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Understanding uplift of the Ethiopian Plateau from longitudinal profile analysis of the Blue Nile drainage system

Prabhat Chandra Neupane
University of New Orleans, pcneupan@uno.edu

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Understanding uplift of the Ethiopian Plateau from longitudinal profile
analysis of the Blue Nile drainage system

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirement for the degree of

Master of Science
in
Earth and Environmental Sciences

by

Prabhat Chandra Neupane

B.Sc. Geology, 2001/M.Sc. Geology, 2004
Tribhuvan University, Nepal

December 2011

*Dedicated to my mother Tulashi Prabha Neupane, Late father Lila Nath Neupane,
my wife kabita Dhital (Neupane), my brother Krishna Chandra Neupane and all
my family members.*

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ABSTRACT

The Ethiopian Plateau is one of the few tectonically-active regions on Earth that is situated in continental rift zones. About 1.6 km deep gorge of the Nile was carved by the Blue Nile River on the Ethiopian Plateau, as the plateau has been experiencing continuous uplift and exhumation in the Cenozoic. Here, we used quantitative analysis of longitudinal river-profile forms and parameters (knickpoint and normalized steepness-index k_{sn}) of the Blue Nile tributaries to tease out regional tectonic signals.

244 knickpoints were examined in the tributaries, majority (>80%) of which are unassociated with lithology or geological structures. Knickpoint distribution throughout the plateau reveals three incision phases. The novel approach of correlation of k_{sn} with mantle tomography suggests that higher and lower k_{sn} values occur above low-velocity and high-velocity zones, respectively, indicating that thermal upwelling beneath the plateau linked to Afar mantle plume largely controls the uplift thus incision of the plateau.

Key words: Ethiopian Plateau; tectonic geomorphology; exhumation; stream profile analysis; knickpoint; mantle tomography.

INTRODUCTION

Landscape morphology created by river systems in tectonically active regions provides valuable clues to decipher the morpho-tectonic history of the region. Numerous works were conducted in major rivers cutting through some of the world's tectonically active regions to derive quantitative estimation of rates and timing of tectonic uplift and crustal deformation. These works include Yellow River of the north-eastern Tibet (Harkins et al., 2007), Trishuli and Burhi Gandaki Rivers in the Nepal Himalaya (Wobus et al., 2006), Colorado River in North American Cordillera (Pederson et al., 2002; McMillan et al., 2006), and Kern and American Rivers in Sierra Nevada in California (Figueroa and Knott 2010). However, all these rivers are situated in continental collisional zones as opposed to those in extensional tectonic setting like the Blue Nile River on Ethiopian Plateau in East Africa (Fig. 1).

Blue Nile, one of the major tributaries of the Nile River, originates from Lake Tana on the Ethiopian Plateau covering a total catchment area of 325,000 km² (Fig. 2) and formed 1.6 km deep Gorge of the Nile. Blue Nile and its five major tributaries feed about 80% of water and 96% of the sediment load (Garzanti et al., 2006) to the Nile River. Extensive incision of the Ethiopian Plateau by the Blue Nile river system, removing more than 93,200 km³ of sediments since 29 Ma, provide important clues of active tectonism of the Ethiopian Plateau, particularly for the late Cenozoic (Gani et al., 2007).



Figure 1: Tectonic map of East Africa, showing various plates, their present movement directions, and East African Rift Systems. Ethiopian Plateau is the focus of this study. Modified after Tesfaye et al., 2003 and Wolfenden et al., 2004

Gani et al. (2007) investigated uplift and incision history of the Ethiopian Plateau using GIS-based regional incision mapping. They argued for three-phase incision history of the plateau since 29 Ma linked to tectonic uplift, where incision rate increased rapidly around 6 Ma indicating a massive uplift of the plateau at that time. This incision history is different than that of Pik et al. (2003) who proposed that present-day topography of Ethiopian Plateau has been persisting since 25-29 Ma, and much of the incision occur within the first 10 million years after

30 Ma. On the other hand, Weissel et al. (1995) proposed that the majority of the Blue Nile incision is due to the flexural uplift of the Western flank of the Main Ethiopian Rift (Fig. 1).

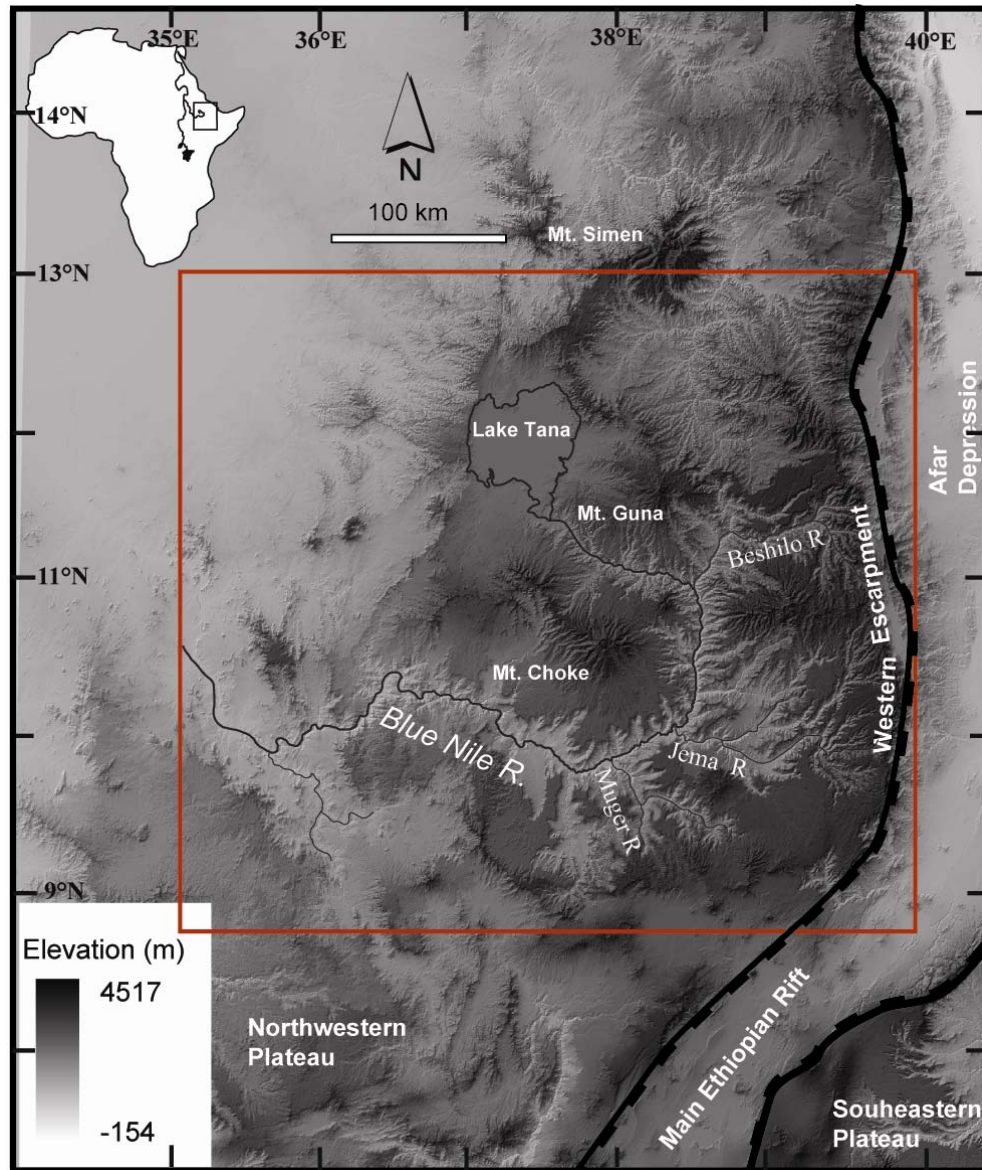


Figure 2 : Location map of the Ethiopian Plateau generated from Hill shade Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) showing topography, Blue Nile drainage network, major shield volcanoes, rift systems and border faults. The study area is indicated by the red box.

In this study, we employed, for the first time, quantitative river profile analysis of the Blue Nile drainage system utilizing Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) (Fig. 3) data to extract tectonic information from profile knickpoints

and steepness index values. The objective of knickpoint analysis is to differentiate and constrain major and minor knickpoints and observe incision phases as explored by Gani et al. (2007). Steepness index values allow us to quantify the variability of uplift throughout the plateau. We also correlated the steepness index values of the tributaries with the mantle tomographic images of the region. Our goal is to put tighter constrain on the link between uplift and incision of the Ethiopian Plateau for a better understanding of the tectonic evolution of the region.

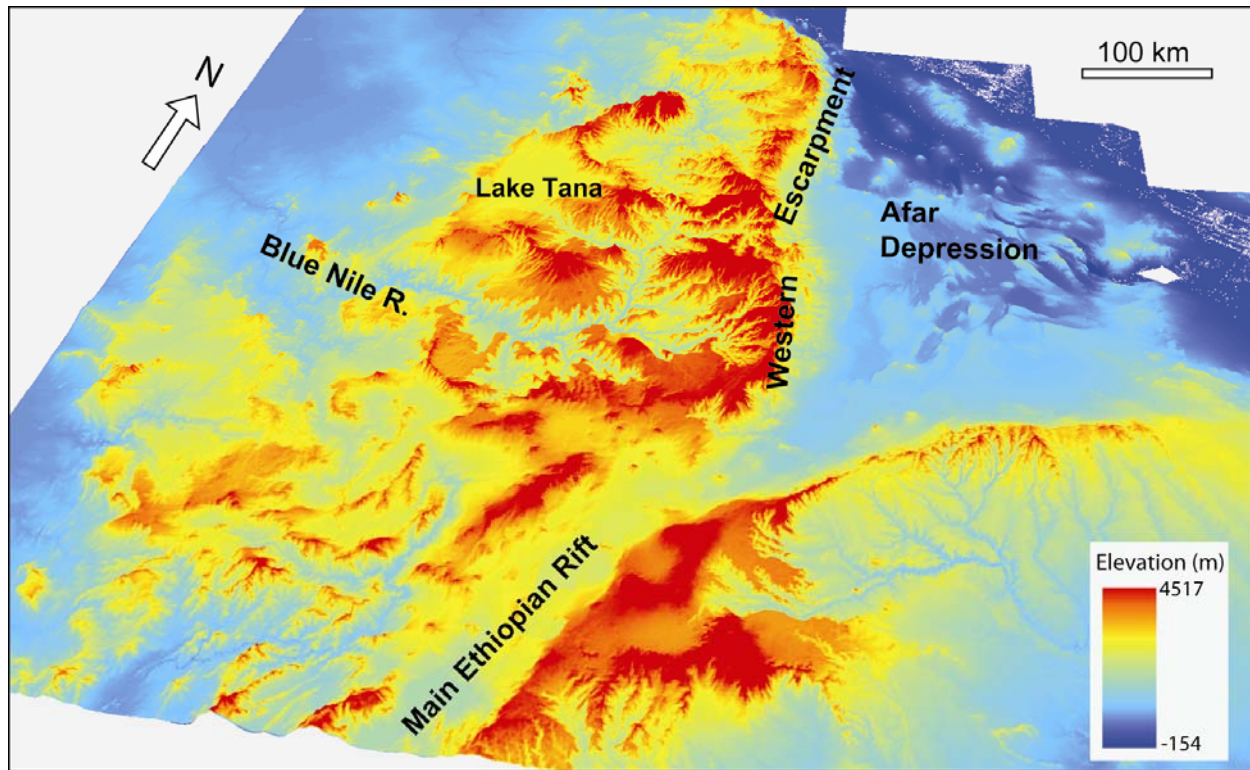


Figure 3: Three-dimensional color-coded perspective view of the Ethiopian Plateau created from SRTM DEM illustrating the Blue Nile drainage Afar Depression and the Main Ethiopian Rift.

GEOLOGY

Regional Geology:

East Africa is one of the tectonically active locations on Earth (Fig 1). The continental extensional history in East Africa started from the Early Permian originating different rift systems of NE-SW trend. This extensional episode was continued by development of several Mesozoic NW-SE extensional basins that served as active depositional rift basins including the Malut, the Mugald, the Melut, the Anza, and the Blue Nile rift basin (Fairhed 1988; Guiraud et al., 2005; Gani et al., 2008).

The continental lithosphere extension is due to the existence of mantle plume beneath the African rift system. Ebinger et al. (1989) advocated for the presence of two mantle plumes beneath East African Rift System: Kenyan plume centered in the Lake Victoria and the Afar plume beneath Ethiopia. Beyene and Abdelsalam (2005) suggested that the Afar mantle plume, series of volcanic activities, and flexural uplift of the Main Ethiopian Rift (MER) are the causes of Ethiopian Plateau uplift. There are some disagreements about the timing of major volcanisms in the study area. Berhe et al. (1987) provided three phases of Trap Series (flood basalt) volcanisms at 50-40, 40-30, and 30-21 Ma, whereas Ebinger et al. (1998) purposed that the volcanism occurred between 45 to 30 Ma. On the basis of $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, Hofmann et al. (1997) argued that the Trap Series volcanism occurred in short period of time around 30 Ma. This huge continental flood volcanism erupted 500 to 2000 m thick basaltic flow, and the cover has been estimated as 500,000 km² area with an estimated volume of 300000 km³ (Mohr and Zanettin, 1998; Hofmann et al., 1997).

The mantle plume beneath the Afar region not only created the volcanism and plateau uplift, it was also a key to the continental breakup and formation of rift-rift-rift triple junction centered in Afar, Ethiopia (Ebinger et al., 1998). The Red Sea rift starting from the Dead Sea to the Afar separates two tectonic plates: the African (Nubian) and Arabian plates. There are many volcanoes formed by the basaltic flow within the rift including Jabal al-Tir. The extension of two plates continues with a rate varies from 7 to 17 mm/year (Ebinger, et al., 2010). Similarly, the Aden Rift, separating the African from Arabian Plates and extending from Owen Fracture Zone in east to Afar in west, experiences a spreading rate of ~17 mm/year (Leroy, Sylvie. 2010). Finally, the third arm of the Afar triple junction is East African Rift System that separates the Nubian Plate from the Somalian Plate and extends, from northeast to southwest, through Ethiopia, Kenya and branches round the Tanzanian Craton before dying out in Mozambique trending NNE to SSW (Beyene and Abdelsalam, 2005). The East African Rift System composed of two branches: eastern and western. The eastern branch characterizes with high volcanic activities whereas the western branch composed of deep sedimentary basins with lakes and sediments. The extension rate of this rift is about 6 mm/year towards the north which gradually decreased to south (Waltham, 2005). The timing of the opening of the Main Ethiopian Rift has been debated. For example, Wolfenden et al. (2004) purposed that it started at 11 Ma but Bonini et al. (2005) argued that the extension of the Main Ethiopian Rift started between 6 and 5 Ma.

Local geology:

The study area belongs to northwestern Ethiopian Plateau, which includes the western-flank of the Main Ethiopian Rift (MER). The Blue Nile, one of the major tributaries of the world's

Oligocene to Quaternary volcanic rocks (Gani et al., 2009) (Fig.4). Similar to the Grand Canyon of the Colorado Plateau, more than 1600 m deep gorge of the Blue Nile in the Ethiopian Plateau is linked to the rapid uplift and exhumation of the plateau in Late Cenozoic (Gani et al., 2007). The Mesozoic sedimentary succession lies in an average elevation of 2.2 km above the sea level, which is roughly the amount of net rock-uplift of the plateau in Cenozoic. Based on the calculation of long-term incision rates of the Blue Nile drainage (Gani et al., 2007), the incision history of the plateau is characterized into three phases. The first phase started from 29 to 10 Ma and is known as slow incision phase with an average rate of 50 to 80 m/Ma. The second phase, known as intermediate phase between 10 to 6 Ma, has a long-term incision rate of 80 to 120 m/Ma. Finally, the rapid incision, third phase started from 6 Ma to present with an average rate of 120 to 320 m/Ma (Gani et al., 2007). This rapid incision thus rapid uplift indicates that the Afar mantle plume is actively arousing the plateau to change its morphological features creating a deeply incised landscape. A recent modeling of the dynamic component of the uplift (i.e. the uplift linked only to mantle convection, and not to other isostatic uplift related to lithospheric deformation) of African continent showed that the Ethiopian Plateau could gain up to 1 km elevation in the past 10 Ma (Moucha and Forte, 2011).

Proposed on the basis of geophysical and geochemical data (McKenzie et al., 1970; Mohr, 1983), the Main Ethiopian Rift (MER), Red Sea Rift, and the Audeen Rift formed at triple junction in Afar region represent large-scale, rift-related normal faults due to the activity of the Afar mantle plume. In the study area, small-scale normal faults, with throws ranging mostly between 5 cm to 20 m are noticed (Gani et al., 2009). The orientation of these faults is mostly NNE and SSE and subordinately NE and NW.

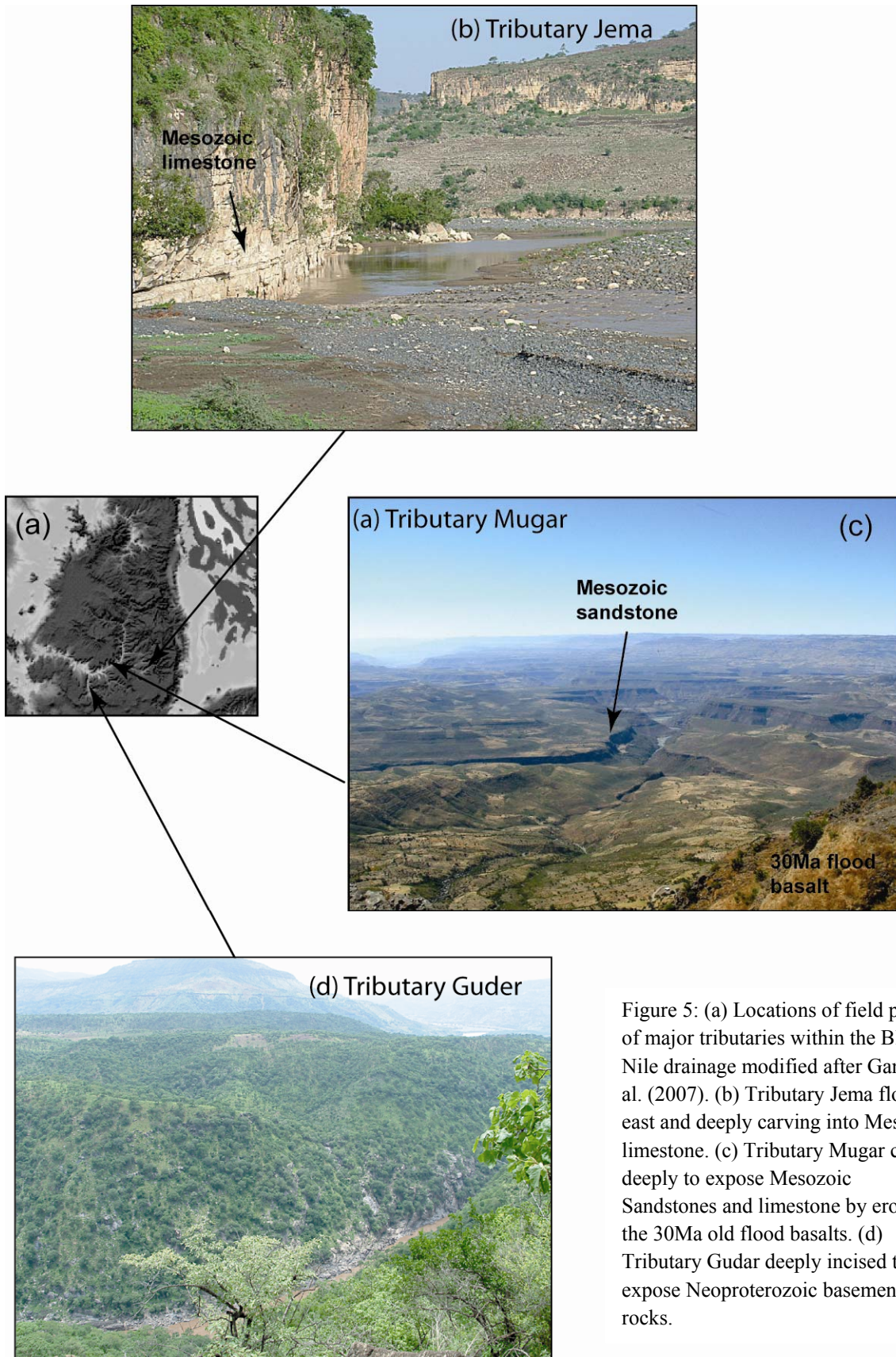


Figure 5: (a) Locations of field photos of major tributaries within the Blue Nile drainage modified after Gani et al. (2007). (b) Tributary Jema flowing east and deeply carving into Mesozoic limestone. (c) Tributary Mugar carved deeply to expose Mesozoic Sandstones and limestone by eroding the 30Ma old flood basalts. (d) Tributary Guder deeply incised to expose Neoproterozoic basement rocks.

DATASET AND METHODOLOGY

Over the decades numerous methods have been applied to determine the uplift and incision history of tectonically active regions. These methods includes thermochronology, isotope analysis, incision mapping, river profile analysis, and cosmogenic dating (e.g. Harrison et al., 1993; Pik et al., 2003; Wobus et al, 2006; Brewer et al., 2006; Gani et al, 2007; Harkins et al., 2007; and references therein). In this paper, we exploit primarily 1) channel morphological features (knickpoint and steepness index) analysis from longitudinal profiles of the Blue Nile River and its major tributaries, and secondarily 2) overlay analysis of mantle tomography data to correlate with those of channel morphologic features (Fig. 6).

River longitudinal profiles

Background

River longitudinal profile analysis is one of the best tools, which investigates landscape evolution, and links topography to tectonics, climate and/or various geologic factors (Weissel and Seidl, 1998; Clark et al., 2004). It is also used to quantify the tectonic uplift of a region assuming that the geological and climatic condition is homogenous, (Whipple, 2004; Wobus, 2006; Kirby, 2007). Moreover, it is one of the powerful tools to determine the incision and uplift history of a region (Synder et al., 2000; Gani et al., 2007; Harkins et al., 2007). Except for very few cases, the steepest landscapes are associated with regions of rapid rock uplift. Hence, the river-profile analysis is quite convincing to predict the meaningful morpho-tectonic information of landscape development in the study area (Wobus, 2006). Ideally, river long-profiles for both bedrock and alluvial rivers are concave in steady-state condition, but abrupt change in concavity may direct

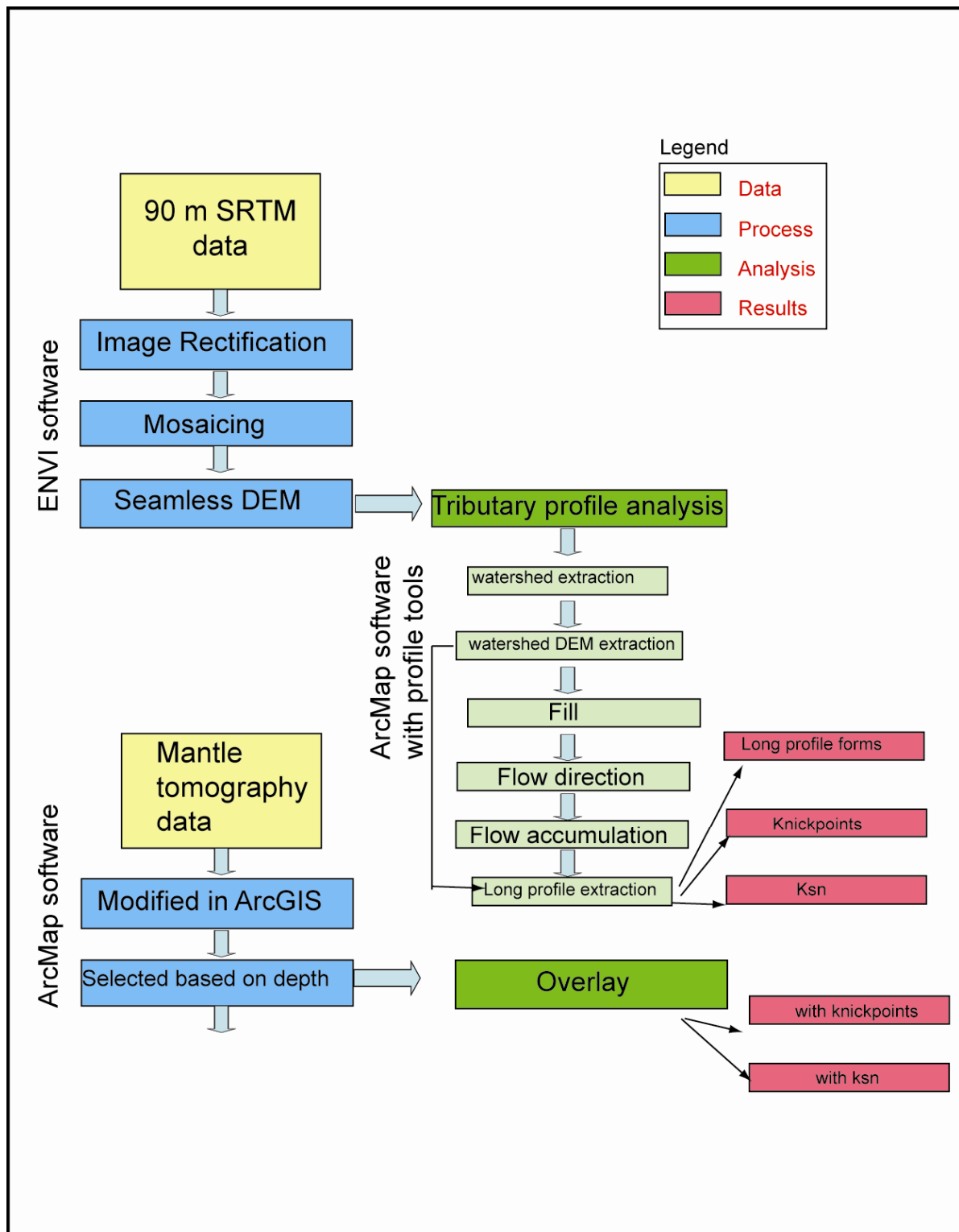


Figure 6: Concept map illustrating various methods and techniques of this study

towards transient or non-steady state phenomenon related to one or more of the above causes (Fig. 8). However, in any tectonic setting, longitudinal profiles of fluvial channels exhibit a power-law scaling relationship between channel slope and drainage area (Wobus et al., 2006). This function has widely been applied in various tectonic regions such as Yellow River in Northern Tibet (Harkins and Kibry, 2007), Noyo River in California (Sklar L, 1998), Red River in Yunnan Province, China (Schoenbohm and Whipple, 2004), and Swailks in the Nepal Himalaya (Kirby and Whipple, 2001) to explain uplift and incision. The function is expressed as:

$$S=k_sA^{-\theta}$$

Where, S is channel slope, k_s is steepness index, A is drainage area θ is concavity index.

Among these parameters, k_s work efficiently when related with uplift history of a tectonically active region. In order to compare the k_s values throughout the region, it needs to be normalized using a reference θ (θ_{ref}) value. This allows correlating variable uplift as a function of normalized steepness (k_{sn}) values. In general, higher k_{sn} value denotes more steepness of channel and lower k_{sn} value represents less steepness of the channel. The k_{sn} is one of the powerful proxies to quantify the tectonics of a region where the lithological, climatic and structural condition is uniform (Wobus et al., 2006; Whipple, 2004; and Kirby, 2007). If there is no differential uplift, the value of k_{sn} should remain unchanged. The k_{sn} value may change from one segment of channel profile to another if the region is undergoing differential uplift. Synder et al. (2000) explained that the channel slope is inversely proportional to drainage area, therefore as the drainage area increase, the slope of the river profile decreases. However, in area like the Ethiopian Plateau where differential uplift is likely (Gani et al., 2007); over-steepening of the river profile is likely, which can be determined by change in k_{sn} .

On the other hand, variable k_{sn} values along a tributary long-profile also indicate presence of knickpoint/s in the channel (Fig. 8). Knickpoints separate the upstream older channel profile from the downstream younger profile in the form of convex zones indicating abrupt change in river slope. This is one of the major geomorphic signals for explaining geological disturbances in a region (Whipple and Tucker, 1999, 2002); The rate of migration of these knickpoints is faster in major stream than in tributaries (Whipple and Tucker, 1999; Crosby and Whipple, 2006) and in some cases newly formed knickpoint propagate farther upstream and remove older knickpoints and erode older profiles (Gani et al., 2007).

Approach

We analyzed 202 tributaries of the Blue Nile draining on the Ethiopian Plateau (Fig. 7). All the tributaries fed into the Blue Nile and flows westward to join the main Nile River.

We used SRTM (Shuttle Rader Topography Mission) derived DEM (Digital Elevation Model) data with x-y resolution of 90m and z accuracy of ± 30 m to extract river longitudinal profiles. SRTM is an international research effort that obtained global DEM covering 56°S to 60°N latitudes to generate the most complete high-resolution topographic data (Nikolakopoulos et al., 2006). Such SRTM elevation data derived from interferometric techniques is efficient not only for constructing accurate 3D topography of wider area such as the Ethiopian Plateau but also for quantitative river profile analysis (fig. 2). We rectified and mosaiced 30 SRTM DEM (Fig .3) tiles to construct a seamless data of the study area for river profile analysis. The long profiles were extracted through ArcGIS and Matlab coding with the help of stream profiler extension tools (profiler, 2007). We used spike removal and took 1000 moving average to smooth the channel data.

debris flow regime (Fig. 8). In each channel profile, we observed slope breaks recorded as knickpoints. We examined all knickpoints from tributary long profiles of the Blue Nile where both major and minor knickpoints are separated to understand the tectonic significance of plateau evolution. Knickpoints of individual streams were categorized according to the vertical relief between the downstream (younger channel profile) and upstream (older channel profile) profiles from knickpoints. Knickpoints with relief greater than and equal to 200 m were categorized as major knickpoints and those with <200 m reliefs were categorized as a minor knickpoints (Fig. 9). We then analyzed the spatial distribution and systematic variation of k_{sn} for individual streams above and below these knickpoints.

Mantle tomography

Background and approach

We used previously published mantle tomographic data of the region (Bastow et al., 2008). These data were combined by two seismic experiments (Bastow et al., 2005; Nyblade and Langston, 2002) using broadband seismic to image upper mantle seismic structure. Our purpose of using these data is to get insight of the upper mantle structure beneath Ethiopian Plateau, so that we can correlate these anomalies with tributary long profile data.

A number of seismic experiments were conducted in the Ethiopian Plateau to understand the mechanism of continental breakup and hot spot tectonism (Nyblade et al., 2002; Bastow, 2005; Bastow et al., 2005, 2008, 2010). To simplify and understand the mantle driven thermal heterogeneity (mantle plume), seismic tomography was developed in 1980's which is a part of seismic imaging to estimate propagating velocities of compressional waves (P-wave) and shear waves (S-wave). Several methods have been developed for this purpose, e.g., refraction travel

time tomography, finite-frequency travel time tomography, reflection travel time tomography, and waveform tomography (Tarantola, 1984; Stewart, 1991; Nolet, 2008).

We gathered tomographic data at variable depths from Ian Bastow by personal communication. These data were in grid extension that we converted into Surfer Grid by OSGeo4w software and uploaded in the ArcGIS. Eight different depths slices (75 km to 400 km) of seismic tomography were selected for further analysis. We correlated the upper mantle P-wave velocity structures at these depths with steepness index (k_{sn}) distribution of the study area to decipher whether high and low k_{sn} values broadly matches with the high and low velocity zones, respectively, beneath the plateau to understand the mantle-driven differential uplift of the plateau in controlling the incision of the Blue Nile (Fig. 13a, b). To the best of our knowledge, this is a novel approach.

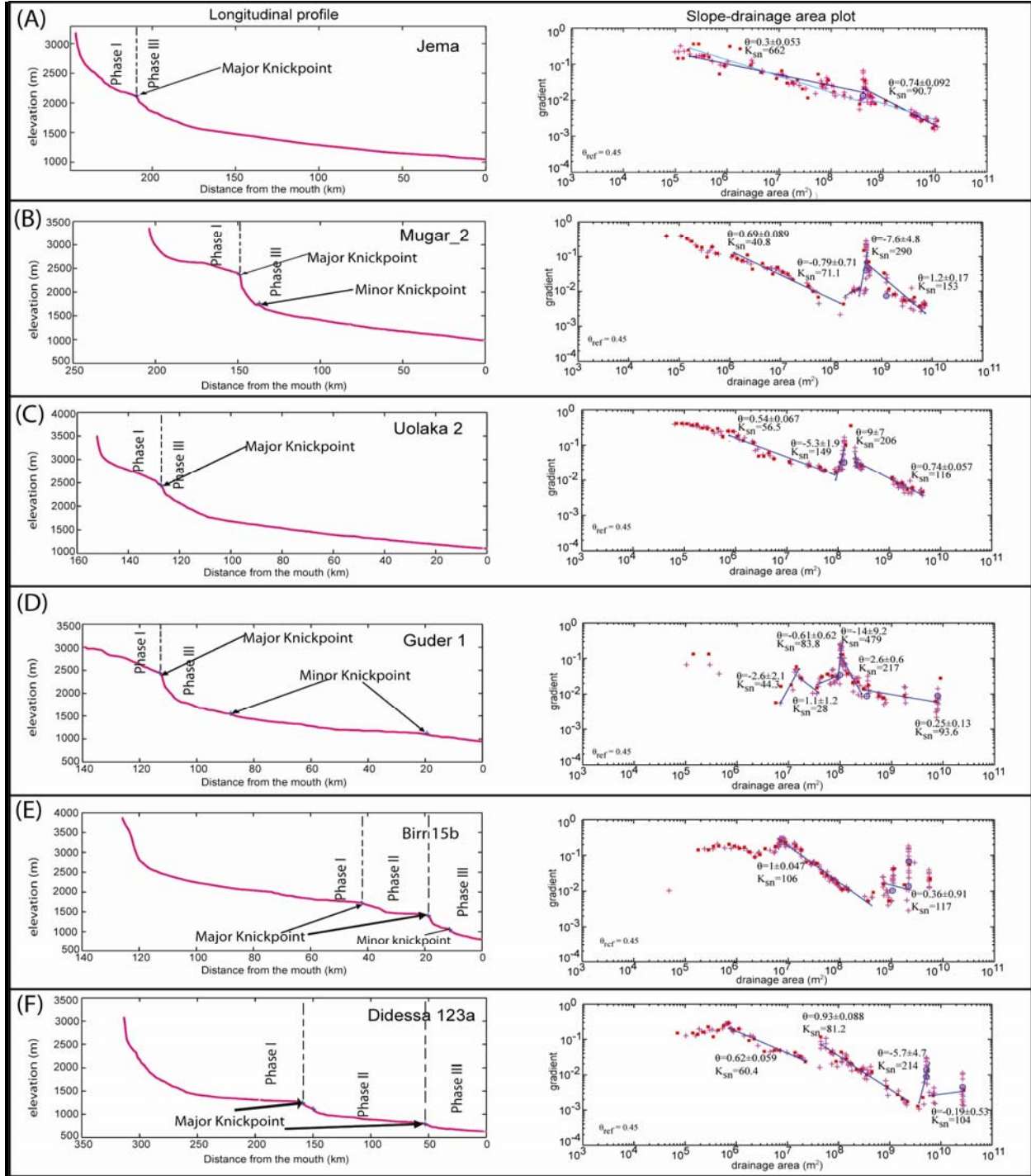


Figure 8: Longitudinal profile analysis of tributary Jema (A), Mugar 2 (B), Uolaka 2 (C), Guder 1 (D), Birr (E), and Didessa 123a (F). For each tributary, first diagram is concave upward long profile with distinct knickpoints depicting the different phase of incision. And second diagram is the plot of gradient versus drainage area (m^2). Steepness (k_{sn}) and concavity indices (θ) are calculated separately above and below the knickpoints from the linear regressions of the slope-area data in log-log plot. Red square represents log-bin average of slope-area data and purple cross is slope area data using 1000 m smoothing window. Open circle shows the location of the knickpoint corresponding to the same location in river long profile.

RESULTS

River long profile

From SRTM generated DEM, a total of 202 longitudinal profiles of major and minor tributaries were extracted throughout the Blue Nile River, starting from Lake Tana to the lowland of Sudan (Fig.7). We focused mainly on two parameters Knickpoints and normalized steepness index (k_{sn}).

Knickpoint distribution

We analyzed 244 knickpoints, both major and minor, in these tributary profiles. We categorized 154 knickpoints within the tributaries as major based on their relief ≥ 200 m and 90 knickpoints

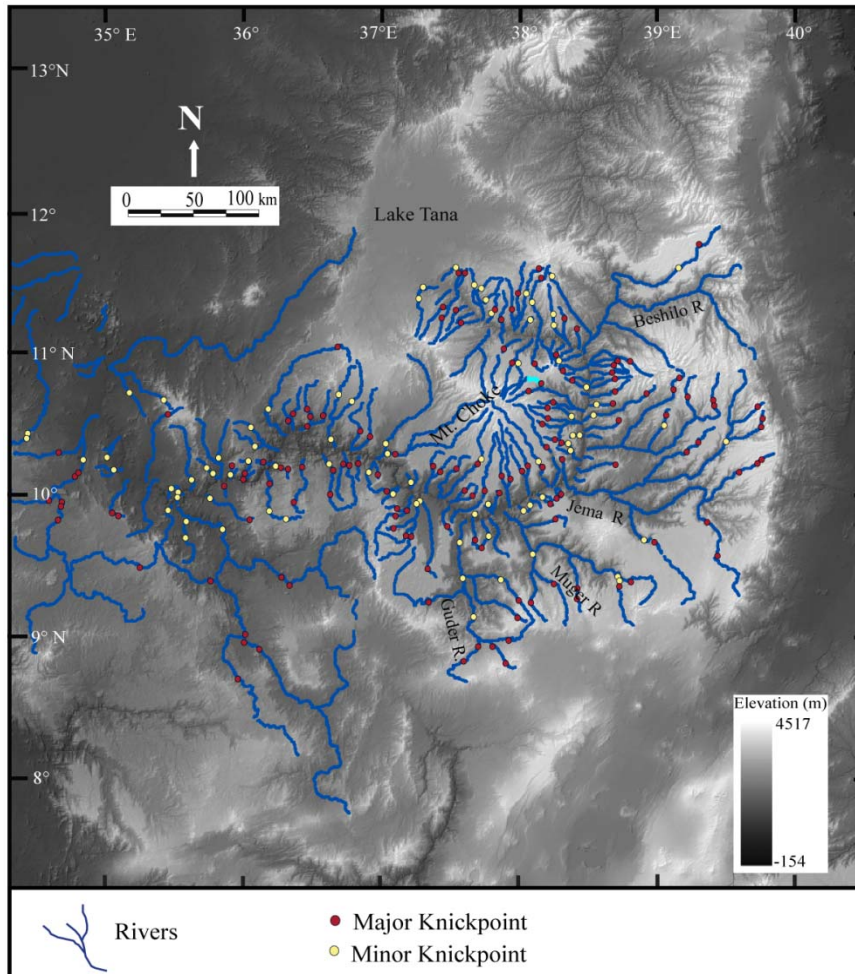


Figure 9: Plot of major and minor knickpoints in SRTM generated shaded relief image with reference to major tributaries of Blue Nile. Red and yellow colors represent major and minor knickpoints, respectively.

with <200 m relief as minor knickpoints (Fig. 9). We excluded 56 knickpoints, that are fault and lithologic boundary controlled, from further analysis.

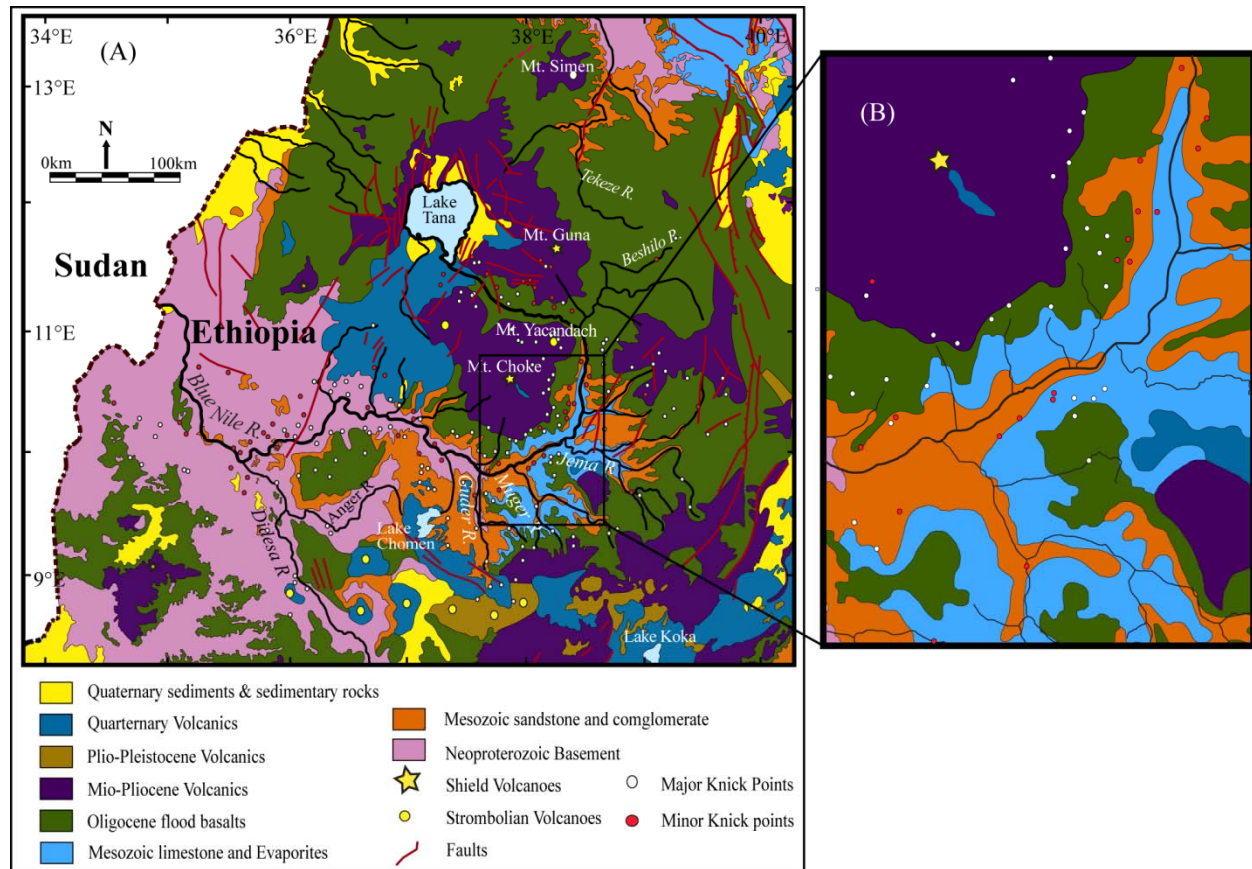


Figure 10: Geological map of the Study area with knickpoint locations. A) Distribution of knickpoints with respect to various lithological units. Very few knickpoints are formed along the lithological and structural boundaries. B) Details of knickpoint locations, which shows that very few knickpoints are located on lithological boundaries, indicating that the formation of majority of knickpoints of the study area is not controlled by bedrock lithology or geological structures.

More than 98% major knickpoints are almost homogeneously distributed, usually at an elevation above 2000 m, in a semi-circular pattern within the Blue Nile drainage, plateau interior, and flanks of Afar Depression and Main Ethiopian Rifts (Figs. 9, 10). The larger tributaries like Muger, Guder, Jema, Didessa, Anger and Beshilo show major knickpoints that are propagated further upstream comparing to those in smaller tributaries (Fig. 9). Knickpoints in

smaller tributaries are mostly located between 2100 m to 2500 m elevation. The knickpoints that are located in a specific elevation contour likely indicate transient wave of incision at a nearly-constant vertical rate (Wobus et al., 2006). Most of the tributary long profiles show zone of concavity below major knickpoints as well as downstream increase in channel slope. The zone of concavity below knickpoints would likely indicate that the knickpoints are migrating upstream as pulses of incision (Nott et al., 1996; Rosenbloom and Anderson, 1994). Many tributaries show two major knickpoints, separating the profiles into three sub-profiles, which indicate three phases of incision in the Blue Nile (similar to what was argued by Gani et al. 2007). In each subprofiles, slope usually increase downstream from knickpoints. Two major tributaries Jema and Uloka along with few minor tributaries also exhibit three phases of incision (Fig. 8).

Majority of the minor knickpoints are non-systematically distributed throughout the plateau, near Lake Tana, close to the mouth of individual tributaries and downstream of the Blue Nile. Most of the major tributaries are devoid of minor knickpoints. Alike major knickpoints, tributary profiles show downstream increase in channel slope that is evidenced from slope area data in long profiles (Fig. 8). These minor knickpoints typically occur between 900 to 1800 m elevations. Both major and minor knickpoints are likely to be transient knickpoints that denote that the plateau is experiencing tectonic forcing (Wobus et al., 2006).

Normalized Steepness (k_{sn}) Pattern

Each of the profiles for larger and smaller tributaries of the Blue Nile shows variable range of k_{sn} values upstream and downstream of the knickpoints. Hence, k_{sn} values upstream and downstream reaches from knickpoints and k_{sn} of knickpoints themselves were analyzed and classified to understand the tectonic behavior of the plateau (Fig. 11).

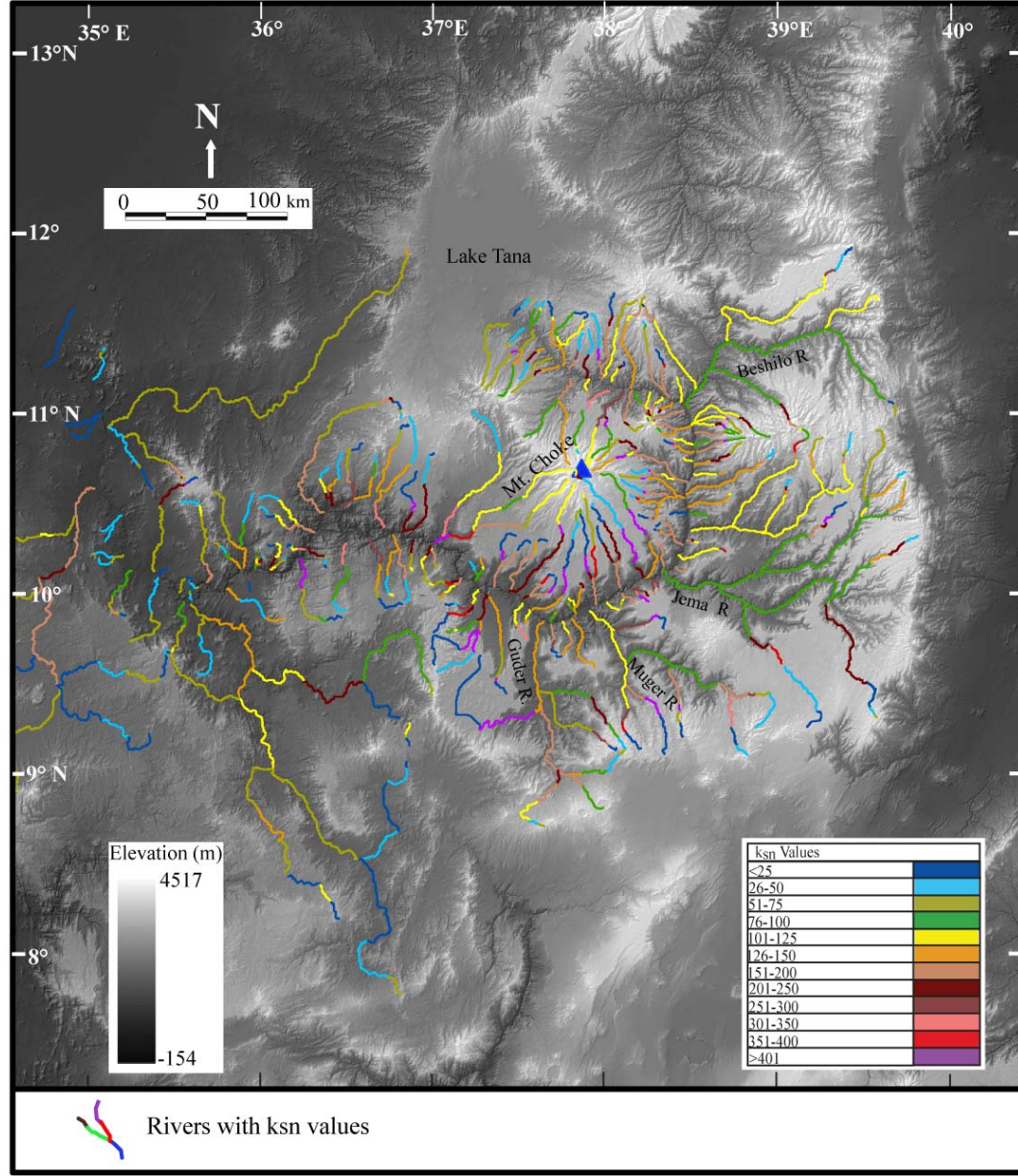


Figure 11: Spatial distribution of normalized steepness indices (k_{sn}) of tributaries of the Blue Nile River. k_{sn} distribution within the Blue Nile basin reveal more complex pattern of landscape adjustment of the Ethiopian Plateau. Larger tributaries such as Beshilo, Jema, Mugar and Guder have lower k_{sn} values than the smaller tributaries. Tributaries in the downstream of the Blue Nile River at the border of Ethiopia and Sudan are less steep; however tributaries originating from the Mt. Choke and tributaries close to the western flank of Main Ethiopian Rift have higher k_{sn} values. Note that the highest k_{sn} values occur in the plateau interior and rift-flank area to the east.

The k_{sn} values range from ~25 to ~401 (Fig. 11, 12) that varies systematically throughout the plateau. k_{sn} values are usually high downstream from knickpoints, and are the highest within the knickpoint zones. We generate a k_{sn} map by classifying ksn values in 12 classes to see the

variation in the distribution pattern throughout the plateau. Generally, regions of higher k_{sn} values (ranges from 126-200) exist in tributaries at both sides of the Blue Nile draining from Mounts Choke, Gish, Guna, and Yacandach. Similarly, high k_{sn} region with same value range also observed with Guder and Mugar tributaries and those draining from the south to the Blue Nile. A zone of high k_{sn} values (126-250) also exists along the margins of the western flanks of

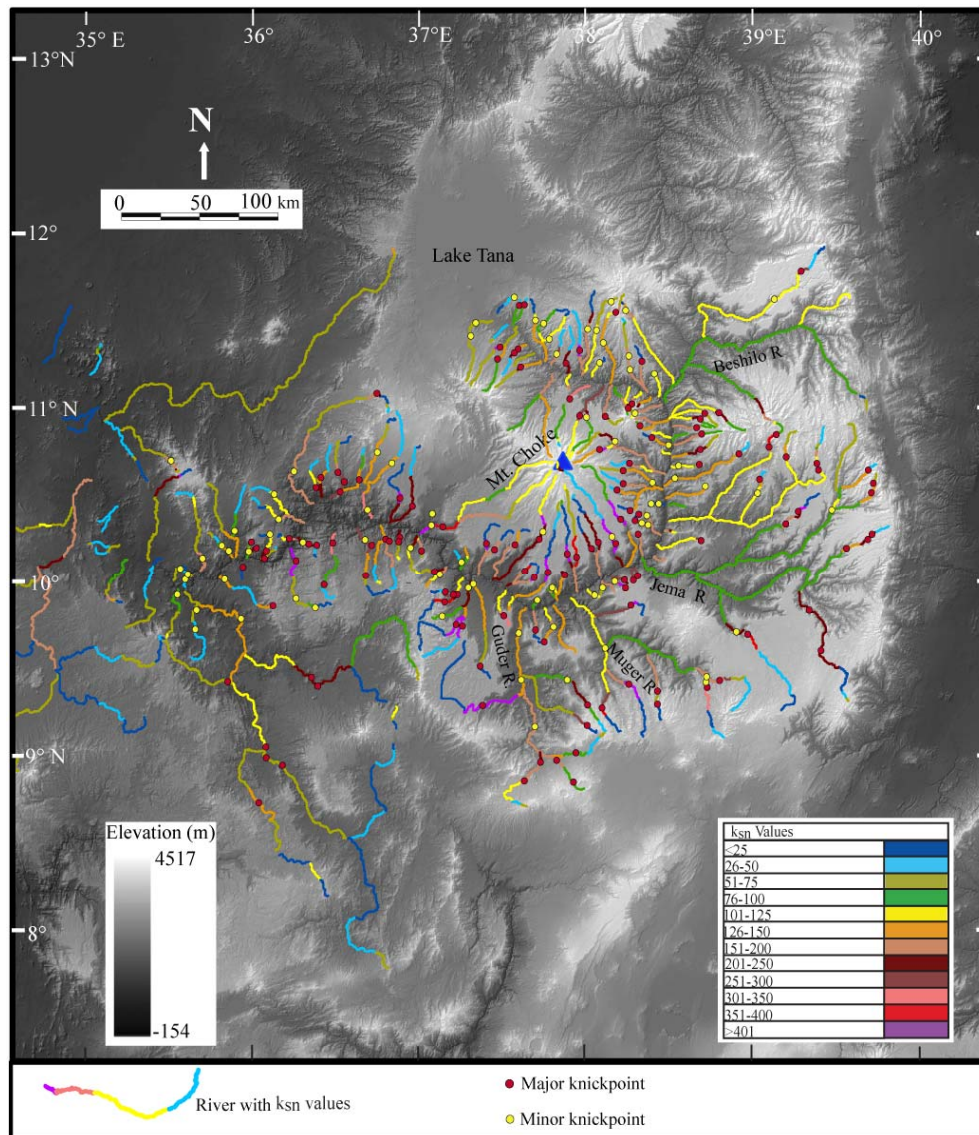


Figure 12: Distribution of knickpoints and k_{sn} values within the Ethiopian Plateau.

the Min Ethiopian Rift and Afar Depression. The lower k_{sn} values < 25 to 75 are found in upstream parts of these tributaries draining from the volcanoes. Among the major tributaries, Beshilo and Jema have lower values ($76-100$) in the downstream reaches that are in contrast to that of the Guder and Muger tributaries. This suggests that high k_{sn} values did not depend on drainage area. Even in the smaller tributaries, high values of k_{sn} are independent of drainage area. Comparing to the minor tributaries, major tributaries exhibit lower k_{sn} values ($76-125$) towards the mouth. From k_{sn} map (Fig. 11), it can be argued that zones of high k_{sn} values indicate high uplift zones of the plateau, and vice versa (e.g. Kirby and Whipple 2003). The high uplift zones follow the central portion of the Blue Nile including Guder and Muger, whereas low uplift zones are essentially localized within the Beshilo, Jema, and Didessa rivers (Fig. 11, 12). The western flank of the Min Ethiopian Rift is tilted towards west due to the rift-flank uplift (Wissel et al., 1995) that is reflected in the high k_{sn} values within the tributaries draining westward from the flank.

Mantle tomography

Out of eight color-coded p-wave velocity depth slices (75km to 400km depths) that illustrate velocity anomalies, we overlay 100 and 150 km depth slices (Fig. 13a, 13b) as they positively correlate with k_{sn} pattern throughout the plateau. The depth slices provide useful information on the mantle velocity that we utilize to understand zones of negative (i.e. lower than normal velocity) p-wave anomalies beneath the Ethiopian Plateau (Fig. 13a, b). Negative anomalies beneath the plateau correspond areas of anomalously hotter and buoyant mantle, thus areas undergoing higher uplift. The tomographic images show anomalously low velocity zone beneath

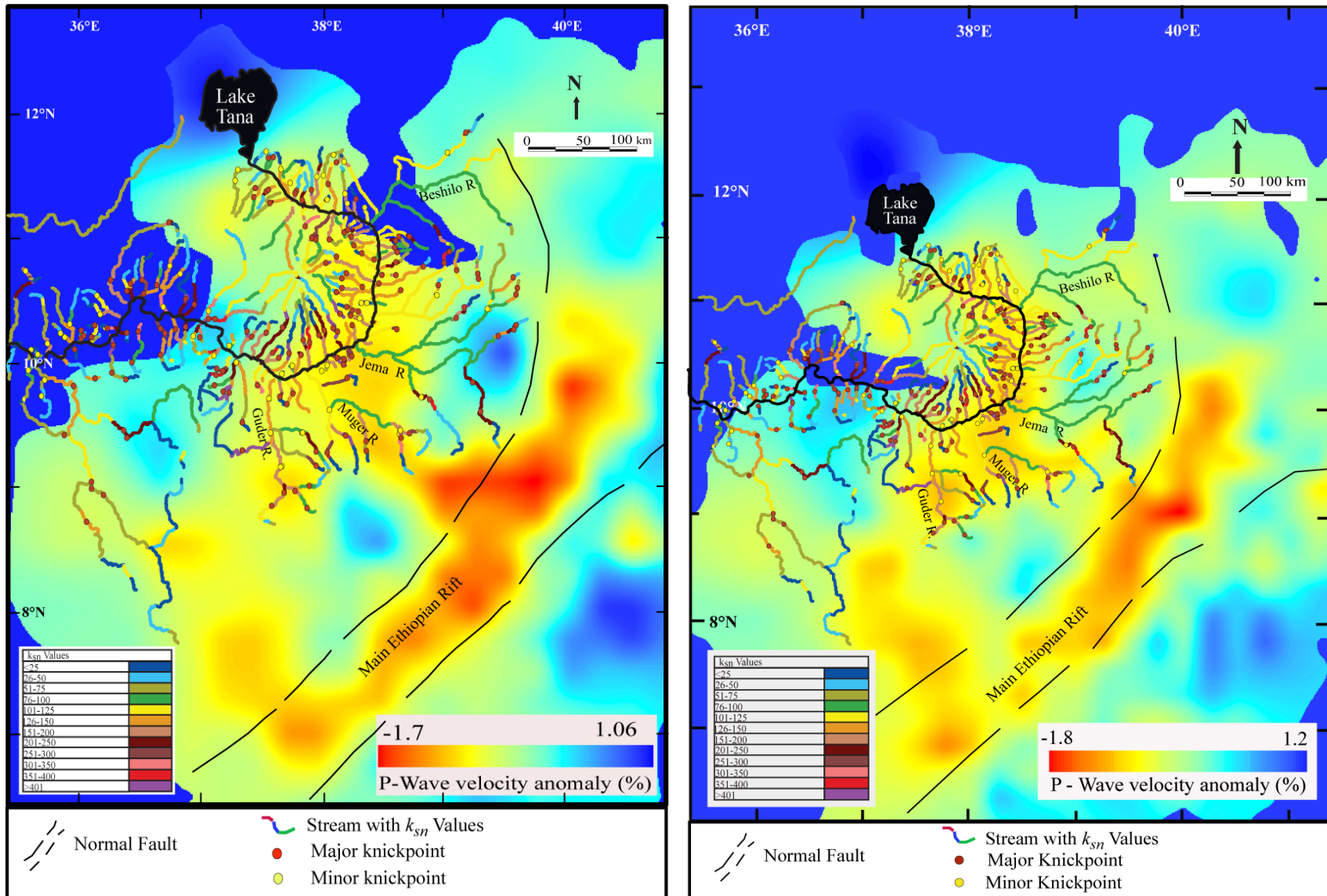


Figure 13: Correlation of P-wave mantle velocity anomaly (velocity data from Bastow et al. 2008) of (a) 100 km and (b) 150 km depth slice with the distribution of knickpoints and k_{sn} values. Higher k_{sn} values and location of knickpoints occur on top of anomalously low velocity zones (i.e. hotter mantle) and lower k_{sn} values follow anomalously high velocity zones (i.e. colder mantle). This indicates that the exhumation of the Ethiopian plateau is largely associated with mantle-driven tectonic uplift of the plateau.

the Main Ethiopian Rift and Afar Depression. The area is also characterized by localized isolated areas of anomalously high velocity zones.

We correlated mantle tomography data with k_{sn} value obtained from the river profile analysis (Fig. 13a, b). Due to the lack of velocity data, we were unable to correlate k_{sn} value downstream of the Blue Nile towards the lowland of Sudan. Broadly, the high k_{sn} zones and locations of the knickpoints occur above anomalously low (negative) velocity zones. This explains that, in the background of overall uplift of the Ethiopian Plateau, the areas with higher k_{sn} values corresponds with rapidly uplifting areas of the plateau. Many of the areas with lower k_{sn} values follow anomalously high (positive) velocity zones, thus experiencing less uplift. Except for the few, major knickpoints are located above the low velocity zones, indicating, again, that the mantle-driven uplift of the plateau controls Blue Nile incision.

DISCUSSION

Although there are numerous tectono-structural studies regarding continental extensional tectonics of the Main Ethiopian Rift, Afar Depression and the Ethiopian Plateau, we applied here, for the first time, quantitative river longitudinal profile analysis to interpret the tectonic history of the plateau. Our results of knickpoint distribution and k_{sn} values (Fig. 11, 12) from river profile analysis are very insightful, which can be correlated with the tectonic information of the region. Although the study area situated in the vicinity of extensional regime, there is no significant influence of normal faults on these tributaries; hence, this study critically deciphers the response of the tributaries due to tectonic perturbation on the plateau.

Our analysis of knickpoints rarely shows single incision phase in the long profiles, instead, majority of the profiles are segmented by two major knickpoints that defines three incision phases, similar to those described by Gani et al. (2007) (Fig. 8). The presence of knickpoints, not controlled by lithology or local structures (Fig. 10), and high slopes in tributary profiles suggests transient response due to change in tectonic processes (e.g. Pierre, 2007) such as tectonic uplift within the plateau. Except for a few, majority of the knickpoints present in the Blue Nile drainage network is indicative of plateau uplift that affected three-phase incision of the study area. Some of the major tributaries like Jema and Beshilo graded out their profiles into more concave shape that is unlike for smaller tributaries of the region, which still preserve knickpoints in part of their profiles. Smaller tributaries are unable to keep pace with the tectonic deformation, hence not yet incised into the plateau to reach a steady-state condition, preserving knickpoints and showing high k_{sn} values. Different incision phases provide insight into the plateau uplift, reflecting fast head-ward migration of younger profiles to erode out older profile that depict. Most of the major knickpoints are located between 2100 m and 2500 m elevation

(Fig. 9) which indicate that these knickpoints are migrating upstream at a constant vertical rate (Niemann et al. 2001).

Analysis of the spatial pattern of k_{sn} values further helps discern incision and uplift of the plateau. The regional incision pattern of Gani et al. (2007) shows a nice correlation with the spatial distribution of k_{sn} values of this study. Higher k_{sn} values are encountered within the tributaries undergoing higher magnitude of incision, whereas lower k_{sn} values are encountered in area of lower magnitude of incision.

Map of k_{sn} values can positively correlate with tectonic uplift (e.g. Snyder et al., 2000; Kirby and Whipple, 2003). It is important to note that the uplift of the plateau is spatially variable. Various lines of evidence presented in this study suggests that the tributaries are likely responding to plume-related uplift of the plateau, as argued by Gani et al. (2007). However, incision of the tributaries located in the eastern margin of the plateau is attributed to isostatic response of the rift-flank uplift. Overall three-phase incision of the plateau might be linked to the long-wavelength uplift generated by rising Afar mantle plume beneath the Ethiopian Plateau. On the other hand, higher k_{sn} values of tributaries originated from the Mt. Choke (Fig. 11) indicate that the incision of these streams are likely controlled by the local, short-wavelength uplift associated with the activities of Miocene shield volcanoes (Keiffer et al., 2004). Finally, the high k_{sn} values in the upstream of the major tributaries (Jema, Muger, Guder) could be the indication of flexural uplift of the western flank of MER around 6 to 5 Ma (Beyene et al., 2005).

Our seismic tomography correlation with k_{sn} distribution also supports this assumption that the incision of the Blue Nile is mainly controlled by mantle-driven, tectonic uplift of the plateau. The velocity-anomaly images at 100 km and 150 km depth positively correlate with the

distribution of k_{sn} values (Fig. 13a, b). Higher k_{sn} values of the major and minor tributaries along the Blue Nile River lies above anomalously low (negative) velocity zones, which indicates areas of hotter mantle thus zones of higher uplift.

The river long profiles with knickpoints and high k_{sn} values within tributaries of the Blue Nile, along with the tomographic data, are keys to our assumption that these rivers are actively responding to the dynamic and isostatic uplift of the Ethiopian Plateau. Proper understanding of the plateau uplift may shed important light in evaluating East African climate shift towards aridity and evolution of hominin in late Cenozoic (Gani et al., 2007).

CONCLUSIONS

Tributary longitudinal profile data obtained from SRTM generated DEM of the Ethiopian Plateau reveals meaningful pattern of knickpoint and steepness index (k_{sn}) distribution in the Blue Nile drainage system. The formation of knickpoints and their upstream migration are not controlled by geological structures or variations of bedrock lithology, but by tectonic uplift of the region that dictated three-phase incision of the plateau. Some high k_{sn} values are encountered within tributaries originating from shield volcanoes in both side of the Blue Nile River and those draining from the western flank of the Main Ethiopian Rift. Incision in these areas is likely controlled by short-wavelength, localized uplift. On the other hand, most of the higher k_{sn} values in various tributaries correlate with negative anomalies of mantle tomography. This explains that the land areas above the hotter (than normal) mantle are likely experiencing higher magnitude of long-wavelength rock uplift, thus driving stream incision. Therefore, the development of Blue Nile drainage and associated incision are largely tectonic controlled, and this incision is still actively ongoing.

REFERENCES

- Bastow, I.D., Pilidou, S., Kendall, J. –M., Stuart, G.W., (2010), Melt-induced seismic anisotropy and magma assisted rifting in Ethiopia: Evidence from surface waves. *Geochem. Geophys. Geosyst.*, 11, Q0AB05, Doi: 10.1029/2010GC003036.
- Bastow, I. D., A. A. Nyblade, G. W. Stuart, T. O. Rooney, and M. H. Benoit (2008), Upper mantle seismic structure beneath the Ethiopian hot spot: Rifting at the edge of the African low-velocity anomaly, *Geochem. Geophys. Geosyst.*, 9, Q12022, doi :10.1029/2008GC002107
- Bastow, I. (2005), Upper-mantle seismic structure in a region of incipient continental break-up: Northern Ethiopian rift, Ph.D. thesis, Univ. of Leeds, Leeds, U.K.
- Bastow, I., G. Stuart, J.-M. Kendall, and C. Ebinger (2005), Upper-mantle seismic structure in a region of incipient continental breakup: northern Ethiopian rift, *Geophys. J. Int.*, 162(2), 479–493, doi:10.1111/j.1365-246X.2005.02666.x.
- Beyene, A., and Abdelsalam, M., 2005, Tectonics of the Afar Depression: A review and analysis: *Journal of African Earth Sciences*, v. 41, p. 41-59, doi: 10.1016/j.jafrearsci.2005.03.003.
- Bonini, M., Corti, G., Innocenti, F., Manetti, P., Mazzarini, F., Abebe, T., Pecskey, Z., 2005. Evolution of the Main Ethiopian Rift in the frame of Afar and Kenya rifts propagation TC1007 *Tectonics* (1). doi:10.1029/2004TC00168.
- Brewer, I.D., Burkank, D.W., and Hodges, K.V., 2006, Downstream development of a detrital cooling-age signal: Insights from $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite thermochronology in the Nepalese Himalaya, in Willett, S.D., Hovius, N., Brandon, M.T., and Fisher, D., eds., *Tectonics, climate, and landscape evolution: Geological Society of America Special Paper 398, Penrose Conference Series*, p. 321–338
- Clark, M., Schoenbohm, L., Royden, L., Whipple, K., Burchfiel, B., Zhang, X., Than, W., Wang, E., and Chen, L., 2004, Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns: *Tectonics*, v. 23
- Crosby, B., and Whipple, K., 2006, Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand: *Geomorphology*, v. 82, p. 16–38.
- Ebinger, Cynthia; *et al.* (2010). "Length and Timescales of Rift Faulting and Magma Intrusion: The Afar Rifting Cycle from 2005 to Present". *Annual Review of Earth & Planetary Sciences* 38 (1): 439–466.
- Ebinger, C., and N. Sleep (1998), Cenozoic magmatism throughout East Africa resulting from impact of a single plume, *Nature*, 395, 788 – 791

- Ebinger, C., Bechtel, T., Forsyth, D., and Bowin, C., 1989, Effective elastic thickness beneath the East African and Afar plateaus and dynamic compensation of the uplifts: *Journal of Geophysical Research*, v. 94, p. 2883–2901.
- Figueroa, A.M., and Knott, J.R., (2010), Tectonic geomorphology of the southern Sierra Nevada Mountains (California): Evidence for uplift and basin formation, *Geomorphology* 123 (2010) 34–45
- Gani N. D., Gani. M. R. and Abdelsalam M. G., (2007), Blue Nile Incision on the Ethiopian Plateau: Pulsed Plateau Growth, Pliocene Uplift, and Hominin Evolution, *GSA Today*, Vol. 17
- Gani N. D., Abdelslam M. G, Gera S., Gani. M. R, (2009), Stratigraphic and Structural Evolution of the Blue Nile Basin, Northwestern Ethiopian Plateau, *Geological Journal*, Vol. 44, Pages 30 – 56
- Guiraud R., Bosworth W., Thierry J., Delplanque A., (2005), Phanerozoic geological evolution of Northern and Central Africa: An overview, *Journal of African Earth Sciences* vol. 43 PP 83–143
- Harkins. K., Kirby E., Heimsath A., Robinson R., Reiser U., (2007), Transient fluvial incision in the headwater of the Yellow River, northern Tibet, China. *Journal of Geophysical Research*, V. 112, Doi: 10.1029/2006JF000570
- Harrison T.M., Copeland. P., Hall. A. S., Quade. J., Burner. S., Ojha. T. P., Kidd. W. S. Fl., (1993), Isotopic preservation of Himalayan/Tibetan Uplift, Denudation, and Climatic History of Two Molasse Deposits: *The Journal of Geology* V. 101, P. 157-175
- Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Yirgu, G., Ayalew, D., Weis, D., Jerram, D., Keller, F., and Meugniot, C., 2004. Flood and Shield Basalts from Ethiopia: Magmas from the African Super swell. *J. of Petrology*. 45, 793-834.
- Kirby, E., N. Harkins, E. Wang, X. Shi, C. Fan, and D. Burbank (2007), Slip rate gradients along the eastern Kunlun fault, *Tectonics*, 26, TC2010, doi:10.1029/2006TC002033.
- Kirby, E., and K. Whipple (2001), Quantifying differential rock-uplift rates via stream profile analysis, *Geology*, 29, 415– 418.
- Leroy, Sylvie. "Recent off-axis volcanism in the eastern Gulf of Aden; implications for plume-ridge interaction." *Earth and Planetary Science Letters* 293.1-2 (2010): 140-153. GeoRef. EBSCO. Web. 6 Dec. 2010.
- McKenzie, D. P., Davies, D., and Molnar, P., 1970. Plate tectonics of the Red Sea and East Africa: *Nature*, v. 226, p. 243-248.

- McMillan, M., Heller, P., and Wing, S., 2006, History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau: *Geological Society of America Bulletin*, v. 118, p. 393–405.
- Moucha, R., and Forte, A. M., 2011. Changes in African topography driven by mantle convection: *Nature Geoscience*, v. 4, p. 707-712.
- Mohr, P., and Zanettin, B., 1988, The Ethiopian Flood Basalt Province, *in* McDougall, J.D., ed., *Continental Flood Basalts*: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 63–110.
- Mohr, P., 1983. Volcanotectonic aspects of the Ethiopian Rift evolution: *Bulletin Centre Recherches Elf Aquitaine Exploration Production* 7, 175–189.
- Nikolakopoulos, K. G., Kamaratakis, E. K., and Chrysoulakis, N., 2006, SRTM vs ASTER elevation products. Comparison for two regions in Crete, Greece: *International Journal of Remote Sensing*. Vol. 27, No. 21, 10 November 2006, 4819-4838
- Niemann, J.D., Gasparini, N.M., Tucker, G.E., and Bras, R.L., 2001, A quantitative evaluation of Playfair's law and its use in testing long-term stream erosion models: *Earth Surface Processes and Landform*, v.26, no.12, p. 1317-1332
- Nolet, G., "A Breviary of Seismic Tomography", Cambridge University Press, 2008
- Nott, J., et al. (1996), Wearing down, wearing back, and gorge extension in the long-term denudation of a highland mass: Quantitative evidence from the Schoalhaven catchment, southeast Australia, *J. Geol.*, 104, 224– 232.
- Nyblade, A., and C. Langston (2002), Broadband seismic experiments probe the East African rift, *Eos Trans. AGU*, 83, 405–410.
- Pierre, D.F., and Festa, A., 2007, Interaction of tectonic, sedimentary, and diapiric processes in the origin of chaotic sediments: An example from the Messinian of Torino Hill (Tertiary Piedmont Basin, northwestern Italy). *GSA Bulletin* 2007, 119, no. 9-10; 1107-1119
- Pik, R., Marty, B., Carignan, J., Lave, J., 2003. Stability of Upper Nile drainage network (Ethiopia) deduced from (U–Th)/He thermochronometry: Implication of uplift and erosion of the Afar plume dome. *Earth and Planetary Science Letters* 215, 73–88.
- Pederson, J., Mackley, R., Eddleman, J., 2002, Colorado Plateau uplift and erosion evaluated using GIS: *GSA Today*, v. 12 (8), p. 4-10.
- Profiler, 2007; New Tools for Quantitative Geomorphology: Extraction and Interpretation of Stream Profiles from Digital Topographic data. *GSA Annual Meeting 2007*.

- Rosenbloom A. Nan and Anderson S. Robert., 1994, Hillslope and channel evolution in a marine terraced landscape, Santa Cruz, California, *Journal of Geophysical Research*, Vol. 99, NO. B7, pp 14,013-14,02
- Sklar L., Dietrich W., 1998. River Longitudinal Profile and Bedrock Incision Models: Stream Power and the influence of sediment supply. American Geophysical Union.
- Schoenbohm L., Whipple K., 2004. Geomorphic constraints on surface uplift, exhumation and plateau growth in the Red River region, Yunnan Province, China: *GSA Bulletin*, Vol. 116 p. 895-909.
- Stewart, R. R., *Exploration Seismic Tomography: Fundamentals*, Society of Exploration Geophysicists, 1991
- Snyder, N., Whipple, K., Tucker, G., and Merritts, D., 2000, Landscape response to tectonic forcing: DEM analysis of stream profile in the Mendocino triple junction region, northern California: *Geological Society of America Bulletin*, V. 112, no. 8, p. 1250-1263
- Tarantola, A., Inversion of seismic reflection data in the acoustic approximation, *Geophysics* 49, pp. 1259, 1984.
- Weissel, J.K., Malinverno, A., Harding, D.J., 1995. Erosional development of the Ethiopian plateau of Northeast Africa from fractal analysis of topography. In: Barton, C.C., La Pointe, P.R. (Eds.), *Fractals in Petroleum Geology and Earth Processes*. Plenum Press, New York, pp. 127–142.
- Weissel, J., and Seidl, M., 1998, Inland propagation of escarpments and river profile evolution across the Southeast Australia passive Continental margin, in Tinkler, K., and Wohl, E., eds., *Rivers over rock: Fluvial processes in bedrock channels*: American Geophysical Union Geophysical Monograph 107, p. 189-206.
- Walt Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E., Pik, R., 1997. Timing of the Ethiopian flood basalt event and implications of Plume birth and global change: *Nature* 389, 838–841. ham, Tony (2005). "Extension tectonics in the Afar Triangle". *Geology Today* 21 (3): 101–107.
- Whipple, K., 2004, Bedrock Rivers and the geomorphology of active Orogens: *Annu. Rev. Earth Planet. Sci.* 2004. 32:151-85, doi: 10.1146/annurev.earth.32.101802.120356.
- Whipple, K.X, and Tucker, G.E., 2002, Implications of sediment-flux-dependent river incision models for landscape evolution: *Journal of Geophysical Research*, V. 107, no. B2, doi: 10.1029/2000JB000044
- Whipple, K.X, and Tucker, G.E., 1999, Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs: *Journal of Geophysical Research*, v. 104, p. 17,661-17,674,

Wobus, C., Whipple, K.X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B., and Sheehan, D., 2006, Tectonics form topography: Procedures, promise, and pitfalls: GSA special paper 398, Penrose Conference Series, p. 55-74, doi: 10.1130/2006.2398(04).

Waltham, Tony (2005). "Extension tectonics in the Afar Triangle". *Geology Today* 21 (3):101–107

Wolfenden E., Ebinger C., Ebinger C., Yirgu G., Deino A and Ayalew D., 2004, Evolution of the northern Main Ethiopian rift: Birth of a triple Junction: *Earth and Planetary Sciences Letter* 224 (2004) 213-228.

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APPENDIX

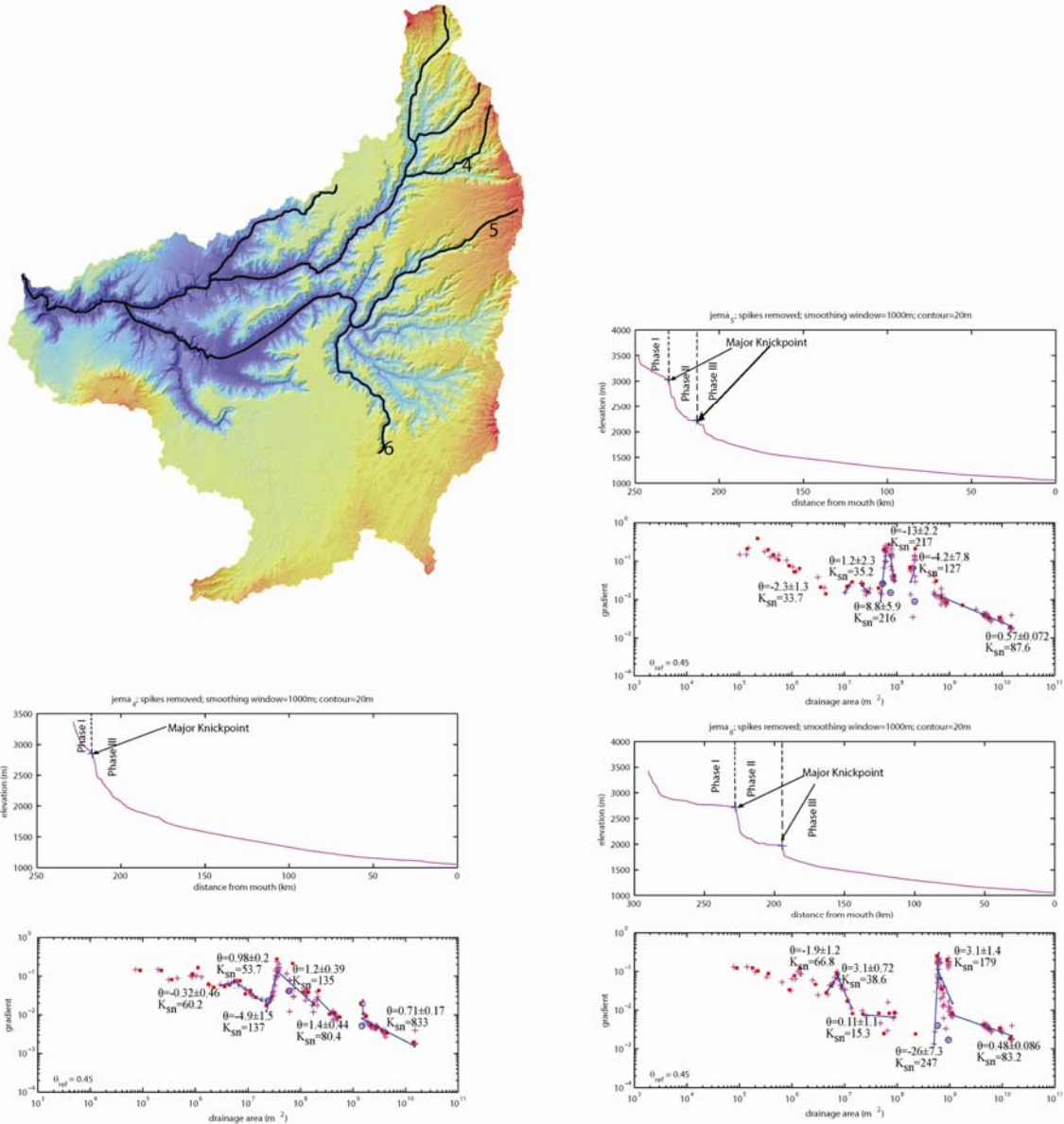


Figure 1(A). Watershed of Jema tributary of the Blue Nile River. (B) Longitudinal profile analysis of tributary Jema. (a) Concave upward long profile with distinct knickpoints depicting the different phase of incision. (b) Plot of gradient versus drainage area (m²). Steepness (K_{sn}) and concavity indices (θ) are calculated separately above and below the knickpoints from the linear regression s of the slope-area data in log-log plot. Red square represents log-bin average of slope-area data and purple cross is lope area data using 1000 m smoothing window. Open circle shows the location of the knickpoint corresponding to the same location in river long profile.

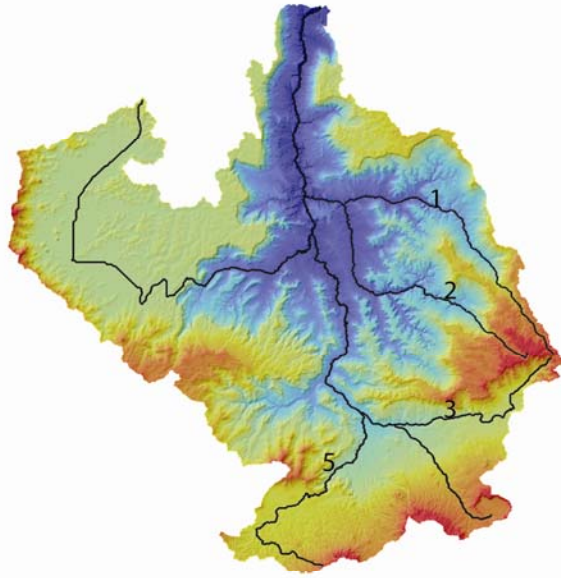
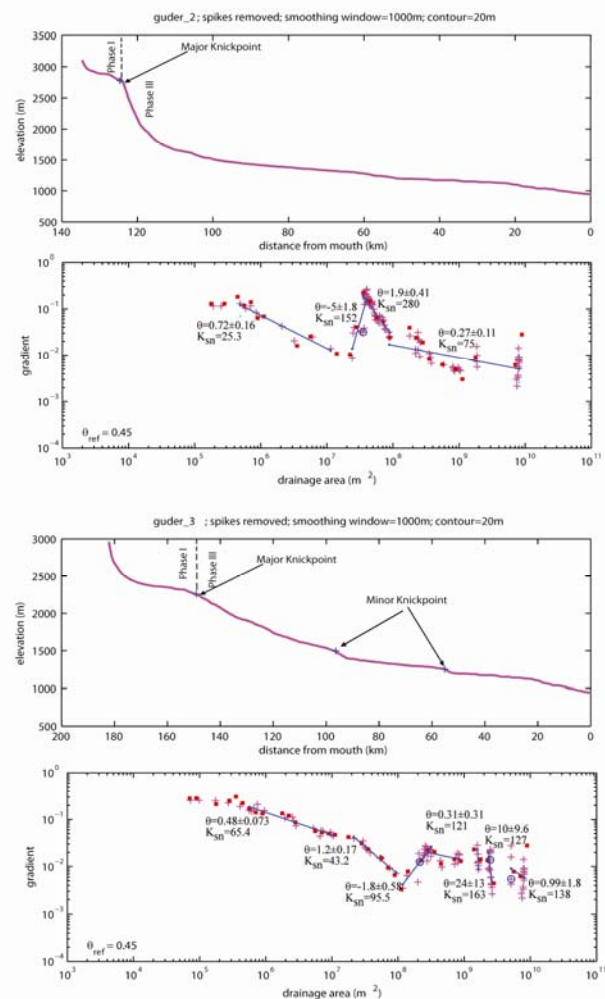
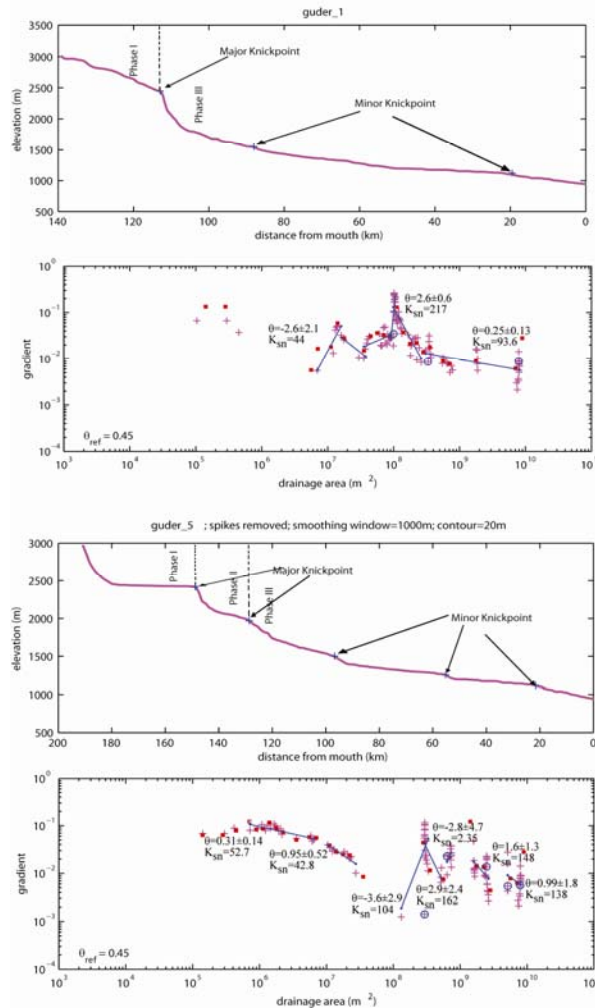


Figure 2. (A) Watershed of Gudar tributary of the Blue Nile River. (B) Longitudinal profile analysis of tributary Gudar. (a) Concave upward long profile with distinct knickpoints depicting the different phase of incision. (b) Plot of gradient versus drainage area (m^2). Steepness (K_{sn}) and concavity indices (θ) are calculated separately above and below the knickpoints from the linear regression s of the slope-area data in log-log plot. Red square represents log-bin average of slope-area data and purple cross is lope area data using 1000m smoothing window. Open circle shows the location of the knickpoint corresponding to the same location in river long profile.



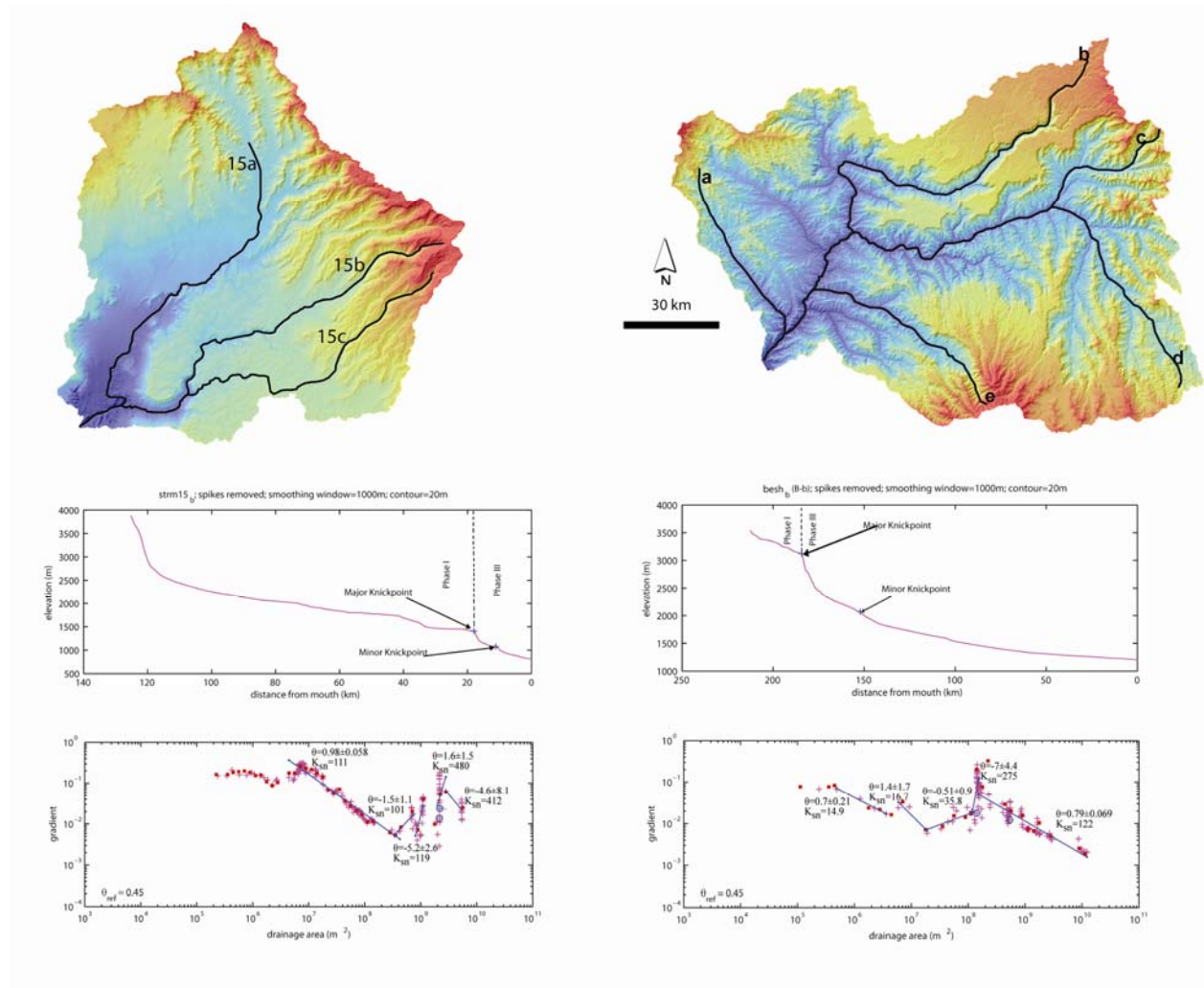


Figure 3. (A) Watershed of Beshilo and 15_b tributaries of the Blue Nile River. (B) Longitudinal profile analysis of tributary Beshilo. (a) Concave upward long profile with distinct knickpoints depicting the different phase of incision. (b) Plot of gradient versus drainage area (m^2). Steepness (K_{sn}) and concavity indices (θ) are calculated separately above and below the knickpoints from the linear regression s of the slope-area data in log-log plot. Red square represents log-bin average of slope-area data and purple cross is lope area data using 1000m smoothing window. Open circle shows the location of the knickpoint corresponding to the same location in river long profile.

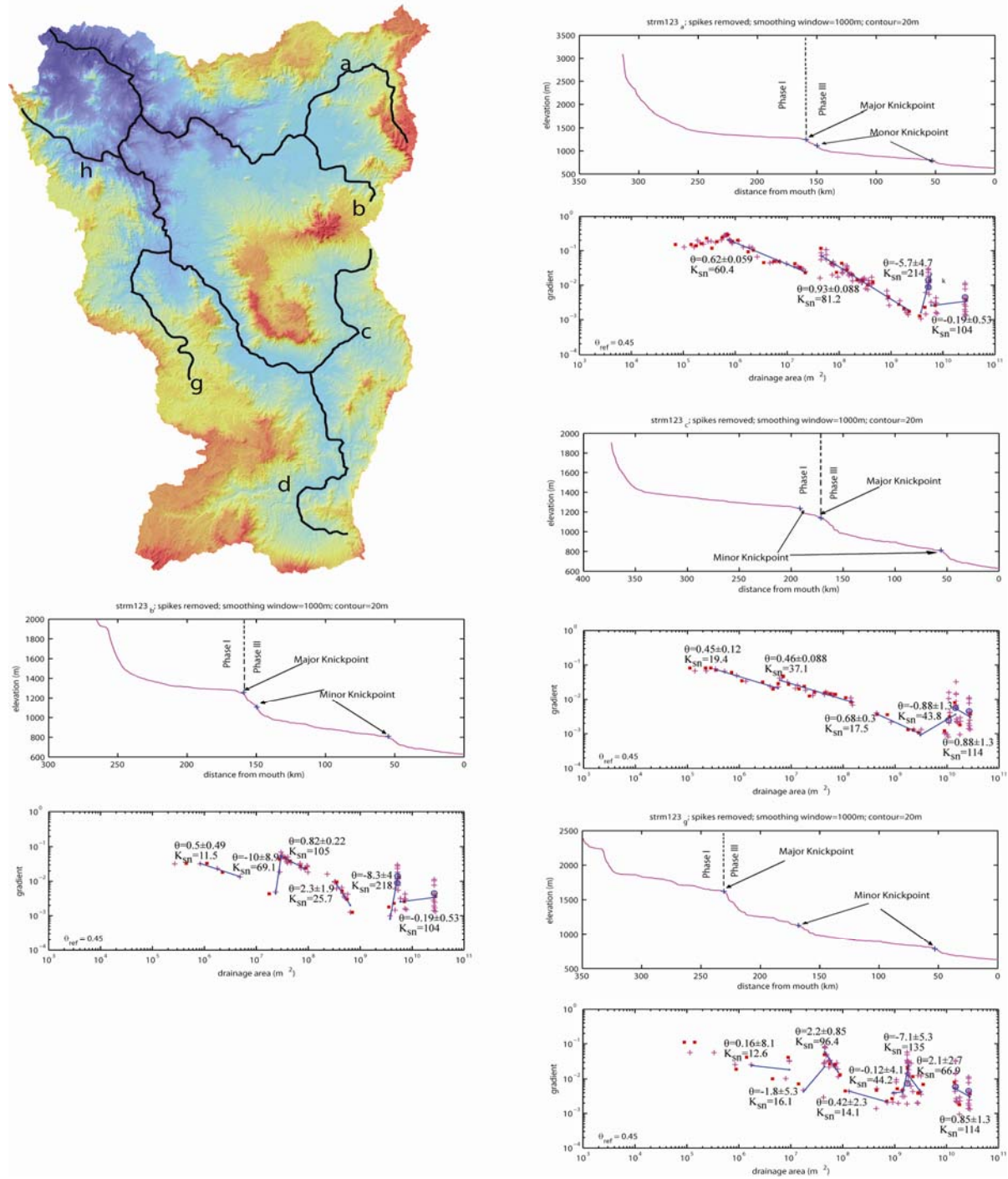


Figure 4. (A) Watershed of no. 123 tributary of the Blue Nile River. (B) Longitudinal profile analysis of tributary Didessa. (a) Concave upward long profile with distinct knickpoints depicting the different phase of incision. (b) Plot of gradient versus drainage area (m²). Steepness (K_{sn}) and concavity indices (θ) are calculated separately above and below the knickpoints from the linear regression s of the slope-area data in log-log plot. Red square represents log-bin average of slope-area data and purple cross is lope area data using 1000m smoothing window. Open circle shows the location of the knickpoint corresponding to the same location in river long profile.

VITA

Prabhat Chandra Neupane was born in Nepal, the country of the Himalayas on April 14th 1979. He is the youngest son among his four brothers. He started his educational journey at the age of 5. From the childhood he was nature lover and was highly fascinated by the meandering rivers, snowcapped mountains and high elevated hills close to his home. During the high school studies, he trekked numerous mountainous places and experienced the unique topographic terrains, orientation of rocks and colorful minerals up close. To decipher the mystery of nature, he took geology as a major during his B.Sc. studies at Tri-Chandra Campus, Kathmandu, Nepal. He continued his M.Sc. in Central Department of Geology, Tribhuvan University and graduated in 2005. After his graduation he started his professional career in Nepal for four years involving as a consultant geologist in different mining companies and also worked as a freelancer geologist.

During his job period, he got many opportunities to get involved in different geological researches conducted by national and international institutions in the Nepal Himalaya. His interaction with various national and international scholars provided him with a new vision and desire for the higher studies and planned to join a reputed university at United States. To fulfill his goals and objectives, he joined the Department of Earth and Environmental Sciences, university of New Orleans, Louisiana in 2010 spring as a graduate student and completed his master's degree in December 2011.