Furthermore Figure2.2.1_9 demonstrates plots of slope vs. log-drainage area that derived for using the same steepness index (100 in our case) and different concavity values. In this case we can see that there is still a good fit between the theoretical and the noisy data but not for all the concavity values. From all the above it is clear that even if there is a correlation between noise and both steepness and concavity indexes there is still a good fit of the regression line for both the true and the noisy data. Of course, further investigation is needed, in order to accurately relate the random noise of the DEMs with the measurable steepness and concavity index.

Furthermore, for the scientific approach of this project we present four maps for the channel steepness (Figure 1.3_3, 2.2.2_1, 2.2.2_3 and 2.2.2_5) and four maps for the channel concavity (Figure 1.3_4, 2.2.2_2, 2.2.2_4, and 2.2.2_6) of the SGM. Each map for steepness and concavity coefficients was derived from the determination of model steepness and concavity coefficients ($K_s$, $\Theta$) from the four different digital elevation models (USGS DEM-10m, USGS DEM-30m, ASTER DEM-30m and SRTM DEM-30m). Moreover USGS DEM-10m will be the guide of our comparisons among the four different DEMs because is the digital elevation model with the highest resolution. We will test our results against the previous knowledge for the SGM.

According to the steepness map that was generated from the USGS DEM-10m analysis (Figure 2.2.2_1) there are good indications that channel steepness could be
related to mapped structures and long-term exhumations rates determined from thermochronology (e.g., Spotila, J., Blythe A., 2002). In general low channel steepness tends to occur within the fault-bounded West San Gabriel (WSG) and Tujunga blocks and high channel steepness again tends to occur within the East San Gabriel (ESG) fault-bounded Mt. Baldy (MB) and Sierra Madre blocks. Specifically on the East San Gabriel block tributaries east11 and east12 appear to have lower steepness values than the same tributaries of the USGS DEM-30m have. Moreover on the West San Gabriel block tributaries west10, west7 and west6 appear also to have lower steepness values than those that came out from the USGS-30m DEM analysis. That is a conclusion that is also supported from our analysis of the SRTM DEM-30m and ASTER DEM-30m. Indeed tributaries east11 and east 12 present low steepness values either for SRTM-30m (Figure 2.2.2_5) or ASTER-30m (Figure 2.2.2_4) channel steepness map. Observing the concavity maps (Figure 2.2.2_2) high channel concavity tends to occur within most tributaries (center1, center2, center3, east1 and east1) of the East San Gabriel (ESG), while the West San Gabriel (WSG) and Tujunga blocks do not appear to have any identifiable organization to the concavity values. The San Gabriel fault zone is also characterized by a non constant concavity (or steepness).

The map of steepness for the same field area, that was generated from the USGS 30m-DEM analysis (Figure 1.3_3) shows almost the same results compare to the one from USGS 10m-DEM. Low channel steepness tends to occur within the fault-bounded West San Gabriel (WSG) and Tujunga blocks and high channel steepness tends to occur within the East San Gabriel (ESG) fault-bounded Mt. Baldy (MB) and Sierra Madre blocks. Furthermore high channel steepness corresponds to young fission ages varying
from 3 to 19.3 millions of years (Permian Triassic/Mesozoic granite) while low channel steepness corresponds to old ages varying from 8.2 to 59.5 millions of years (Pre-Cambrian granite).

Observing the concavity maps (Figure 1.3_4) high channel concavity tends to occur within the most tributaries (center1, center2, center3, center4, center5, center6, east4, east11 and east12) of the East San Gabriel (ESG), Mt. Baldy (MB) and Sierra Madre blocks, while the West San Gabriel (WSG) and Tujunga blocks do not appear to have any identifiable organization to the concavity values. The San Gabriel fault zone is also characterized by a non constant concavity (or steepness in this case) value. Thus we gave a limited ability to correlate the concavity coefficient with the important factor of fault geometry.

The steepness (Figure 2.2.2_5) and concavity (Figure 2.2.2_6) maps from the SRTM-30m DEM analysis present, in general, a very good fit with the results from the USGS DEM-10m. It is important to note that steepness values on the West San Gabriel block presents a more identifiable organization and varying from 35 to 115. Additionally, observing the concavity values on the East San Gabriel block we see a more recognizable arrangement to the concavity values that vary from 0.4 to 1.5. In this case, the San Gabriel Fault zone, presents a clearer appearance compared to the USGS-30m DEM analysis, and it is characterized by an almost constant range of high steepness values varying from 150 to 200.

Finally and according to the steepness map that was generated from the ASTER 30m-DEM analysis (Figure 2.2.2_3) only tributary center2 appears to have higher steepness value compared to the steepness values than derived from the USGS DEM-
10m. In addition observing the concavity values (Figure 2.2.2.4) on the East San Gabriel block it can be seen that there is a more identifiable pattern to the concavity values, (compare to USGS DEM-10m), that varying from 0.4 to 0.7. Besides on the East San Gabriel block tributaries east4 and east12 appear to have higher concavity values than those that were derived from the USGS DEM-10m analysis, but almost the same concavity values as those that were derived from the USGS DEM-30m analysis.

3. Conclusions

3.1 Evaluation of different data sources

The application of different smoothing options for the plots of slope-area analysis and the calculation of steepness and concavity values of the tributaries of the SGM suggests that a 600meter window size is an optimum size with the more reliable information and the better noise elimination. This argument is stronger especially for extracting channel information such as steepness values that appear to have a better fit with a 600meter window size, while concavity values and their pattern do not allows us to strongly support that same idea. In contrast using unsmoothed data or 200m smoothing window size, slope points of the river profile seem to have great dispersal that limits our ability to accurately define steepness and concavity indexes. Finally, by using 1000 meters smoothing window size, the smoothness is so high that can create the deformation of many original features of the river profile.
Furthermore, even if there is a good indication that random noise cannot strongly affect our regression analysis and the calculation of steepness and concavity coefficients, further investigation is required to describe analytically the correlation between random noise, steepness and concavity coefficients. Perhaps the estimation of the level of the random noise with the lowest deviation between the theoretical steepness and concavity values and the noisy ones is a good future investigation.

The comparison between the accuracy among the USGS DEM-10meters and the three different data sources of the digital elevation models (SRTM-30meters, ASTER-30meters and USGS-30meters) for the area of the SGM suggests that steepness and concavity maps from the SRTM-30m DEM analysis presents a good fit with the 10meters higher resolution DEM of USGS. SRTM DEM is the only DEM that presents a more identifiable organization to the steepness values for the West San Gabriel block. Additionally SRTM DEM is the only DEM with a more recognizable arrangement to the concavity values for the East San Gabriel block.

Steepness map from the ASTER-30meters DEM appears to have a good fit with the USGS DEM-10meters, although the concavity map appears to have partially a good fit with the USGS DEM-10meters.

Finally the maps of steepness and concavity, that was generated from the USGS DEM-30meters analysis shows almost the same results compared to the one from USGS 10m-DEM. The differences between the two DEMs of USGS (10 and 30meters) were specific tributaries with slightly different steepness and concavity values. Those differences can be easily explained from the lower resolution of the USGS DEM-30meters. All the above results can be supported with the Figure 3.1_1 that demonstrates
the plots of steepness index of SRTM-30meters, ASTER DEM-30meters and USGS DEM-30meters vs. steepness index of USGS DEM-10meters that derived from the same segment of the same tributary. Additionally Figure 3.1_2 demonstrates the plots of concavity index of SRTM-30meters, ASTER DEM-30meters and USGS DEM-30meters vs. concavity index of USGS DEM-10meters that derived from the same segment of the same tributary.

In conclusion we suggest that USGS DEM-10meters and SRTM DEM-30meters provide a promising method to accurately quantify differential steepness values through stream profiles analysis for the area of the SGM in Southern California. Of course that does not mean that we underestimate the accuracy of the ASTER DEM. But after a careful examination and knowledge of other DEMs for other field areas, it was clear that the ASTER DEM of the SGM did not have the expected high quality. This conclusion can be supported by the fact that the original ASTER DEM appeared to have many clouds and shadows that might affected the accuracy of our results.

Moreover the distribution of the concavity values on Figure 3.1_2 does not allow us to make any direct conclusion for the estimation of the most accurate DEM. We hope that further investigation will define the method to accurately quantify differential concavity values for the area of the San Gabriel Mountains.
3.2 Interpretation of Tectonics from Stream Profile Extraction Methods

According to the steepness and concavity maps that were generated from the four different digital elevation model analysis (USGS DEM-10m, USGS DEM-30m, ASTER DEM-30m and SRTM DEM-30m, DEMs), there is strong evidence that channel steepness and concavity could be related with the known tectonic structures and the erosion rates determined from the previous knowledge (e.g., Spotila, J., Blythe A., 2002). Furthermore the high steepness values that derived from our analysis and mostly characterize the East San Gabriel block agree with the bold relief throughout the entire eastern half and display a representative range varying from 115 to 200.

This conclusion can be also supported from the concavity map that was generated from the SRTM DEM analysis. The East San Gabriel block is characterized by high concavity values with a representative range varying from 0.4 to 1.5. In contrast low steepness values, which also derived from our analysis, for the West San Gabriel block agree with the lower relief throughout the westward side and display a representative range varying from 35 to 115.

Furthermore, the fact that fission-track ages from the MB block are younger, (indicating faster exhumation), than fission-track ages from WSG block, (indicating slower exhumation), for similar elevation patterns, implies that the faster exhumation would produce steeper slopes and that the uplift of ESG block must have started sooner than in WSG block. The only theoretical explanation we could give for the Western San Gabriel block is that it was uplifted recently and is experiencing a transient response,
with a response time that was similar to that of the Eastern San Gabriel Mountain (mostly Mt. Baldy) block.

In the eastern part of the range, specifically in the MB block, the river profiles together with their steep slopes and young fission-track ages, suggest that this block is also close to steady state. This can be supported from the fact that knickpoints in one catchment (in the same block) tend to be at different elevations compared to knickpoints in adjacent catchments, signifying that they are stationary. In contrast the West San Gabriel block seems not to be in steady state. In this case knickpoints occur at similar elevations in adjacent catchments. This can also be supported by the fact that the western region shows lower relief and often has relatively flat surfaces at high elevations suggesting relatively recent and incomplete drainage maturity.

Finally we believe that the eastern region of the San Gabriel Mountain is controlled by a high rock uplift rate while the western region is controlled by a low rock uplift rate. Furthermore we suggest that between the western and the eastern region of the SGM an active fault zone must be present. (Figure 3.2_1) This tectonic zone is responsible for the apparent differentiation in rock uplift rates between the two mountain regions. This conclusion comes to agree with the previous knowledge that suggests faster exhumation (high steepness values) and high erosion rates of the ESG block and slower exhumation (low steepness values) and lower erosion rates of the WSG block. A more systematic and focusing investigation in the area between the western and the eastern region will set the stage for a better understanding of what controls the tectonic pattern of the SGM in Southern California.
4. ACKNOWLEDGMENTS

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Regarding the writing of this project, I have benefited substantially from the comments, discussions and critical reviews by Ass. Professor Kelin X. Whipple and the Administrator of the Education Office of the Earth Atmospheric and Planetary Sciences department, Vicki McKenna. I thank each of these individuals for their efforts.

Finally I would like to dedicate my thesis to my parents Dimitris and Voula Spyropoulos, my brother George Spyropoulos and my fiancé Thomas Koutsoukis for all their psychological support.

Katerina D. Spyropoulou
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6. FIGURES
Figure 1.2.1

Tributary center 2

USGS DEM-10 meters

- Distance from divide (km)
- Elevation (m)

- Drainage area (m^2)

- Slope

- m/n = 0.48 ± 0.051
- ukn = 241
- R^2 = 0.79
- m/n = 0.45 ukn = 138
- Fit between 1e+006 and 7.6e+007
Figure 1.3.1

San Gabriel Mountains, Southern California

Legend

- **8.4** Fission age in millions of years
- \(\) fault zone
Figure 1.3_2

Erosion rate (mm/yr)

- Red: 0.3-2
- Orange: 0.2-2
- Blue: 0.2-0.4
- Dark blue: 0.04-0.2

Western Block
Bakery Block
San Gabriel Fault Zone
Sierra Madera Block

34°
Figure 1.3_3

CHANNEL STEEPNESS IN SAN GABRIEL MOUNTAINS

Legend

- Blue: 21.71 - 75.00
- Green: 75.01 - 115.0
- Red: 115.01 - 150.0
- Brown: 150.01 - 262.8

Steepness index $K_s$

USGS 30m

Tributary labels:
- Center 1,..,6
- West 1,..,10
- East 1,..,12

Knickpoint
Figure 1.3_4

CHANNEL CONCAVITY IN SAN GABRIEL MOUNTAINS

Legend

-0.9233 0.2000

0.2001 0.4000

0.4001 0.6000

0.6001 15.47

concavity index ($\Theta$)

tributary labels

center 1,...,6
west 1,...,10
east 1,...,12

knickpoint

USGS 30m
Figure 2.2.1_2

ASTER DEM 30m RESOLUTION

FILLED DEM
Different smoothing options for tributary West 2, from a USGS 10m DEM

- **200m Window size**
  - $m/n = 2.1 \pm 1.1$
  - $u_{km} = 1.55e+016$
  - $R^2 = 0.25$
  - $m/n_2 = 0.45$ $u_{km_2} = 122$
  - $R^2 = 0.29$
  - $m/n_2 = 1.09e+007$
  - Fit between $1.8e+008$ and $7.6e+008$

- **Unsmoothed data**
  - $m/n = 1 \pm 0.39$
  - $u_{km} = 1.09e+007$
  - $R^2 = 0.29$
  - $m/n_2 = 1.09e+007$
  - $R^2 = 0.29$
  - $u_{km_2} = 121$
  - Fit between $9.7e+007$ and $7.5e+008$

- **600m Window size**
  - $m/n = 2.1 \pm 1.1$
  - $u_{km} = 1.55e+016$
  - $R^2 = 0.25$
  - $m/n_2 = 0.45$ $u_{km_2} = 122$
  - $R^2 = 0.29$
  - $m/n_2 = 1.09e+010$
  - Fit between $1.8e+008$ and $7.6e+008$

- **Unsmoothed data**
  - $m/n = 1 \pm 0.39$
  - $u_{km} = 1.09e+007$
  - $R^2 = 0.29$
  - $m/n_2 = 1.09e+007$
  - $R^2 = 0.29$
  - $u_{km_2} = 121$
  - Fit between $9.7e+007$ and $7.5e+008$

- **1000m Window size**
  - $m/n = 2.1 \pm 1.1$
  - $u_{km} = 1.55e+016$
  - $R^2 = 0.25$
  - $m/n_2 = 0.45$ $u_{km_2} = 122$
  - $R^2 = 0.29$
  - $m/n_2 = 1.37e+009$
  - Fit between $1.8e+008$ and $7.6e+008$

- **Unsmoothed data**
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  - $u_{km} = 1.09e+007$
  - $R^2 = 0.29$
  - $m/n_2 = 1.09e+007$
  - $R^2 = 0.29$
  - $u_{km_2} = 121$
  - Fit between $9.7e+007$ and $7.5e+008$
Different smoothing options for tributary Center 2, from a USGS 10m DEM

- **200m Window size**
- **Unsmoothed data**

- **600m Window size**
- **Unsmoothed data**

- **1000m Window size**
- **Unsmoothed data**
Figure 2.2.1_5

Different smoothing options for tributary East 1, from a USGS 10m DEM

- 200m Window size
- Unsmoothed data

- 600m Window size
- Unsmoothed data

- 1000m Window size
- Unsmoothed data
### Table 2.2.1

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Figure 2.2.1_6

- **EAST1**
  - Window Size (m)
  - $K_S$ values for USGS10, SRTM30, ASTER30, USGS30

- **CENTER1**
  - Window Size (m)
  - $K_S$ values for USGS10, SRTM30, ASTER30, USGS30

- **EAST4**
  - Window Size (m)
  - $K_S$ values for USGS10, SRTM30, ASTER30, USGS30

- **CENTER2**
  - Window Size (m)
  - $K_S$ values for USGS10, SRTM30, ASTER30, USGS30

- **EAST11**
  - Window Size (m)
  - $K_S$ values for USGS10, SRTM30, ASTER30, USGS30

- **CENTER3**
  - Window Size (m)
  - $K_S$ values for USGS10, SRTM30, ASTER30, USGS30
Figure 2.2.1_7

EAST1

Window Size (m)

CENTER1

Window Size (m)

EAST4

Window Size (m)

CENTER2

Window Size (m)

EAST11

Window Size (m)

CENTER3
Figure 2.2.1_8
Figure 2.2.2_1

CHANNEL STEEPNESS IN SAN GABRIEL MOUNTAINS

Legend

USGS 10m

steepness index (Ks)

- 32.36 75.0
- 75.01 115.0
- 115.1 150.0
- 150.1 175.9

tributary labels

center 1,..,3
west 1,..,10
east 1,..,12

knickpoint
Figure 2.2.2_2

CHANNEL CONCAVITY IN SAN GABRIEL MOUNTAINS

Legend

-0.6384 0.2000
0.2001 0.4000
0.4001 0.6000
0.6001 2.0200

concavity index ($\Theta$)

tributary labels

center 1,..,3
west 1,..,10
east 1,..,12

knickpoint
Figure 2.2.2_3

CHANNEL STEEPNESS IN SAN GABRIEL MOUNTAINS

Legend

- **Blue** 29.61 75.0
- **Green** 75.01 115.0
- **Red** 115.1 150.0
- **Brown** 150.1 203.4

steepness index (Ks)

**ASTER 30m**

tributary labels

center 1,...,6
west 2
east 1,..., 12

knickpoint

55
Figure 2.2.2_4

CHANNEL CONCAVITY IN SAN GABRIEL MOUNTAINS

Legend

<table>
<thead>
<tr>
<th>Color</th>
<th>Concavity Index (Θ)</th>
</tr>
</thead>
<tbody>
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<td></td>
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<tr>
<td>0.2001 0.4000</td>
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<td>0.4001 0.6000</td>
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<tr>
<td>0.6001 0.7731</td>
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</tr>
</tbody>
</table>

ASTER 30m

- concavity index (Θ)
- tributary labels
- knickpoint
Figure 2.2.2_5

CHANNEL STEEPNESS IN SAN GABRIEL MOUNTAINS

Legend

- Blue: 35.23 75.0
- Green: 75.01 115.0
- Red: 115.1 150.0
- Brown: 150.1 202.4

SRTM 30m

Steepness index (Ks)

Tributary labels

- Center 1,..6
- West 1,..10
- East 1,..12

Knickpoint
Figure 2.2.2_6

CHANNEL CONCAVITY IN SAN GABRIEL MOUNTAINS

Legend
-0.1817 0.2001 0.4001 0.6001
center 1,..,6
west 1,..,10
east 1,..,12

SRTM 30m concavity index (Θ)

tributary labels

knickpoint
Figure 3.1_2

- SRTM30
- ASTER30
- USGS30

θ (200m window size)
USGS10m

θ (600m window size)
USGS10m

θ (1000m window size)
USGS10m
Legend

- **8.4** Fission age in millions of years

- fault zone

- Suggested fault zone