

**COMPARATIVE COMPLEXITY OF CONTINENTAL DIVIDES ON FIVE  
CONTINENTS**

**A THESIS**

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**BY**

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## **1. Introduction**

“Measurement of the shape, or geometry, of any natural form- be it plant, animal or relief features is termed morphometry” (Strahler, 1969). However, in geomorphology “morphometry may be defined as the measurement and mathematical analysis of the configuration of the earth’s surface and of the shape and dimensions of its landforms” (Clarke, 1970). Morphometric studies in the field of hydrology were first initiated by R.E. Horton and A.E. Strahler in the 1940s and 1950s. The main objective of this work was to discover holistic stream properties from the measurement of various stream attributes. In fact, morphometry incorporates quantitative study of the area, altitude, volume, slope, profiles of the land and drainage basin characteristics of the area concerned (Singh, 1972). R.E. Horton applied morphometric analysis to a variety of stream attributes, and from these studies he proposed a number of laws of drainage composition. The basin morphometry includes the analysis of the characteristics of linear, areal and relief aspects of fluvially originated drainage basins. Basin morphology is the study of the shapes of the features of drainage basins, that is, all fluvial features that are bounded by the drainage divide (Matthew et. al, 2004).

The geometry of natural basin drainage networks has always attracted great interest of water resources researchers (Smart, 1972; Abrahams, 1984; Chutha and Dooge, 1990). The drainage basin is considered to be the fundamental unit in hydrology. Drainage basin helps in studying the movement of water within the hydrological cycle,

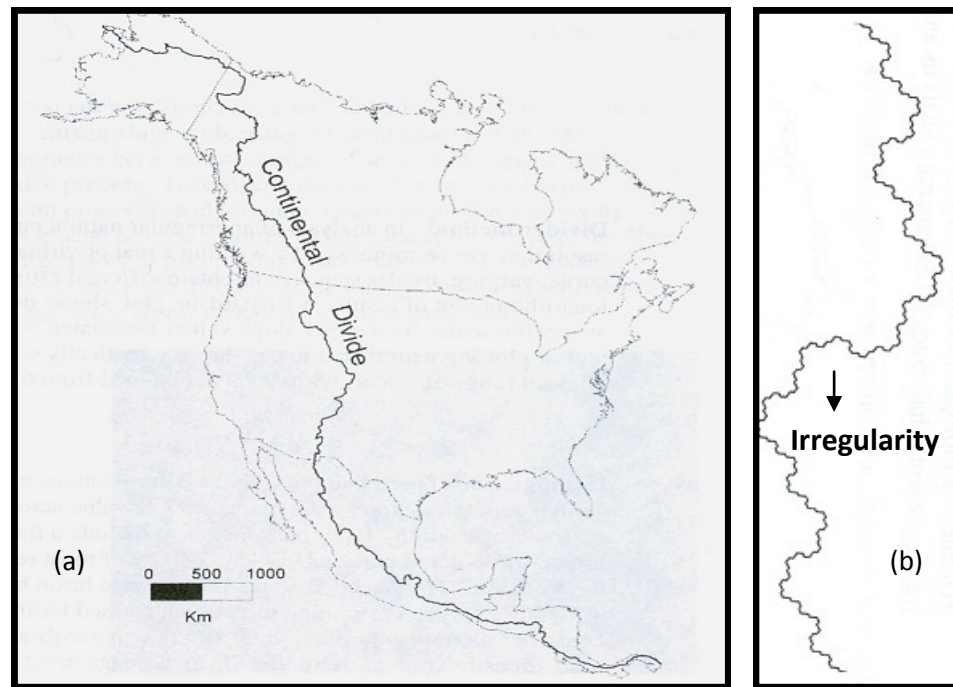
because water that discharges from the basin outlet originated as the sum of precipitation falling on the basin.

Morphometric analysis provides quantitative description of the basin geometry to understand initial relief, inequalities in the rock hardness, structural controls, recent diastrophism, geological and geomorphic history of a drainage basin (Strahler, 1964). The geometry of the basin shape is of paramount significance as it helps in the description and comparison of different geometry of the drainage basins. It helps in understanding the processes of drainage basin evolution and to aid in prediction of the basin outputs such as sediment, water, energy (Matthew et. al, 2004).

### **1.1 Significance of continental divides**

Landscape is a dynamic entity, continually undergoing change as a result of the action of geomorphological processes. Gradually, this ongoing continuous change of landscape in turn affects the morphology of the drainage divide, which is the three dimensional line connecting the crests of elevated terrain that separate two drainage basins. Continental divides represent the limits of the largest drainage basins of the earth and are composed of partial boundaries of many smaller drainage basins. A continental divide is considered as a line that divides the flow of water, where the drainage flows into different ocean bodies, or, where one side of the drainage flows into an ocean body and other becomes a part of an interior drainage basin. Investigation of a continental divide offers the best

opportunity for comparison of watershed boundary form statistics across a broad range of scales (Rice-Snow, 1992).



**Figure 1: (a) Continental divide showing irregularity along its path and (b) Conceptual view of multiscaled irregularity, from artificial fractal curve.**

Irregularity of a drainage divide affects the predictability of sediment distribution to sedimentary basins. The more irregular it is the more likely that sediment from a specific locale will discharge on both the sides of continental divide. The less irregular it is the more likely that sediment from any locale will discharge on one side of continental divide. The degree of irregularity may help in study of the effect of terrain characteristics on the river course. The more irregular drainage divide, the more impermeable the terrain

and vice-versa. The application of fractal analysis to drainage basin boundaries may also shed some light on the correction procedures that can be applied to the calculation of shape variables such as the perimeter (Breyer et al., 1992). Influence of topographic relief on drainage basin irregularity in Prince Edward Island, Canada suggests that hill region shows higher boundary irregularity (Rice-Snow, 2009). Simultaneously, the degree of irregularity may give a vivid picture of the stage of basin development.

## **1.2 Drainage Divide Irregularity**

Continental divide boundaries as depicted in map view are irregular curves having twists and bends over a large scale of range (Figure 1). These twists and bends are considered as the geometry of the drainage divide in plan view. To our knowledge few studies in the past have focused on irregularity in drainage basin boundaries. This work on the other hand, deals with irregularity on continental divide traces worldwide.

Scheidegger (1970, pp.7-9) includes mountain crests and other watersheds in a general discussion of geomorphic “wiggly lines”. He also states that natural geomorphological lines which are wiggly introduce certain complications. Close inspection of these lines show that they are extremely complex and difficult to determine. Also these wiggles tend to disappear as the scale of the map gets smaller. Many of the drainage divide irregularities exhibit a much greater level of complexity with increasing resolution.

Nikora et al. (1997) compared fractal dimension and sinuosity data for meandering and braided channels and suggested that the fractal approach can be used as an alternative

quantitative technique for river channel description. Many studies indicate that fractal geometry can be useful in the analysis and modeling of particularly complex geomorphic features, including shorelines, river networks, and topographic features (Goodchild, 1987). Mandelbrot (1967) derived the word fractal from the Latin fractus, which means “fragmented” or “irregular.”

The shapes of many natural features such as coastlines, rivers, ecosystem boundaries and river networks are scaling. Richardson (1961) measured the length of the frontiers and coastlines of several European nations using divider method. Mandelbrot (1967) was the one who first represented this property of scaling mathematically by the use of fractal dimension for analysis of coastlines, introducing the concept of fractals in 1975. Barenblatt (1984) and his co-workers proposed fractal dimension as a new quantitative characteristic of the degree of dissection of the ocean bottom and acoustic basement relief.

According to Klinkenberg (1992) “fractal dimension and associated variogram parameters have potential as useful general geomorphometric parameters and, like the results of any other general geomorphometry study, they could be used to bring to light those spatial variations and structures in the land surface that geomorphology attempts to explain.” Milne (1991) stated, “Fractal models of landscape structure provide the elements of calculus for quantifying and predicting the multiscale dynamics of landscape processes.” Meakin (1991) also stated that fractal geometry provides a much more complete and realistic description of most structures in geology and geophysics than does Euclidean geometry and will revolutionize the study of geomorphology.

The analysis of fractal dimensions introduced by Mandelbrot (1967) has been widely adopted in several fields such as analysis of natural objects, chaotic trajectories (strange attractors). Mandelbrot (1983, pp.59) points out analogies between artificial branching fractals of various types and “watershed trees” intertwined with river drainage nets. Ghosh (2000) in his study utilized the fractal patterns to model the geometry of channel that relates the variability of bedform orientations to channel sinuosity. Snow (1989, pp.99) analyzed a diverse set of twelve stream channel planforms indicating at scales relevant to river meandering, river traces are most reasonably treated as fractal curves. This analysis method provided a natural, objective calculation of river sinuosity as well as other parameters that more completely specify channel planform.

In the literature, one can find several examples that analyze basin boundary irregularity these artifacts using fractal method. Melton (1989) mentions the idea that basin boundaries are similar to fractals such as the Koch curve but then summarily discards it. Lai (1993, unpublished) has presented several preliminary studies on the application of fractals on drainage basins. The understanding of such relationship between the basins and its hydrologic response gives an insight in preparing engineering designs of irrigation and flood control systems. Richardson “divider” analysis of six drainage basin outlines from southern Indiana, and of an additional six from larger U.S. basins, suggest that basin boundaries are fractal or near –fractal shapes (Breyer & Snow, 1991). Fractal characteristics of drainage basin boundaries in Puerto Rico have consistent degrees of irregularity, characterized by fractal dimension values ranging from 1.06 to 1.12, regardless of prevailing climate or underlying rock type (Rice-Snow, 1998).

Puente et al. (1995) worked to address the extent of self similarity in natural catchments. His results implied that the catchments are not strictly self-similar, and Horton laws exhibit spatial variability within river basins. He suggested extensions should be carried out to study the validity of self-affinity on the catchment's network and sets of divides. Furthermore a reevaluation of fractal dimension formulas based on Horton ratios need to be carried out.

Some studies have analyzed drainage divides by treating these divides as fractal structures, using scaling laws that characterize fractals. The irregular curves of continental divide boundaries depicted in a map view can be investigated as fractal geometric forms which are characterized by fractal dimension;  $D$ . Following Richardson's work (1961), Mandelbrot (1967) proposed coastlines boundaries as fractal curves for which the fractal dimension exceeds the topological dimension 1. The fractal character of drainage divide has been documented in different areas (Rice-Snow, S., 2009, Relief control of drainage basin boundary irregularity, Prince Edward Island, Canada; Rice-Snow, S., 2004, Extreme High and Low Degrees of Drainage Divide Wandering, Conterminous U.S. Continental Divide; Carter, B.L., and Rice-Snow, S. 2001, Fractal characteristics of the Alaska Continental Divide). The Northern American Continental divide trace (Rice-Snow, 1997) shows characteristics of an inhomogeneous fractal curve having a fractal dimension of 1.08 for step sizes ranging from 20 to 560 km, and a value of 1.05 for coarser resolutions.



### **1.3 Controls on drainage divide placement/ form**

Parameters controlling the irregularity along the continental divide depend on the local environment of the region such as climate, topography, relief, geology and tectonics. Dury (1948) studied the migration of divides in the neighborhoods of Northampton and found readjustment of the streams to glacial interference. Harris and Mix (2002) suggest that regional climate change provides a mechanism for long term erosion of tropical South America and perhaps shaping the drainage basin. Detailed study of Karamana River and Nambiyar River basin reveals that geomorphic processes and drainage characteristics are markedly varied due to different climatic conditions (Aneesha et al., 2007, thesis unpublished paper). The Karamana River basin shows humid climate. This climate encourages more precipitation and results in streams, providing running water and, thereby, erosion of the basin surface.

The drainage divide of different regions experiences several phases of cycles of erosion and the irregularity along the divide evolves very slowly over long period of geological time. Thus the drainage divide show superimposed effects of climate and tectonic factors resulting in complexity in their general characteristics. The operation of several geomorphic processes during a single cycle of erosion introduces complexity along the divides. For example, in hot arid region wind is the dominant geomorphic process but fluvial process becomes very active at intervals when there is occasional heavy rainfall, thus controlling the divides.

On the other hand relief plays a primary role in determining complexity along the divide of that region. For example, fractal characteristics of the Alaska continental divide

illustrated that the lowland sections with scattered mountains characteristically have better integrated drainage systems, whereas lowland sections with moderately high rugged mountains have a poor drainage system (Carter et al, 2001). A better integrated drainage system produces less complexity along the divide than a poor drainage system. Also at Prince Edward Island in Canada, the drainage boundaries in hill regions show a higher degree of complexity than those in plain regions (Rice-Snow, 2009).

Besides climate and relief, nonuniform erosion due to geologic controls causes irregularities at the continental divide. Hasbargen and Paola (2000) proposed that instability of drainage lines could be explained in terms of differential resistance to erosion. Drainage divides which display sharp changes in direction or extreme asymmetries may also be indicative of structural influence. For example, in northwestern California, drainage patterns follow fault zones and channel confinement is influenced by structural controls (Madej, 2003).

The degradation process is also conditioned by the resistance of the rock. Resistance varies with rock's chemical composition, its structure relationships and the local climate. For instance, Karamana basin in west coast of India shows resistant character of lithology resulting in low infiltration and therefore causing more runoff (Aneesha et al., 2007, unpublished). Furthermore, there are cases where river profiles are controlled by lithology. For instance, Summerfield (1995) advocated that at the continental scale the steep gradients of the lower reaches of many African rivers and the presence of major knickpoints such as the Victoria Falls on the Zambezi, the rapids on the Zaire, the Augrabies Falls on the Orange, and the Ruacana Falls on the Kunene, imply

a continuing adjustment of the fluvial system to crustal deformation and the role of lithology in maintaining discontinuities in river long profiles. Rice-Snow (2004) proposed that segments of U.S. continental divide traversing through sedimentary bedrock display lower degree of wandering than those traversing igneous–metamorphic and mixed lithologies. However, for the present study, bedrock geology is not studied. Geology traversing through segments of the continental divides includes more than one segment making it difficult to construct definite divisions.

Some studies indicate that shifts of the drainage divide may be tectonically controlled. Tectonic events such as uplift, subsidence, folding and faulting are important factors for creating irregularity along the drainage divide. The complexity along the drainage divide is typically caused by changes in base levels of erosion. These are caused by negative or positive changes (fall or rise) in sea levels, which are in turn, a result of tectonic events, such as subsidence of coastal land or rise of floor, or due to subsidence of the sea floor.

Tectonic movement influences rivers, for example, in first case across the course of a large river if land is uplifted, the river continues in its course by cutting an antecedent gorge. In second case if a river is back-tilted, it cannot run uphill and so is reversed. From these two cases it is observed that the Upper Murray in southeast Australia cut antecedent gorges across uplifting fault blocks whereas the coastal rivers are reversed by back tilting with massive reorganization of the drainage (Ollier, 1995). Major divides are not only formed by uplift but also by subsidence. For example, subsidence of the Murray Basin in southeast Australia diverted rivers from flowing north to the Eromanga Basin rather than the uplift of the Canobolas Divide (C.D.Ollier, 1995).

In the Alps the shifting of the drainage divide is considered to be tectonically controlled (Kuhlemann, 2001).

Drainage divide in some regions is associated with erosional escarpment. Measurements of 24 escarpments suggest that sinuosity, and the rate at which it increases, depends upon the location of maximum uplift, the geometry of the preescarpment drainage system, and margin age (Ari et al., 2002). The study shows that the role of age in determining escarpment sinuosity is expressed by the distinction between the average sinuosity of passive margin escarpment and continental rift escarpments. The result is the passive margin escarpments have sinuosity values in the higher end of range 2.8 to 0.7 whereas the continental rift escarpments have sinuosity values in the lower end ranging from 1.8 to 0.8. From these results, we can see that escarpment sinuosity reflects the type of margin (that is arch or shoulder type), local lithologic and structural conditions and age to the development of great escarpments. The study shows that the continental rifts with shoulder type margins have low sinuosity values ranging from 1.0-1.9 while arch-type margins have wide range of sinuosity values ranging from 1.2-3.5. The higher sinuosity value of arch type margins compared to shoulder type margin suggests that margin's type influences escarpment sinuosity by determining the frequency of large escarpment-crossing, and thus sinuosity producing, drainage systems. Escarpment with an arch type passive margin allows more possibility for high sinuosity of the drainage divide trace, than would a shoulder type margin (Matmon et al., 2002).

Ollier's (1995) work on the Great Divide of Southeast Australia found that in places the drainage divide has moved from its original tectonic position as a result of headward erosion of rivers, which has created a Great Escarpment, with occasional river capture or diversion. Dumitru et al. investigated the evolution of mountain belt in southeast Australia and concluded that there had been uplift and erosion along the east and south coastal regions, and that uplift and erosion were much less in areas 100 km inland (C.D.Ollier, 1995). In addition, Nott et al. (2000) observed northeastern Australia continental drainage divide has remained stationary since the Middle Jurassic. This result (Nott et al., 2000) was found to be contrary to models of the evolution of highlands adjacent to passive continental margins which results in irregularity along the continental divide.

In addition, the uplift associated with the peripheral bulge produced by sediment loads may provide tectonic feedback mechanism that affects drainage divide (Driscoll and Karner, 1993). Wegmann et al. (2007) proposed a new analysis that quantifies the differences between the location of the present-day drainage divide from divides synthetically generated from filtered topography to determine the relative impact of tectonic and dynamic mantle influences on landscape development. For example, drainage divides within the greater Yellowstone region synthesized from topography filtered at 50, 100, and 150 km wavelengths show that the locations of these divides are controlled by both dynamic and flexural mechanisms in the eastern greater Yellowstone region, while in the western greater Yellowstone region they are controlled only by flexural mechanisms. The location of the actual divide deviates from its predicted

position in the filtered topography where tectonic controls, such as active faults (e.g., Centennial and Teton faults), have uplifted large footwall blocks.

There are observations indicating that drainage divide connecting Mulki Lake on the west coast and Pulicat Lake on the east coast in India is still undergoing compression and uplift, related to the north-south oriented regional stress field (Subrahmanya, 1996). During late Dockum time onward, the drainage divide separated two basins approximately in the vicinity of central New Mexico due to tectonic controls (Riggs et al., 1997). The drainage divide of the Zhujiang River in China follows important active tectonic zones (Li, 1996). Comparable evidence from Australia and the Appalachians suggests that many apparent anomalies in large scale drainage patterns may be attributable to long-lasting or resurgent crustal influences (Boom, 1998). Vertical epeirogenic displacement might influence drainage networks, river terraces, lake shorelines, and many other geomorphic features.

#### **1.4 Study Objective**

Many researchers have considered different controls affecting map view forms of drainage divides. None have attempted a comparative evaluation of several controls affecting the map-view complexity of continental divides worldwide. The present study aims to identify and integrate possible factors affecting the degree of irregularity of continental divides, as expressed by their fractal characteristics. This study will have two goals:

1. To evaluate three factors causing irregularity along the traces of continental divide for five different continents. The factors to be studied are: climate, relief and tectonic environment.
2. To evaluate the relationship between the fractal dimension and uplift rate of each mountain range to be studied.

## **2. Methodology**

### **2.1 Database**

In this study, traces of six continental divides and associated tectonics environment and topography are delineated from the National Geographic Atlas of the World and the Atlas of World Physical Features respectively. The climate of each continent is derived from Maps of World ([www.mapsofworld.com](http://www.mapsofworld.com)). Data regarding the geomorphology of each continental divide are collected from Wikipedia ([www.wikipedia.org](http://www.wikipedia.org)), Britannia ([www.britannia.com](http://www.britannia.com)) and World Atlas ([www.worldatlas.com](http://www.worldatlas.com)). The continental divide segments are digitized by hand from map printouts using Rockworks software in point mode. The average map distance between two digitized points is 15 km.

### **2.2 Divider Method**

The divider method is one of the principal methods of fractal analysis. This method of analysis, and the one used in this study, was put forth by Richardson (1961). In brief, the length of a wiggly line on a map is measured by walking a map divider along it with divider points set at a particular spacing (Richardson, 1961). In general the measured line length becomes greater as finer point spacing is used, taking minute details of wiggles into consideration. Richardson used this method for determining the irregularity along coastlines and other national boundaries and constructed a log–log plot of estimated total length against step length, with results approximating straight lines

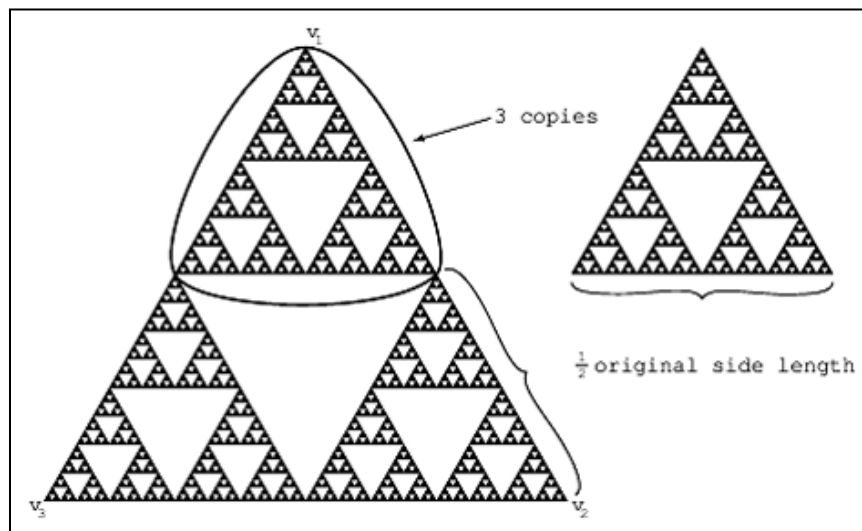


with finite slope. Such a plot provides a spectrum of degree of trace irregularity at various scales. Though Richardson did not assign any particular value to the plot's finite slope, Mandelbrot (1967) proposed that the slopes of linear Richardson plots estimate the fractal dimension ( $D$ ). He indicated that such a result expresses the statistical self-similarity that is characteristic of a fractal curve, with the slope of the plotted line equal to  $1-D$ , where  $D$  is the fractal dimension of the wiggly line on the map. Thus, a Richardson plot gives test both for fractal character in the basin boundary curve and an estimate of the fractal dimension,  $D$ .

For diverse natural and anthropogenic phenomena,  $D$  value has been estimated using divider analysis, for example, Mandelbrot (1975); Longley and Batty (1989); Andrieu (1994) Mark and Aaronson (1984). Analyzing these plots raises question regarding the character of true self-similarity. True self-similarity is most often applied to mathematically created data sets, which include some types of wiggly lines (Matthew et al., 2004, unpublished). Xu et al., 1993 considered self-similarity as scale invariance or scale independence where each small portion, when magnified, can reproduce exactly a larger portion. Stanley (1986) divided fractals into exact fractals and statistical fractals (Xu et al., 1993). According to his interpretation, exact fractals, considered as regular fractals that show self-similarity, are not expected to appear in nature. Statistical fractals display fractal characteristics when average properties are examined, are statistically self-similar, and can appear in nature (Xu et al., 1993). For example, on an average certain fern leaves have been shown to be self similar; even though every single fern leaf is not a

fractal (<http://www.brotherstechnology.com/docs/fractals.pdf>). On an average, elements of this natural structure are similar under magnification.

So there are basically two types of fractals, artificial fractals demonstrate exact self-similarity over a long or infinite range of scale whereas natural fractals typically exhibit an average self-similar character over a limited range of scale. An artificial fractal form is sierpinski gasket. It can be seen from the image given below that this structure can be explicitly constructed to obey self-similarity over a varied range. Natural fractal forms for example lighting, coastlines, rivers, etc demonstrate a limited range of self-similarity. Outside this scale range, the self similarity either ceases to exist or starts with different  $D$  value over another range of scale. In the divider method used in this thesis, this is revealed as scatter plots that are grouped into two or more parts with distinct slopes corresponding to their  $D$ -values, on the Richardson plot.



**Figure 2: Sierpinski Gasket**

The divider method was originally a manual process with a paper map or scaled representation of a feature, or the feature itself, and physical set of map dividers. The divider is set to a constant length size and walked along the feature from the starting point until the end point of the feature reached. The biggest limitation with this manual method was the limited number of step sizes that could be measured practically. Computer technology has made this data collection burden easier and addressed some issues of accuracy. To have results accurately measured in a Richardson plot, it is important to collect large number of estimated curve lengths for various step sizes. The more data points on the plot, the better the true nature of the relationship will be revealed.



**Figure 3: Digitizing Table**

One main difference between the manual divider method and the computerized divider method is that the manual method analyzes points from the continuous curve, while the computerized divider method analyzes a curve represented by a series of digitized points that make up the line (Matthew et al., 2004).

### **2.3 Divider Method used in this Project**

Rockworks software provides an essential tool in analyzing features using the divider method. The software supports digitization of point along the curves. The digitized data is then opened in Microsoft word and fed into the FORTRAN program Divider2. Divider2 is written in- house by Professor Scott Rice-Snow. It is not a commercial program. It will test any number of step sizes specified by user. For each step size it does 50 random walks to the two end points. This emerges with average results avoiding chance inclusion of non-representative length estimates, especially for large step sizes. This software has eased the burden of creating a Richardson plot. Inputs include the smallest step length, the longest step length, number of different step lengths used in the fractal analysis and a four digit large odd integer. The purpose of large integer is to seek random numbers for placement of walk starting points. The above control values used for these analyses are kept the same for all analyses in this study. With the spacing between the digitized points being approximately 40 km, the minimum step size of approximately 10 km and the maximum step size of approximately 1000 km. The minimum step length is approximately 32 km and the maximum step length is

approximately 330 km. Number of different step lengths used in the fractal analysis is 40-60 data points and the 4 digits large odd integer is 9999.

The output of the program records the step size, the average estimate trace length and the minimum and maximum lengths calculated for each step size. The log converted data values are then plotted using Microsoft Excel (MS Excel) and the plots are interpreted for relationships, one of which includes the estimation of D. The plot  $x$ -axis corresponds to the log step length in km and the  $y$ -axis to log estimated trace length in km. Richardson plot slopes for each continental divide are calculated with MS Excel and are used to estimate D values. Linear plot segments are initially identified by visual inspection. Linear regression is performed on those plot segments using an MS Excel routine. The pattern of residuals around best fit lines is inspected to evaluate linearity. In certain cases, the Richardson plot is found to be piece-wise linear. In these cases, linear regression is performed on each segment resulting in multiple D values.

## **2.4 Classification of segments**

For the study, each factor has been divided into different zones; each including different segment traces. The present study considers factors at continental scales, excluding the micro-details for each continental divide traces. As a result, they have been divided into the following categories.

Climate has been divided into four major zones namely tropical, temperate, arid and polar. Tectonic settings are classified into ongoing ocean-ocean convergence,

ongoing ocean-continent convergence, ongoing continent-continent convergence, ancient convergence, extensional, passive margin and stable plate interior. Relief has been divided into three categories: mountains, hills and plains.

## **2.5 Summary Data plots**

Graphs are plotted for each control factors, with X- axis showing control categories such as climates, relief and tectonic settings and Y-axis with the fractal dimension of continental divide traces. A mean value is computed and considered for all categories that include three or more points. For the uplift rate, actual values of the uplift are considered.

The co-efficient of determination ( $R^2$ ) is applied to the uplift plot to determine how well the regression line fits the actual data points. It is the coefficient of correlation between the outcome and the values being used for prediction, and its value varies from 0 to 1. The  $R^2$  value is calculated using MS Excel to evaluate the strength of the relationship between the uplift rate and the fractal dimension (D). An  $R^2$  value of 1.0 or close to 1.0 would indicate that the regression line perfectly fits the data. This means that there is a strong relationship between the uplift rate and fractal dimension. A value less than 0.5 would indicate that the resulting line is not a strong control of fractal dimension.

### **3. Geomorphic Environment**

#### **3.1 Africa**

Africa is the second largest continent on our planet. In the north the continental divide is that between the watersheds of the Nile and the Congo; in the west, the divide is deflated by the Great Rift Valley, and in the south of the continent, the divide is between the watersheds of the Congo, Zambezi, Limpopo, Okavango and Orange Rivers. The African continental divide as depicted in map is found to be running through Rifted shields in the north and northeast, Gondwana shields in the southwest, and Caledonian and Hercynian remnants in the extreme south. According to climatological-morphological zones, the northern part is in arid zone with uneroded plains, sand deposited plains, and alluvial fan development. The northeast and southwest part is a marginal tropical zone with extensive plain development. The extreme southern part is a mixture of a subtropical zone with mixed relief formations and extra-tropical zone with less extensive valley formation (National Geographic Atlas of the World and the Atlas of World Physical Features).

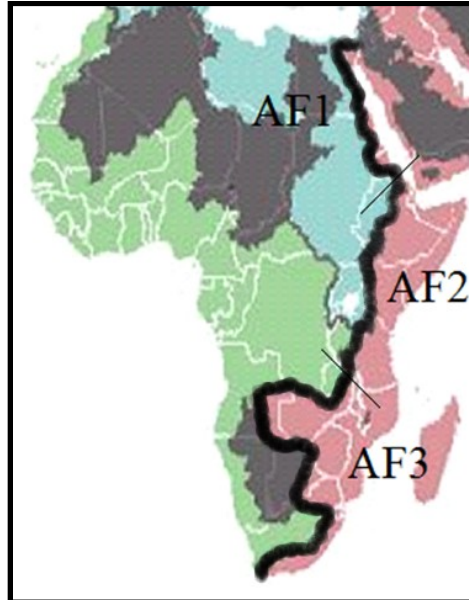
##### **3.1.1. Tectonics**

In the case of Africa, the present landscape is very much a product of the breakup of Gondwana and the tectonic processes associated with this event. The other major influence since the creation of Africa as a distinct continental block has been the

continuing events of rifting and volcanism that have occurred. Such tectonic mechanisms account for certain specific characteristics of present-day Africa. One is the series of broad upwarps rising to altitudes of several hundred meters or more above the surrounding terrain. These are evident as the long recognized marginal upwarps which run parallel to the coastline in several areas and which are bordered on their seaward side by sharp topographic discontinuity in the form of a major escarpment, or series of escarpments. The central part of the African drainage divide runs along the East African rift system which represents the spot of initial continental rifting and active volcanoes. In the East African Rift System, the upwarps and volcanism provide some support for active rifting mechanism. The African drainage divide runs along the major faults except for the central part.

For the present study African continental divide has been divided into three segments: northern, central and southern.





**Figure 4: African Continental divide**

### **3.1.2. Northern Segment**

The northern region through which the continental divide runs shows mixture of recent alluvium, well-consolidated sedimentary rocks along with weakly consolidated sedimentary rocks, ancient metamorphic and associated intrusive igneous rocks and fine-grained ashy or glassy extrusive igneous rocks. The northern segment lies in an arid to semi-arid region. Due to this type of climate, high rate of evaporation takes place with slight and irregular rainfall leading to low to moderate stream frequency. This results in formation of desert areas. Topographical regions traversed by the northern segment include plains, hills, and low tablelands and widely spaced mountains. It shows area of major and minor faults along the continental divide. The northern segment runs along the rift valley. Also this segment is part of arid regions which are without surface drainage.

### **3.1.3. Central Segment**

The central segment through which the continental divide runs shows extrusive igneous rocks and ancient metamorphic and associated intrusive igneous rocks. The central region traversed by the African continental divide experiences semi-arid to tropical wet and dry climate. High stream frequency is found in these areas of the central segment as it receives considerable amount of rainfall. This results in rivers flowing at some time every year on the surface, even if it is for a few days and then draining into interior basins becoming part of areic regions without surface drainage. Soils in this segment are tropical ferrallitic which have limited capacity to hold available water which explains to their stream frequency to be moderate to high. The central segment continental divide runs along Great Rift Valley in east Africa. Topographically, this segment lies in widely spaced mountains.

### **3.1.4. Southern Segment**

The continental divide running through the southern segment shows mixture of ancient metamorphic and associated intrusive igneous rocks, weakly consolidated sedimentary rocks, mixed or intermingled rock types and well consolidated sedimentary rocks. Climatically, this segment experiences tropical wet and dry, semi-arid to subtropical dry summer, and humid oceanic. The southern segment shows regions of low to moderate stream frequency because of low precipitation. The southwest segment through which the continental divide runs is areic without surface drainage. Soils observed are reddish to gray desert margin soils of the tropics, tropical ferrallitic soils,

and undifferentiated mountain soils. Extreme parts of the southern segment show areas of folded mountains known as “Great Karoo” and major faults along the continental divide. Topographical regions traversed by southern segment include hills and mountains.

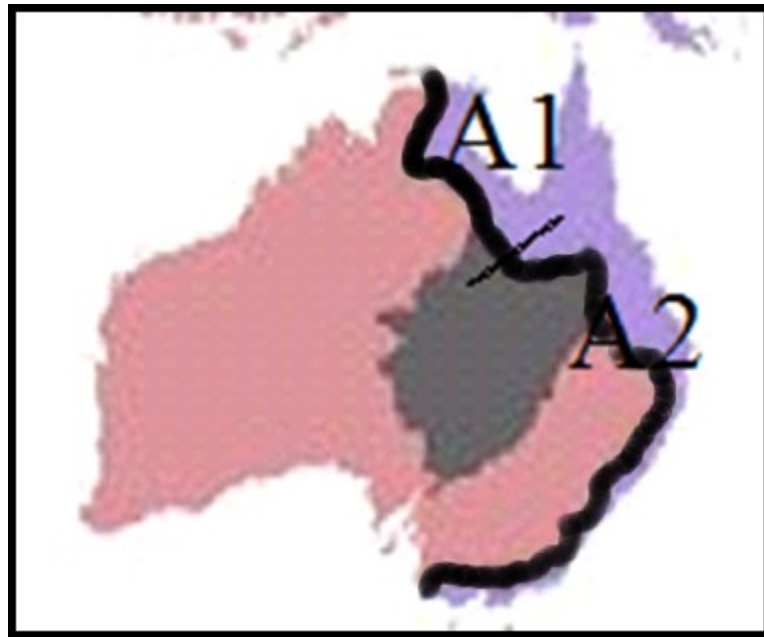
### **3.2. Australia**

In the northeast, the continental divide is that between the watersheds of Burdekin-Belyando and Dawson and in the south the divide runs along the watershed of Murray-Darling. The Australian continental divide is found to be running through Gondwana shields in the northwest, sedimentary rocks in the northeast, and alpine system in the northeast and south southeast. According to climatological – morphological zones the north northwest part and the northeast part of the continental divide are in a marginal tropical zone with extensive plain development. The central part is an arid zone with uneroded plains, sand deposited plains and alluvial fan development. The southeast region is a subtropical zone with mixed relief formations, and the extreme southern portion is an extra tropical zone with less extensive valley formation.

#### **3.2.1. Tectonics**

Australia has experienced geological forces such as tectonic uplift of mountain ranges in its early history. With its present location being in the middle of the tectonic plate, it does not show active volcanism; although, it experiences minor earthquakes.

For the present study the Australian continental divide has been divided into two segments; the northern and southern parts.



**Figure 5: Australian Continental divide**

### **3.2.2. Northern Segment**

The northern region through which the continental divide runs shows a mixture of intermingled rock types and well consolidated sedimentary rocks. The northern segment lies in semi-arid region formed by rain shadows as a result of eastern highlands which block the path of moisture and precipitation. Thus, the frequency of streams is moderate. The extreme northern part experiences tropical wet and dry climate. Topographical regions traversed by the northern segment include plains, hills, and low tablelands.

### **3.2.3. South Segment**

The southern segment shows areas of complex folds and major faults along the continental divide. This region traversed by the Australian continental divide experiences a humid subtropical climate resulting in high stream frequency, with associated karst development. Topographical regions traversed by the south segment mainly consist of mountains. Australia's high escarpment in the southeast region is associated with an arch type of passive margin.

### **3.3. South America**

In South America, the continental divide runs along the Andes, but the divide does not run along the highest peaks of the mountain system. In the north, the continental divide is that between the watersheds of Magdalena and Orinoco, in the west, it is between the watersheds of Amazon, Lake Titicaca and Salar de Uyuni and Parana and in the south the continental divide lies between the watersheds Rio Colorado and Chubut. Traces of the South American continental divide are found to be running through the Alpine System. According to climatological-morphological zones, the northern part is in a marginal tropical zone with extensive plain development. The central part through which the continental divide runs lies between marginal tropical zone with extensive plain development and subtropical zone with mixed relief formations, and the southern part lies in extra-tropical zone with less extensive valley formation.

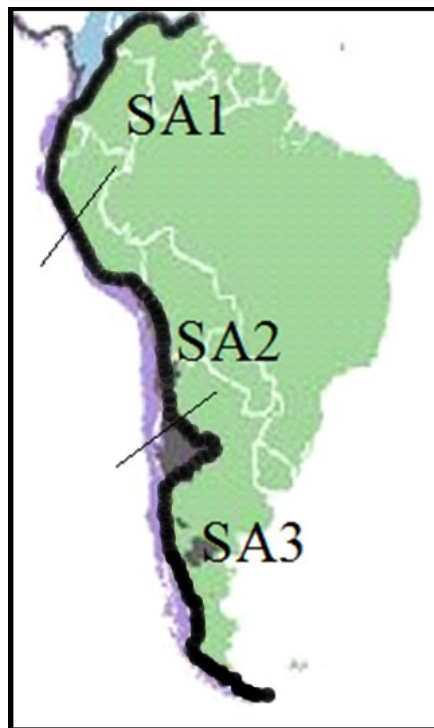
### **3.3.1. Tectonics**

Endogenic and exogenic forces have been at work over the long geological history of the continent. This brought about many drastic changes in its shape and relief, leading to its present surface and structural characteristics. The tectonic evolution of the Andes extends back into the Paleozoic with terrain accretion dominating up to the Mesozoic. When the sediments were uplifted by the earth's crust movement, they were intensely folded and faulted, thus forming the ranges of the Andes. The present mountain belt was developed mainly during Mesozoic to Recent as a result of the east dipping slab and the opening of the Atlantic Ocean.

According to early hypotheses, the formation of the Andes through which the continental divide traverses was considered due to crustal growth by magmatic processes. Though there are evidences supporting structural shortening which are limited to the Eastern Cordillera and the Subandean fold and thrust belt. In the Altiplano, which lies in central South America and is the most extensive area of high plateau and Western Cordillera, crustal structures are obscured by sedimentation or volcanism (Montgomery et al. 2001). Overthrusting from east to west seems to have been responsible for the elevation of the eastern Peruvian ranges. The entire system is, therefore, the result of a long series of changes, some cataclysmic, others operating more slowly and persistently (Carlson, 1952). After occurrence of cataclysmic processes a long period of modification and weathering interceded before another disruption took place. The result is a very complexly folded system. The northern Andes are a high seismic area, as are some parts

the central and southern part of Andes. The Andes are dominated by volcanic peaks of impressive height - for example, Mount Aconcagua rises to a height of 22,835 feet (Snead, 1972). The Andes run through active volcanoes such as at Mount Cotopaxi in the north segment and Mount Aconcagua toward the south.

The continental divide has been divided into three segments: northern, central and southern.



**Figure 6: South American Continental Divide**

### **3.3.2. Northern Segment**

The northern region through which the continental divide runs shows mixed or intermingled rock types, mainly areas of complex folds and faults. The extreme north of the segment experiences tropical wet and dry climate resulting in high stream frequency while the northwest segment observes a semi-arid climate which results in low-moderate stream frequency. Topographical regions traversed by the northern segment include mountains and depressions or basins. This segment is deflated by a rift valley. It is also associated with a major limestone region. It is a humid landform area where erosional features such as cirques are dominant.

### **3.3.3. Central Segment**

Structurally the central regions also shows the dominance of extrusive igneous rocks such as fine grained, ashy or glassy and mixed or intermingled rock types. Topographical regions traversed by the central region are mountains and experience a highland type of climate where temperature and precipitation vary with elevation. Depression results from a rift valley. Dry or arid landforms areas are found west of this segment in the “Atacama Desert.”

### **3.3.4. Southern Segment**

This region is mainly an area of complex folds and faults with mixed or intermingled rock types. Topographical regions include mountains, hills, and low tablelands. Southwest region shows depressions caused by a rift valley. This segment lies



in a humid oceanic region which encourages moderate precipitation with high stream frequency.

### **3.4. Eurasia**

Eurasia is a large landmass comprised of traditional continents of Europe and Asia. In the northwest of Europe, the continental divide is that between the watersheds of Dalalven, Glomma-Laagen, Kemijoki, Lake Ladoga and North Dvina and in the southwest the divide is between Tagus, Duero, Garonne, Loire, Seine, Rhine and Maas, Weser, Elbe, Oder and Daugava. In the central region of Eurasia, the continental divide runs between the watersheds of Volga, Ob, Yenisey and Lena and in the northeast of Asia the divide lies between Kolyma and Indigirka.

The trace of Eurasia continental divide as illustrated in map the is found to be running through Caledonian and Hercynian remnants, Laurasian shields and Sedimentary covers outside shield exposures northwest of Europe; in the central region, the divide runs through Sedimentary covers outside shield exposures, and Caledonian and Hercynian remnants, and in the northeast, and southeast of Europe runs through the alpine system.

According to climatological- morphological zones, the northwest and southwest of Europe, Central region and Northeast of Asia lies in extra-tropical zone with less extensive valley formation; the extreme region southwest of Europe lies in subtropical zone with mixed relief formations; the extreme region northeast of Asia experiences

subpolar zone with extensive valley formation and southwest of Asia lies in marginal tropical zone with extensive plain development.

### **3.4.1. Tectonics**

Europe is characterized by great variety in the age of its structural elements and their development. Presently, Europe comprises various crustal blocks which have been assembled over geological time. There is a fragment of the late Proterozoic continent of Laurentia, initially a part of a North American-Greenland landmass in the extreme northwest of Europe. Generally, Europe's continental basement is divided into two large and distinct regions- in the north and east a stable Precambrian craton known as the East European Craton, and in the south and west a mobile belt, comprising crustal blocks that have become successively attached to the ancient cratonic nucleus (Plant et al.). In Europe, the precise locations of separate terranes, fault-bounded blocks of continental crust, usually smaller than microcontinents are poorly exposed and concealed beneath younger rocks. In addition, the change of older rocks in later orogenies has resulted in collages of relatively small shear zone defined terranes. Thus, the crystalline basement of western and central Europe comprises of a complex varied crustal elements, accumulated during various Precambrian orogenic cycles followed by the Phanerozoic Caledonian, Hercynian and Alpine orogenies. During this period of complex crustal evolution, prior consolidated crustal elements were repeatedly remobilized. Hence, the basement provinces of western and central Europe are defined by the latest orogenic event affecting

that portion of crust. This causes widespread metamorphic modification and in some cases the intrusion of calc-alkaline igneous rocks.

The oldest Precambrian basement provinces of western and central Europe comprise the East European and Hebridean cratons, the stable Cadomian blocks of the London Platform and the East Silesian Massif, and the Caledonian, Variscan and Alpine fold belts. The Caledonian orogenic cycle of Late Cambrian and earliest Devonian period reflects the collision of the late Proterozoic continents of Baltica, Laurentia and Avalonia, a part of Gondwana. Additionally, deformation of Caledonian fold belts is confined to outcropping Palaeozoic massifs (Plant et al.). Pre-Alpine basement rocks of Caledonian and Variscan and Hercynian age outcrop in scattered areas of Alps, and are most abundant in central Europe, where high grade crystalline rocks are exposed north of the extensive uplift and erosion caused by the Alpine orogeny. Data from the Alps indicate that there were at least two distinct major episodes of tectonic activity, one during the Cretaceous and a later one in the Tertiary convergence.

To the north of the Alps, a foreland basin had developed in late Eocene times, its depocenter migrating northward in response to loading and flexure of the lithosphere caused by the continental collision of Europe and Africa. To the south of the Alps, a foredeep in which syntectonic sediments accumulated was linked to the south-vergent thrusting in the southern Alps. The Alps continue to be altered by a crustal stress system, associated with crustal thickening. Central Alps rising topography is balanced by the beginnings of extensional collapse tectonics. Fold belts at the Alpine northern front of the

Alpine belt record the latest supracrustal trace of the Europe vergent collisional suture. Recent interpretations based on deep seismic data and geology shows thrust sheet involving pre-tectonised crust intruded by arc magma, overlain by Mesozoic passive margin sediments and Oligocene to Pleistocene foredeep fill. The convergence direction between Eurasia and Africa-Arabia gradually changed and was dominated by dextral translations during the Neogene and Quaternary period. This coupled with the development of intra-Alpine shear systems, the concentration of crustal shortening to the Western Alps (Plant et al.). Moreover, Northwestern Europe is tectonically more active, in terms of seismicity, vertical motions and volcanism (S.Goes et al. 2000).

Asia is the youngest and most structurally complex continent. The geomorphology of Asia exhibits an extremely complex geologic history that shows the active deformations largely responsible for the existing landforms. The Asian continent is considered to be the result of Cenozoic deformation and is associated with collisional tectonics. For example during the late Cenozoic period, the Tibetan Plateau uplifted and gravitational spread caused extension in the high Tibetan Plateau and compression in eastern China. Today gravitational spread is the dominant driving force for Asian tectonics (Zhang et al., 2006).

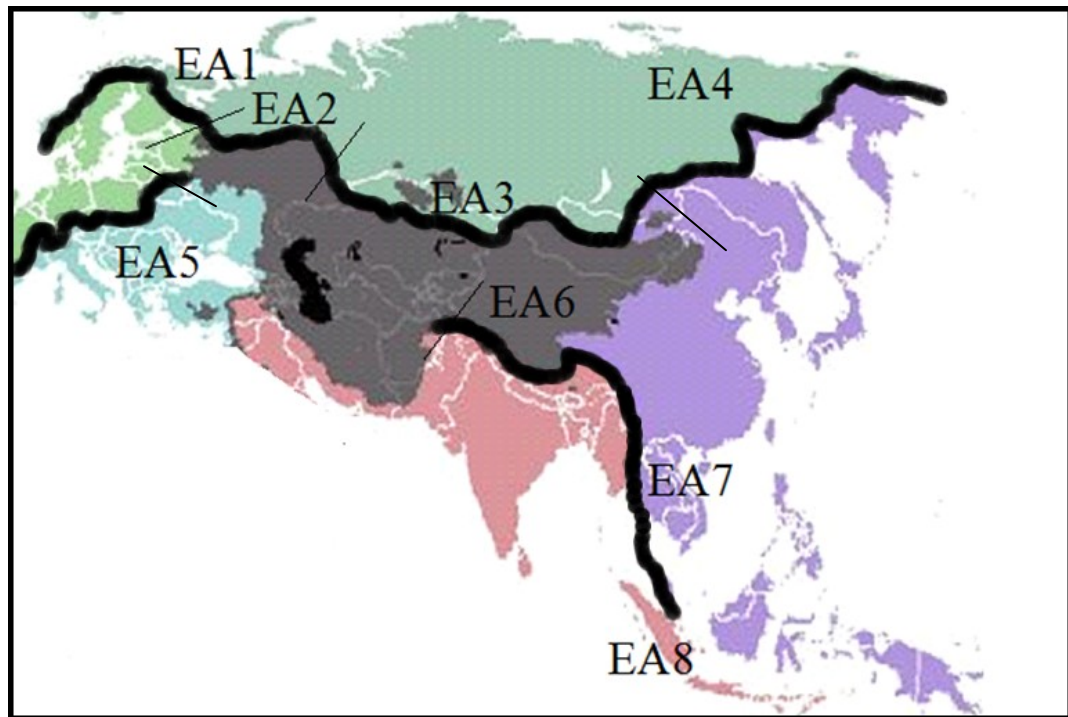
The mountainous terranes of Northeast Asia hold the key to the tectonic evolution of a major and geologically complicated region of the world. The tectonic development of the region results in a series of cratons, craton margins, oceanic plates, active rifts, and orogenic collages of the present day Northeast Asia continent. Tectonostratigraphic

terrane, which are composed of igneous arcs, accretionary wedge and subduction zone complexes, passive continental margins and cratons are overlapped by continental margin arc and sedimentary basin assemblages. The key events in the tectonic history of Northeast Asia are – (1) the formation of the North Asian Craton during the breakup of a late Precambrian supercontinent; (2) during the late Precambrian and early Paleozoic, establishment of an active subduction zone along the present day, southern margin of the North Asian Craton; (3) during the late Paleozoic, closure of oceans between Siberia, Baltica, Kazakhstan and north China; (4) during the Triassic and Jurassic, progressive closure of the Mongol –Okhotsk Ocean between Sino-Korean and the North Asian Cratons to form the core of present day North east Asia; (5) during the Late Jurassic through early Cenozoic, accretion of allochthonous terranes along the northern margin of the Northern Asian Craton, and along the margin of Eastern Asia; (6) for the first time in the early Cretaceous, formation of a continuous continental complex between the Russian Northeast and Northwestern North America; and (7) in the Cenozoic, formation of continental margin arcs and back arc basins along the entire Pacific facing margin of Northeast Asia (Warren et al., 2008).

Eastern Asia is situated along the strong continental earthquake belts. The continental earthquake belt is distributed randomly on eastern Asia and may reach a distance more than 2000 km from the boundary of plate collision. The current tectonic activity in Asia is the consequence of a continental collision between India and Eurasia. Continental reconstructions show steady convergences of India and Eurasia since the last

Cretaceous. Seismic data comprising the spatial distribution of earthquakes, associated fault plane solutions, and surface deformation and geologic evidence of recent tectonic activity imply deformation in a broad zone extending as much as 3000 km northeast of the Himalayas. Although in the late Cretaceous and early tertiary the boundary between Eurasia and India plates was probably relatively narrow, evidence suggests that deformation now is spread over a large part of Asia. Recent research consider most of the large scale tectonics of Asia to be a result of the India-Eurasia continental collision, which apparently not only created the Himalayas but also rejuvenated an old orogenic belt 1000km north of the suture zone ( Molnar et al., 1975).

For Eurasia the continental divide has been divided on the basis of relief Northwest of Eurasia (including Alps, Central low lying areas), Northeast of Eurasia and Southeast of Eurasia (including Himalayas, Islands arc in Sumatra and Malayasia).



**Figure 7: Eurasia Continental divide**

### **3.4.2. Northwest of Eurasia**

The northwest region through which the continental divide runs shows mixture of well-consolidated sedimentary rocks and ancient metamorphic and associated intrusive igneous rocks. The extreme south of northwest region through which the divide runs lies in humid oceanic climate which encourages moderate precipitation resulting into moderate to high streams frequency. The central part of the northwest segment as depicted in the map shows a mixture of two climates, humid continental and subarctic, consequently distributing precipitation throughout the year. The result is high stream

frequency. The northern northeast region experiences a tundra type of climate which results in permafrost. Topographically this region is traversed by mountains, hills and low tablelands. Also it lies in the vicinity of a major fault and rift valley namely Oslo graben. In the northwest region the continental divide runs through Kjolen Mountains which is a part of Caledonian belt.

The southwest region through which the continental divide runs shows mixture of weakly-consolidated sedimentary rocks, mixed or intermingled rock types and well consolidated sedimentary rocks. In the southwest region the continental divide experiences cool summer and semi-arid to the Marine West Coast, which is a humid oceanic climate, which encourages moderate precipitation throughout the year. Topographically this region is traversed by mountains and hills namely the Alps. The continental divide in this region runs along major and minor fault and also along a rift valley namely Rhine graben.

#### **3.4.3. Northeast of Eurasia**

The northeast region through which the continental divide runs shows mixture of rock types; mainly areas of complex folds and faults, and ancient metamorphic and associated intrusive igneous rocks. The northeast region of Asia through which the divide runs lies in humid and subarctic climate. The humid climate encourages precipitation distributed fairly evenly throughout the year. In the subarctic climate, most of the precipitation falls in the summer. This results in moderate stream frequency. Topographically this region is



traversed by mountains. It lies in the vicinity of major and minor faults. In the northeast region the continental divide runs through Kolyma and Cherskin mountains.

#### **3.4.4. Southeast of Asia**

The southeast region through which the continental divide runs shows mixture of rock types; mainly areas of complex folds and faults. This southeast part experiences a mixture of tropical wet and dry climate. In region of tropical wet climate rainfall is heavy resulting in high stream frequency. Soils in this segment are ferrallitic soils, undifferentiated mountain soils and tropical ferrallitic soils which have limited capacity to hold available water explains their stream frequency to be high. Topographically, this segment lies in mountains, hills and low tableland. Erosional feature cirque and fiords occurs in the Himalayas, which is a proof of mountain glacial erosion.

#### **3.5. North America**

North America is the third largest continent on our planet. In the north, the continental divide is between the watersheds of the Yukon and Mackenzie; in the central, the divide is between the watersheds of Fraser, Columbia, Mississippi, Colorado, Rio Grande and Brazos, and in the south of the continent, the divide is between the watersheds of Rio Grande de Santiago, Balsas and San Pedro and Usumacinta. The divide in Great Lake is between the watersheds of Mississippi, Nelson and Saint Lawrence. North American continental divide as depicted in the map is found to be running through Alpine system. According to climatological- morphological zones, the

extreme northern part is subpolar zone with extensive valley formation. The northern part is a mixture of a extra-tropical zone with less extensive valley formation and subtropical zone with mixed relief formations. The southern part is a marginal tropical zone with extensive plain development.

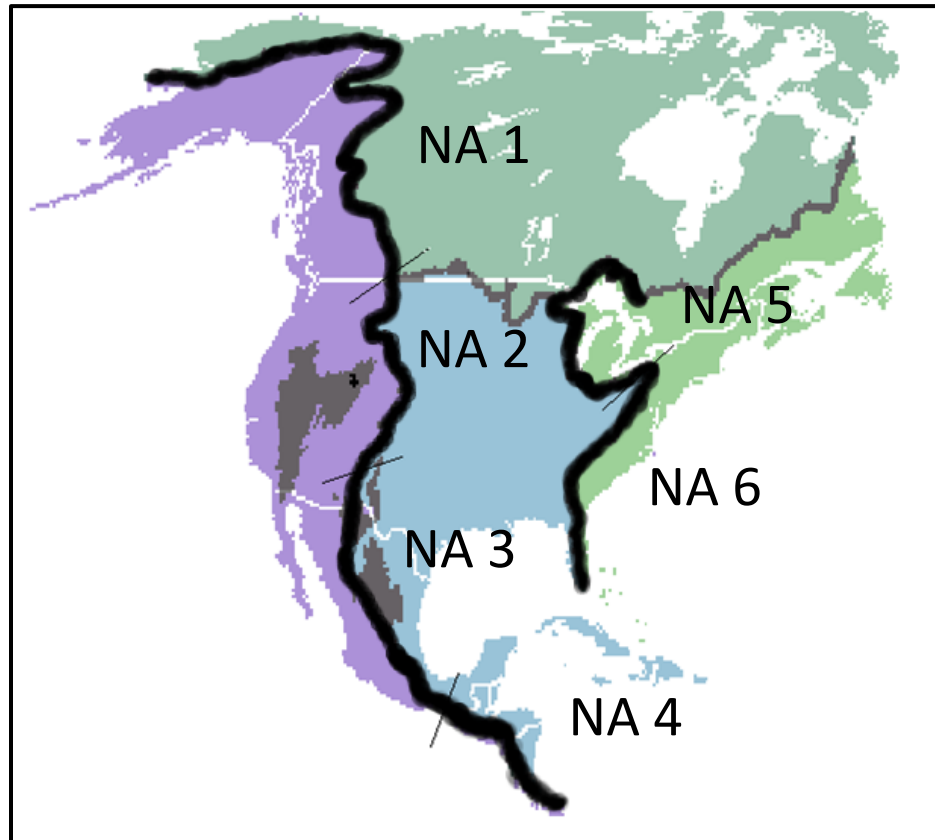
### **3.5.1. Tectonics**

North America is the largest fragment of a continent assembled in the Paleoproterozoic and since then has collided twice to form supercontinents, all continents gather together. The older collision is characterized by Mesoproterozoic (1600-1000 Ma) Grenville Orogen, and the resulting supercontinent Rodinia had an approximate age span of 1050-750 Ma. The younger supercontinent is Wegener's Pangaea, which had an age span of 300-150 Ma. Wegener's Pangaea was conjoined with North America along the Appalachian Orogen and its connections around the Gulf of Mexico (Ouachitas), East Greenland (Caledonides) and Arctic Canada (Franklin). North America was involved in most of the salient tectonic events of the past three billion years. The Rocky Mountains, Appalachian and the Gulf of Mexico and the Central America are the products of convergent margin tectonics (Reese et al., 1997). The tectonic history of western North America throughout most the opening of the Atlantic is marked by compressional tectonics (Bokelmann, 2002). The stress field at the western edge of the stable continent is currently compressional to the north of Montana up to Alaska, but the extensional Basin and Range in the western United States represents an exception in this large-scale

pattern. This exception is explained as an effect of internal gravitational forces (Jones et al., 1996), and it may occur even if there is compressional stress field acting from outside (Bokelmann, 2002).

Lithosphere of southern North America was built by progressive addition of a series of dominantly juvenile volcanic arcs and oceanic terranes accreted along a long-lived southern plate margin. During each episode of addition of juvenile lithosphere, the transformation of juvenile crust into stable continental lithosphere was facilitated by voluminous granitoid plutonism that stitched new and existing orogenic boundaries (Whitmeyer et al., 2007). Thus, Proterozoic history records a prolonged period of juvenile additions to the growing continent. Rocks exposed in central region of the continent record the formation of a rifted continental margin, sedimentation upon that newly formed margin and the development of an igneous arc as subduction processes formed new crustal materials that were added to pre-existing craton (Bickford et al., 1986). The orogenic system of the southern margin of the continent formed during a late Paleozoic collisional-subductional event, resulting in closure of the Rheic Ocean as the Laurentian Plate was subducted beneath a northward-advancing South American (Gondwanan) continental-margin arc (Poole et al., 2005).

For the present study North American continental divide has divided into 6 segments- Northern rockies, Southern rockies, Basin and range, Island arc, Great lakes and Appalachians.



**Figure 8: North America Continental divide**

### **3.5.2. Northern Rockies**

The northern rockies through which the continental divide runs shows mixture of rock types, well consolidated sedimentary rocks and fine grained, ashy or glassy extrusive igneous rocks. This segment lies in polar to continental climate. Due to this type of climate, precipitation is distributed fairly evenly throughout the year leading to moderate to high stream frequency. Topographical regions traversed by the northern rockies include mountains. It shows area of major and minor faults along the continental divide. This region is dominated by tropical ferrallitic soils which have limited capacity to hold water leading to high stream frequency.

### **3.5.3. Southern Rockies**

The southern rockies through which the continental divide runs shows mixture of rock types; mainly areas of complex folds and faults, well consolidated sedimentary rocks and fine grained, ashy or glassy extrusive igneous rocks. The southern rockies experiences semi-arid to arid climate while extreme southern region lies in tropical dry climate. Due to semi-arid to arid climate, high rate of evaporation takes place with slight and irregular rainfall leading to low to moderate stream frequency. This results in formation of desert areas. Tropical dry climate results in moderate precipitation. The result is moderate stream frequency. Topographical regions traversed by the southern rockies include mountains and widely spaced mountains. This region is dominated by gray desert margin soils and undifferentiated mountain soils which have porosity capacity to hold water leading to low stream frequency.

### **3.5.4. Basin and Range**

The basin and range through which the continental divide runs shows mixture of rock types, well consolidated sedimentary rocks and fine grained, ashy or glassy extrusive igneous rocks. This segment lies in semi-arid climate. Due to this type of climate, precipitation is not distributed evenly throughout the year leading to low stream frequency. Topographical regions traversed by the widely spaced mountains. It shows area of major faults along the continental divide. This region is dominated by desert areas which encourage active erosion due to less moisture content.

### **3.5.5. Island Arc**

Island arc through which the continental divide runs shows mixture of rock types and fine grained ashy or glassy extrusive igneous rocks. This segment lies in tropical climate. Due to this type of climate, precipitation is distributed evenly throughout the year leading to high stream frequency. Topographical regions traversed by the mountains. This region is dominated by undifferentiated mountain soils.

### **3.5.6. Great Lakes**

Great Lakes through which the continental divide runs shows well consolidated sedimentary rocks. This segment lies in temperate climate. This region is dominated by swamps, marshes and lakes along with moderate stream frequency. Topographical regions traversed by the hills and plains. This region is dominated by podzolic soils.

### **3.5.7. Appalachians**

Appalachians through which the continental divide runs shows well consolidated sedimentary rocks, ancient metamorphic and associated intrusive igneous rocks. This segment lies in temperate climate. Due to this type of climate, precipitation is distributed evenly resulting into moderate stream frequency. Topographical regions traversed by the hills and mountains. This region is dominated by red and yellow soils of the tropics.

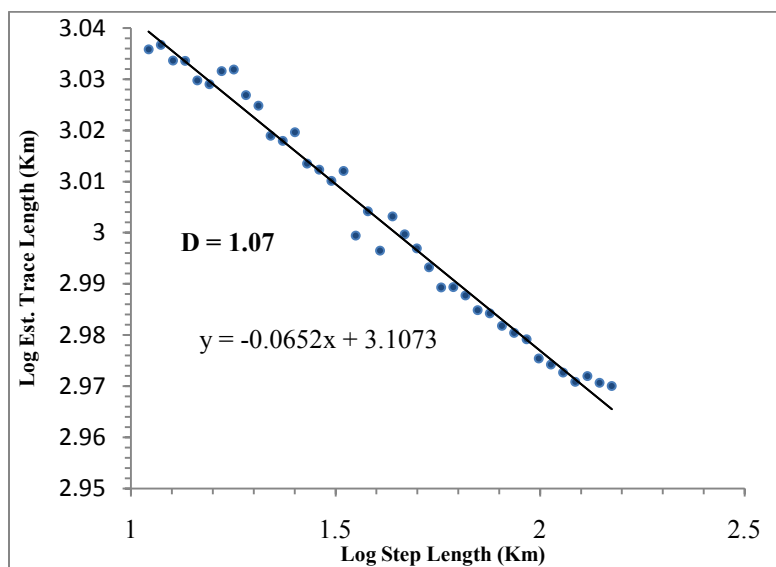
## **4. Evaluation of Results**

### **4.1. Africa**

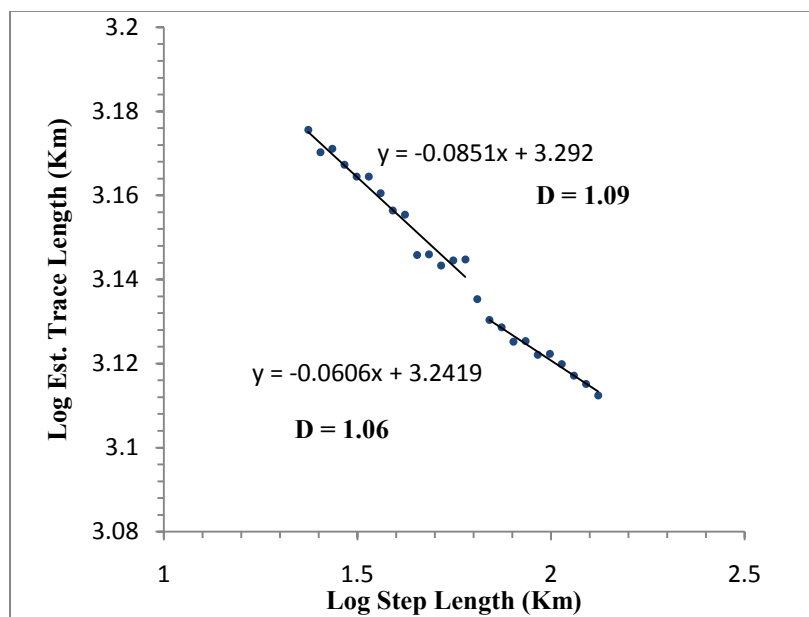
The African continental divide has been divided into three segments- northern AF1, central AF2 and southern AF3. The AF1 segment located north is homogeneous. The plot shows a linear fit line for entire data set. The slope of trend line is -0.07. The D value is measured for only linear fit line. The linear fit means this continental divide traces have similar geometry in scale. There is a small amount of numerical/experimental/ digitization error. This error manifests itself as departure of the points from the linear fit. The maximum departure from the fit is 0.09%. For uniformity, this departure is reported as a percentage of the absolute maximum value of the Log estimated trace length. The D value for the AF1 is 1.07.

The AF2 plot in the central part is divided into 2 sections each of which shows separate linear trend. The slope of trend line at fine scale is -0.09 and at coarse scale is -0.06. The maximum departure for this section is 0.29 %.

AF3 plot in southern region is homogeneous. This section traversing through folded mountains with major faults has characteristic D value of 1.11. The derived estimates of fractal dimension for African continental divide range from 1.06 to 1.11. In this case, higher D values within the region may be associated with mountainous topography.

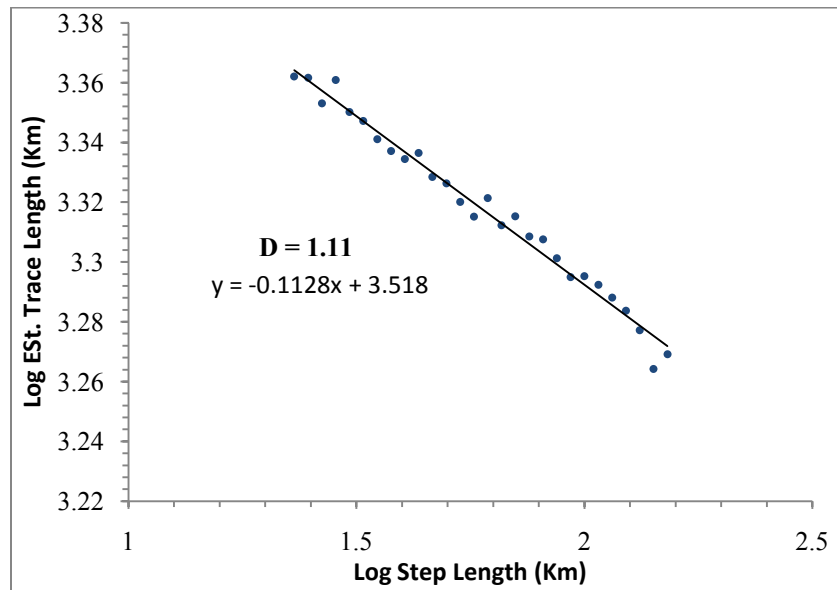


**Figure 9. Richardson plot for AF1 segment.**



**Figure 10. Richardson plot for AF2 segment.**



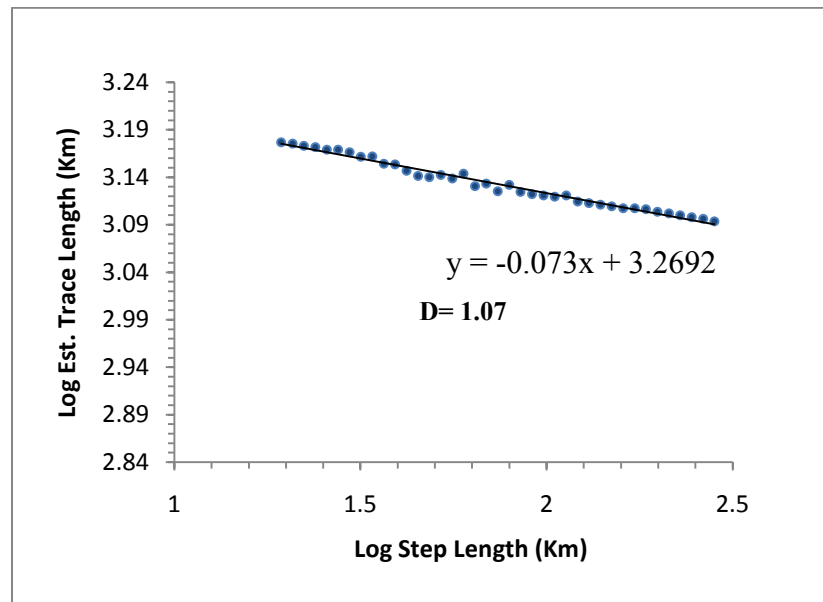


**Figure 11. Richardson plot for AF3 segment.**

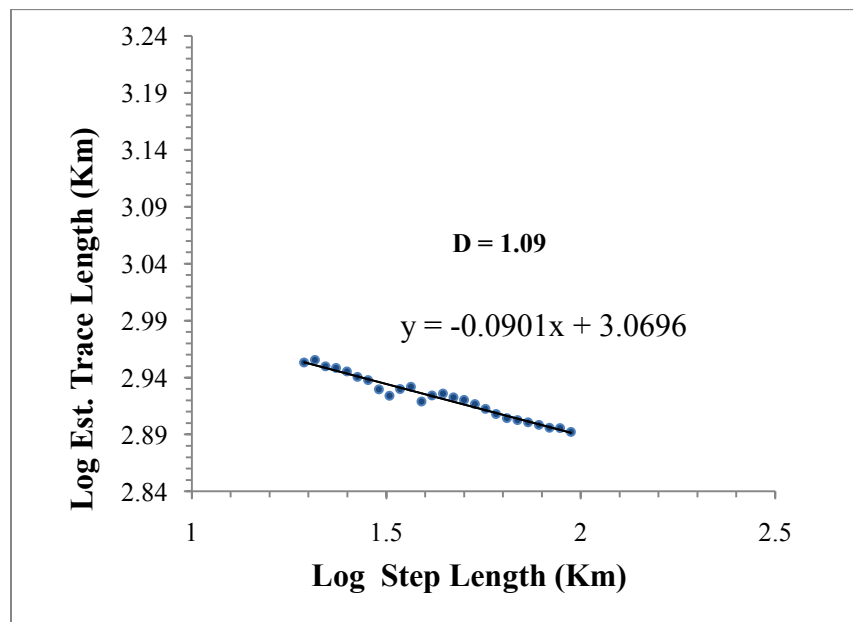
## 4.2. Australia

The Australian continental divide has been divided into two fragments; the northern part A1 and southern part A2. A1 and A2 are homogeneous plots. A1 segment has a slope of trend line  $-0.07$ . The maximum departure from the fit is  $0.09\%$ . The fractal dimension calculated for the A1 is  $1.07$ .

The slope of trend line for A2 is  $-0.09$  and the maximum departure from the fit is  $0.06\%$ . The fractal dimension calculated for the A2 is  $1.09$ . This indicates that the southern segment trace has higher degree of irregularity. The high fractal dimension may be correlated to the hill topography and temperate climate. The low fractal dimension for the A1 segments may be associated with low relief resulting in less complexity along the continental divide.



**Figure 12. Richardson plot for A1 segment.**



**Figure 13. Richardson plot for A2 segment.**

### 4.3. South America

The South American continental divide has been divided into three segments; the northern part SA1, central part SA2 and southern part SA3. SA1 and SA2 Richardson plots are divided into 2 segments each of which shows separate linear trend. The slope of trend line for SA1 at finer scale is -0.06 and at coarser scale -0.08. The maximum deviation from the fit is 0.07%. The fractal dimension calculated for the SA1 segment at finer scale is 1.06 and at coarser scale is 1.08.

The slope of trend line calculated for SA2 is -0.03 at fine scale and at coarse scale is -0.05. The maximum departure from the fit at fine scale is 0.21% and at coarse scale is 0.33%. The fractal dimension measured at finer scale is 1.04 and at coarser scale is 1.03.

SA3 Richardson plot is homogeneous and the slope of trend line is -0.04. The maximum departure from the fit is 0.33%. The fractal dimension calculated is 1.04. The South American continental divides not show much high degree of complexity along the traces.

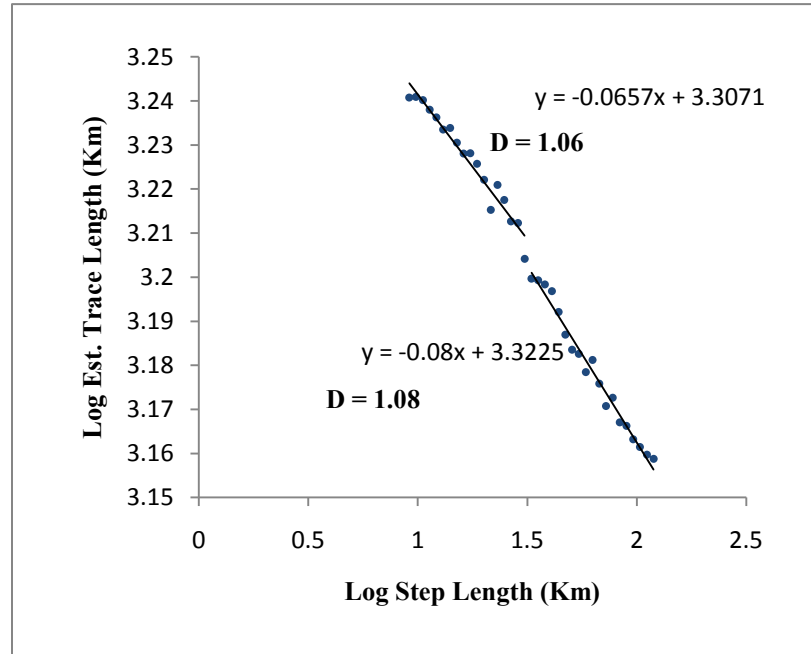


Figure 14. Richardson plot for SA1 segment.

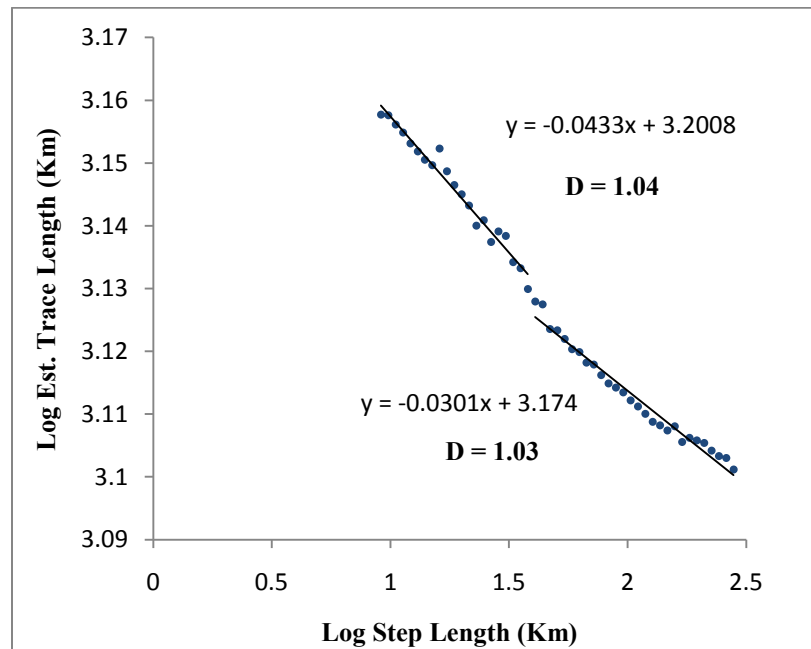
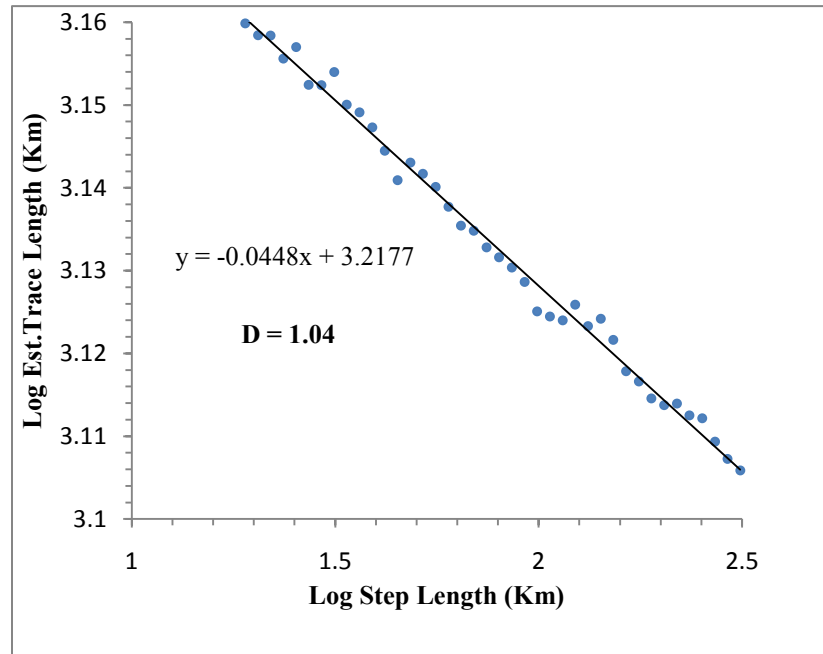


Figure 15. Richardson plot for SA2 segment.



**Figure 16. Richardson plot for SA3 segment.**

#### **4.4. Eurasia**

For Eurasia the continental divide has been divided into 8 sections – the northwest part EA1 and EA2, the central part EA3, the northeast part EA4, the southwest part EA5, the southeast part EA6, the island arc in southeast part EA7 and EA8.

The EA1 Richardson plot is divided into 3 sections showing a heterogeneous plot. Each of which show separate linear trend. The slopes of trend line for 2 sections are -0.02 and for the 3<sup>rd</sup> section are -0.01. The maximum departure from the fit for the first 2 sections is 0.12 % whereas for the 3<sup>rd</sup> section is 0.14 %. The fractal dimension for EA1 which is traversed by Kjolen Mountains is 1.02 at fine scale and 1.01 at coarse scale.

EA2 and EA3 is homogeneous plot with a slope of trend line of -0.15 and -0.19 respectively. The maximum error calculated from the fit for each of these sections is 0.15 %. The D values calculated for EA2 and EA3 are 1.15 and 1.19 respectively.

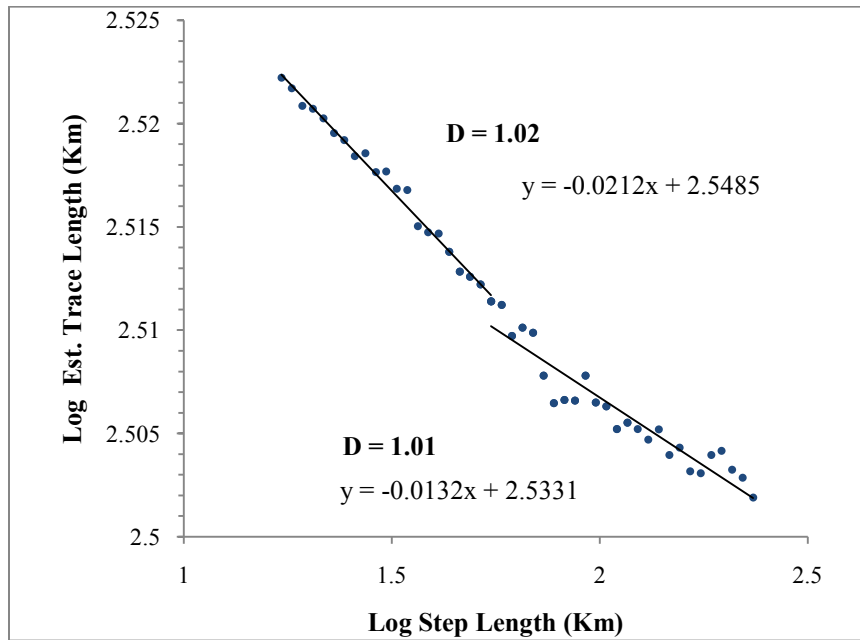
The EA4 Richardson plot is divided into 2 segments with separate linear trend of  $-0.09$  at fine scale and  $-0.12$  at coarse scale. The maximum departure from the fit is 0.11 % at fine scale and 0.04 % at coarse scale. The EA4 segment that runs through Kolyma and Cherskin mountains shows D value of 1.10 at fine scale and at coarse scale is 1.12.

EA5 section is divided into two linear segments with separate linear trends. The segment at fine scale shows a slope of trend line of  $-0.11$  and at coarse scale  $-0.18$ . The maximum departure from the fit at fine and coarse scale is 0.22 % and 0.05 % respectively. The D value calculated for the EA5 segment which is traversed by Alps is 1.11 and 1.18 at fine and coarse scale respectively.

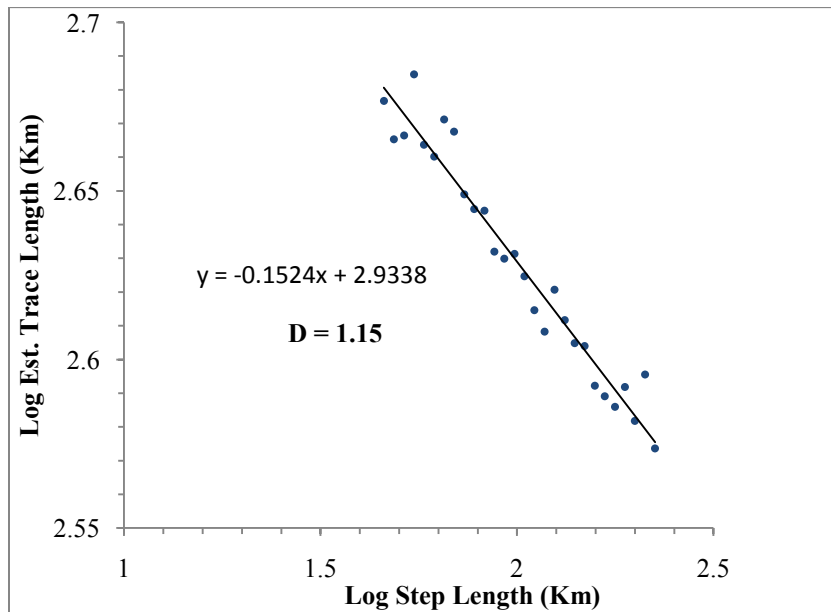
The EA6 section which is traversed by Himalayas shows a D value of 1.12 and 1.05 at finer and coarser resolution respectively. The estimated D value for an island arc EA7 running through Malayasia is 1.05 at fine scale and 1.03 at coarse scale. Furthermore, D value measured for an island arc EA8 running through Sumatra is 1.04 and 1.01 at fine and coarse resolution respectively.

Thus the higher values of fractal dimension may be associated with mountainous topography namely Alps in EA5, Himalayas in EA6 and Kolyma and Cherskin

mountains in EA4 of Eurasian continental divide. In addition to topography, tectonic events such as complex folds and faults may be correlated with the increase in D value.



**Figure 17. Richardson plot for EA1.**



**Figure 18. Richardson plot for EA2.**

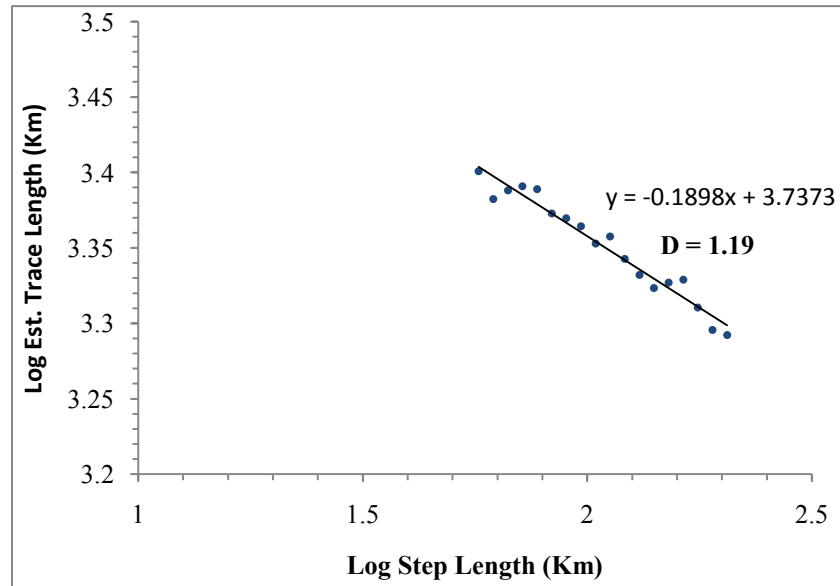


Figure 19. Richardson plot for EA3 segment.

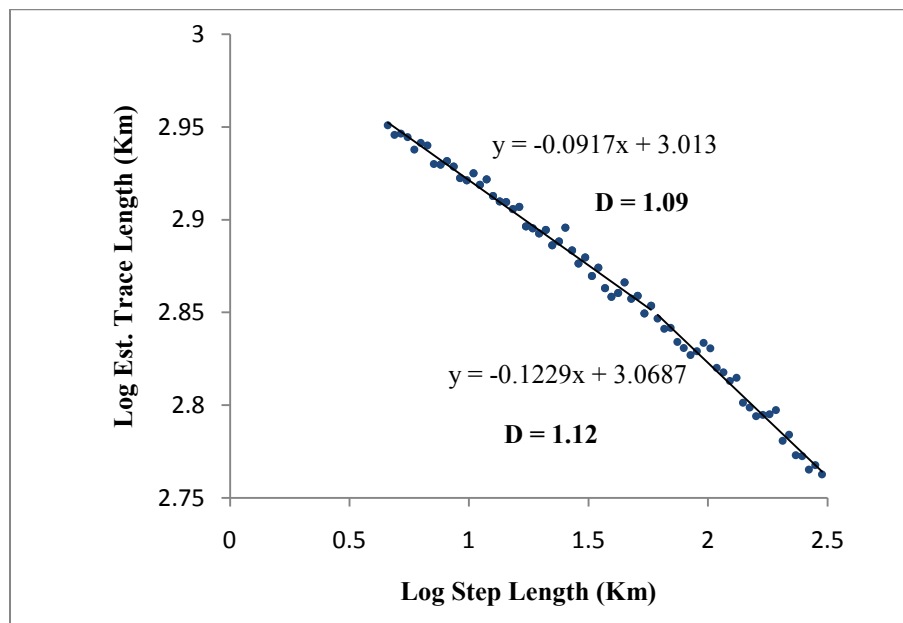


Figure 20. Richardson plot for EA4 segment.



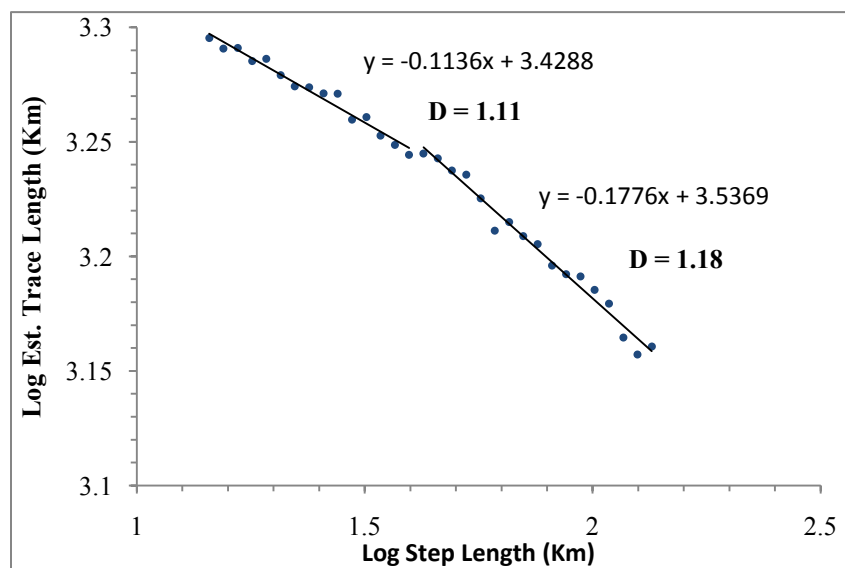


Figure 21. Richardson plot for EA5 segment.

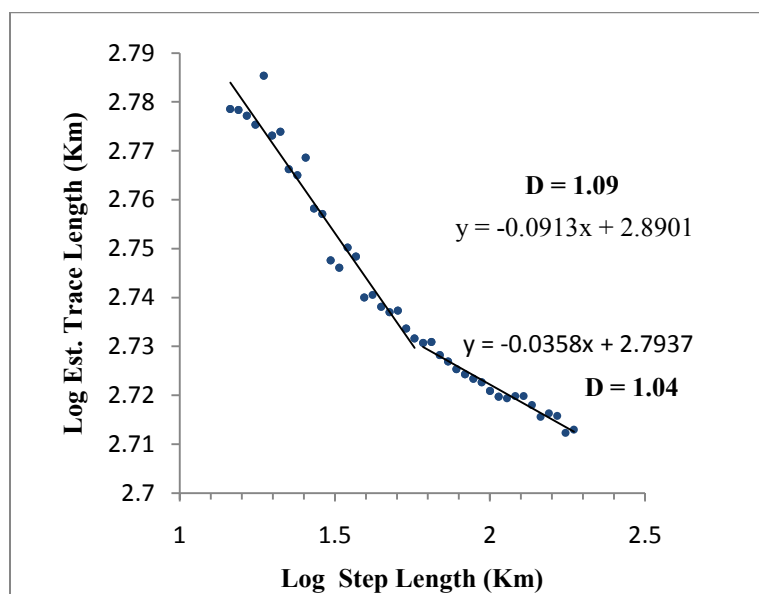


Figure 22. Richardson plot for EA6 segment.

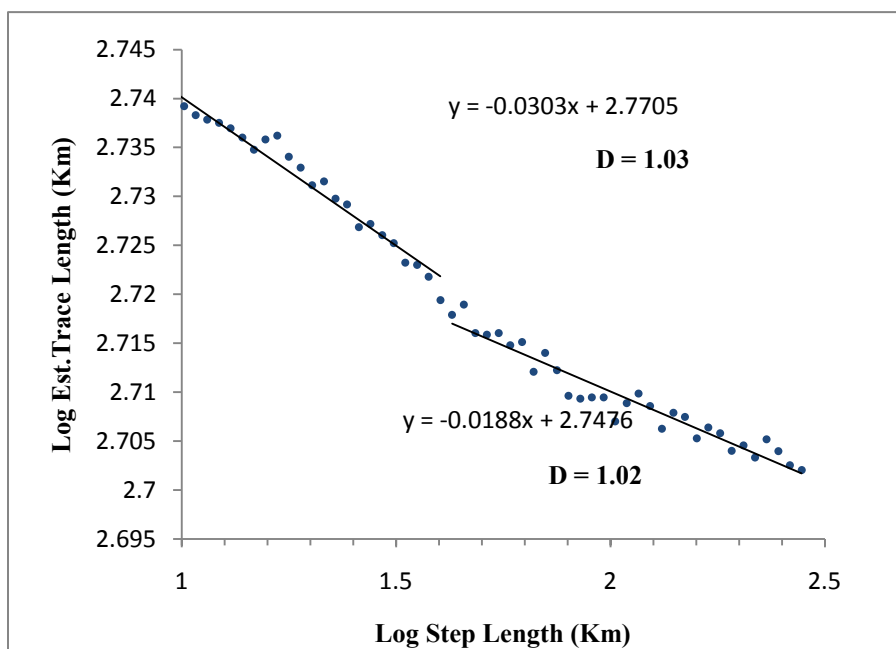


Figure 23. Richardson plot for EA7 segment.

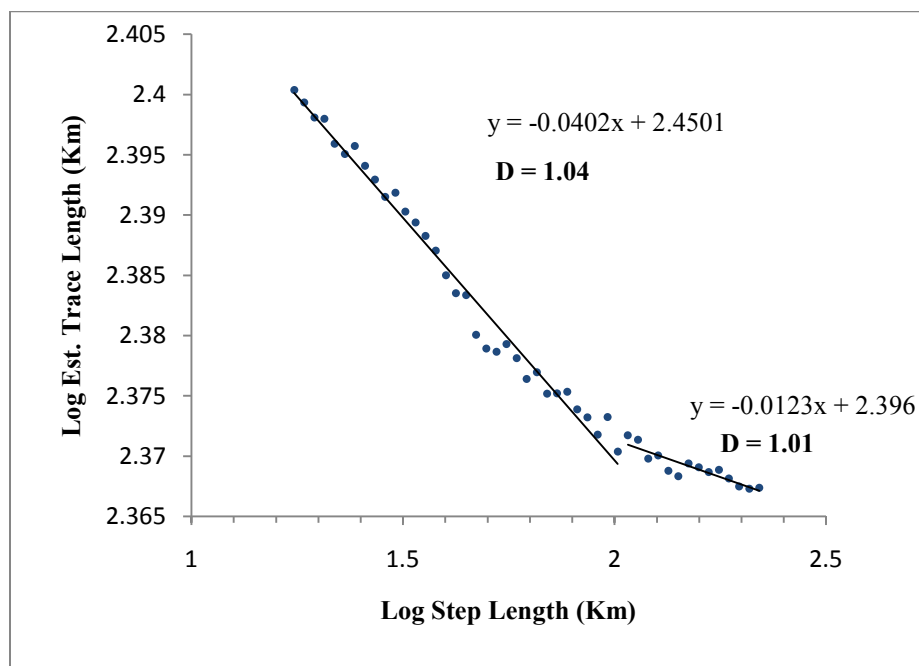


Figure 24. Richardson plot for EA8 segment.

#### 4.5. North America

North American continental divide has been divided into 6 sections- Northern Rockies NA1, Southern Rockies NA2, Basin and range NA3, Island arc NA4, Appalachians NA5 and Great Lake NA6.

NA1 and NA2 are divided into 2 segments with separate linear trend. The slope of trend line at fine and coarse for NA1 is -0.13 and -0.05 respectively. The maximum departure from the fit is 0.2 % and 0.35 % at fine and coarse scale respectively. At fine scale the estimated D value for NA1 is 1.13 while at coarse scale is 1.05. For NA2 the slope of trend line at fine and coarse scale is -0.1 and -0.04 respectively. The maximum departure from the fit at fine and coarse scale is 0.07 % and 0.14 % respectively. For NA2 the D value calculated at fine scale is 1.10 and at coarse scale is 1.04.

NA3 and NA4 are homogeneous plots with slope trend of -0.09 and -0.04 respectively. The maximum departure calculated for each of these homogeneous plots is 0.32% and 2.29%, respectively. The D values for NA3 and NA4 and NA6 are 1.09 and 1.04 respectively.

NA5 is heterogeneous plot with a slope trend of -0.02 at fine scale and -0.01 at coarse scale. The D value calculated for NA5 which is traversed by Appalachians is 1.02 at fine scale and 1.01 at coarse scale. NA6 plot is homogeneous with a slope of trend line -0.16. The maximum departure calculated from the fit is 0.23 %. High mountainous relief traversing through NA1 and NA2 and arid climate in NA2 and NA3 may have cause this contrast between the D values.

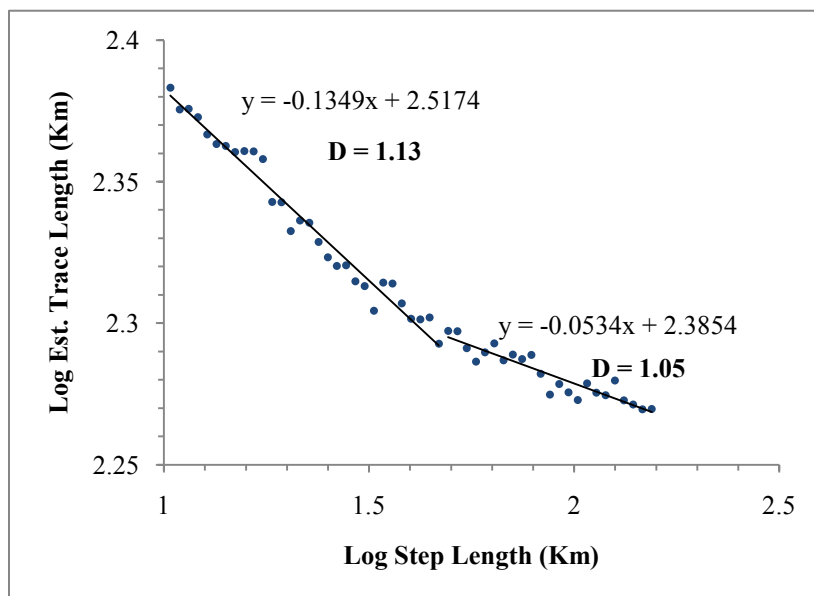


Figure 25. Richardson plot for NA1 segment.

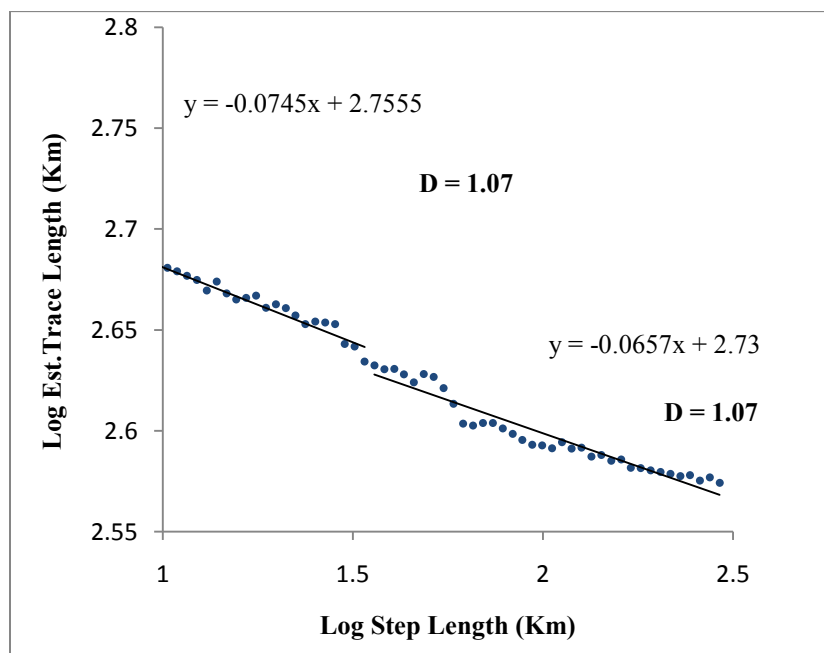


Figure 26. Richardson plot for NA2 segment.

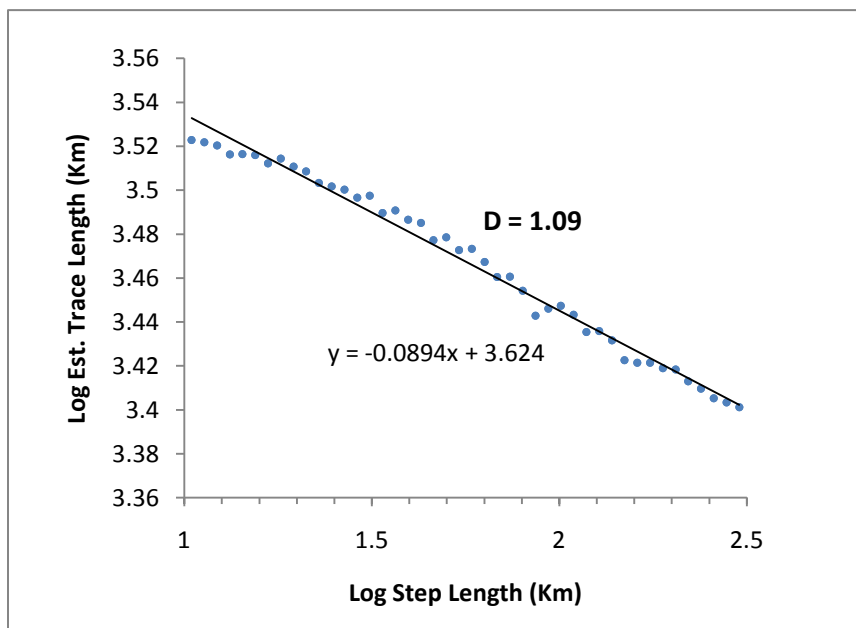


Figure 27. Richardson plot for NA3.

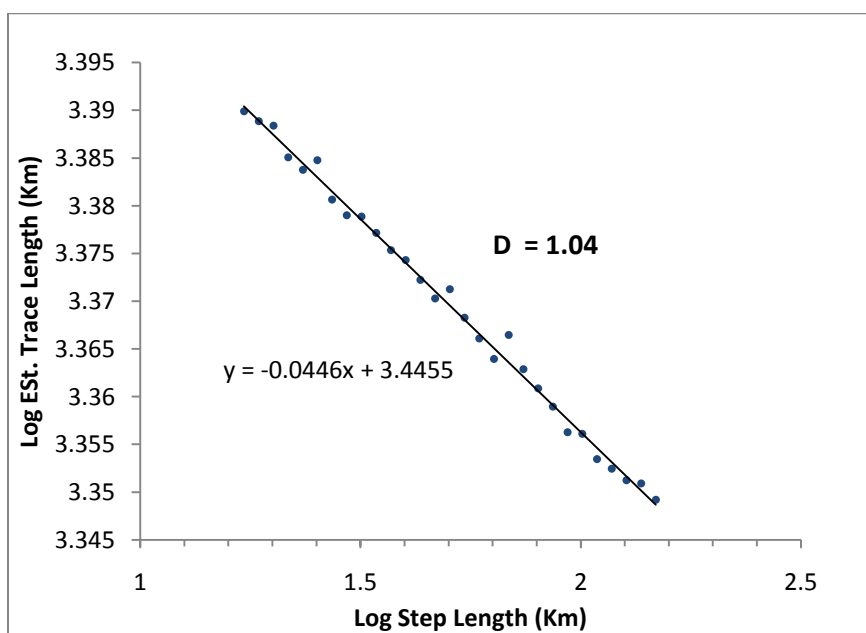


Figure 28. Richardson plot for NA4.

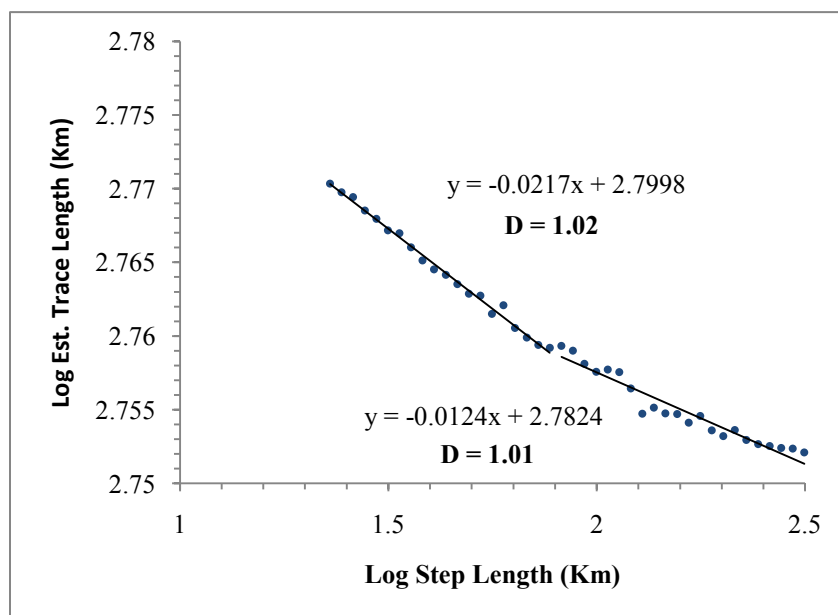


Figure 29. Richardson plot for NA5.

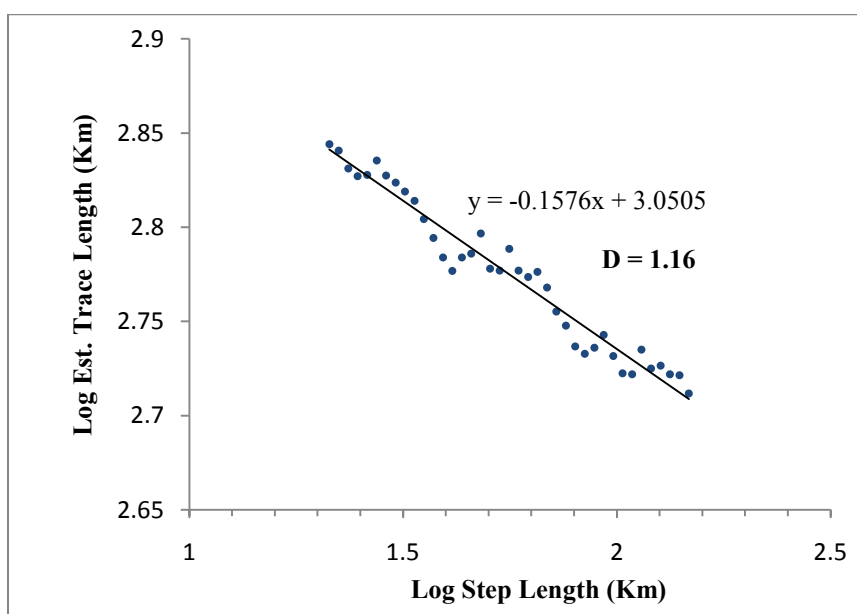


Figure 30. Richardson plot for NA6.

## 5. Significance of Control factors

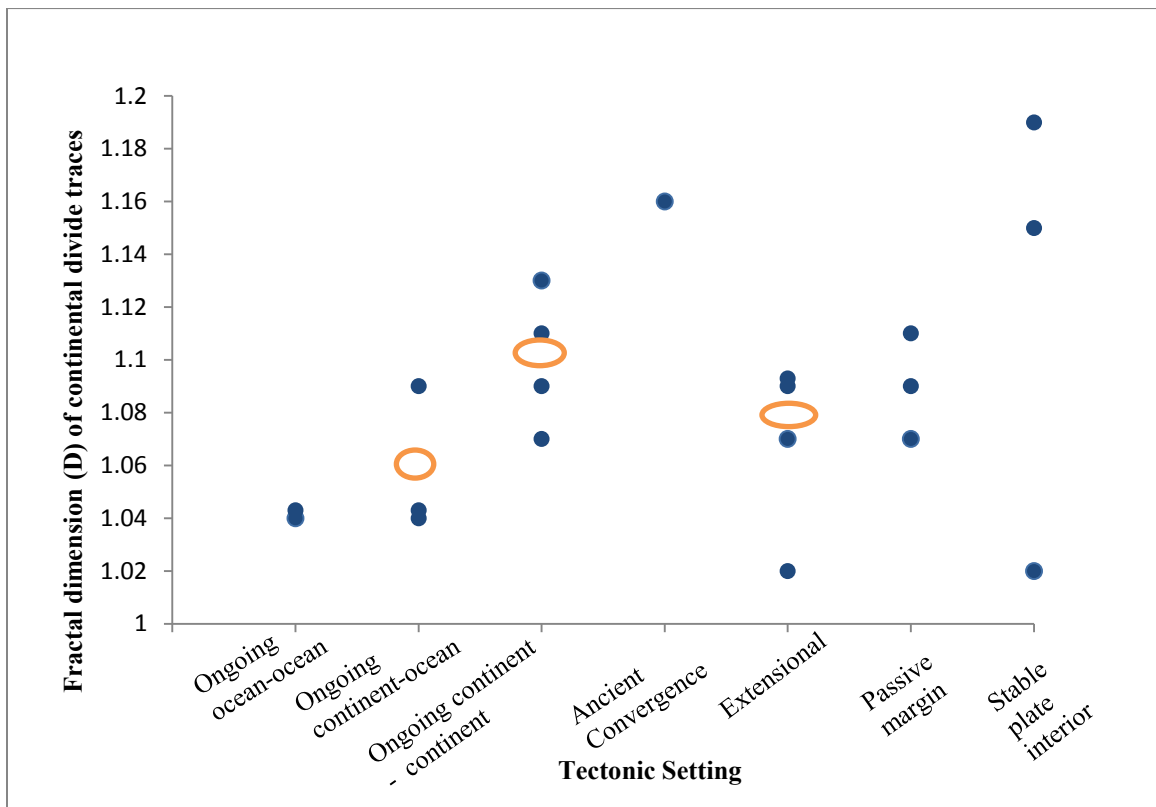
### 5.1. Significance of tectonic settings

Tectonism has given us a landscape of incomparable diversity and complexity. Such complexity can be observed in the traces of continental divide as depicted in map view. Tectonic settings include ongoing ocean-ocean convergence, ongoing ocean-continent convergence, ongoing continent-continent convergence, ancient convergence, extensional, passive margin and stable plate interior.

<b>Table 1. Continental divide segments in each tectonic settings</b>	
<b>Tectonic Settings</b>	<b>Segments</b>
Ongoing Ocean- ocean convergence	NA4, EA7, EA8
Ongoing ocean –continent convergence	SA1, SA2, SA3, EA4
Ongoing continent- continent convergence	EA6, NA1, NA2, EA5
Ancient convergence	NA6, EA7
Extensional	NA3,AF1, AF2, EA1
Passive margin	A1, A2, AF3
Stable plate interior	NA5, EA2, EA3

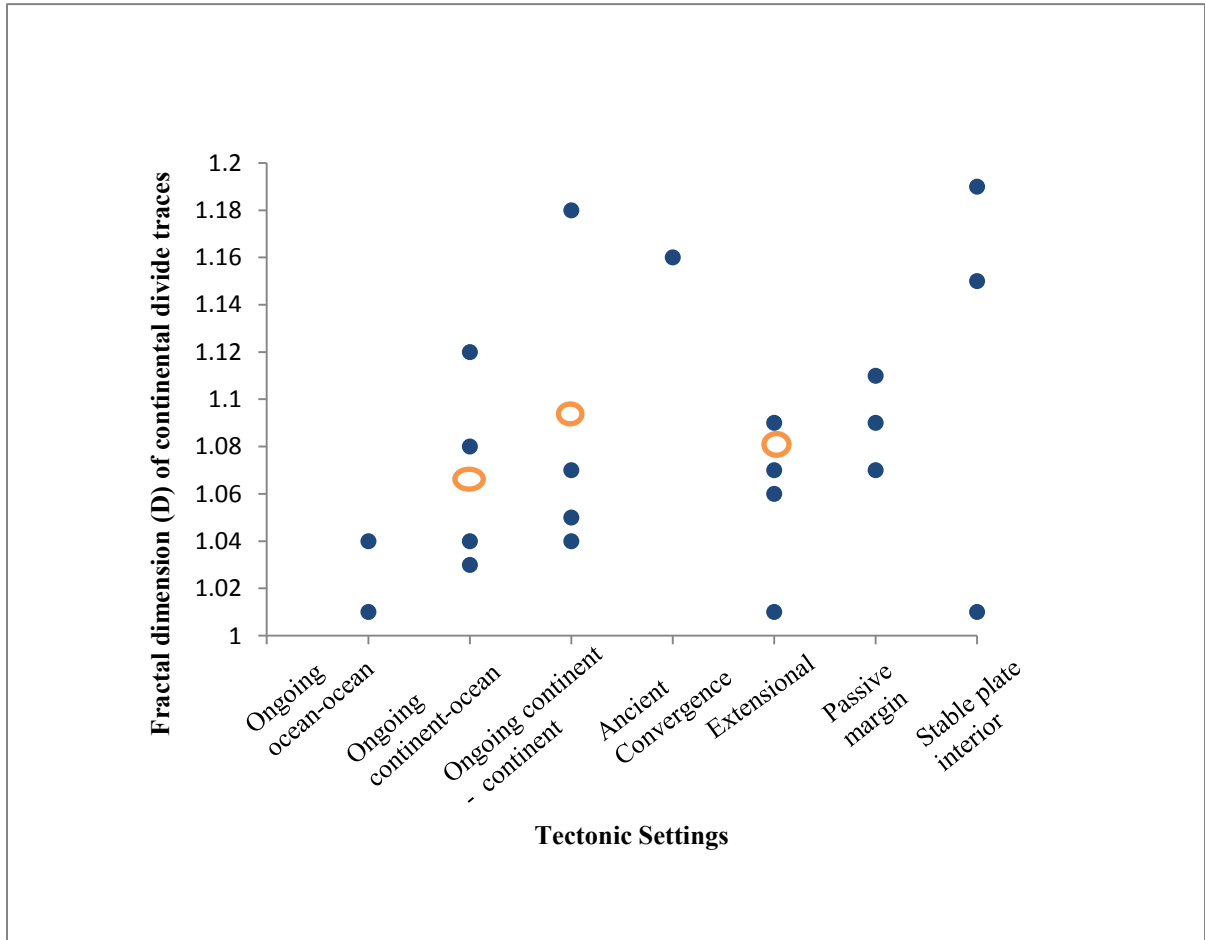
To evaluate the relationship between tectonic settings and fractal dimension of each continental divide segments a graph is plotted with X- axis showing tectonic settings and Y-axis with the fractal dimension of continental divide traces. A mean value is

computed and considered for all categories that include four or more points. The mean value at fine and coarse scales show an initial rise followed by a decrease. Consistent high mean value is found in ongoing continent-continent convergence at fine and coarse scale.



**Figure 31. Relationship between tectonic settings and fractal dimension of continental divide traces at fine scale. Orange oval circles are mean values.**





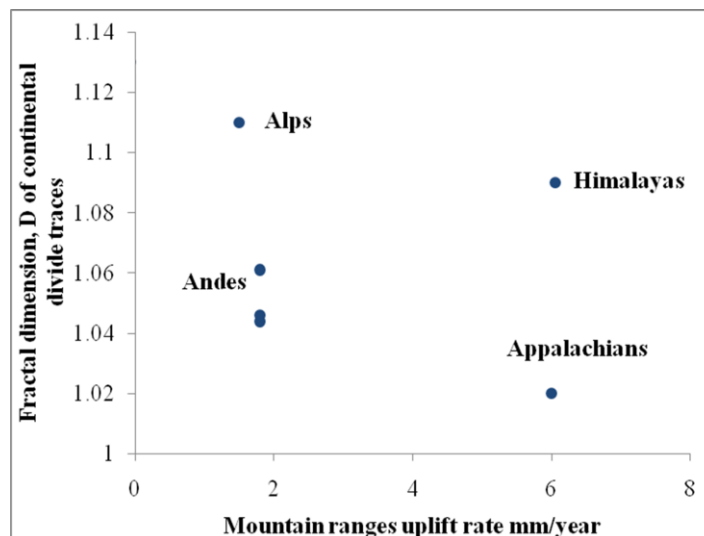
**Figure 32. Relationship between tectonic settings and fractal dimension of continental divide traces at coarse scale. Orange oval circles are mean values**

## 5.2. Significance of uplift rate in mountainous environment

The Himalayas shows a high uplift rate of 0.1-12 mm/year followed by the Appalachians with 6 mm/year. Andes show an uplift rate of 3 mm/year and Alps show an uplift rate of 1-2 mm/year. The average and maximum values for these uplift ranges have been considered.

At finer scales of inspection, the relationship between the uplift rate and fractal dimension, while showing some inverse relationship, is very weak. This suggests that uplift rate does not significantly affect the complexity of the drainage divides at distance ranges less than 70 km.

At coarse scales of inspection, the complexity, and the corresponding fractal dimension, decreases with an increase in uplift rate. It is previously been reported an increase in uplift can cause an interruption in fluvial cycle of erosion leading to shortening of cyclic time due to advancement of the stage of the erosion cycle. Similarly, a decrease in uplift can lead to lengthening of the cyclic time because the stage of the erosion cycle is pushed back (Singh, 1998). This could potentially explain the corresponding inverse relationship between the uplift rate and the fractal dimension (complexity) at coarse scale.



**Figure 33. Relationship between average uplift rate and fractal dimension of continental divide traces at finer scale.**

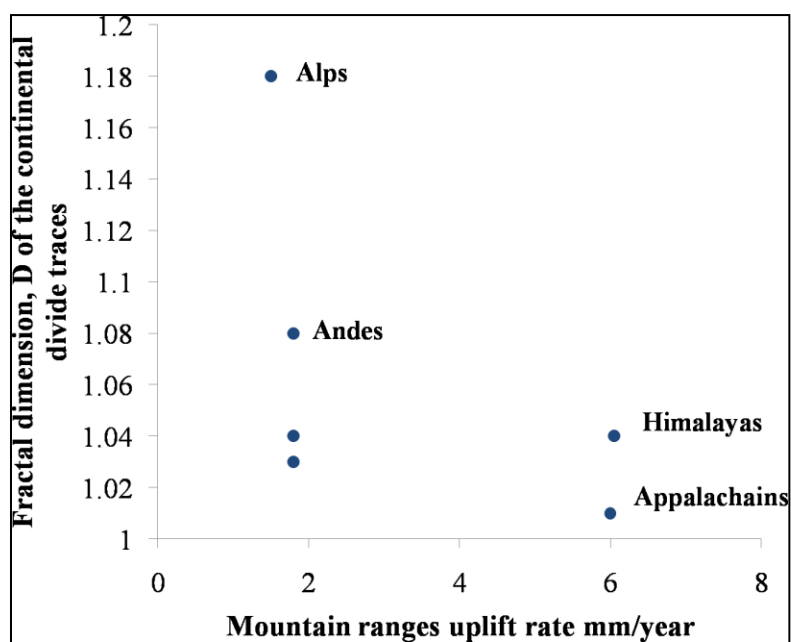


Figure 34. Relationship between average uplift rate and fractal dimension of continental divide traces at coarse scale.

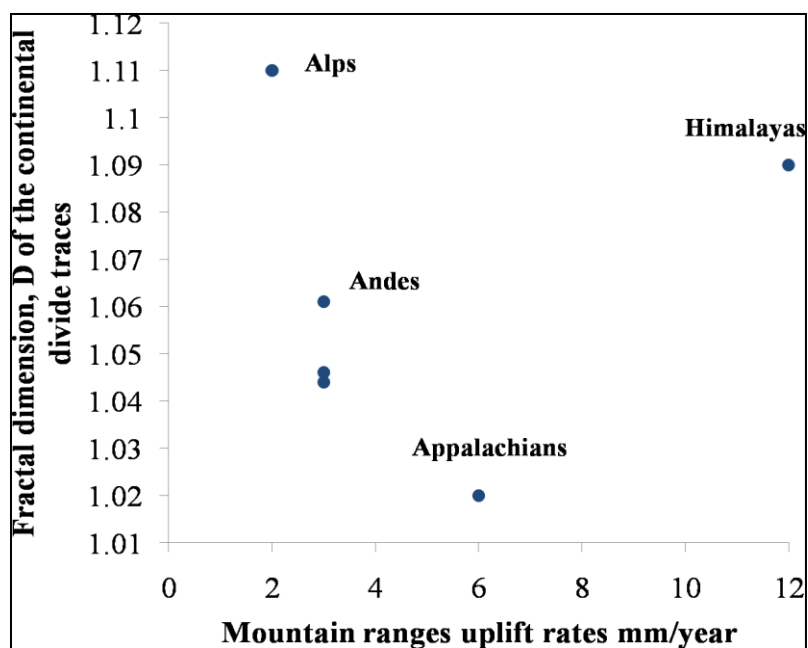
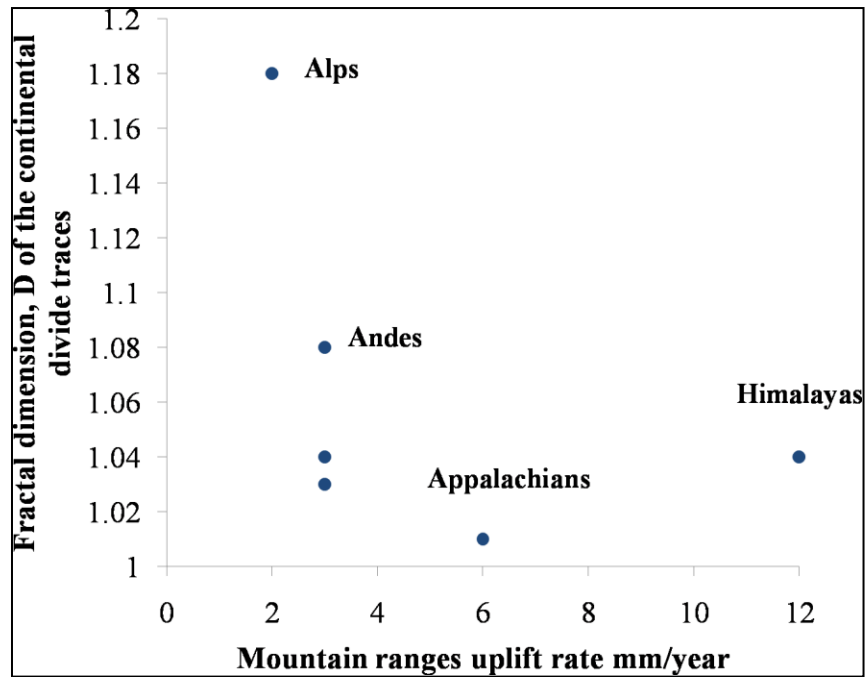


Figure 35. Relationship between maximum uplift rate and fractal dimension of continental divide traces at finer scale.



**Figure 36. Relationship between maximum uplift rate and fractal dimension of continental divide traces at coarse scale.**

### 5.3. Significance of climate

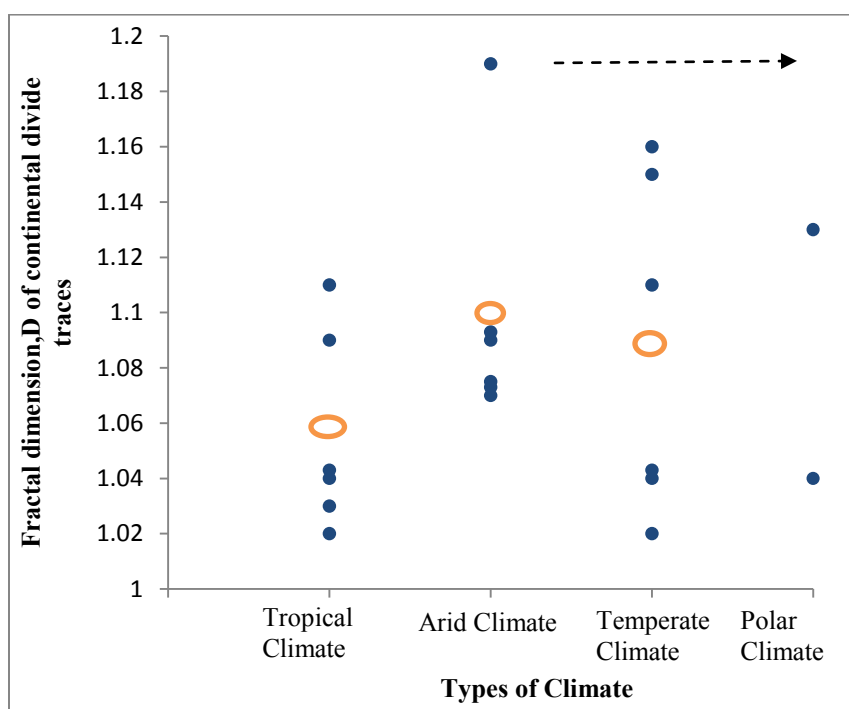
Variability of continental divide trace irregularity is affected by many factors, one of which is the climatic condition. For the study, four major climate zones have been considered: tropical, arid, temperate and polar. These climates have been ordered according to latitudes.

<b>Table 2. Continental divide segments in each Climatic zones</b>	
<b>Climate</b>	<b>Segments</b>
Tropical	AF3, SA1, NA5, EA7, EA8
Arid	EA3, NA2, NA3, AF1, AF2, A1
Temperate	EA5, EA6, A2, SA2, SA3, EA1, EA2, NA6
Polar	EA4, NA1

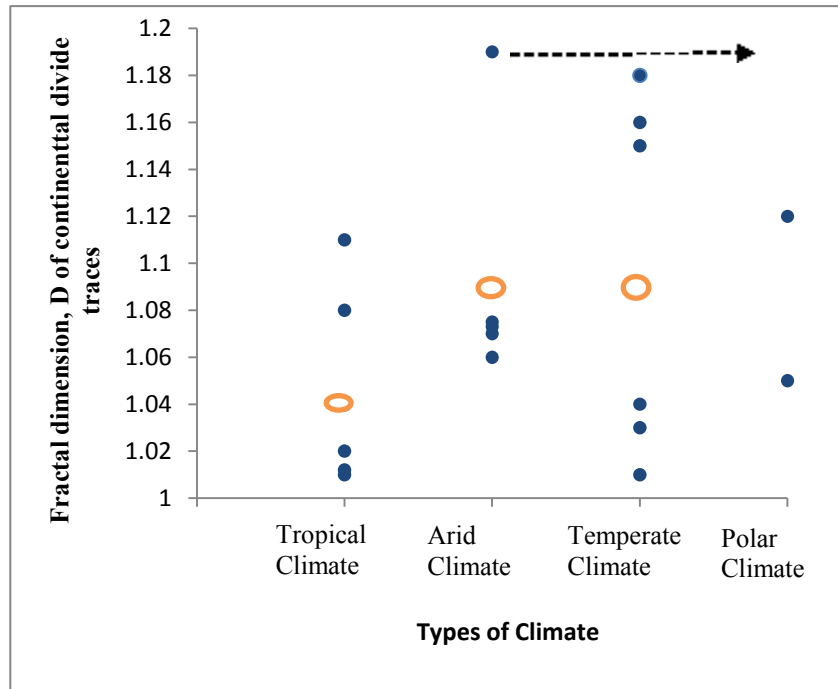
Tropical zone mean values are minimum, at both scales. Temperate zone values have notably broad range at both fine and coarse scales of inspection. Also, the geometry of the continental divide traces appears similar across the temperate and arid climates. Arid zone tend to cluster with similar D values except for one high D value. This D value is 1.19 calculated for the EA3, segment of central Eurasia. It is worth mention here that this segment passes through cold deserts, Gobi desert and Kyzyl-Kum. This could be reasonably classified as polar zone; if we overlook this high D value the clustering of D values displayed by the arid zone demonstrates a strong effect on the complexity of continental divide.

Continental divide traces in tropical climate show lower divide complexity. Possible reasons for lower divide complexity in tropical climate may be attributed to either the inability of increased precipitation to result in erosion, or to the inability of the increased erosion to lead to complexity. In addition, there might also be other

factors drowning out the effect of the increased precipitation.



**Figure 37. Relationship between climate and fractal dimension of continental divide traces at fine scale. Orange oval circles are mean values.**



**Figure 38. Relationship between climate and fractal dimension of continental divide traces at coarse scale. Orange oval circles are mean values.**

#### 5.4. Significance of Relief

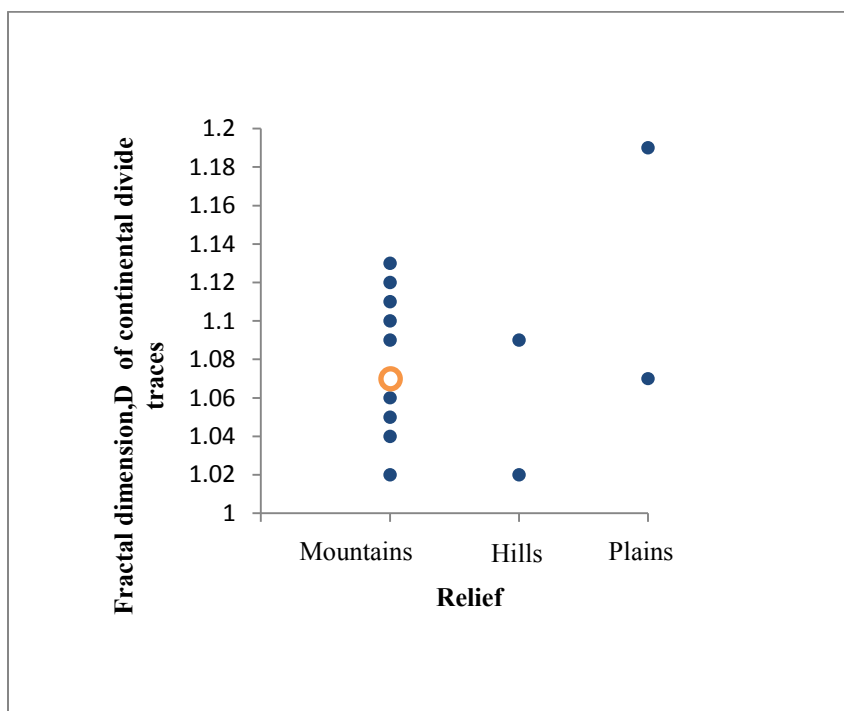
The effect of relief on the complexity of the continental divide trace has been demonstrated by sorting the results into three generalized relief categories: mountains, hills and plains.

<b>Table 3. Continental divide segments in each relief</b>	
<b>Relief</b>	<b>Segments</b>
Mountains	AF1, AF2, AF3, SA1, SA2, SA3, EA4, EA1, EA2, EA5, EA6, EA7, EA8, NA1, NA2, NA6, NA3, NA4
Hills	A2, NA5
Plains	EA3, A1

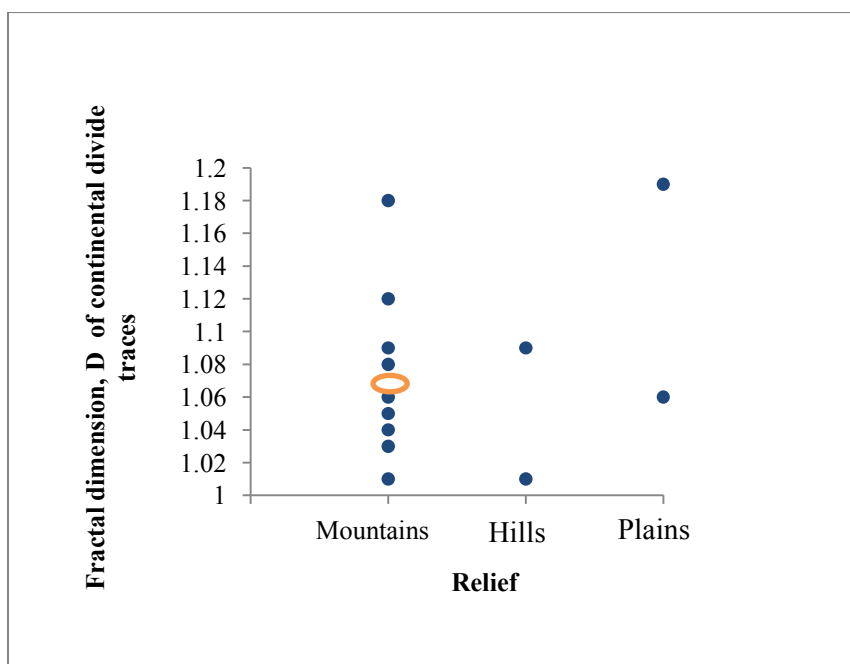
At the fine and coarse scale there are broad ranges of D values for divide segments traversing mountains, suggesting that there may be other factors causing complexity.

The segments traversing plains show high mean D values. The plain topography of the central Eurasia continental divide crosses scattered mountains ranges such as Urals and Altai Mountains and major rivers namely the Irtysh, Ob and Yenisey rivers, resulting in high D values. Hills, being moderately low in relief compared to mountains, display low D values. Thus, the continental divide trace traversing plain topography also traverses through scattered mountains which may be the cause of complexity along the divide trace.





**Figure 39. Relationship between relief and fractal dimension of continental divide traces at fine scale. Orange oval circles are mean values.**



**Figure 40. Relationship between relief and fractal dimension of continental divide traces at coarse scale. Orange oval circles are mean values.**

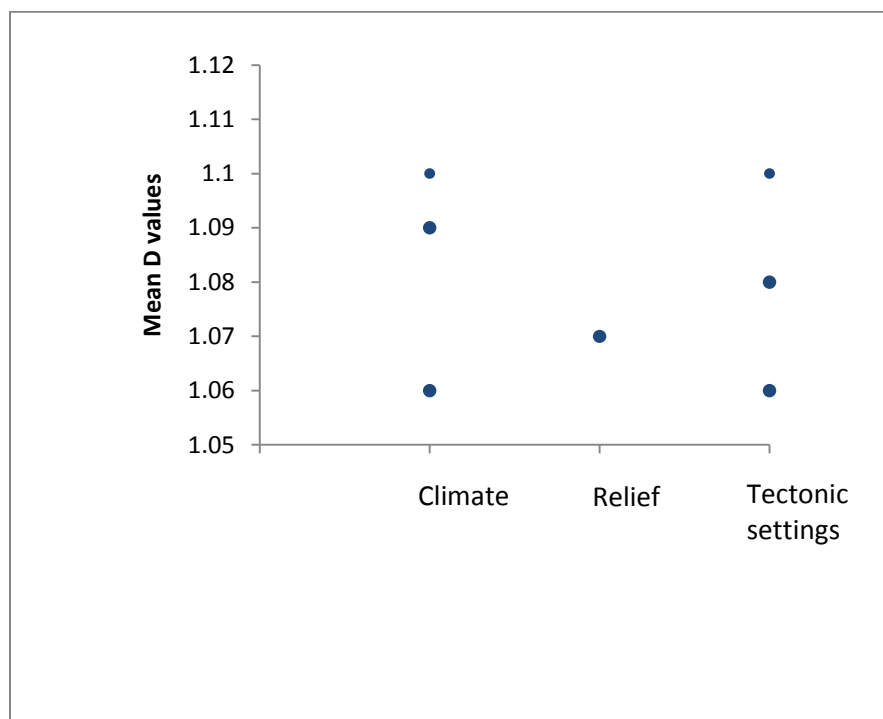
## 6. Conclusion

The main focus of the present study is to identify and integrate the factors affecting the degrees of irregularity of continental divides traces, as expressed by their fractal characteristics, which is measured by the divider method. The factors studied are climate, relief and tectonic environment. The second objective of this study is to determine the relationship between uplift rates and divide trace fractal dimension.

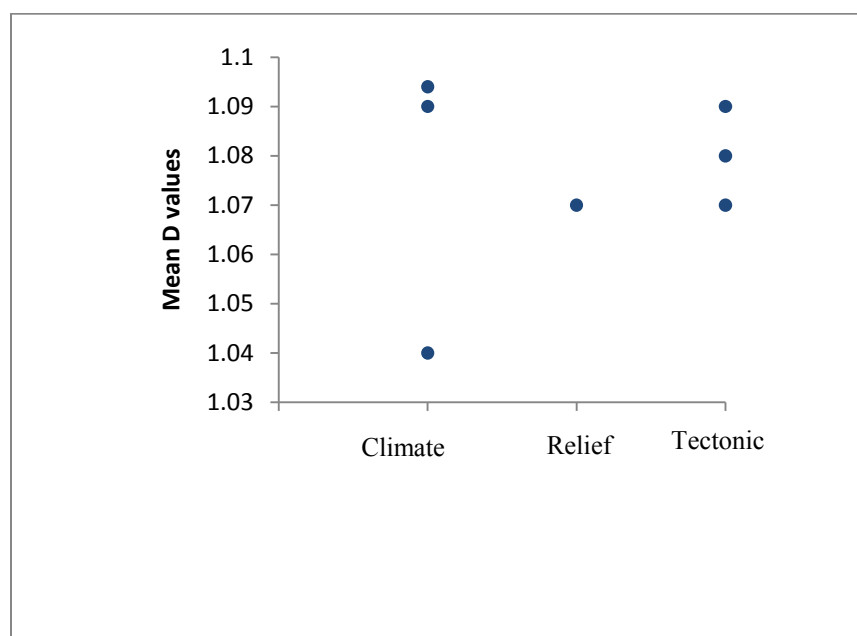
**Table 4. Factors potentially affecting divide trace complexity with respective mean standard deviations of divide segment fractal dimension values at both fine and coarse scales.**

<b>Factors</b>	<b>Fine Scale</b>	<b>Coarse Scale</b>
Climate	0.039	0.051
Tectonic	0.037	0.045
Relief	0.056	0.064

The following observations can be made from Table 4. The relatively low standard deviation values computed for climate and tectonic environment demonstrate their strength as factors affecting the complexity of continental divide traces. In other words, the fractal dimension results show more compact groupings when classified according to these factors. In particular, the degrees of irregularity of continental divide traces at fine scale are strongly affected by both climate and tectonics. Finally comparatively high standard deviation values obtained for relief suggest that it be ranked below both climate and tectonic environment as a factor affecting the complexity of continental divide traces.



**Figure 41. Graph showing the mean D values for continental divide segments sorted by each factor at fine scale.**



**Figure 42. Graph showing the mean D values for continental divide segments sorted by each factor at coarse scale.**

To evaluate relative significance of controls in another way, a graph showing the mean D values for divide segments sorted by various factors was plotted for both fine and coarse scale (Figure 31 and 32). A mean value is computed and considered for all categories that include four or more data results. The spread of the mean values is an indicator of the amount of control exercised by the factor on the continental divide traces. The lack of diversity of relief, results in a single mean value. Broadest dispersal of values displayed seems to suggest that climate is a strong factor at fine and coarse scale while tectonic environment is strong at fine scale. It is interesting to note that this somewhat contradicts the interpretations obtained from standard deviation analysis. Specifically, the results are found to be consistent in case of fine scale while inconsistent in case of coarse scale. However these results do not contradict the general conclusion that climate and tectonic environment play the major role in determining the continental divide traces complexity.

Thus, there is a relatively strong relationship between climate and fractal dimension (Figure 29 and 30, Chapter 5). Continental divides traversing through arid and temperate climates show high complexity. This may be linked to observations made in the literature of Geomorphology (Arthur L Bloom, fig.15-8, pg.339), that attribute greater runoff to lack of adequate precipitation to maintain continuous vegetation cover.

There is an at least equally strong relationship between tectonic environment and divide complexity. Study of the mean values of fractal dimension for tectonic settings (Figure 25 and 26, Chapter 5) seems to indicate that high complexity along the divide

traces may be the result from ongoing continent-continent convergence while low complexity along the continental divide traces is found for ongoing ocean-ocean convergence and in extensional zones.

The second objective of this study is to evaluate the relationship between uplift rate and fractal dimension. The fractal dimension at fine scales follows a weakly inverse relationship with uplift rate. At coarse scale, there is stronger inverse relationship between uplift rate and fractal dimension (Figure 33- 36).

Thus from the tested factors it may suggested that the continental divide segments with temperate climate traversing through ongoing continent- continent and ongoing ocean –continent convergence (for example EA4, EA5, SA2 and SA3) showing high D value, may result in more complexity of the way sediments are shed from distinctive local source areas toward both sides of the divides. In addition those divide traces (for example NA4 and EA7) traversing regions with tropical climate and ongoing ocean – ocean convergence, with less complexity, will more effectively shed sediments on one side of divide.

Future work may focus on application of similar techniques to study the effect of various factors at micro scale on continental divide irregularity possibly employing field survey techniques (e.g Mercurio, 2004; Rice-Snow, 2009). Also more detailed data, especially in case of relief, may provide a deeper and a more complete understanding of the various factors affecting the complexity along the continental divide traces.

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