MORPHOMETRIC ANALYSIS OF ACTIVE TECTONIC IMPRINTS AT THE JUNCTION OF BÜYÜK MENDERES AND BOZDOĞAN GRABENS, WESTERN ANATOLIA

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ABSTRACT

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Analysis of the basin asymmetry and morphometric indices is an effective methodology to detect surface signatures of active tectonic processes and to understand the differential uplift. Thus, basins controlled by active faults with different orientations provide a unique opportunity to evaluate fault controlled tilting. In this study, a morphometric analysis is conducted by means of the analytical capabilities of numerical computing and GIS software for an area characterized by orthogonal normal faults and nearly homogeneous lithology situated at the junction of Büyük Menderes and Bozdoğan graben systems. The morphometric parameters such as isobase, incision, surface roughness and basin asymmetry parameter; T-index are extracted to recognize tectonic control on drainage network development, basin morphology and landscape evolution. In order to reveal the useful and consistent information some output maps have been modified and new maps such as "DEM-Isobase" derived from output maps have been generated. Watershed based variations of output maps and new maps have been produced for further analysis by using the mean values of each parameter which have been calculated within each watershed. Tectonically controlled watersheds have been interpreted to be dominant around active faults. For this reason, analysis has concentrated on the areas around active faults. Fault based analysis reveals that dominant asymmetry direction along the western part of Büyük Menderes fault is toward SW indicating the possible uplift of the south east of Madran horst. The results of morphometric analysis conducted in this thesis study also enable to discuss the comparison of the tectonic activities of Büyük Menderes and Bozdoğan faults and shows that Bozdoğan fault is more active on the drainage network development, basin morphology and landscape evolution compared with Büyük Menderes fault.

Keywords: Basin asymmetry, Morphometric indices, Büyük Menderes Graben, Bozdoğan Graben, GIS

ÖZ

BATI ANADOLU, BÜYÜK MENDERES GRABENİ VE BOZDOĞAN GRABENİNİN KESİŞİMİNDE AKTIF TEKTONİK İZLERİNİN MORFOMETRİK ANALİZİ

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Havza asimetrisi ve morfometrik indislerinin incelenmesi aktif tektonik süreçlerin yüzey işaretlerini tespit etmek ve diferansiyel yükselimini anlamak için etkili bir yöntemdir. Bu yüzden; farklı yönelimlerdeki aktif faylar tarafından kontrol edilen havzalar, fay kontrollü devrilmeyi değerlendirmek için eşsiz bir fırsat sağlar. Bu çalışmada morfometrik incelemeler, sayısal hesaplamalar ve CBS yazılımları kullanarak, Büyük Menderes grabeni ve Bozdoğan grabeninin kesişiminde neredeyse homojen litolojiye sahip ve birbirine dik normal faylar tarafından karakterize edilmiş bir alan içinde yürütülmüştür. Drenaj gelişimi, havza morfolojisi ve yüzey şekillerinin evrimi üzerindeki tektonik kontrolü tanımlamak amacıyla isobase, insizyon (relatif rölyef) ve yüzey pürüzlülüğü gibi morfometrik parametreler ve basin asimetri indisi olan T faktörü kullanıldı. Tektonik etkiyi anlayabilmek için üretilen bazı haritalarda değişiklikler yapılmış ve bu haritalardan türetilen "DEM-Isobase" gibi yeni haritalar oluşturulmuştur. Sonraki analizler için incelenen tüm parametrelere ait değerlerin ortalamaları her bir parametre ve havza için ortamalamaları alınarak havza bazlı değerlere çevrilmiştir. Tektonik kontrollü havzaların fayların çevresinde baskın olduğu gözlemlenmiştir. Bundan dolayı, analizlerde aktif fayların çevresindeki havzalara yoğunlaştırılmıştır. Faya bağlı analizler Büyük Menderes fayının batı kısmında baskın asimetri yönünün güneybatı olduğunu ortaya çıkarmakta ve bu durum Madran horstunun kuzeydoğu kısmında olası bir yükselimin göstergesidir. Bu tez çalışmasında yapılan morfometrik analizler ayrıca Büyük Menderes ve Bozdoğan faylarının tektonik aktivitelerini tartışma fırsatı sağlamış ve bu analizlerin sonucunda Bozdoğan fayının drenaj gelişimi, havza morfolojisi ve yüzey şekillerinin evrimi üzerindeki tektonik kontrolünün Büyük Menderes fayından daha fazla olduğu düşünülmektedir.

Anahtar kelimeler: Havza asimetrisi, Morfometrik indisler, Büyük Menderes Grabeni, CBS

To my dear family,

And to my beloved husband…

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TABLE OF CONTENTS

LIST OF FIGURES

FIGURE

LIST OF TABLES

TABLES

CHAPTER 1

INTRODUCTION

Geomorphometry is the science of quantitative analysis of land surface (Pike, 2000). It covers the measurement, statistical and mathematical analysis of the structure of the earth's surface, form and extents of its landforms. Morphometry highlights the land-surface parameters extracted from digital elevation models in operation (Evans, 2012).

Morphometric analysis is termed as analysis and quantitative description of landforms use in geomorphology practices. These practices may be applied to a landform or to a drainage basin and many of quantitative measurements have been used to extract slope of channels, valley sides and other variables such as the type and the extent of drainage network and relief. The morphometric analysis of a basin provides a quantitative explanation of the drainage system, which is guiding the characterization of basins (Strahler, 1952). Basin characterization and hydrological properties of basins give clue about the predominant climate, geomorphology, geology and structural implications of the watershed area. Morphometric analysis is helpful in understanding the relation and/or variation of major watersheds. Several variables; geology, geomorphology, structure, tectonic activities and seasonal changes resulted in variation of vegetation and soil type of the area, affect the drainage system development depending on the time and location (Magesh et al., 2012a).

Morphometric indices, as powerful analysis tools, investigate the interplay of tectonics, lithology, and climate of mountain channels and structures. GIS techniques are useful nowadays for surveying different morphometric parameters of the drainage basins, since for the control and examination of spatial information; they give an adaptable environment and a powerful device (Pareta and Pareta, 2011).

1.1 Purpose and Scope

The Aegean region is one of the most active regions subjected to an N–S extension in the world (Dewey & Sengör, 1979). The Büyük Menderes Graben (BMG) is one of the major east-west Graben structures located in Aegean region with 125 km long and 8-12 km wide dimensions (Bozkurt, 2000). The basin is surrounded by the E-W trending Küçük Menderes Graben in the north and four Mio-Pliocene depressions (from west to east, the Çine, Bozdoğan, Karacasu, and Denizli basins) with approximately N-S trends are located in the south of the BMG (Ocakoğlu et al., 2014). The Bozdoğan Graben is about 10 km wide and 30 km long. In the north part of Bozdoğan basin, the bounding fault of main Graben trends approximately N-S direction. However the fault starts to trend NW-SE direction about 20 km south of the intersection with the floor of the Büyük Menderes Graben.

The study area is located at the junction of Büyük Menderes and Bozdoğan Grabens shaped by normal faults. There are two main trends seen in the area which are representing nearly E-W trend of Büyük Menderes fault and N-S trend of Bozdoğan fault. Basins controlled by active faults with orthogonal orientations provide a unique opportunity to evaluate fault controlled tilting.

This study aims to show possibilities of morphometric analysis of Digital Elevation Model (DEM) by interpretation of morphotectonic features of areas of active deformation. The morphometric parameters such as isobase, incision, surface roughness and basin asymmetry parameters; T-index is extracted to recognize tectonic control on drainage network development, basin morphology and landscape evolution. The purpose of this study is to evaluate active extensional tectonics by means of morphometric analysis conducted using the analytical capabilities of numerical computing and GIS software. In this thesis, the effects of active tectonics processes on drainage basins and terrain and basin morphology are being studied considering homogeneous lithology. The software outputs have been analysed to correlate with existing structures and accordingly for the interpretation of new and /or unidentified structures and fault-controlled tilt direction.

There are two main criteria for the selection of study area which are characterized by orthogonal normal faults, as mentioned above and existence of nearly homogeneous lithology. These two conditions provide an advantage to minimize effects of lithological contrast and focus on mainly tectonic control and differential uplift.

1.2 Study Area

The study area which has been named as the junction of Büyük Menderes and Bozdoğan Grabens located in western Anatolia within the Aydın province in the vicinity of Yenipazar and Bozdoğan settlements. The area has approximately 33 km x 42 km extent covering nine 1/25,000 scaled topographic map sheets which are M20a3, M20b3, M20b4, M20c1, M20c2, M20c3, M20c4, M20d2 and M20d3.
The location map of the study area is given below in figure (Figure 1).

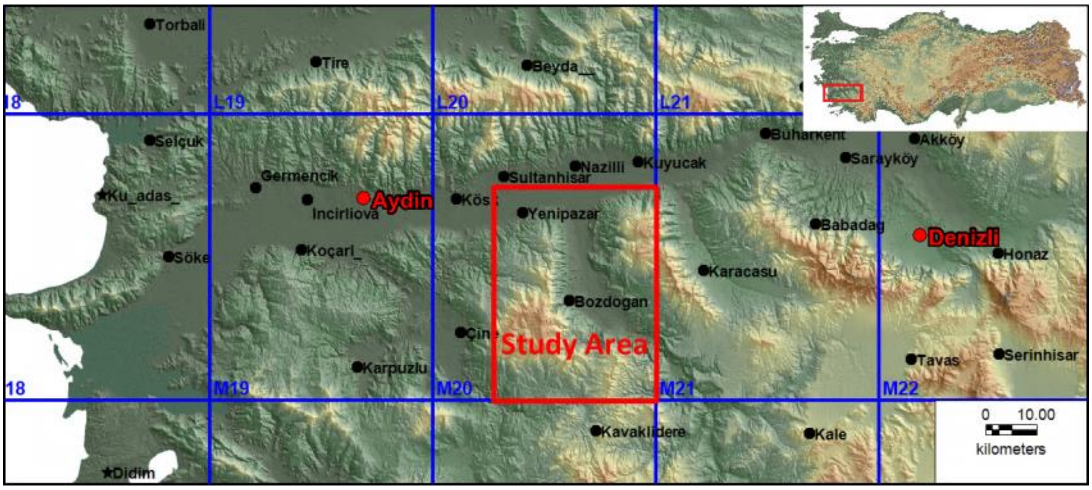


Figure 1 Location map of study area

The study area is characterized by horst and graben structures, which are Madran horst, Bozdoğan Graben, Karıncalıdağ horst from the West to East and Büyük Menderes Graben at the North. These horst and graben structures and bounding normal faults controls the topography. Variations in morphology are remarkable in the central part of Büyük Menderes and Bozdoğan basins. The Bozdoğan is deeply dissected by the Akçay creek and also the Büyük Menderes Graben is highly incised by Büyük Menderes River. This situation leads to form broad valley at about 50–90 m above sea level suitable for deposition of fluvial sediments. The probable basement uplift in the northern basin margin results in formation of thick alluvial fans (Ocakoğlu, et al., 2014; Figure 2)

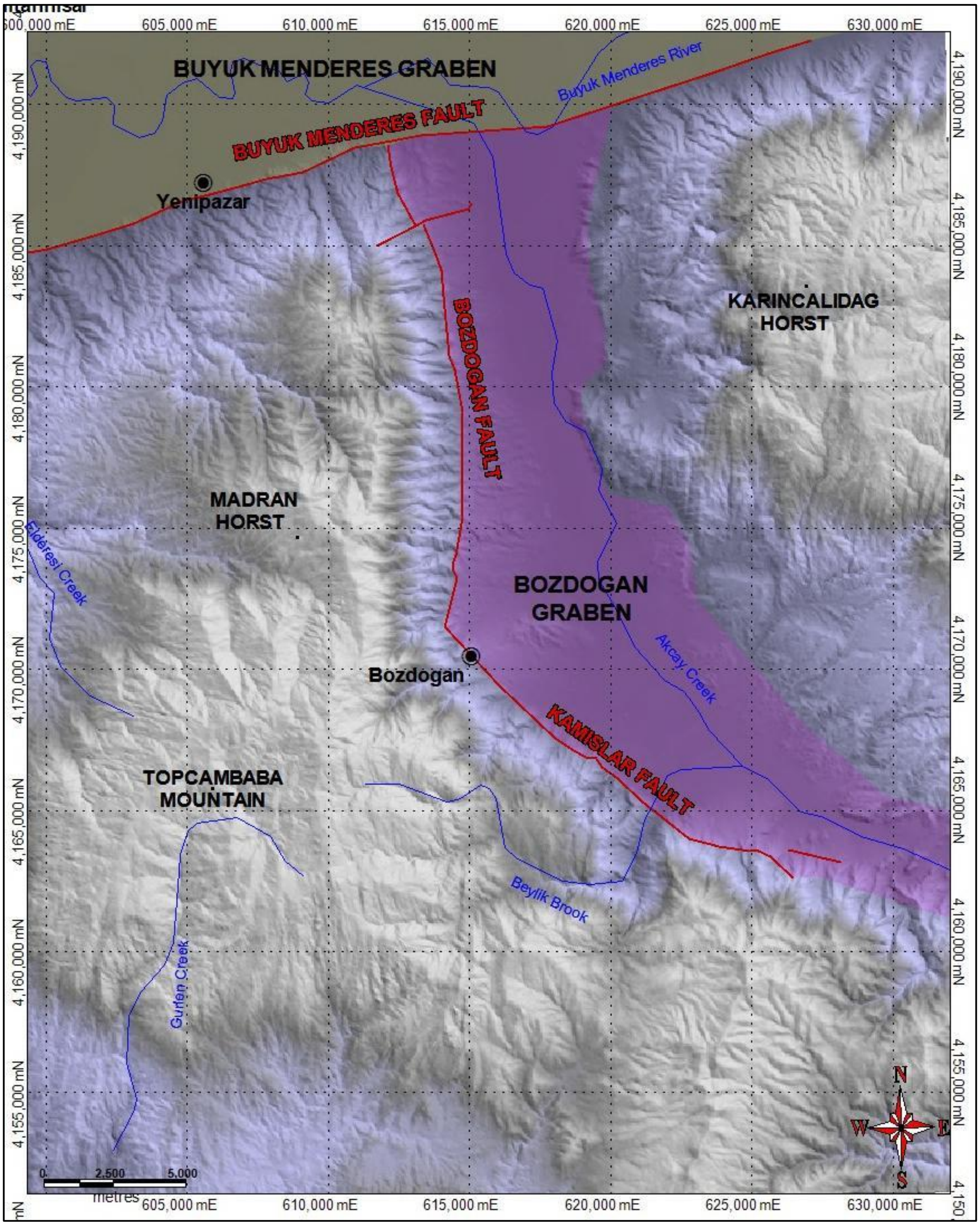


Figure 2 Geographical setting map of study area

1.3 Previous Studies

The geology and tectonic settings of Büyük Menderes and Bozdoğan Grabens are subjected to many studies.

Paton (1992) examined the relationship between faulting, geomorphology and drainage in south-western Turkey. In this study the rotation of sedimentary beds in the footwall blocks of faults and gravity data are also used to constrain amount of extension across the area.

Bozkurt (2000) studied Miocene fluvio-lacustrine, coal-bearing red clastic sediments exposed along the northern margin of the Büyük Menderes Graben in order to determine the timing of extension. And his study in 2004 is about the granitoid rocks of the southern Menderes Massif, which are the evidence for Tertiary magmatism in an extensional shear zone. He defines lithological successions of Menderes Massif and states that the intensity of metamorphism increases toward the core.

Gürer et al. (2009) studied progressive development of the Büyük Menderes Graben. They present and interpret new stratigraphic and structural data gathered by the detailed geological mapping project aiming the production of more than 20 sheets for the Büyük Menderes Graben region for two years.

Ocakoğlu et al. (2014) studied tectono-sedimentary evolution of the Karacasu and Bozdoğan trending obliquely to modern Grabens in the Central Menderes Massif. As a result of analysis carried out in terms of morphology, basin fill architecture, and structure, they stated that the modern Büyük Menderes Graben bounded by high-angle normal faults in the north caused a progressive drop of base level and resulted in southward developing fluvial incision since the Late Quaternary in the studied basins.

GIS based morphometric analysis becomes commonly used method by 2000s. There is no geomorphometry study conducted around this study area, however many studies about morphometric analysis are carried out all around the world. Some examples of these studies are given as follows:

Perez-Pena et al. (2010) carried out a geomorphic sturdy in the Sierra Nevada by examining drainage patterns and mountain front characteristics to analyse local deflections and types of rock uplift.

Temme (2010) developed T-Vector Utility which enables extraction of T-factor as an automatedprocess in order to accelerate T-vectors calculations. Viveen et al. (2012) used this application as a part of the study on the evaluation of tectonic activity on the NW Iberian Atlantic margin.

Shahzad and Gloaguen (2011a,b) developed a MATLAB based application called TecDEMin order to analyse stream flow parameters and morphometric data and they applied TecDEM tool to the digital elevation data of Kaghan Valley.

Siddiqui (2014) applied TecDEM tool to evaluate the influence of neo-tectonics on landscape evolution in the Emilia Romagna Apennines.

Daxberger et al. (2014) developed an ArcGIS-compatible tool called ValleyMorphTool for the extraction of the parameters such as V_f-ratio and T-factor and applied this tool on 3366 watersheds to extract stream asymmetry parameters for the calculation of T-factor data in the southern Central Andes and used the extracted indices to delineate tectonic processes and their influence on landscape development.

CHAPTER 2

GEOLOGY

The pre-Oligocene bedrock in south-western Anatolia consists of: (1) the metamorphic Menderes Massif; (2) the Beydağları crustal block with an unknown basement overlain by a thick platform of Mesozoic carbonates; (3) the Lycian nappes composed mainly of Mesozoic cherty carbonates and late Mesozoic–Paleogene ultramafic rocks; and (4) the Antalya nappes dominated by ophiolites (Alçiçek and Jimenez-Moreno, 2013).

The metamorphic basement rocks of Menderes Massif are mostly exposed within the study area. As shown in the geological map adapted from 1/500000 scaled geological map of Turkey, generated by MTA and modified in 2002, the Precambrian metagranite and gneisses and Palaeozoic schist and metasediments comprise the dominant lithology of the area. The Miocene – Late Pliocene limestone and continental units (conglomerate & sandstone alternations) of Dandalas formation are seen locally inside the Bozdoğan basin, commonly in the southern part of the Graben (Figure 3). The youngest units of both basins, which are Quaternary (alluvium & alluvium fans) show an unconformity and an erosional base and also include the fluvial deposits of existing rivers.

There are 3 active normal faults existing in the study area; nearly E-W trending Büyük Menderes fault, bounding the Büyük Menderes Graben at the south margin, N-S trending Bozdoğan fault and NW-SE trending Kamışlar fault which form the western margin of Bozdoğan Graben (Figure 2).

The detailed information about the lithologies and tectonic development of the study area is given in the following sections.

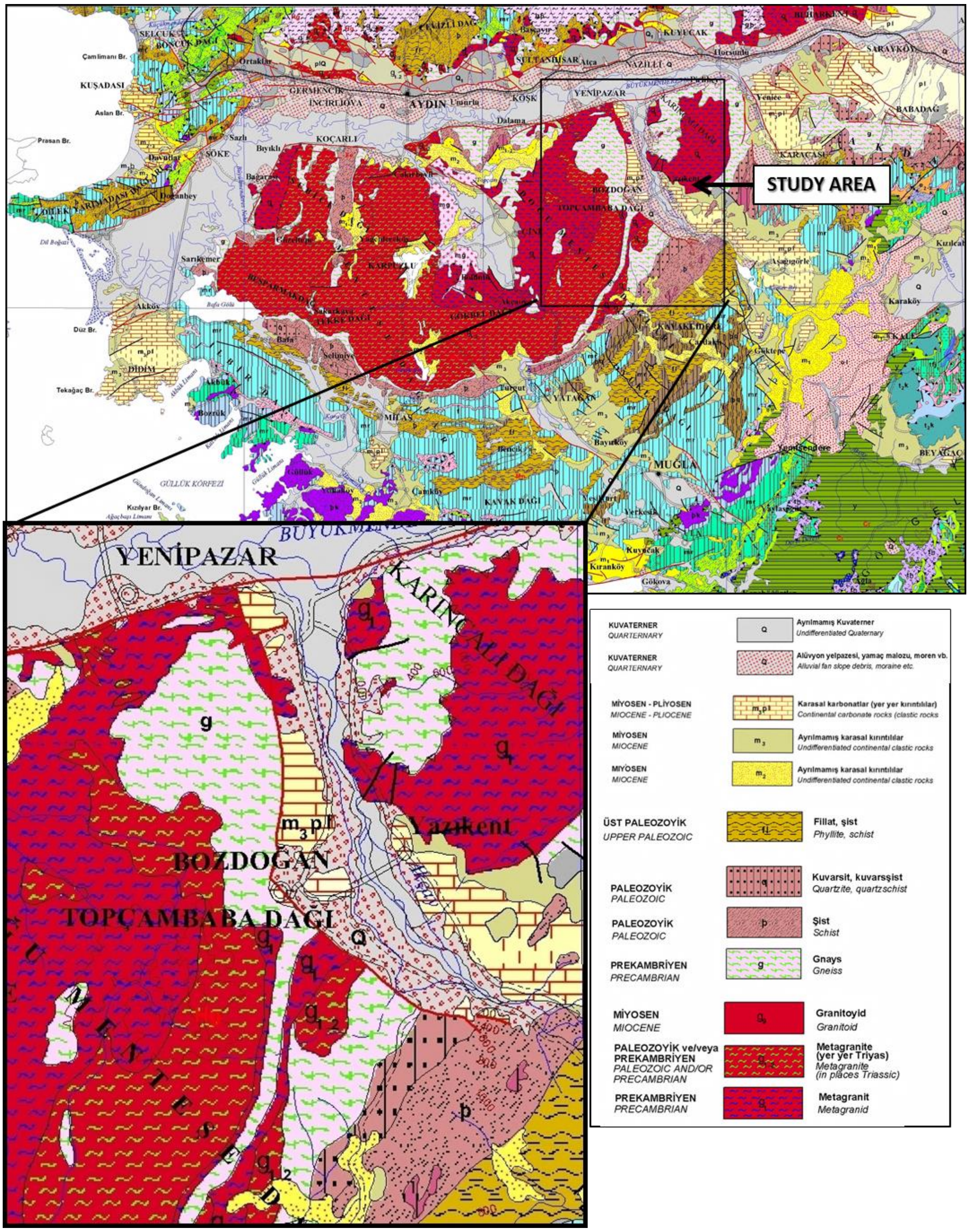


Figure 3 Geological Map of Study Area adapted from MTA, 2002

2.1 Geological Setting

2.1.1 Büyük Menderes Graben

The Büyük Menderes Graben is a 140 km long and 2.5 – 14 km wide arc shaped structure bounded by themetamorphic rocks of Menderes Massif. The width of Graben increases from east to west so it is defined as an asymmetrical Graben (Gürer et al., 2009).

Two major rock groups are which are characterized in the Büyük Menderes Graben. They are pre-Neogene basement and Neogene-Quaternary sedimentary cover (Gürer et al., 2009).

2.1.1.1 Basement

The pre-Neogene basement is composed of mainly Proterozoic–Mesozoic highly metamorphic rocks, the Menderes Massif (Gürer et al., 2009; Figure 4). The Menderes Massif is a crustal-scale, NE–SW-trending elongated metamorphic culmination which consists of three lithological successions; (1) core (mostly augen gneiss) at the base, (2) Palaeozoic low-grade metasediments (schist cover), and (3) Cenozoic marble-dominated sequence (marble cover). The intensity of metamorphism increases toward the core (Bozkurt, 2004).

The core of massif has two distinct types of granitoid rock which are orthogneiss (augen gneiss) and leucocratic metagranite. The leucocratic metagranite had intruded into orthogneiss and both are unconformably overlain by Neogene sediments (Bozkurt, 2004).

2.1.1.2 Cover Units

Sedimentary rocks in the Büyük Menderes Graben region have been formed by Neogene–Quaternary crustal deformation during the development and evolution of thehorst and Graben zone. Three litho-stratigraphic units termed A, B and C, are present in the Büyük Menderes Graben region. All of the units display depositional as well as tectonic contact with the basement metamorphic rocks (Gürer et al., 2009, Figure 4).

Unit A

This unit is composed of mainly of northwards tilted continental clastic sediments lie between the metamorphic rocks of the Menderes Massif in the north and the present-day Graben bounding faults in the south. This unit comprises a broadly coarsening-upwards sequence with a total thickness of c. 2 km (Cohen et al., 1995). At the basement, lithology is reddish, coarse-grained, well cemented, poorly sorted, polygenetic conglomerate composed of clasts derived from the underlying metamorphics and minor but widespread interbedded lignites. Above the conglomerates, siltstone, mudstone and shale alternations, together with conglomerates and pebbly sandstones are present (Bozkurt, 2000).

Laminar to trough-like cross-bedding, pebble imbrication, graded bedding and normal-type growth faults are common in this unit (Cohen et al., 1995).

Unit B

This unit consists of alternations of sandstone, siltstone, mudstone and claystone with approximately horizontal, massive, cobble to boulder conglomerates. Conglomerates crop out to the south of the tilted sediments of unit A.

Unit B has east-west trending, high-angle normal faults along the contacts, both with the deformed sediments of unit A to the north and the younger basin-fill sediments (unit C) to the south (Bozkurt, 2000).

Unit C

They comprise mainly of marginal alluvial fan and graben-floor sediments. The northern margin of the Büyük Menderes Graben is distinct by many steep, well-developed, alluvial fans of diverse size, aligned in a narrow zone. The source of the alluvial fan sediments is the metamorphic basement, unit A and B sediments. The alluvial fans grade into fine-grained basin-floor sediments along the Büyük Menderes River. In places, the alluvial fans coalesce and degrade and result in a fault-parallel alluvial fan apron. These sediments, with the present-day configuration of the Büyük Menderes Graben, are juxtaposed with unit B sediments along high-angle graben-bounding normal faults (Bozkurt, 2000).

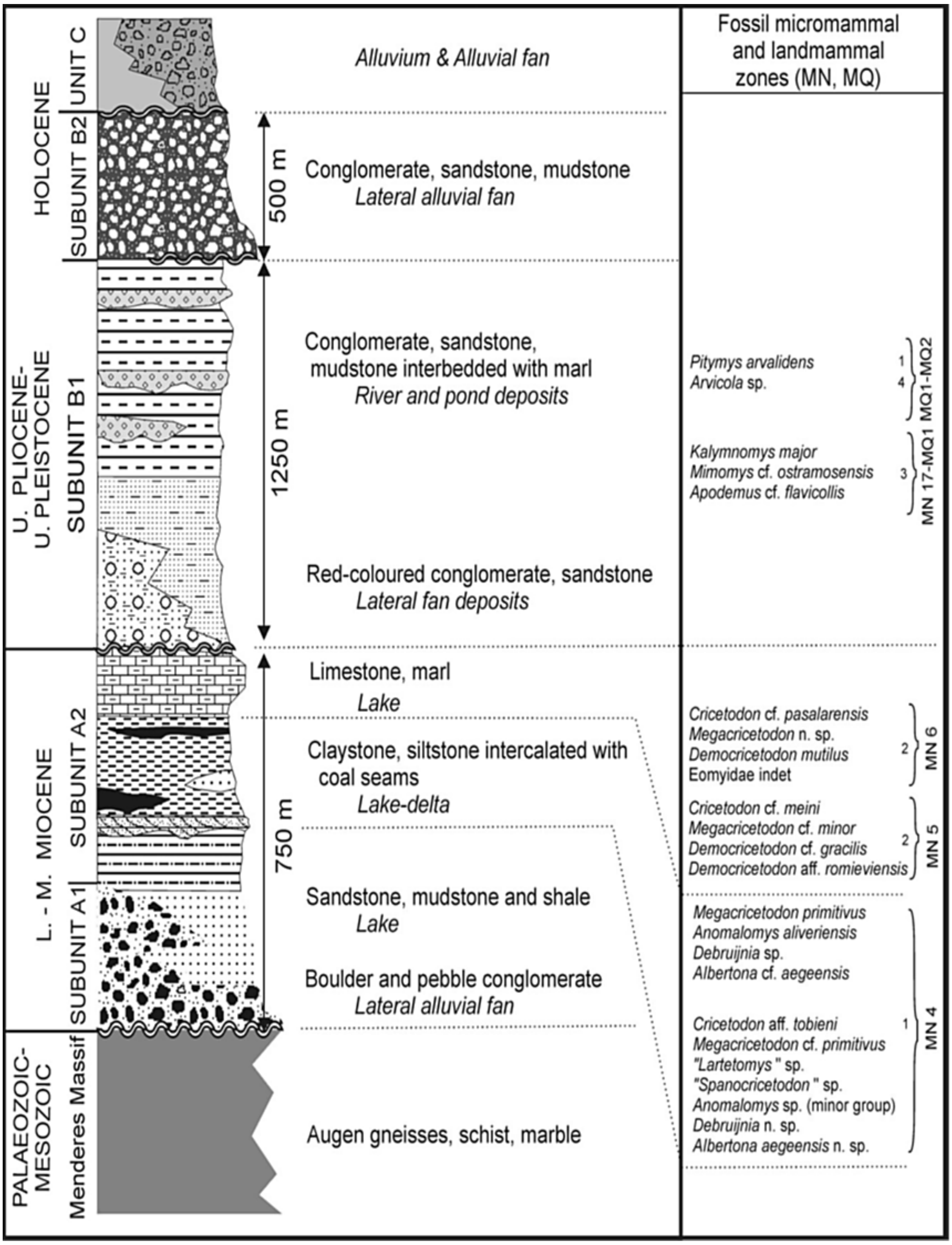


Figure 4 Generalized columnar section of the Büyük Menderes Graben (Gürer et al., 2009)

2.1.2 Bozdoğan Graben

The Bozdoğan Graben is arcuate half graben structure with 10 km wide and 30 km long dimensions. This basin has metamorphic rocks of the Menderes Massif at its basement. The sedimentary successions of Dandalas group lie over the basement with an unconformity. The youngest deposits of the basin show an unconformable, erosional base and include the fluvial deposits of modern rivers, local basin-margin alluvial fans, extensive colluvial (talus) aprons, and modern soil cover (Alçiçek and Jimenez-Moreno, 2013).

2.1.2.1 Basement

The oldest Menderes massif rocks on the horst are Precambrian migmatite and gneiss, which are overlain by Paleozoic marble and quartz-schist (Konak and Göktaş, 2004). The upper part of this succession is represented by Mesozoic marble and schist (Figure 5). The grade of metamorphism has progressively decreased upward (Bozkurt and Oberhansli, 2001).

2.1.2.2 Cover units

The cover units comprises of 2 litho-stratigraphic units separated by an unconformity. The lower unit, called the Dandalas group (Miocene-Early Pliocene infill), comprises 2 interfingering formations: Damdere and Karacaören formations. The estimated maximum thickness of the Dandalas group in the Bozdoğan Graben is 1100 m based on the elevation of the basement beneath the basins (–300 m) and the uppermost depositional surface of the unit (800 m). The upper unit is the Karacasu formation (Late Pliocene-Quaternary infill) which overlies unconformably the Dandalas formation (Ocakoğlu et al., 2014, Figure 5)

Damdere Formation

In the Bozdoğan Graben, the Damdere formation, consisting of yellow-colored, well-organized sandstone-conglomerate alternation, forms the lower part of the basin-fill succession and overlies the bedrock unconformably, passing upwards into the Karacaören Formation (Açıkalın, 2005).

Sedimentation was controlled by the basin's southern boundary fault. The unit thickness is approximately 150m. The paleo-channels grade upwards into fine-grained sandstones, siltstones, and reddish massive and organic-rich mudstone deposits (Alçiçek and Jimenez-Moreno, 2013).

Karacaören Formation

The Karacaören formation typically consists of two units:

1. Lower unit consists of the alternations of sandstone, marlstone, mudstone, and clayey limestone, and dolomite
2. Upper unit consists of two subunits which are alternations of sandstone, marlstone, diatomite, cherty marlstone and limestone, and clayey limestone and dolomite and overlying alternations of bituminuous shale, marlstone and bioclastic dolomite (Alçiçek and Jimenez-Moreno, 2013).

The thickness of this formation varies up to 210 m and it locally includes a rich diatom and ostracoda fauna (Açıkalın, 2005).

Karacasu Formation

The Karacasu formation overlies Dandalas group unconformably in the southern part of the basin however in the northern part of the basin it extends on the metamorphic bedrock also with an unconformity (Açıkalın, 2005).

The thickness of Karacasu formation reaches up to 70 m. This formation is composed of two units:

1. Lower unit of matrix-supported coarse grained conglomerates alternating with reddish laminated siltstone mudstone and massive mudstones, and
2. Upper unit of weakly cemented, yellowish- to brownish-gray conglomerates, sandstones, and mudstones with sulfur-bearing nodules with vertebrate remains, including equids and bovids (Alçiçek and Jimenez-Moreno, 2013).

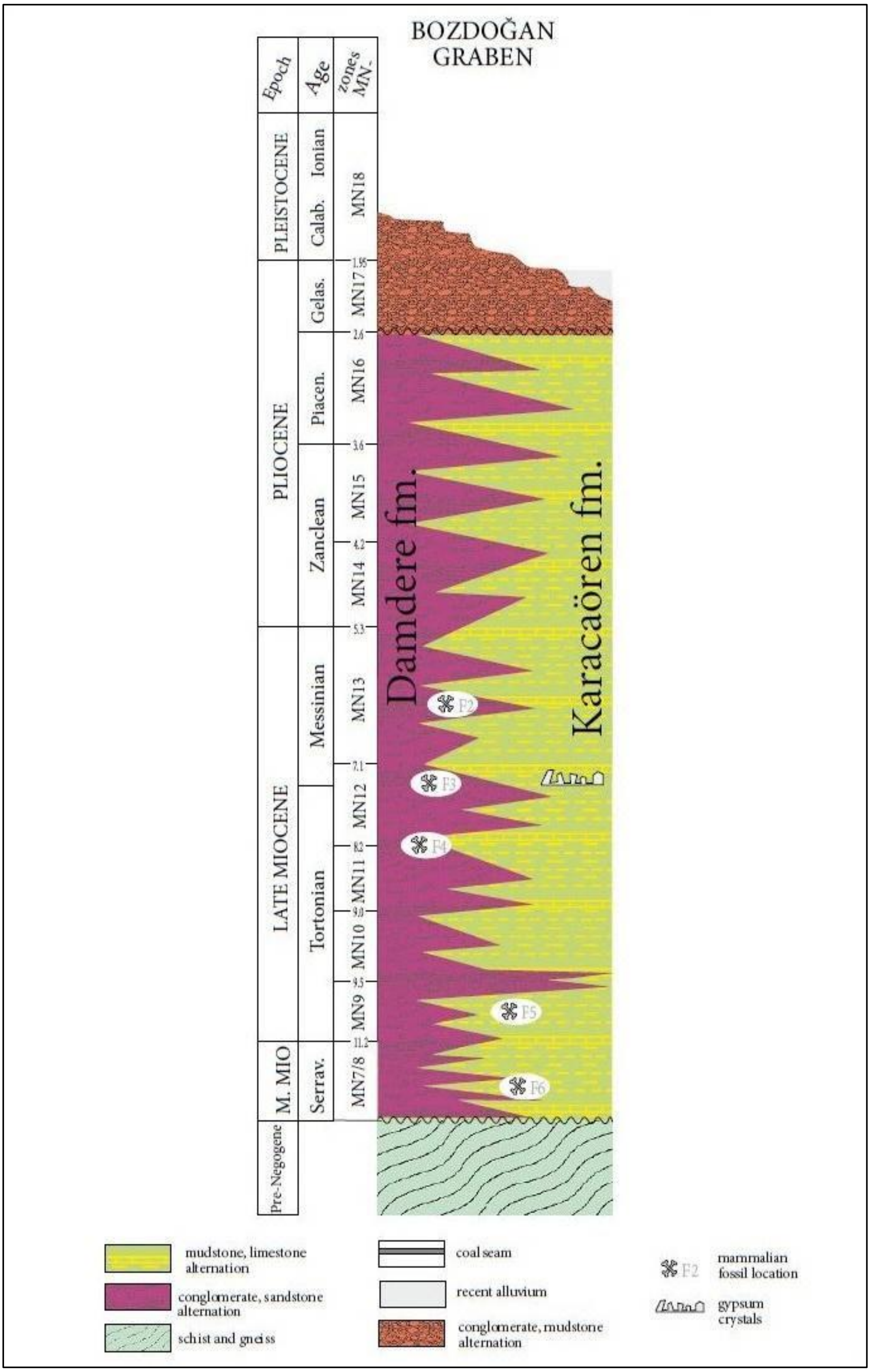


Figure 5 Generalized columnar section of the Bozdogan Graben (Ocakoğlu et al., 2014)

2.2 Tectonic Setting

The Aegean region is one of the most active regions subjected to an N–S extension in the world (Dewey & Sengör, 1979). Four different models have been considered to explain the origin of the extension; (a) the back-arc spreading model, (b) the orogenic collapse model, (c) the tectonic escape model, and (d) the two stage graben model (orogenic collapse/roll-back and tectonic escape)(Gürer et al.,2009).

The Plio-Quaternary N–S extension in Aegean region had the combined effects of the two continuing processes. These two successive and independent complex tectonic activities are indicated by oblique and normal fault systems in the Büyük Menderes Graben (BMG) region. The first activity is an E–W extension related to N–S contraction and transpression which are responsible for the development of NW- and NE-trending conjugate pairs of oblique faults controlling Early–Middle Miocene basin formation. The second one is the change in tectonic regime from E–W extension to N–S extension controlling the formation of the Büyük Menderes Graben by three progressive stages of deformation. The first stage of extensional deformation was responsible for the development of the E-trending Büyük Menderes Detachment Fault (BMDF). The second stage was the formation of approximately E–W-trending high angle normal faults synthetic and antithetic to the BMDF and the final stage was the migration of the Büyük Menderes Graben to the present day position (Gürer et al., 2009).

Three types of major structures occur along the northern margin of the Büyük Menderes Graben: (1) an inactive, presently low-angle, normal fault; (2) west-northwest-east-southeast to northwest-southeast folds within the unit A sediments; and (3) approximately east-west high-angle, graben-bounding normal faults (Bozkurt, 2000).

Different tectonic processes during Neogene–Quaternary times created a network of fault systems and several basins, filled by continental deposits. This fault network is dominated by E to NE and NW orientation. Two systems of faults have been recognized: (1) approximately NE and NW-trending sub vertical oblique faults adjacent to Unit A; (2) E–W faults adjacent to units B and C.

The second system can be subdivided into: (a) a major E-trending low-angle fault, the Büyük Menderes Detachment Fault, and (b) secondary listric high-angle faults, segmented for distances over 10 km (Gürer et al.2009).

Three major valleys cut the south side of the Büyük Menderes Graben. One of them is Bozdoğan Graben which seems to be bounded by normal faults. The historical seismicity studies, morphological analysis of the range-fronts in the field and also on the Landsat images, the tilting direction of in the Neogene sediments and alluvial fan development propose that the valley is bounded on their west sides by large, east dipping normal faults (Paton, 1992).

There exist 3 main faults in the Bozdoğan Graben; the Bozdoğan fault in the north, the Kamışlar fault in the center, and the Güvenir fault in the south. The Bozdoğan fault extends 18 km with N-S direction from the northern tip of the Graben to Bozdoğan in the south. This fault consists of several left and right stepping segments of 3–5 km long. At Bozdoğan, the graben margin suddenly bends and it extends another 18 km with nearly N40W direction. As it approaches at the SE tip, it shows E-W trend. This segment is called the Kamışlar fault (Ocakoğlu et al., 2014; Figure 2).

Clear slickenside measurements carried on these faults reveal the presence of a normal slip with a slight dextral component. Moreover, 200 m south of Kamışlar, a reverse-to-thrust fault has examined between the metamorphic basement and the Mio-Pliocene lacustrine sediments. The NW trending Güvenir fault appears at the western margin of the Kemer Hydroelectric Dam. This has been exhumed as a result of deep and selective erosion of the Akçay creek (Ocakoğlu et al., 2007).

The Bozdoğan Graben is deeply incised by the Akçay creek to form a broad valley at about 50–90 m above sea level where a thin veneer of fluvial sediments was deposited. The Mio-Pliocene terrestrial and lacustrine sediments are tectonically opposed to the basement metamorphic rocks throughout the fault trace. However, no morphological evidence is available that shows modern activity (Ocakoğlu et al., 2014)

There are minor faults sub parallel to the Güvenir in the southwest of Bozdoğan. They are noticeable because of the straight mountain front in the middle of the metamorphic terrain fault consistent with highly steep scarps (Ocakoğlu et al., 2014).

The eastern and western sides of this horst include a thin veneer of Mio-Pliocene fluvial sediments, which are the correlatives of the upper portion of the Bozdoğan Graben basin fill (Ocakoğlu et al., 2007).

2.3 Instrumental Seismicity

In order to observe the seismic imprints of active faults, a regional seismicity map of Western Anatolia is presented in Figure 6. Faults bounding the Büyük Menderes and Bozdoğan Grabens within the study area and near vicinity are characterized by lack seismic activity compared to other parts in Western Turkey which may be due to released tectonic stresses during historical earthquakes.

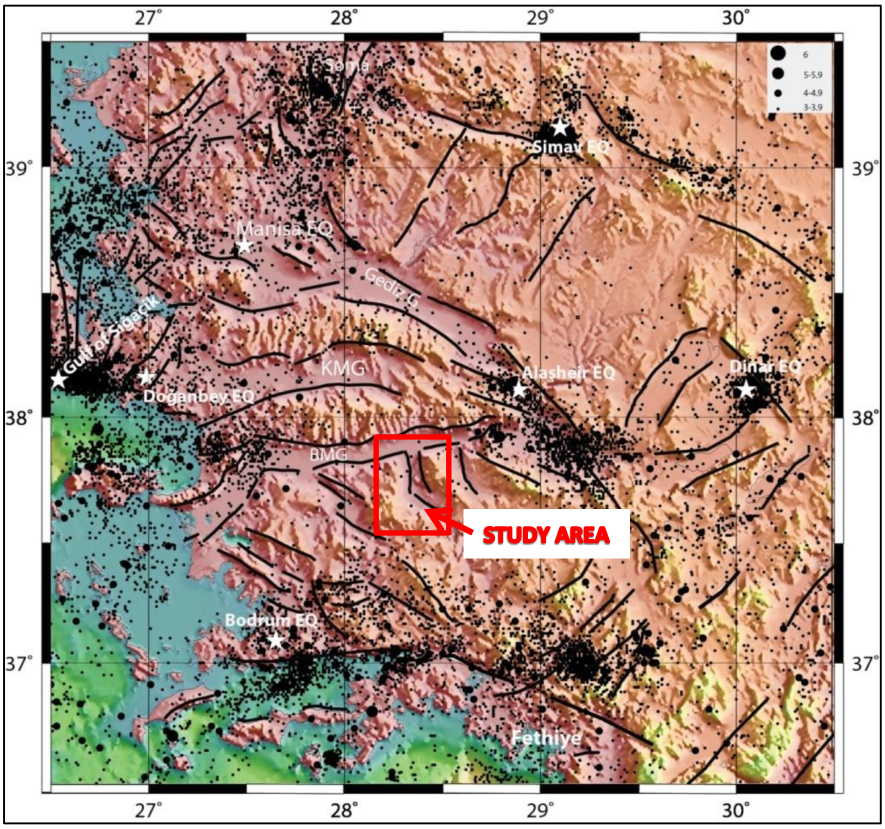


Figure 6 Seismicity Map of Western Anatolia taken from Shah (2015). The seismic catalogue is obtained from KOERI (M≥3) for the period of 1990-2013. Stars show the epicenters of major events occurred in the region.

CHAPTER 3

MORPHOMETRIC INDICES

Morphometric indices are powerful tools for the study of the relationship of tectonics, lithology, and climate on mountain channels and landscapes. The morphometric parameters such as Isobase, Incision, Vertical Dissection, and T-index are extracted to recognize tectonic control on drainage network development, basin morphology and landscape evolution.

Detailed information about the morphometric indices used in this study is given below.

3.1 Isobase

The Isobase term represents the sense of a "line of equal uplift" (Leverington et al., 2002). Isobase lines characterize erosional surfaces which have been formed due to recent tectonic and erosional events (Golts and Rosenthal, 1993, Cox, 1994).

An Isobase surface is a digital continuous surface generated from a set of points with equal elevations. An Isobase map represents a map of drainage network showing the relative position of stream segments which can be organized to the Strahler stream order. Isobase maps are prepared by interpolating the elevation at the location of streams in given Strahler order. This stream order is suggested by Golts and Rosenthal (1993) and Grohmann (2004) to be selected as 2^{nd} and 3^{rd}.

The spatial distribution of stream elevations corresponding to the Isobase values is a useful tool for the interpretation of underlying geology. Hence, anomalies in the isobase surface can be related with the change in local conditions such as faulting and lithological variations. This method can be applied for analysis paleo-water tables deformed by isostasy or faulting, former lake shoreline benches, glacial basin paleo-profiles or paleo-altimetry datasets.

Shahzad and Gloaguen (2011a,b) developed a MATLAB based application called TecDEM in order to analyse stream flow parameters. This tool enables an automated generation of isobase, incision, vertical dissection maps. It is possible to select streams with a specific Strahler order and process on them. They applied TecDEM tool to the digital elevation data of Kaghan Valley as case study and inferred that the results of this TecDEM application correlate well with previous tectonic evolution models for this region.

3.2 Incision

The incision parameter corresponding to the relative relief is a utility for computing relative elevation. The elevation difference from the peak of the highest mountain to the valley bottom in a region is regarded as relative relief (Kühni and Pfiffner, 2001).

Incision parameter is calculated by measuring the difference between the maximum and minimum elevation in a moving window. The shape and size of this moving window affects the calculation of relative relief. The calculation of Relative Relief (incision) should be large enough to include at least two major ridges and/or valleys otherwise the results will not show relative relief but simply the slope gradient (Shahzad and Gloaguen, 2011b).

Siddiqui (2014) applied TecDEM tool to evaluate the influence of neo-tectonics on landscape evolution in the Emilia Romagna Apennines. The morphometric indices such as Isobase, Incision, and Surface Roughness were extracted by terrain analysis in order to recognize tectonic and/or lithological control on basin morphology and landscape evolution. The areas showing high incision rates are assumed to have experienced a significant uplift in correspondence to steep slopes and high stream gradients. It is observed that growing trend of incision rates from NE to SW corresponds well with the higher relative uplift and steep slope gradients, associated with the NW-SE oriented out of sequence thrust faults and strike-slip faulting.

3.3 Vertical Dissection

The surface roughness i.e. vertical dissection is useful for studying morphological characteristics of a region (Grohmann, 2004; Grohmann et al., 2007). It is an indicator of topographic heterogeneity. Surface roughness is extremely high in highly deformed regions.

The vertical dissection of a region is defined as the variation from vector normal planes to surface normal planes. As seen in figure, surface roughness is described as the ratio between surface area and flat area (Grohmann, 2004; Figure 7).

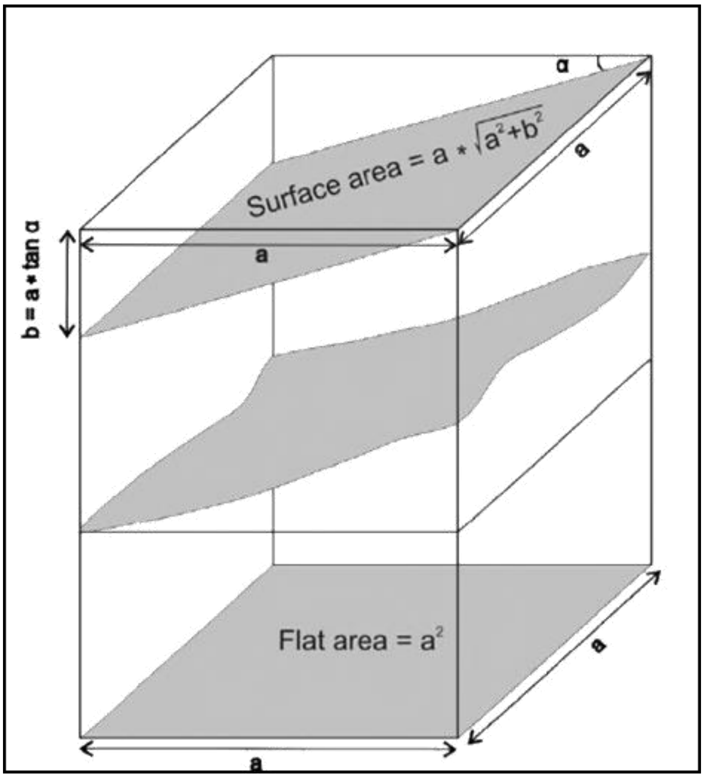


Figure 7 Geometric relationship, between vector normal plane and surface normal plane, used to calculate surface roughness parameters (Grohmann, 2004)

The roughness of a landscape describes how deep and narrow it is dissected by erosion. It is quantified by the vertical variations of a real surface from its ideal form. If the surface is rough, these variations are large; if the surface is smooth, they are small (Siddiqui, 2014).

Siddiqui (2014) used this parameter to evaluate the influence of neo-tectonics on landscape evolution in the Emilia Romagna Apennines. In this study, the bands of high values of Surface Roughness are interpreted as the uplifted block locations along thrust and strike-slip fault zones. The high surface roughness values were evaluated consistent with the young highly dissected areas. High surface roughness in the SW part of the study area was observed giving rise to more incised relief and it gave clues about the active deformation and recent tectonic uplift. It is concluded that the calculated results fit to the recent tectonic uplift of the region and shows strong positive correlation with the geological structures and neo-tectonic activity of the study area.

3.4 Basin Asymmetry

The transverse topographic symmetry factor (T-index) was first proposed by Cox (1994) in order to study the stream asymmetry and identify tilted drainage basins in the tectonically active regions. The transverse topographic symmetry factor is calculated by following equation (Cox, 1994):

$$T = \frac{D_a}{D_d} \qquad \textit{(eqn. 3.1)}$$

Where D_a is the distance from the active meanderbelt midline to basin midline (measured perpendicular to a straight line segment fit to the channel), and D_d is the distance from the basin divide to the basin midline (Figure 8, Cox, 1994, Siddiqui, 2014).

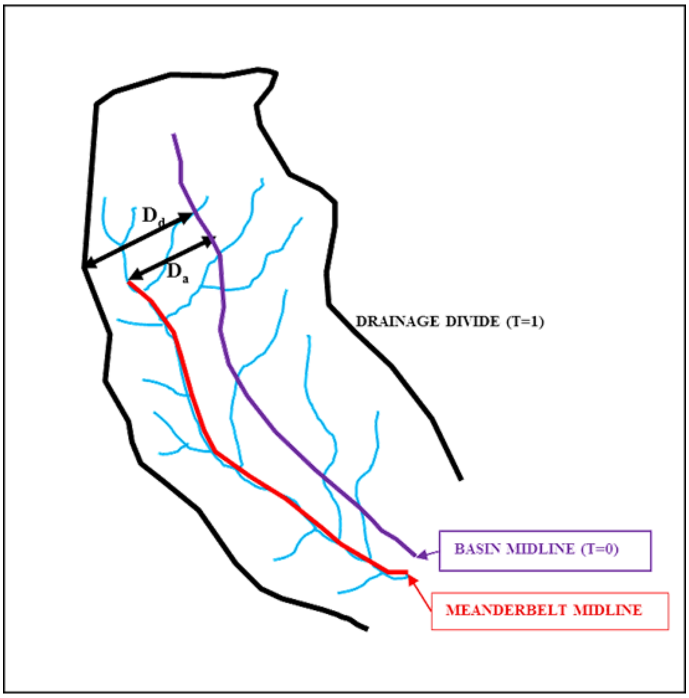


Figure 8 Sketch showing T-vector calculation adapted from Cox, 1994

T-factor of the drainage system is calculated by dividing the length of the streams in equal representative segments upon the length of the stream in study area. T-vector is a two dimensional vector having a length equal to T-index value and a dimension perpendicular to the segment of the stream. The calculated T-index values are between 0 and 1 indicating complete symmetry and complete asymmetry, respectively. The direction of vector shows the movement of river segment with respect to the basin midline. Statistical analysis is applied to define direction of stream migration, the magnitude and a measure of dispersion. The dominant direction is determined calculating the resultant vector and its direction is the mean direction of all the calculated vectors (Davis, 2002).

Temme (2010) developed T-Vector Utility which enables automated T-factor extraction in order to speed up calculations of T-vectors. This utility is a stand-alone ascii-raster based tool using DEM, watershed grid as inputs and giving T-vector grid and other optional .asc maps as outputs. Viveen et al. (2012) used this application as a part of the study on tectonic activity assessment on the NW Iberian Atlantic margin. They indicated that although on Quaternary, basin asymmetry analysis is useful in the evaluation of block tilting, does not provide useful information on

Holocene since a long time is required for drainage basin asymmetry in order to develop as opposed to block tilting. They also mentioned that tilt parallel to the direction of the main stream cannot be assessed.

Daxberger et al. (2014) developed an ArcGIS-compatible tool called ValleyMorphTool for automated extraction of T-factor parameter. Daxberger et al. (2014) specified that the data extraction methodology on the studies of Bull and McFadden (1977) and Cox (1994) and the computation procedure is the same with the T-Vector Utility developed by Temme (2010). The standalone script version of the ValleyMorphTool was further provided for use outside of ArcGIS. 3366 watersheds were used to extract stream asymmetry parameters for the calculation of T-factor data in the southern Central Andes. The interpretations of these indices were consistent with previous studies conducted in the area. Daxberger et al. (2014) remarked that the fully functional ValleyMorphTool provides useful opportunities for satellite based studies on Quaternary deformation of large and remote areas and therefore it improves the efficiency of tectonomorphic surveys.

CHAPTER 4

METHODOLOGY AND IMPLEMENTATION

This thesis study was carried out at four main stages: (1) literature survey about morphometric and basin asymmetry analysis, (2) selection of study area characterized by normal faults, (3) computer based analysis in GIS environment and (4) evaluation of the software outputs.

The computer based analysis was conducted using multiple software: TecDEM (Shahzad and Gloagen, 2011), ValleyMorphTool (Daxberger et al., 2014), ArcGIS and TNTMips.

4.1 Data

Digital Elevation Model (DEM) in GeoTIFF format, with 25 x 25 m horizontal resolution, is the main data of the thesis study. The digital elevation data of nine 1/25000 scaled topographic map sheets, M20a3, M20b3, M20b4, M20c1, M20c2, M20c3, M20c4, M20d2 and M20d3, corresponding to the junction area of the Büyük Menderes and Bozdoğan basins composes the input data. The Digital Elevation Models (DEMs) are generated from the digital topographical contours with 10m spacing. The drainage network lines, watershed polygons etc. which are derived from DEM have been also used as input data (Figure 9).

The geological map and fault lines were adapted from 1/500.000 scaled geological map of Turkey, generated by MTA and modified in 2002 (Figure 3). Study area is characterized by metamorphic rocks of Menderes Massif and 3 active normal faults namely, Büyük Menderes fault, Bozdoğan and Kamışlar faults (Figure 2).

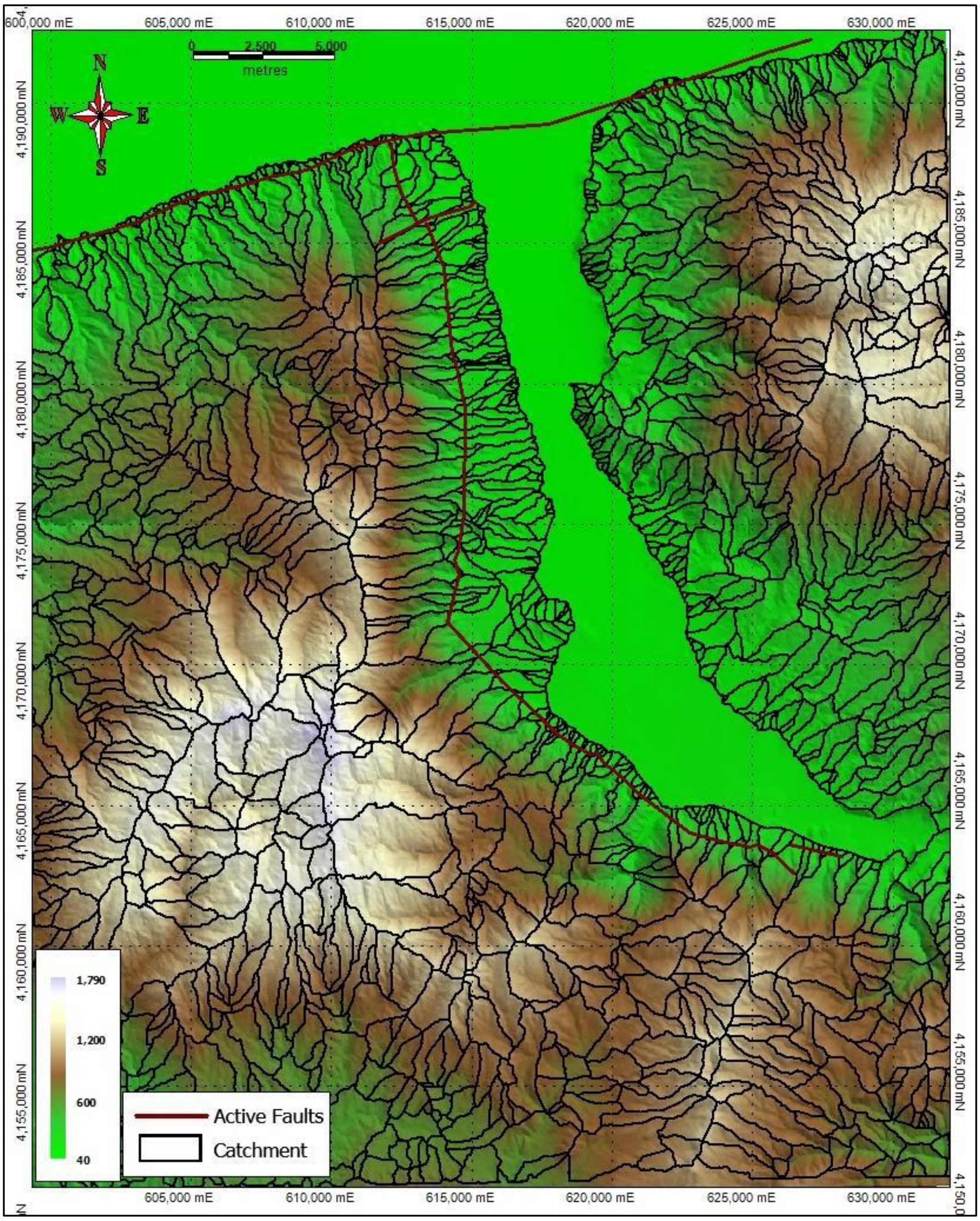


Figure 9 Input DEM and manually corrected watershed polygons on it

4.2 Computation of Isobase, Incision and Vertical Dissection

TecDEM is a MATLAB-based application, developed by Shahzad and Gloaguen (2011a).This MATLAB application enables the extraction of morphometric parameters through the DEM-based stream flow analysis (Shahzad and Gloaguen, 2011b). This semi-automated application uses only Digital Elevation Model (DEM) data as input. This is a tool which uses digital elevation models in GeoTIFF format as input. After importing DEM, we continued with stages of drainage network preparation: depression fill, flow grid and contributing area calculations. Flow grids are generated based on the D8 algorithm. The D8 algorithm is the most commonly used and well understood method for resolving flow directions on a topographic surface. It routs flow on each pixel of DEM to possible downward pixel bases upon the lowest neighbouring slope. DEM, with no depression, was derived from original DEM and the flow grid by D8 algorithm was generated using this DEM. The contributing area refers to the number of pixel contributing flow to a specific stream. These numbers of pixels are then converted to area in square km by using DEM resolution (Shahzad and Gloaguen, 2011b).

Second step was the drainage network and watershed extraction. It is necessary to select streams with a specific Strahler order and process on then. Additionally, a threshold area value required for calculation for flow accumulation must be given in square km. In this study streams with 2nd and 3rd Strahler order is used to process and minimum threshold area is selected as 1 km^2.

The extracted drainage network and basins were used for morphometric, stream profile and basin analyses. The parameters, used in this thesis study for morphometric interpretations, were analysed by “Spatial Statistics” function. This function provides automatically generated isobase, incision and vertical dissection maps (Figure 10). The only required user parameter is the moving window size which can be entered in pixels and varies from region to region and extent of the study area (Shahzad and Gloaguen, 2011a).

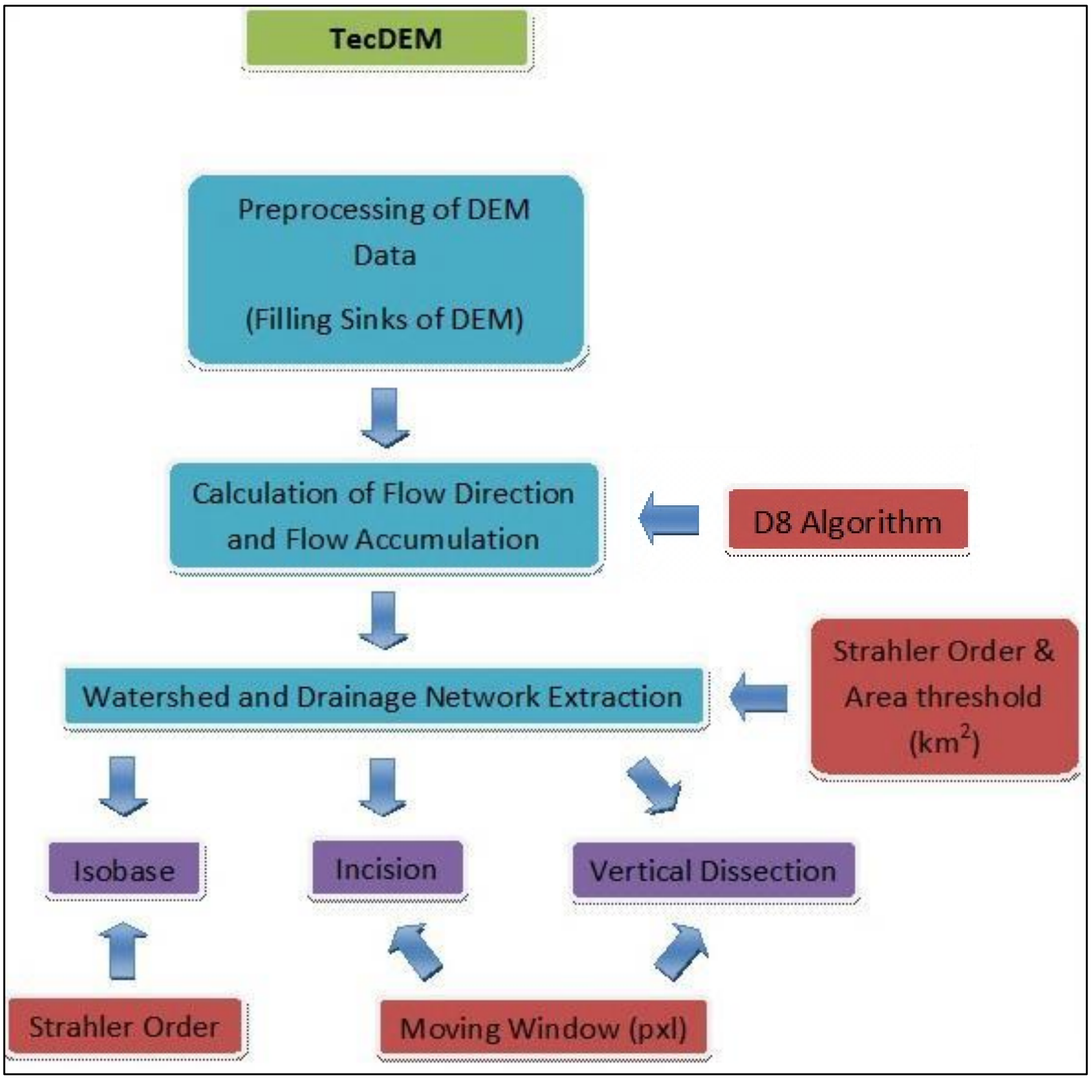


Figure 10 Flowchart of TecDEM

4.2.1 Isobase

The isobase map with 25m x 25 m grid dimensions is obtained manually by converting all of the stream lines obtained from DEM into elevation points and applying inverse distance weighting for surface interpolation using ArcGIS software. The manually created Isobase map is shown in Figure 11.

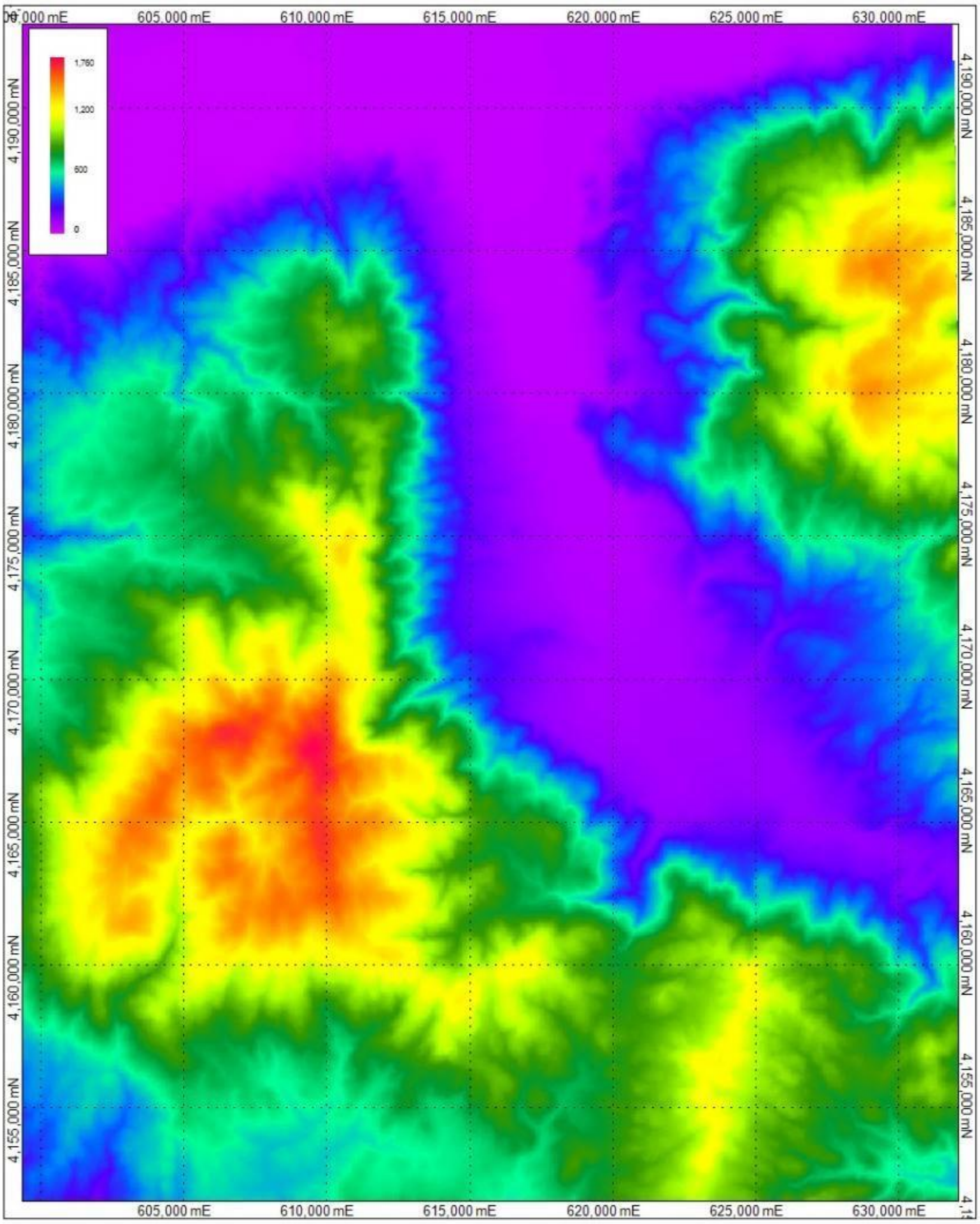


Figure 11 Isobase surface generated manually

4.2.2 Incision

The incision map is obtained from TecDEM software using a moving window. The size of the window has been set as 10 pixels which lead to a 25 m resolution (Figure 12).

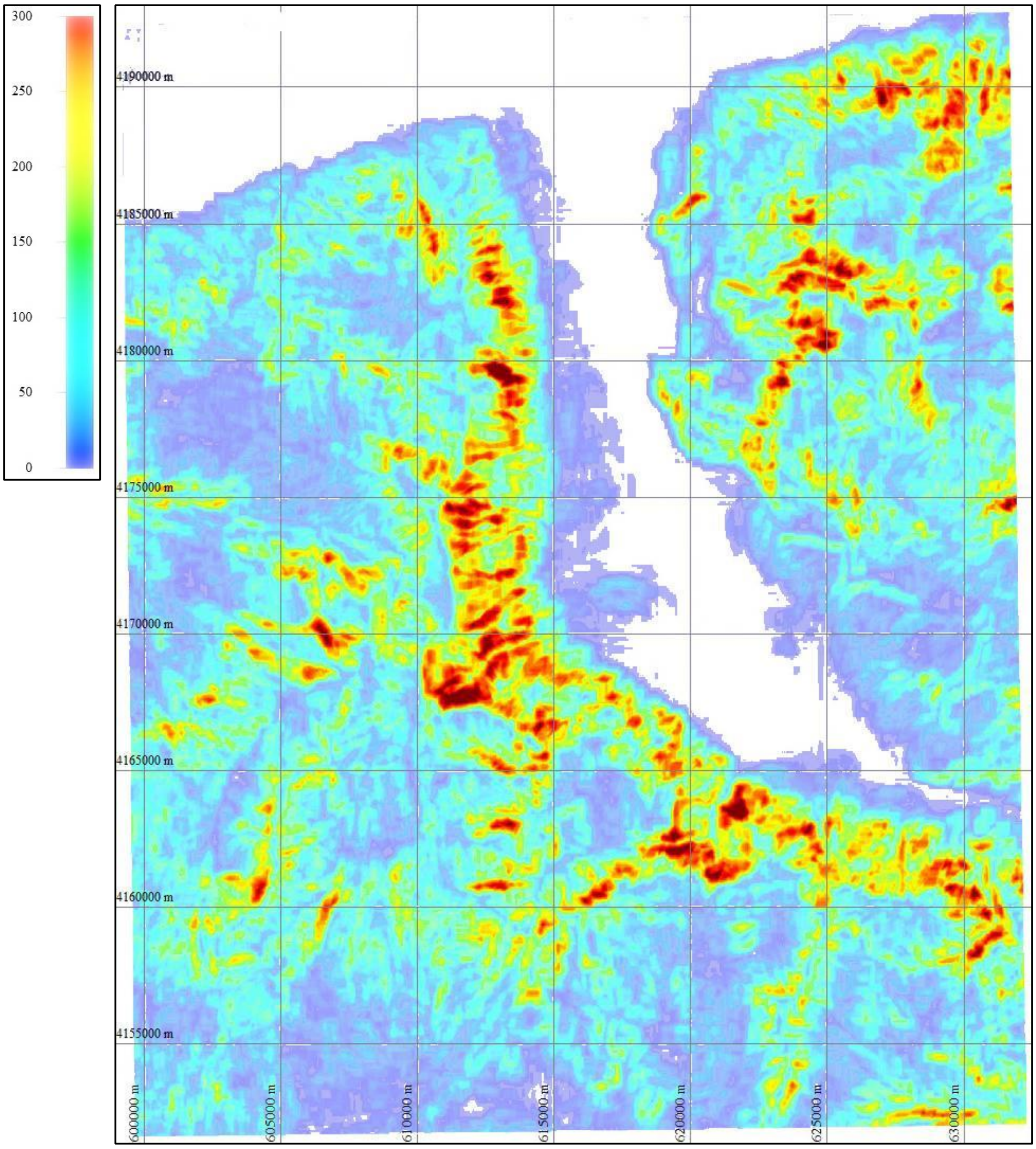


Figure 12 Incision Map created using TecDEM application

4.2.3 Vertical Dissection

The vertical dissection map is obtained from TecDEM software again using a moving window with similar size which gives 25 m resolution (Figure 13).

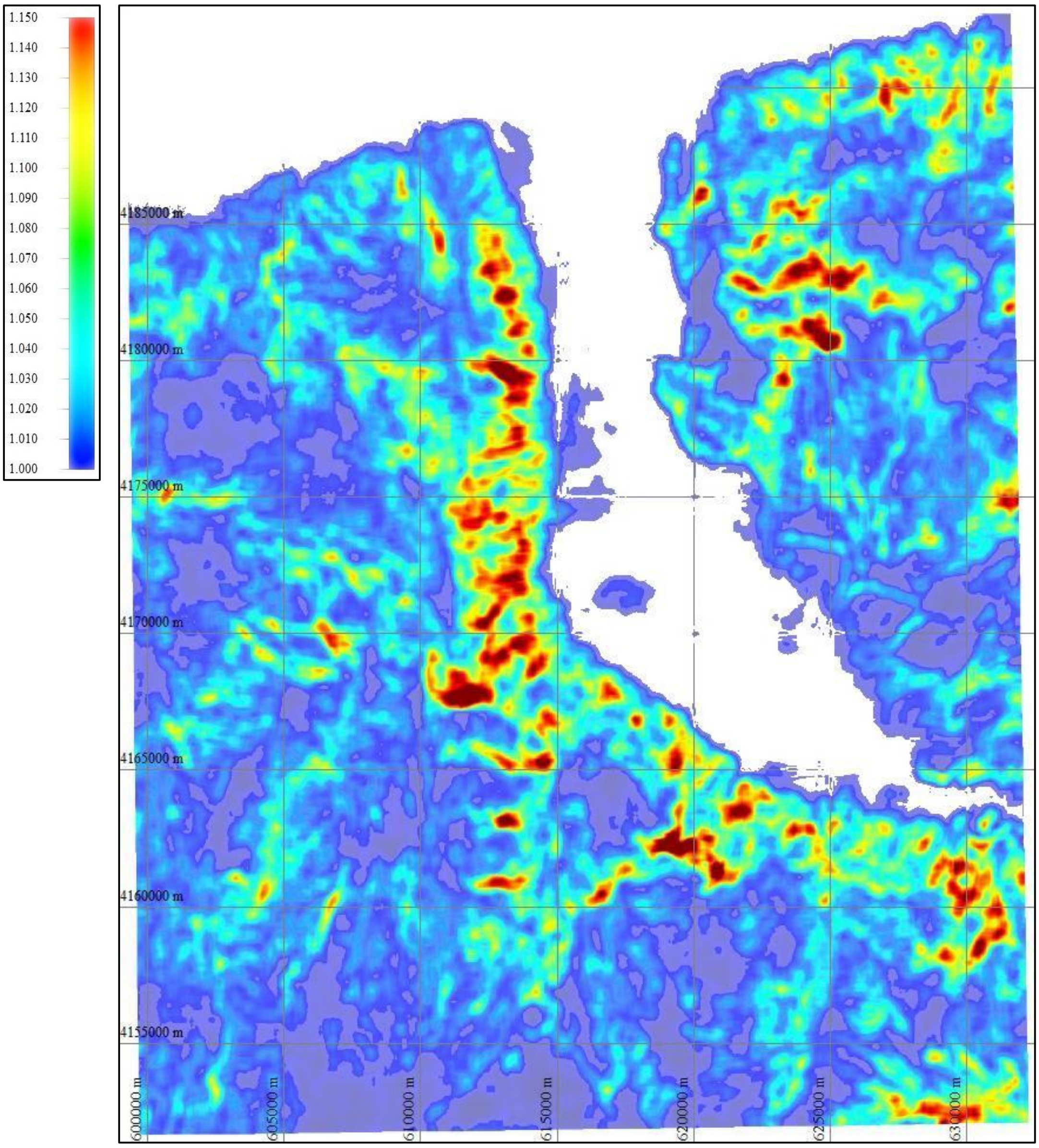


Figure 13 Vertical Dissection Map created using TecDEM application

4.3 Identification of Stream Asymmetry (T-factor)

ValleyMorphTool is an ArcGIS-compatible (especially ArcGIS version 10.1) application for the extraction of the stream asymmetry parameters such as T-factor (Daxberger et al., 2014). This application requires DEM data and also digital watershed areas for the extraction of T-vectors as an automated process. This tool requires raster grids of digital elevation models such as SRTM or ASTER DEMs In addition, polygons of selected watersheds should be imported as shape file.

Data pre-processing have been performed by using both the Arc Hydro extension and the Hydrology tool in ArcGIS (Daxberger et al., 2014). These pre-processing contains the detection and then removal of sink cells, cells with drainage values which are undefined, generation of flow direction raster from each cell to steepest down slope neighbour and generation of flow accumulation raster showing accumulated flow into each cell, respectively (Figure 14). Similar to TecDEM flow grids are generated based on the D8 algorithm. The D8 algorithm is the most commonly used and well understood method for resolving flow directions on a topographic surface. It routs flow on each pixel of DEM to possible downward pixel bases upon the lowest neighbour slope. In order to create a D8 flow grid, a depressionless DEM should be generated from original DEM. The contributing area refers to the number of pixel contributing flow to a specific stream. These numbers of pixels are then converted to area in square km by using DEM resolution (Shahzad and Gloaguen, 2011a). Watershed areas are delineated by stream flow accumulation grid and the threshold area value in square km, then stored as a polygon shape file. In this study, the minimum threshold area to define a region as a watershed is selected as1 km^2 which is same as used in TecDEM applications.

In this study, more than 1500 watershed polygons have been extracted using ArcHydro toolbox extension (Daxberger et al., 2014). The output polygons have been reviewed and manually corrected by visual interpretation on digital elevation model (Figure 8). The corrected 1267 watershed polygons have been processed by the Valley Morph tool in order to extract T-vectors.

The ValleyMorph Tool uses the methodology suggested by Cox (1994) and follows the procedure developed by Temme (2010) for T-vector extraction. Firstly the determination of the lowest point of the watershed and the farthest point from the lowest point of the watershed is a must. The lowest and farthest points of the watershed are connected by a straight line called as the long axis. A series of lines are created at a given interval, starting from the lowest point up to the farthest point, where each line or cross section intersects with the long axis at right angles. In this study, cross sections are created with an interval of 150 m. By means of these cross sections midpoints are extracted in order to generate watershed midline. Another cross section sets were produced orthogonal to the watershed midline and the river midline and the drainage divides were generated at a given interval. Using the length of transect line from watershed midline to main stream (D_a) and the length from midline to watershed divide (D_d), the magnitude of T vectors have been calculated by the equation 3.1 where the direction of transect lines gave the direction of T-vectors. The calculated individual T-vectors on the watershed polygons are given in Figure 15.

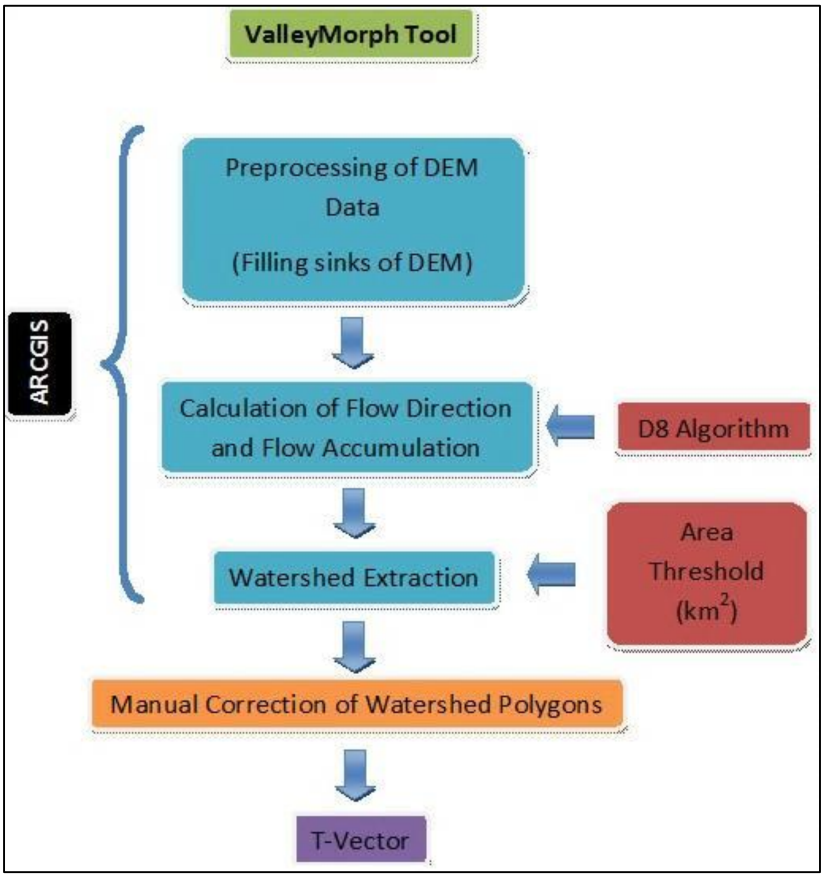


Figure 14 Flowchart of ValleyMorph Tool

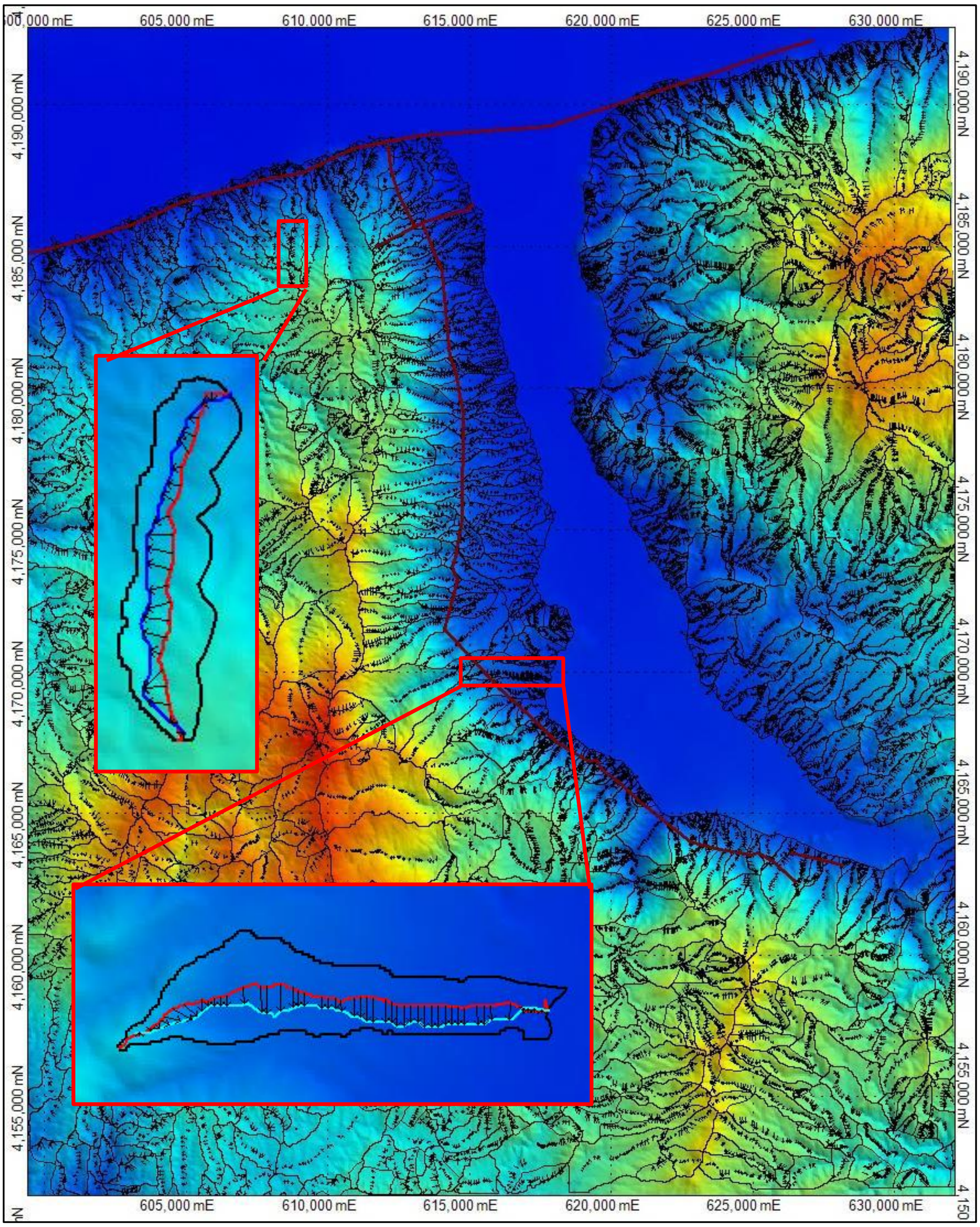


Figure 15 The individual T-vectors given on DEM and close views of watersheds (red lines: watershed midline, blue (light blue) lines: main river, arrows: T-vectors)

4.4 2-D Swath Profiles

The swath profiles were firstly described by Baulig as projected profiles in 1926. The profile lines which are equally spaced intersect the contours inside a swath. A swath profile involves extending the original profile line to a rectangle of a given width, swath, the elevation data are recorded along lines perpendicular to the profile line (Figure 16). The recorded elevation data is composed of computed mean, minimum and maximum values (Hergarten et al., 2014)

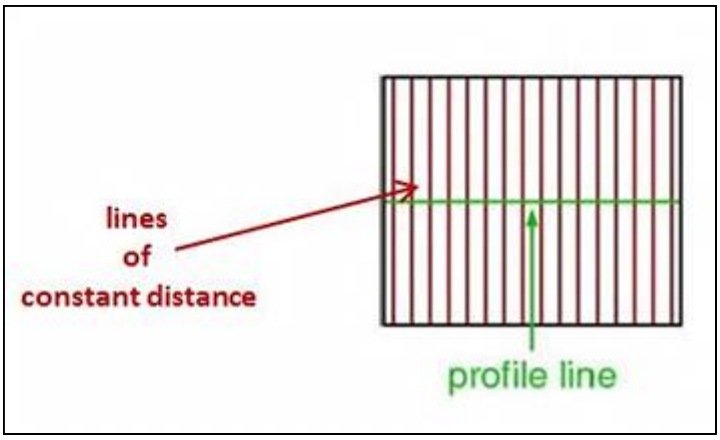


Figure 16 Illustration of ordinary swath profiles

Swath profile analysis is considered to be an improved, Digital Terrain Model (DTM) based version of traditional cross-section analysis. To avoid arbitrariness of simple line profiles, the swath method horizontally expands the cross-section line into a rectangular swath (Telbisz et al., 2013).

This kind of profile can give an extensive perspective of altimetric behaviour helping for the determination of inclination of huge topographies (Grohmann, 2004). Morphological features such as terraces or large-scale slopes or peak elevations are to be presented by elevation profiles but it is difficult to select a single profile which would show all of these features. In tectonic studies, there is often a need to depict and measure the maximum and/or average height of different structural units. Topographic swath profile analysis can be a useful tool (Telbisz et al., 2013).

Grohmann (2004), construct swath profiles from ASCII files with cumulative length in meters, raster value (elevation), east and north coordinates. In his work, he concluded that swath profiles allowed identification of altimetric levelling of the Chapada de Canga Plateau. Some steps in the profiles were related with an E–Wnormal fault with south block down; this fault can also be seen as an anomaly in orientation of isobase lines, as pointed out in previous works.

In this study, swath profiles with 2000m width and 45000 m length have been generated along N75E, N25E and N15W directions which are conformable to the directions of studied active faults (Figure 17). The resolution of swaths is 100m.

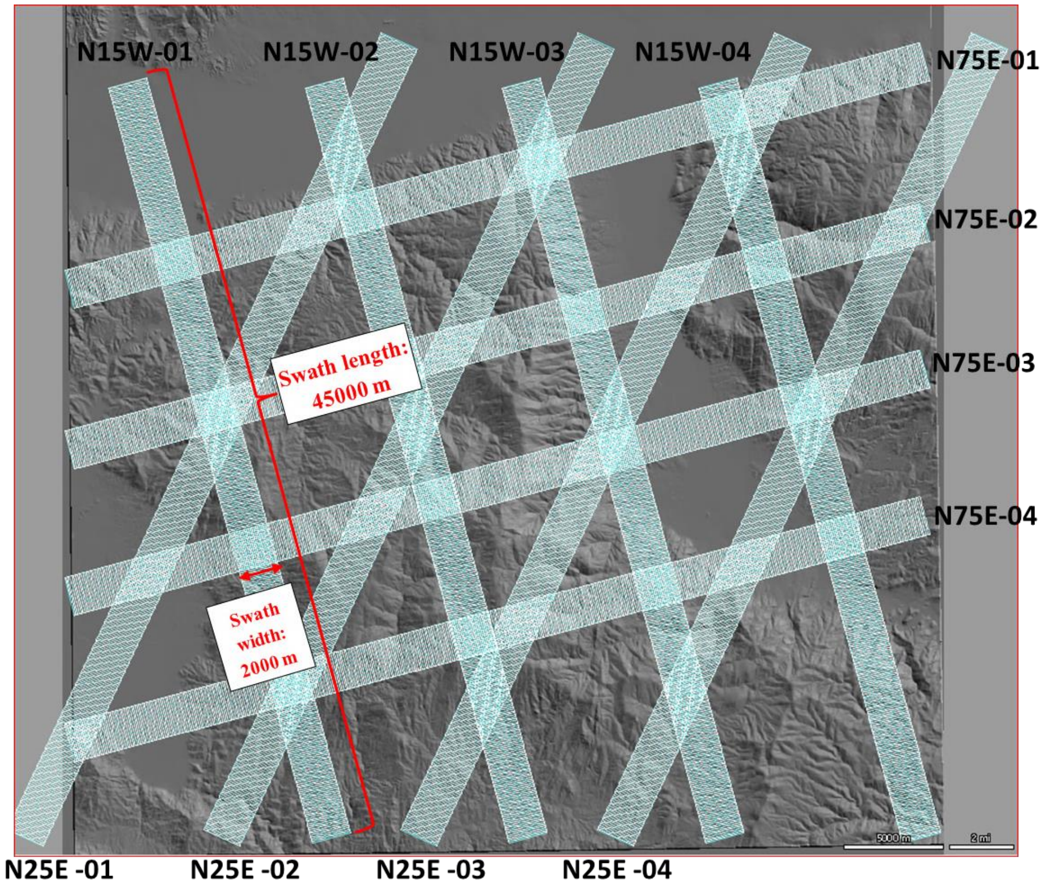


Figure 17 Swath profile properties and directions

An example of swath profiles generated for this study is given in Figure 18.

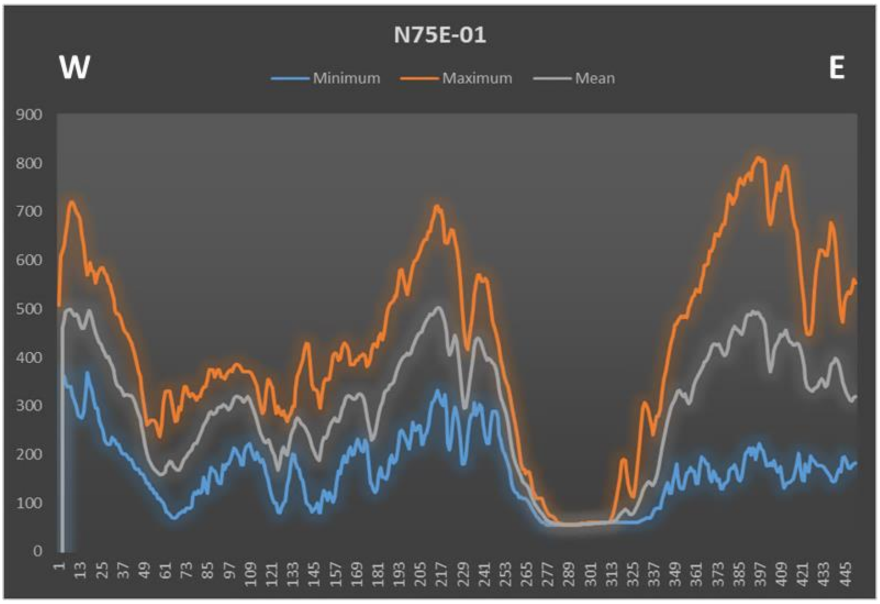


Figure 18 Profiles along N75E-01 swath

CHAPTER 5

RESULTS

The final part of this thesis study is the evaluation of results obtained from computer based analysis. In order to reveal the useful and consistent information fitting to the purpose of the study, we need to modify some outputs, generate new maps derived from output maps and determine areas where we have robust data.

5.1 DEM-ISOBASE

Using the Isobase surface generated manually in ArcGIS and the Digital Elevation Model of our study area, a new map called "DEM – ISOBASE" has been generated by subtracting the Isobase surface from DEM surface (Figure 19 and 20)."DEM – ISOBASE" map provides similar results with incision, however, this surface is more conceptual and fine resolution compared with Incision surface. The resulting map needed some correction. It contained negative values originated from interpolation used in generation of Isobase map. These negative values have been replaced by zero. The corrected values extend from 0 to 240 and it has 25 x 25 m cell dimensions. The "DEM – ISOBASE" map is given in Figure 20.

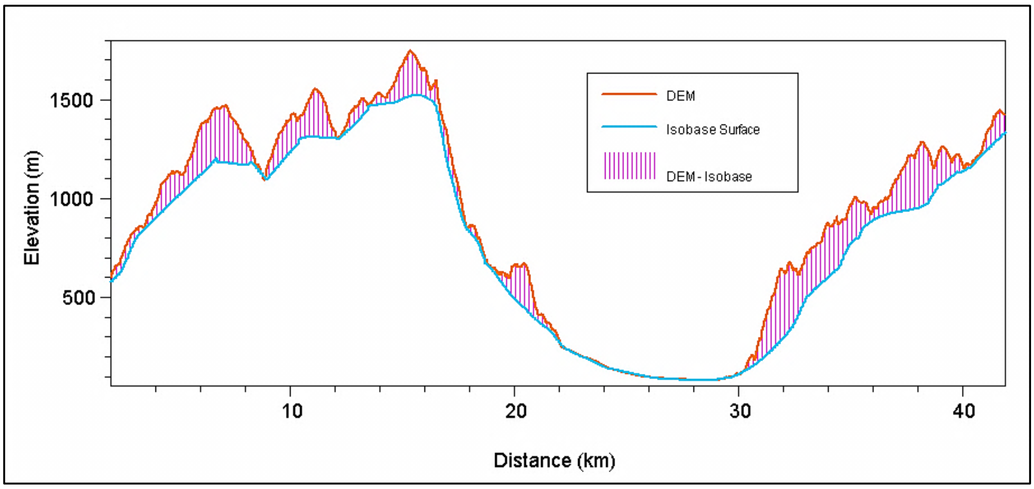


Figure 19 Conceptual profiles showing calculation of “DEM-Isobase” values

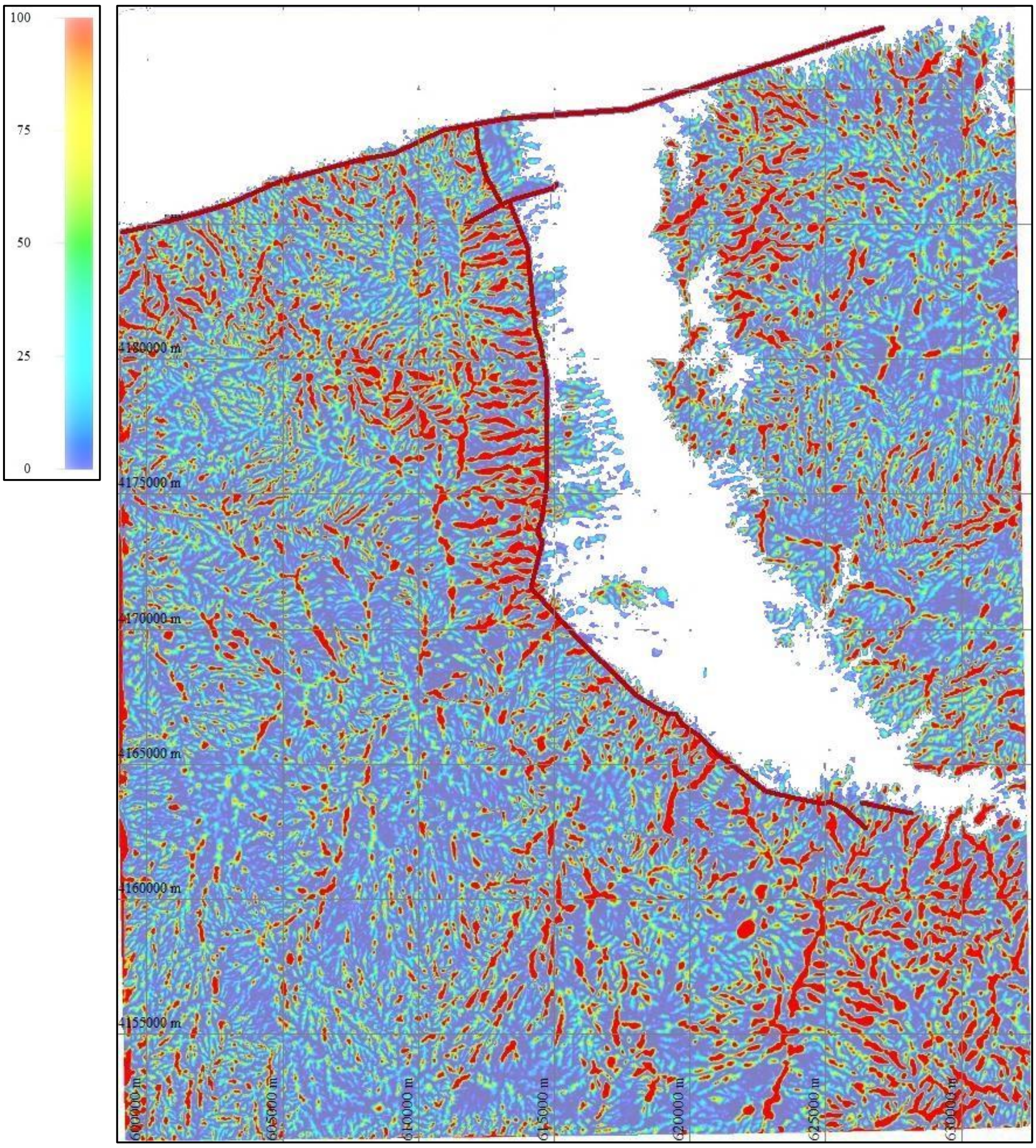


Figure 20 “DEM – ISOBASE” surface

5.2 Swath Profiles

The computed swath profiles with similar orientations are grouped together and shown in Figures 21, 22 & 23.

Along N75E-01 swath, parallel to the orientation of Büyük Menderes fault we have more rough profiles comparing with the swath profiles of similar directions (Figure 21). This fact can show that surface roughness is high along this swath. Also the difference between maximum and minimum elevations is high along N75-01 swath (Figure 21). Even in the eastern part Büyük Menderes fault, which is located on Karıncalıdağ horst the difference is extremely high. These high values are related with high incision rates. In the Bozdoğan Graben the difference between maximum and minimum profiles approaches zero.

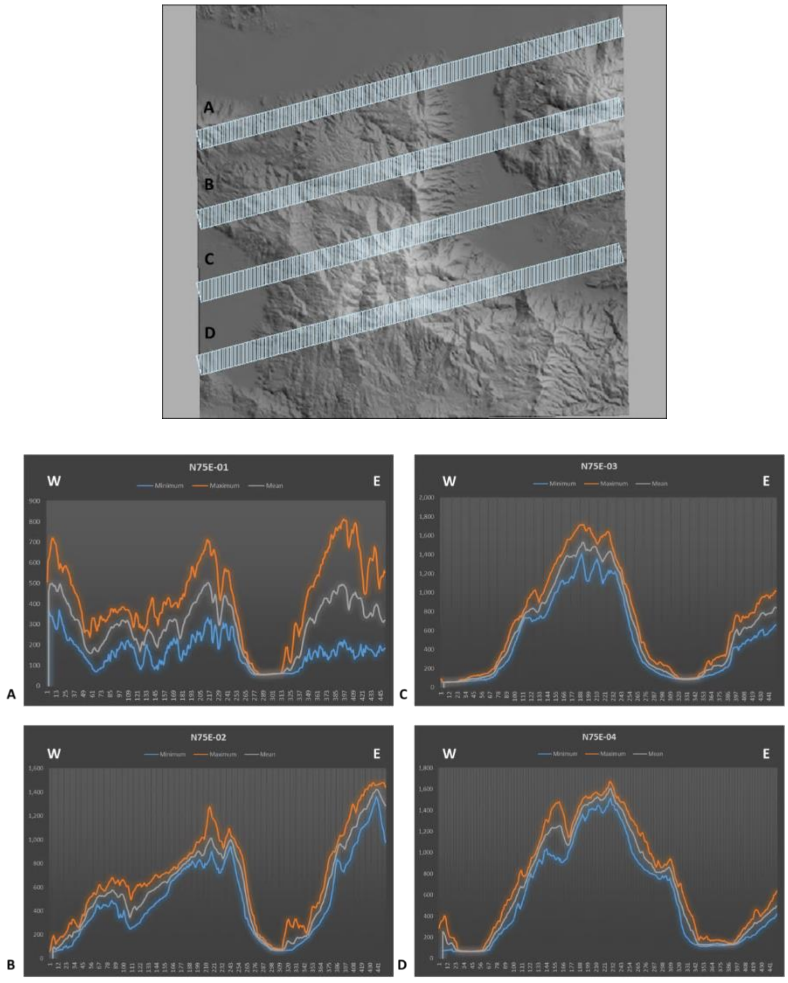


Figure 21 Swath profiles along N75E direction

The swath profiles along N15W direction are nearly parallel to the orientation of Bozdoğan fault. Along N15W-03 and N15W-04 swaths we have rough profiles corresponding to high surface roughness values (Figure 19). At the northern part of N15W-03 swath the difference between maximum and minimum profiles is relative high leading to the high incision rates. This area where (max- min) difference is relatively high correspond to the intersection of Büyük Menderes and Bozdoğan faults on Madran horst. Additionally, the northern part of N15W-04 swath which is falling on Karıncalıdağ horst near Büyük Menderes fault has also high differences between maximum and minimum profiles (Figure 22).

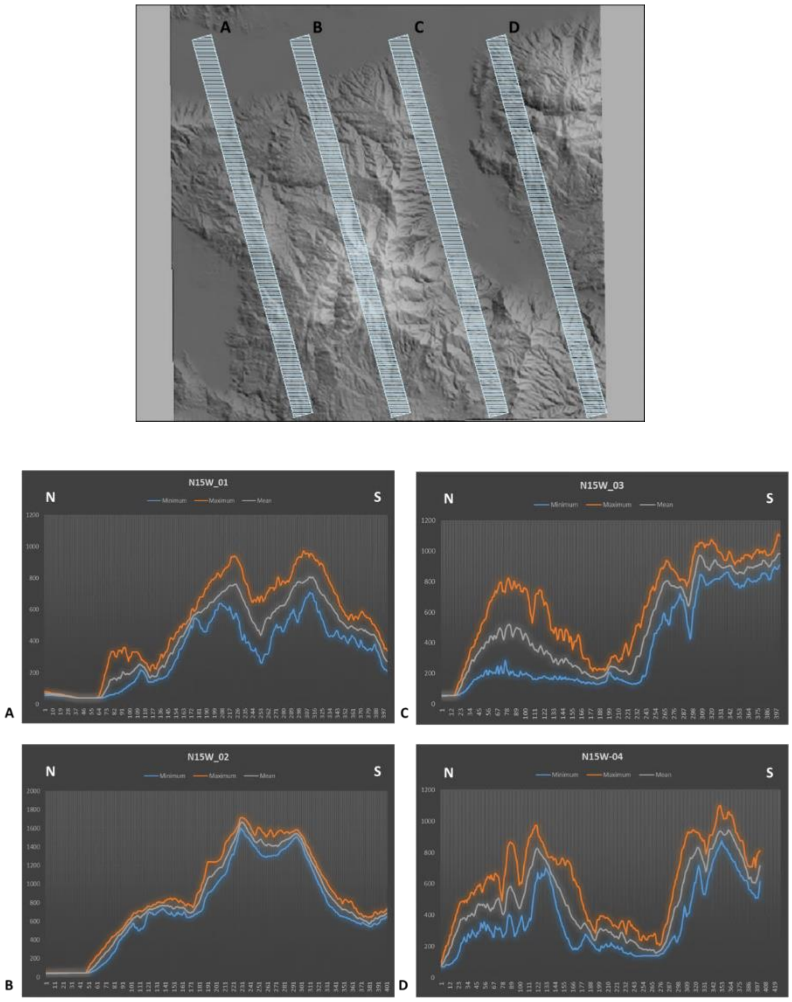


Figure 22 Swath profiles along N15W direction

In the northern part of N25E-02 swath thickness between minimum and maximum profiles is remarkable, as mentioned in above sections, indicating the high incision rate . This part of the swath is falling in the same region with the northern part of N15W-03 swath which refers to the intersection of Büyük Menderes and Bozdoğan faults on Madran horst. Profiles of N25E-03 swath have high surface roughness, hovewer as seen in Figure 23, maximum, mean and minimum profile are very close indicating that the low incision values along this swath.

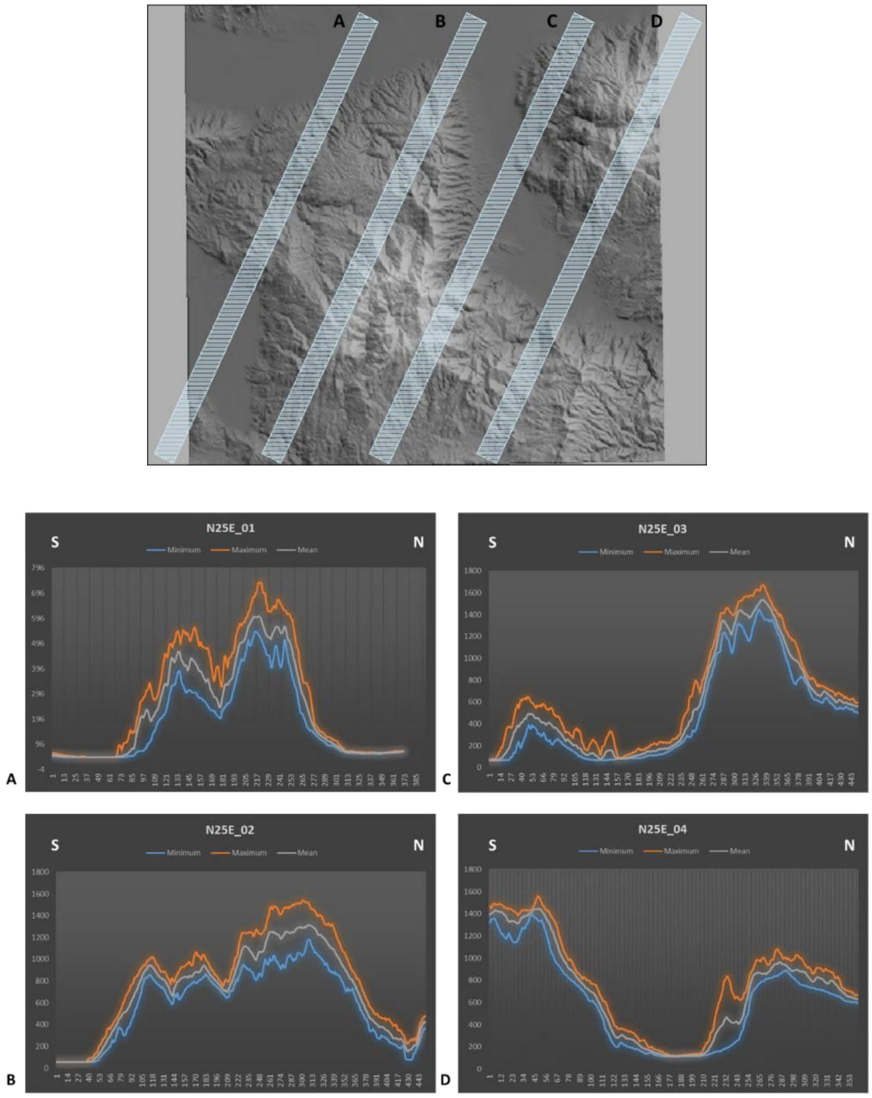


Figure 23 Swath profiles along N25E direction

5.3 Watershed Based Analysis

Isobase, Vertical Dissection, Incision and “Dem-Isobase” which define surfaces have been converted into watershed based databases. To do this, the minimum, maximum and mean values of each parameter have been calculated within each watershed and these values have been assigned to watersheds as new attributes. Thus watershed based thematic maps of Isobase, Vertical Dissection, Incision and “Dem – Isobase” have been created and shown in Figures 24, 25, 26 and 27. Once, they are compared visually with their associated raster maps, the watershed based thematic maps of the mean values are observed to represent original data better.

Topographic variations can be studied using an Isobase map (Grohmann, 2004). Anomalies in Isobase map are consistent with regional morphologic structures. Isobase values are gradually increasing towards southwest and northeast coherent with increasing elevation. Also there are sharp changes observed along Bozdoğan and Kamışlar fault between footwall and hanging wall of the faults. Foot wall blocks comprise watersheds with relatively high isobase values. Along Büyük Menderes fault this contrast cannot be remarked. However on the eastern segment of Büyük Menderes fault, Isobase values are relatively high compared with the western sector (Figure 24).

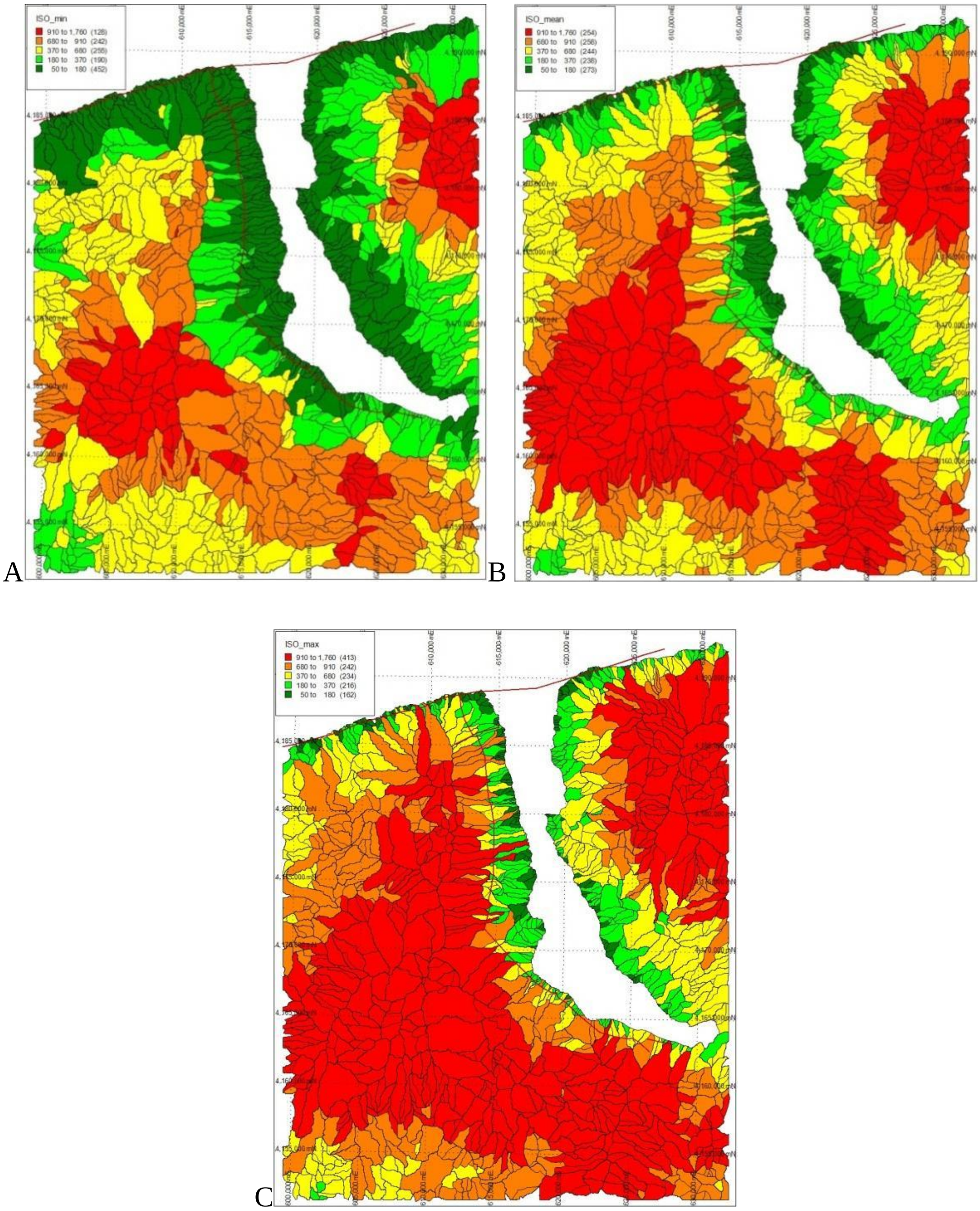


Figure 24 Watershed based maps of minimum (a), mean (b) and maximum (c) Isobase values

Increasing trend of incision rates along N-S and NW-SE directions correlates well with the horsts of Bozdoğan and Kamışlar faults. Watersheds with high insicion anomalies are dominant on the upthrown block of Bozdoğan fault and the watersheds with low mean incision rates are mostly located on the downthrown block of Bozdoğan fault. Some watersheds are extending on both sides of the fault. These watersheds have intermediate values originating from averaging low and high values. The contrast in incision values between the blocks of Bozdoğan fault is not visible along the Büyük Menderes fault. This can be caused by that Bozdoğan fault is located at the boundary of metamorphic units and Pliocene units although Büyük Menderes fault is the contact between metamorphic units of Madran horst and quaternary units of Büyük Menderes graben. However on the east sector of Büyük Menderes fault, in the study area, watersheds show higher rates. When whole map evaluated, higher relative relief is not relating with high elevations (Figure 25).

Vertical Dissection map shows anomalies generally in the same watersheds where high incision rates are observed. High surface roughness in the study area is correlated with more incised relief which is giving clues about active tectonic deformation. Likely in the incision map, increasing N-S and then NW-SE trend of vertical dissection reveals along Bozdoğan and Kamışlar faults. However along Büyük Menderes fault vertical dissection values are varying from intermediate to low, except the eastern sector. This fact can be interpreted that these faults are more active on relative uplift compared with Büyük Menderes fault (Figure 26).

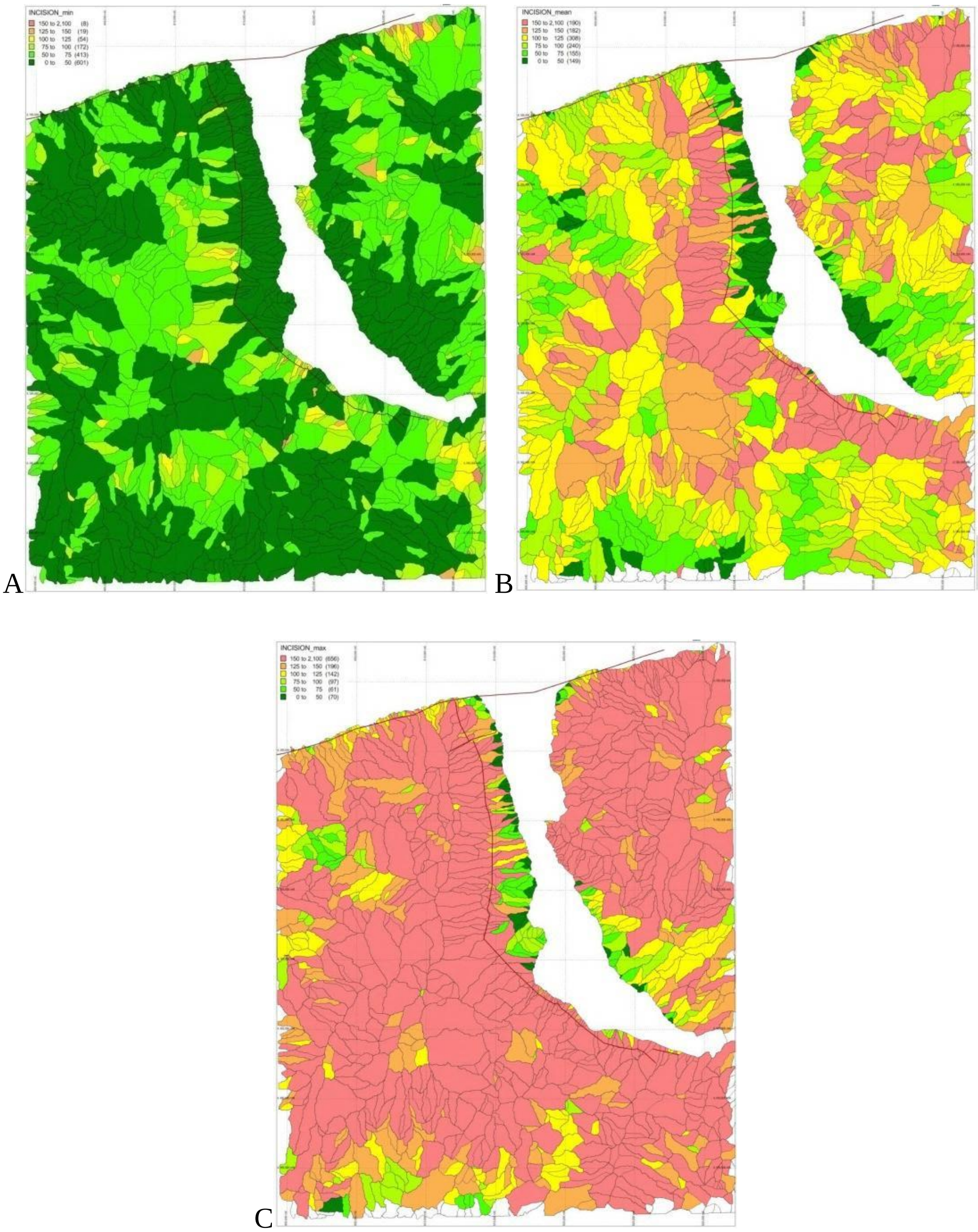


Figure 25 Watershed based maps of minimum (a), mean (b) and maximum (c) Incision values

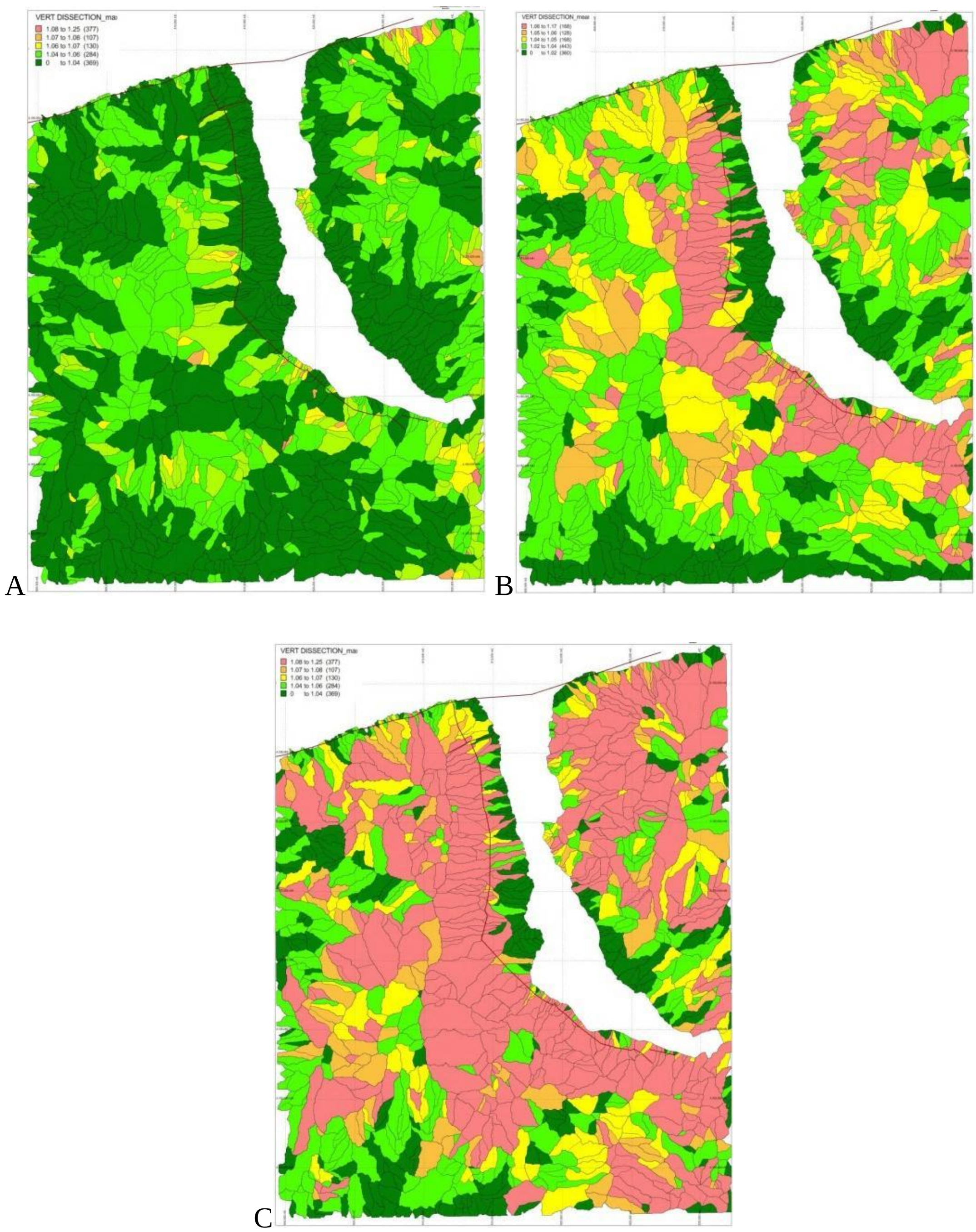
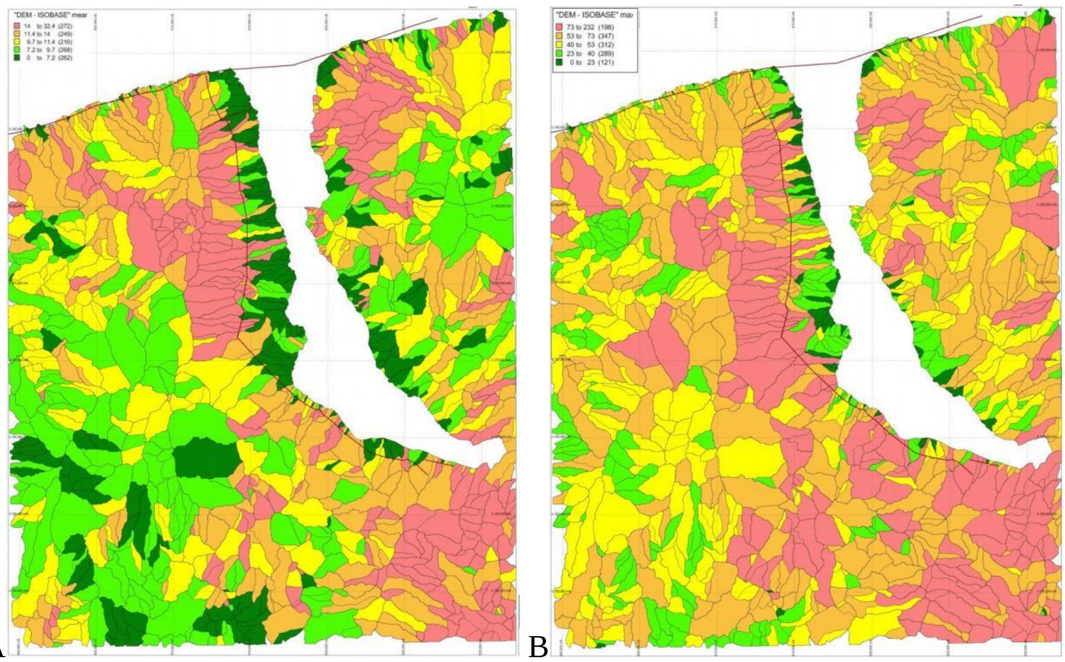


Figure 26 Watershed based maps of minimum (a), mean (b) and maximum (c) Vertical Dissection values

Dem – Isobase surface gives the difference between maximum (current topography) and minimum (base level) elevations like incision. Theoretically, Dem – Isobase and Incision maps should be similar. In DEM - Isobase map, we see the same anomalous trend on the horst of Bozdoğan fault and the low relative relief in the graben. Along the Kamışlar fault we cannot see the high anomalous values that reveal in incision map. These watersheds have mostly intermediate values however a contrast in DEM-Isobase values is visible between the footwall and hanging wall block of Bozdoğan and Kamışlar fault that has been evaluated in incision map. Bozdoğan and Kamışlar which are normal faults, have lower values on their upthrown block compared with downthrown block.

Additionally anomalous watersheds are dominant at the south-eastern part of the map where Palaeozoic quarzite and schists are exposed and in the north-western part of Karıcalıdağ horst. This anomaly in the Karıcalıdağ horst existing at the eastern margin of Bozdoğan graben can be give clue about the existence of a normal fault mentioned in the study carried out by Ocakoğlu et al. (2014); however, this anomaly should be compared with asymmetry maps.

The variations from Incision surface are resulted from the difference between production methodologies. Incision is a smoothed map due to the usage of moving window. Therefore we can consider that DEM-Isobase surface is more reliable. Additionally anomalous watersheds are dominant at the southern part of Kamışlar fault where Palaeozoic quarzite and schists are exposed and in the north-western part of Karıcalıdağ horst.



A B

Figure 27 Watershed based maps of mean (a) and maximum (b) DEM-ISOBASE values

In order to identify non uniform uplift and tilting that may be related to tectonic motions, we also analysed resultant T-vectors using a watershed based approach. At first, the individual T-vectors within each watershed are averaged. Figure 28 shows the magnitude averages of T-vectors calculated for each watershed.

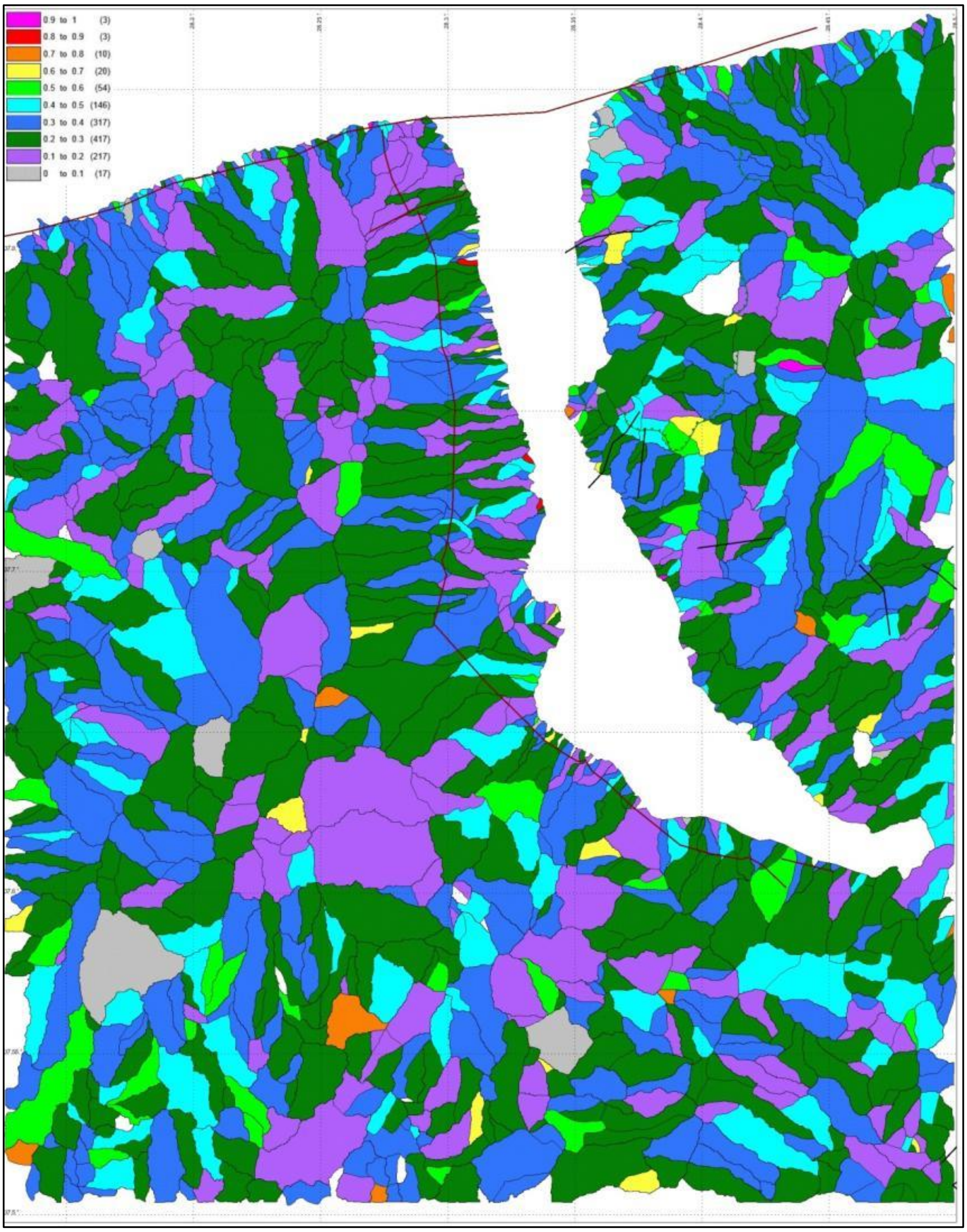


Figure 28 Watershed based thematic map of average T-vector magnitudes

To identify frequency distribution of averaged T-vector magnitudes, their occurrence rate at different magnitude levels are displayed with a histogram (Figure 29). The number of T-vectors bigger than 0.25, is significantly low compared to lower values suggesting that asymmetry signal is only robust once the signal is stronger than 0.25. Smaller values are most likely represents artifacts that may be related to methodology and/or data. Thus, we defined 0.25 level as a threshold and only analysed watersheds displaying stronger, more robust asymmetry signals (Figure 30).

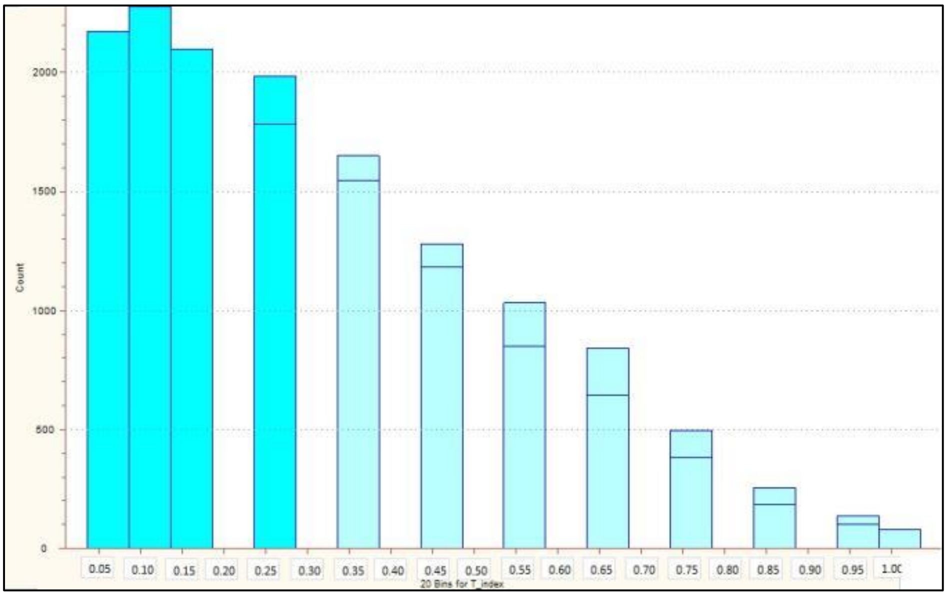


Figure 29 Histogram of T-index values of individual T-vector

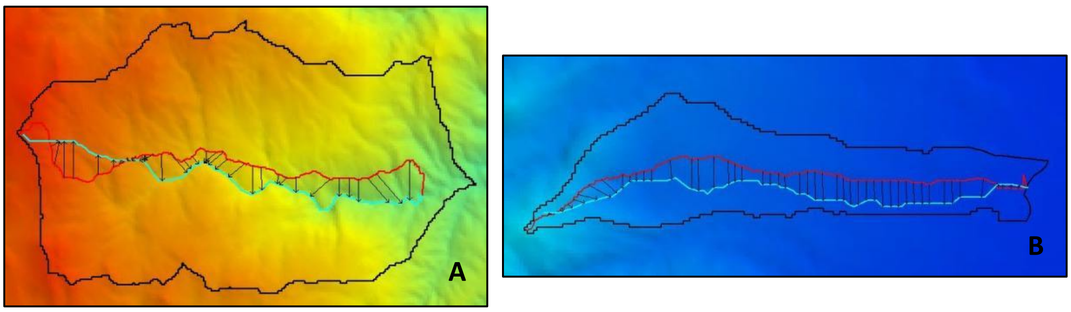


Figure 30 Close views of watershed with mean T-index ≤0.25 (a) and mean T-index> 0.25 (b)

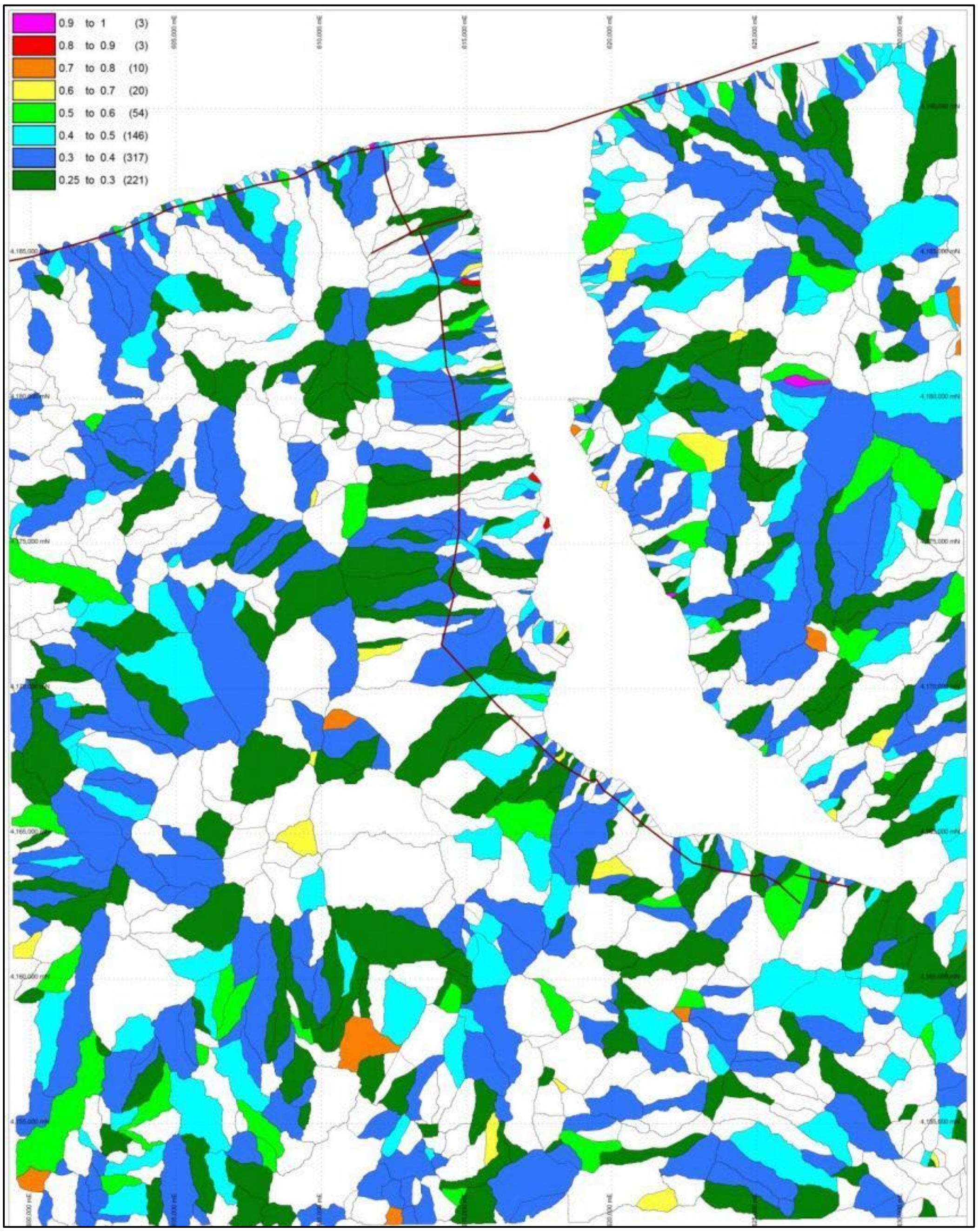


Figure 31 Watershed based thematic map of average T-vector magnitudes with threshold at 0.25

Watersheds, with mean T-vector magnitudes above threshold, comprise 60 % of total watersheds. As seen in Figure 31, blue coloured watersheds are dominant representing the range of mean T-index from 0.3 to 0.5.

At first, the average magnitude of T-vector within each watershed is calculated using all individual T-vectors identified for the watersheds. The watersheds displaying average T-vector magnitudes smaller than 0.25 are regarded as less reliable and possibly affected by artifacts related to data and processing methodology. Thus, they are eliminated from further analysis related to asymmetry.

After finding the catchments displaying rather strong asymmetry signal with average T-vector magnitudes greater than 0.25, directions of individual T-vectors within these watersheds are first sorted into 4 main directional quadrants as it is shown in Figure 32 and the number of individual T-vectors in each direction class is calculated. Then, the quadrant represented by maximum vector population is accepted as the watersheds directional mod where average direction of its population is used as the dominant T-vector direction of the watershed.

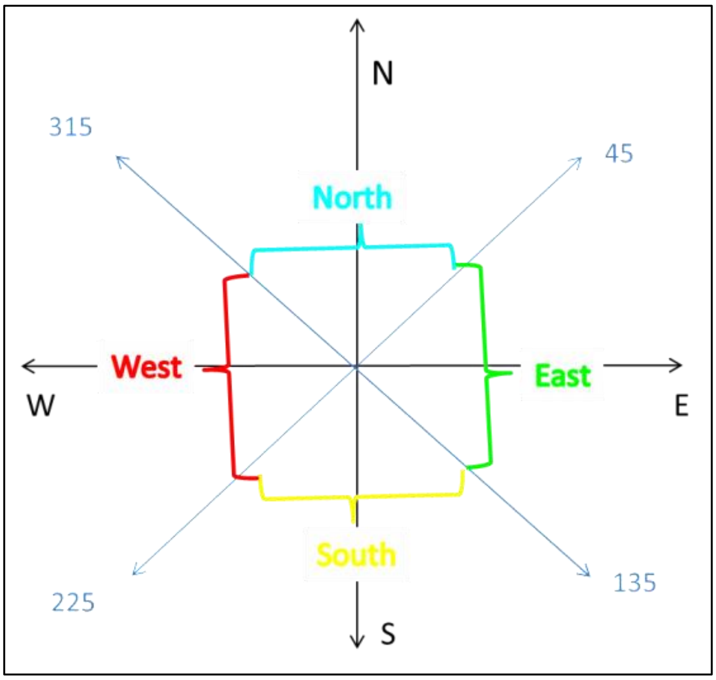


Figure 32 Sketch showing quadrants

Some watersheds have more than one dominant direction. These kinds of watershed polygons were termed as “bimodal” in this study. In the case of bimodal catchment, the sum of magnitudes are calculated and compared. In order to quantify the degree of bimodality, the ratio between number of individual T-vector within dominant population and the total number of individual T-vectors within the watershed is calculated. Visual inspection showed that the asymmetry directions of watersheds having ratios smaller than 0.4 are strongly bimodal. Thus, threshold value for bimodality has been chosen as 0.4 and watersheds with ratios below this value have been considered as bimodal and have been also excluded from further analysis related to asymmetry (Figure 33).

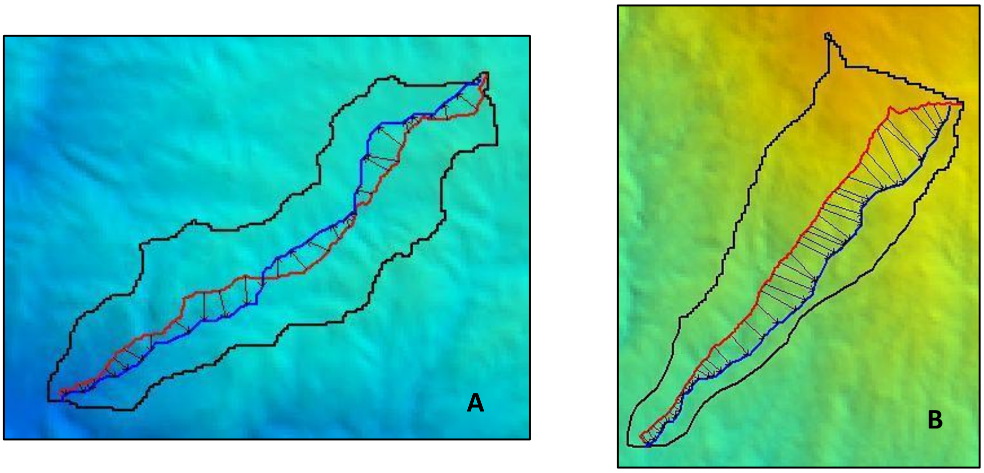


Figure 33 Close views of watershed with bimodality ratio <0.4 (a) and bimodality ratio ≥0.4 (b)

To evaluate the resultant watershed based asymmetry signals, the asymmetry maps are produced using colour coding for the dominant direction mods (quadrants) of the analysed watersheds and computed average T-vectors of the dominant quadrants are displayed with arrows within the watersheds. The dominant asymmetries of watersheds obtained for the study area are shown in Figure 34. It is worth to note that the identified directions indicate the direction of stream migration in other words opposite direction with respect to relative tilting or uplift.

The watersheds considered as bimodal comprise 3% of total watersheds characterized by mean T-indexes above threshold. 97% of these watersheds are used for further evaluations.

On the western part of footwall of Büyük Menderes fault in the study area red watersheds are dominant corresponding to westward stream asymmetry. On the eastern part of footwall block two clusters with opposite asymmetry directions are exposed. Their asymmetries are oriented eastward and then westward, that is towards each other.

Along Bozdoğan fault, stream asymmetries are mostly north and south oriented. There is no remarkable trend observed along the Bozdoğan fault except the region, around the southern part of fault, where it intersects with Kamışlar fault. In the mentioned area southward asymmetry vectors are dominant suggesting the possibility of relative uplift and tilting towards north resulted from the N-S active tectonics.

Around Kamışlar fault asymmetry directions are relatively random. Nevertheless there is a localization of green watersheds; representing south east directed shifting of streams, in the middle sector of this fault.

Additionally, red watersheds are clustered in the south western sector of study area. This indicates that westward stream asymmetry is dominant there suggesting possible relative uplift. However this region should be studied in details by lineament analysis and/or field studies.

According to the observations mentioned above we can make an inference that Bozdoğan and Kamışlar faults are more active on relative uplift.

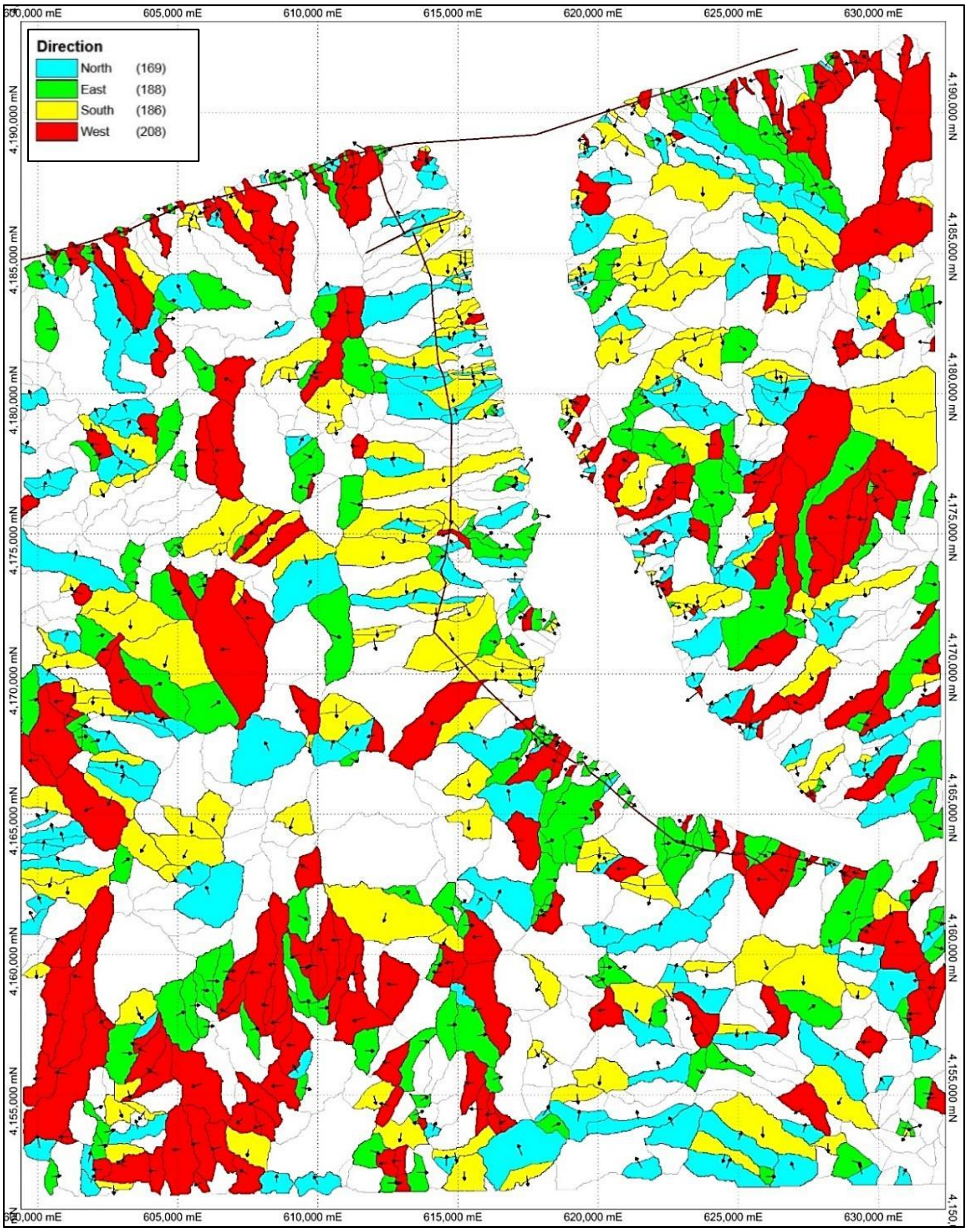


Figure 34 Thematic map of mean T-vector directions of watersheds with asymmetries greater than 0.25and low level of directional bimodality (greater than 0.4)

5.3 Analysis around Active Faults

After examination of the Isobase, Incision, Vertical Dissection maps given in Chapter 4 and “DEM – Isobase” map given in Section 5.1, we have noticed that the remarkable anomalies in these maps have been seen in the areas around the active faults. That is, tectonically controlled watersheds are distinct on the horsts of active faults. Therefore this stage of the thesis study has concentrated on the analysis around active faults. However all active faults could not be considered together because they have different orientations. Active faults have been analysed in 4 individual parts depending on the position and trend directions as shown in Figure 35. Also the watersheds around these faults, which have been focused, are displayed in mentioned figure.

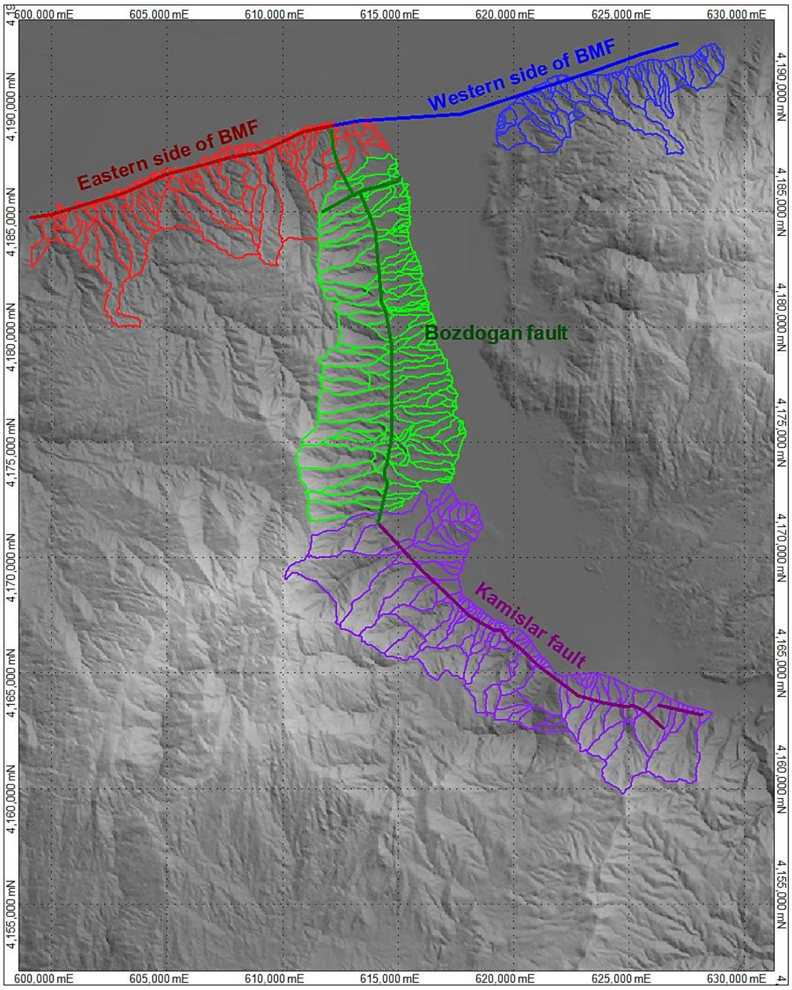


Figure 35 Active faults and watersheds around active faults

The first part of the analysis around active faults consists of determination of new asymmetry directions classified according to orientations of active faults (Figure 36). This enables us to highlight the displacement depending on the movements of active faults. The schematic views of assigned directions considering fault trends are given as follows. Note that these directions have been colorized in thematic maps using the colour of the close geographic direction, which have been classified in general asymmetry maps given in Section 5.1.

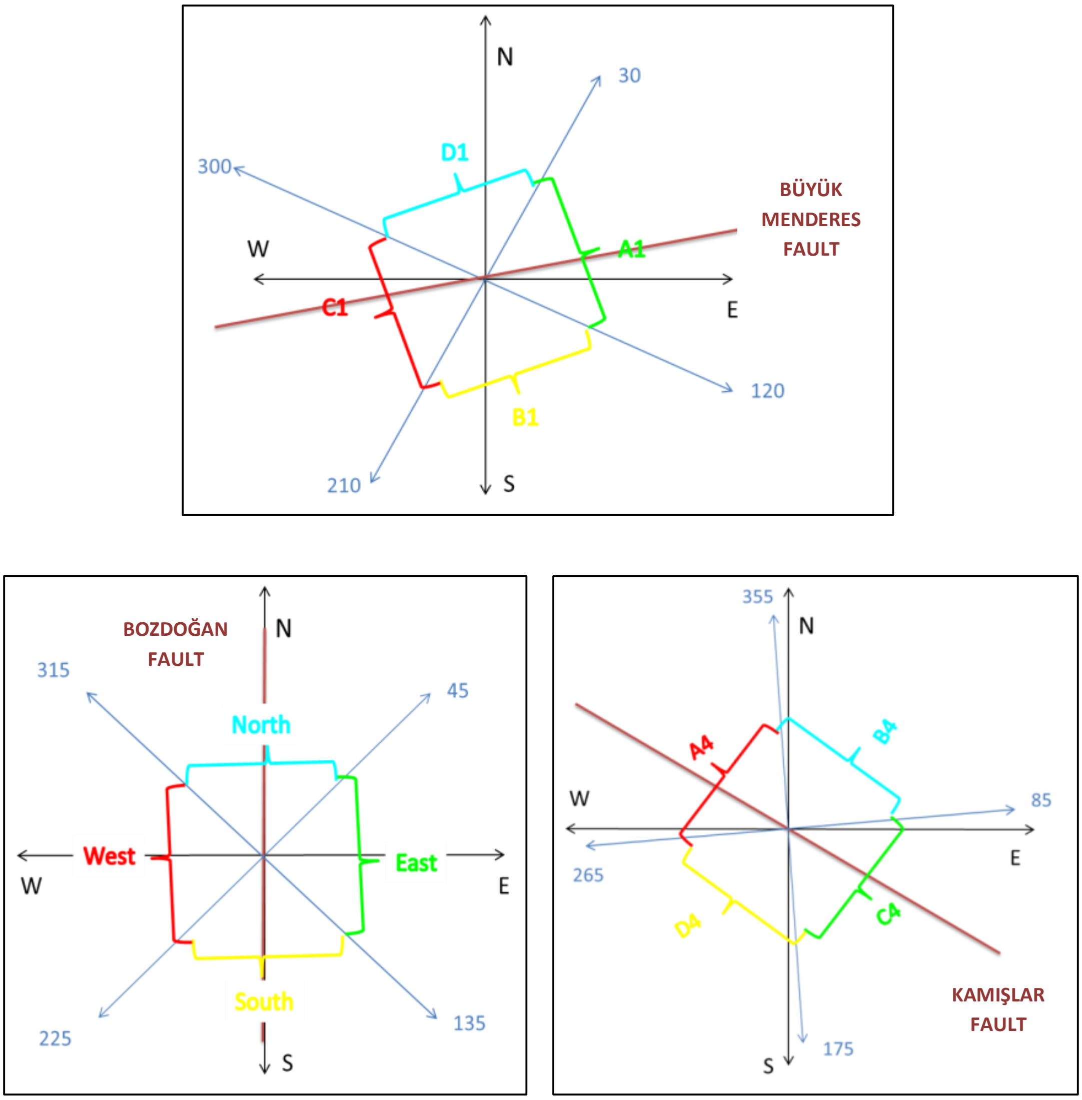


Figure 36 Sketches showing directions assigned based on active faults

For the reason of that the direction quadrants used in the general map showing all watersheds characterized by mean T-vector greater than 0.25 and low level of directional bimodality that is ratio greater or equal to 0.4 (Figure 34) is different from the quadrants of assigned directions based on fault trends, bimodality ratios in fault based maps are different from the ratios in general map for some watersheds. And it is possible that some watersheds are considered bimodal (ratio < 0.4) according to the assigned although they exist in general bimodality map. We presume that fault based maps provide reliable information due to the study intensity and details.

The thematic map of watershed around the western side of Büyük Menderes fault is showing that the direction of asymmetry is dominantly towards south west (Figure 37). The movement along this fault is towards west, indicating possible tilting towards north east and relative uplift of the eastern part of this area, which can be resulted from the tectonic activity of the nearly N-S oriented Bozdoğan normal fault.

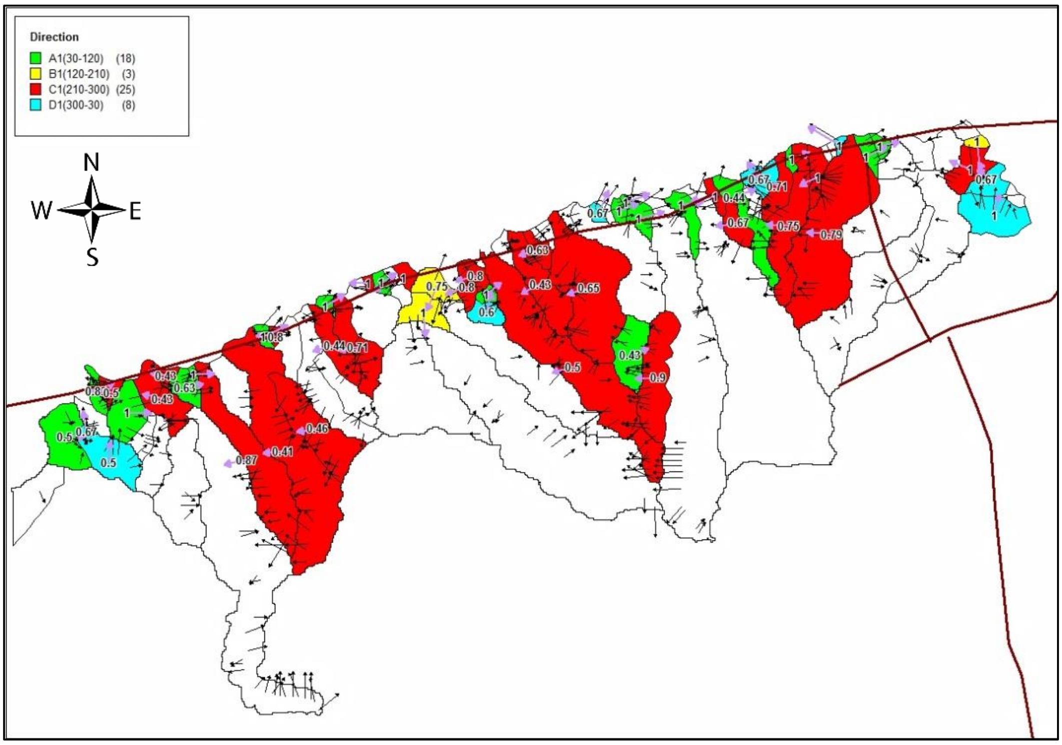


Figure 37 Thematic map of T-vectors around the western side of Büyük Menderes fault (for watersheds with ratio greater than 0.4)

As seen in thematic map of watersheds around the eastern side of Büyük Menderes fault dominant direction is changing along the fault. In the western part of the region asymmetries are towards west then directions are seen towards opposite direction, east and finally in the eastern part they turn back to dip towards west (Figure 38). This observation gives us a clue about the existence of an antiformal structure.

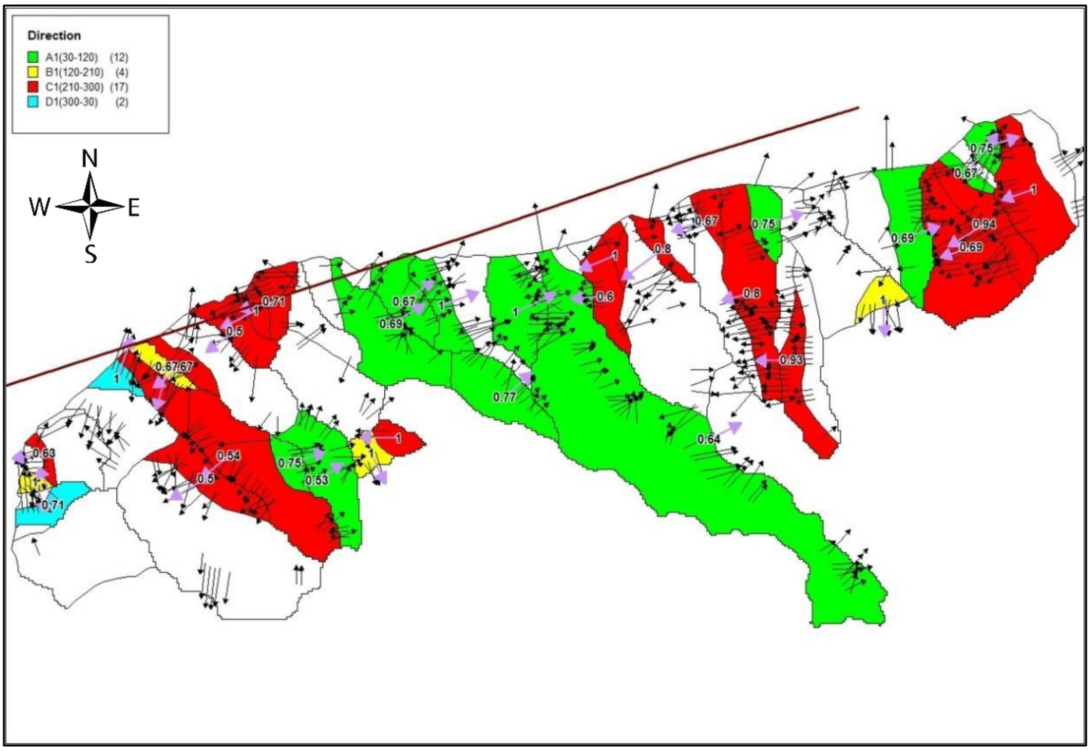


Figure 38 Thematic map of T-vectors around eastern side of Büyük Menderes fault (for watersheds with bimodality ratio greater than 0.4)

Along Bozdoğan fault, stream asymmetries are mostly north and south oriented. We cannot give comment on the activity of Bozdoğan fault because watersheds are mostly N-S oriented which is perpendicular to the fault orientation. These watersheds can be record the activities of N-S trending features such as Büyük Menderes fault if exist. There is no dominant trend observed along the northern sector of Bozdoğan fault (Figure 37). Asymmetries can be interpreted as random there. However around the southern part of fault southward asymmetry vectors are dominant suggesting the possibility of relative uplift and tilting towards north resulted from the N-S active tectonics (Figure 39).

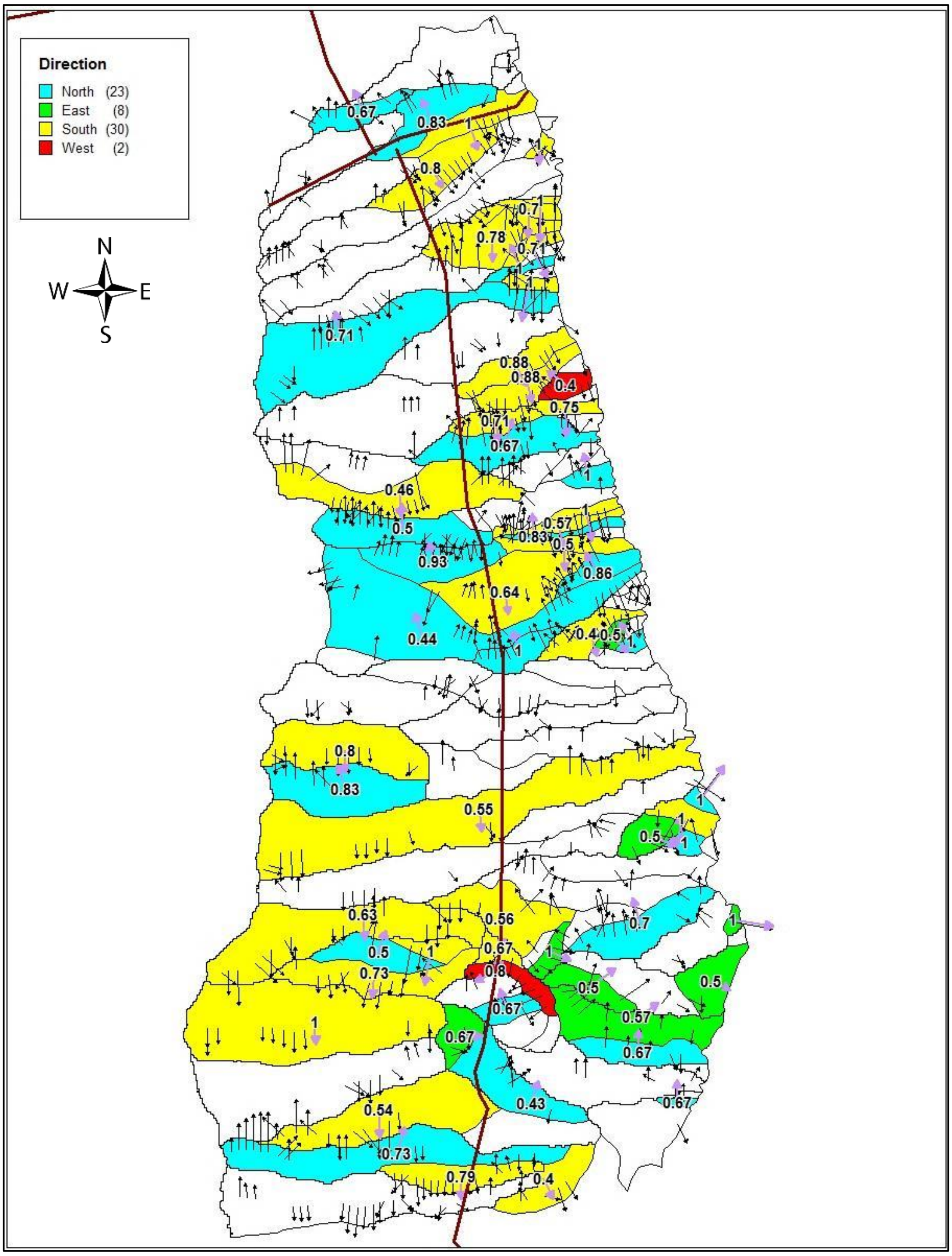


Figure 39 Thematic map of T-vectors around Bozdoğan fault (for watersheds with bimodality ratio greater than 0.4)

Although NE and SW oriented stream asymmetries, represented by green and red coloured watersheds, are dominant, the distribution of these two colours is mostly random except the southern part of the fault. Around the southern sector of Kamışlar fault two clusters with opposite asymmetry directions which are NE and SW (respectively) are observed (Figure 40).

Despite the orientations of Bozdoğan and Kamışlar faults are close to each other, it can be interpreted that these faults are belonging to different fault systems. As seen in Figures 39 and 40, their asymmetry directions, thought to be the indicator of relative tilting, are completely different as seen in Figures 39 and 40.

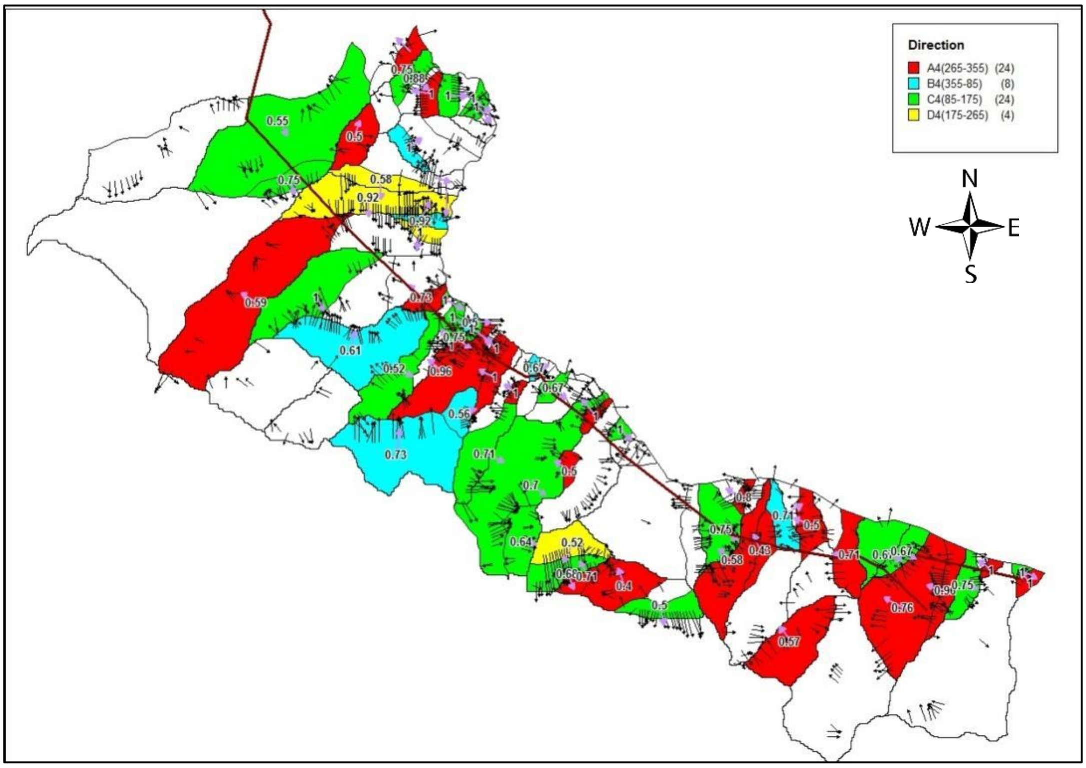


Figure 40 Thematic map of T-vectors around Kamışlar fault (for watersheds with bimodality ratio greater than 0.4)

CHAPTER 6

DISCUSSION & CONCLUSIONS

In this thesis study, morphotectonic features of areas of active deformation have been interpreted by means of morphometric analysis of DEM. The morphometric parameters such as isobase, incision, vertical dissection and T-index have been used to evaluate tectonic control on drainage network development, basin morphology and landscape evolution. The resulting maps have been obtained from computer based analysis conducted by means of GIS softwares. In order to reveal the useful and consistent information some output maps have been modified and new maps such as "DEM-Isobase" derived from output maps have been generated. Watershed based variations of output maps and new maps have been produced for further analysis by using the mean values of each parameter which have been calculated within each watershed. Finally tectonically controlled watersheds have been interpreted on the horsts of active faults which led to the following fault based interpretations.

1. Western side of Büyük Menderes Fault ,
    a. Along this fault we cannot see a sharp contrast in Isobase values between footwall and hanging wall blocks which is observed on the watersheds along Bozdoğan and Kamışlar faults and Isobase values are relatively low compared with the other fault segments.
    b. Incision and Vertical Dissection values are relatively low compared with the watersheds of the footwall of block of Bozdoğan and Kamışlar faultssuggesting that the morphotectonic imprints of this fault segment is less pronounced compared to other fault segments.
    c. DEM-Isobase map shows the dominancy of watersheds with moderate values. However there is no sharp changes observed or no

contrast interpreted between horst and graben that is visible along Kamışlar fault.

d. The direction of asymmetry and stream migration along this fault segments dominantly towards south west indicating possible tilting towards north east and relative uplift of the eastern part of this segment which can be resulted from the tectonic activity of the nearly N-S oriented Bozdoğan normal fault.

2. Eastern side of Büyük Menderes fault,
    a. Isobase values on the horst are relatively low compared with the values on the horsts of Bozdoğan and Kamışlar. However there is an increasing trend towards the eastern part of the fault.
    b. There is an increasing trend in incision and vertical dissection values toward southern part of footwall of eastern side of Büyük Menderes fault.
    c. Unlike incision and vertical dissection maps, high anomalous DEM-Isobase values reveal on the western part of this fault suggesting significant amount of stream undercutting.
    d. Dominant asymmetry direction is changing along the fault possibly related to presence of differential fault motions. In the western and eastern sections of the fault segment asymmetries are towards west and in the middle stream migration are recorded towards east.

3. Bozdoğan fault
    a. Sharp changes in Isobase values along Bozdoğan fault between footwall and hanging wall of the faults. Footwall blocks comprise watersheds with relatively high isobase values.
    b. Watersheds with high incision anomalies are dominant on the footwall block of the Bozdoğan fault and the watersheds with low mean incision rates are mostly located on the hangingwall block. The contrast in incision values between footwall and hangingwall blocks is imply the active nature of Bozdoğan fault which is located at the boundary of metamorphic units and Pliocene units.

c. A similar contrast is also visible across the Bozdoğan fault on recorded vertical dissection values. While the footwall block is characterized by high values and hangingwall block displays low relative relief.
d. Along Bozdoğan fault, stream asymmetries are mostly north and south oriented. There is no dominant trend observed along the northern sector of Bozdoğan fault. Thus asymmetries can be interpreted as random there. However on the southern part of footwall block asymmetry vectors are dominant suggesting the possibility of relative uplift and tilting towards north.

4. Kamışlar fault,

    a. Isobase values are relatively high on the horst of Kamışlar fault compared with the low values of graben.

    b. Incision and Vertical Dissection values are very high on the upthrown block compared with downthrown block. This can be linked to the activity of this fault.

    c. Watersheds with high insicion anomalies are dominant on the footwall block of the Kamışlar fault and the watersheds with low mean incision rates are mostly located on the hanging wall block.

    d. Although NE and SW oriented stream asymmetries are dominant, their distribution is mostly random except the southern part of the fault. Around the southern sector of Kamışlar fault two clusters with opposite asymmetry directions which are NE and SW (respectively) are remarkable.

Additionally, following items are observed independent from the fault based analysis:

1. Anomalies in Isobase map are consistent with regional structures. Isobase values are gradually increasing towards southwest and northeast compatible with increasing elevation.

2. Watersheds with westward stream asymmetry are exposed in the south western sector of study area. This suggests possible relative uplift and tilting towards south which should be studied in details.

Table 1 summarizes the fault based descriptive explanations about the Isobase, Incision, Vertical dissection, DEM-Isobase and stream asymmetry (T-vector) parameters mentioned above. Isobase, Incision, Vertical dissection and DEM-Isobase values are categorized as “low, moderate and high” comparing all the watersheds around the active faults. Regional asymmetry directions studied along the related faults are given in this table. If there is more than one dominant direction or directions are random along the faults, relevant information is also stated in the table.

Table 1 Summary table of fault based analysis

	Western part of BMF	**Eastern part of BMF**	**Bozdoğan fault**	**Kamışlar fault**
Isobase	low	low to moderate	moderate	moderate
Incision	low to moderate	moderate to high	high	high
Vertical Dissection	low to moderate	moderate to high	high	high
DEM -Isobase	moderate	moderate to high	high	high
Asymmetry	Towards SW	First towards SW , then NE and again SW	N-S , no dominant trend	NW-SE, no dominant trend

Figure 41 gives schematic map of regional anomalies of Isobase, Incision, Vertical Dissection and DEM-Isobase values and directions of regional asymmetry vectors (t-vector, blue bold arrows, Figure 41). This map has been generated based on the summarized morphometric parameters listed in Table 1. The possible uplifted area interpreted by means stream asymmetry analysis and located at the junction of Büyük Menderes and Bozdoğan faults highlighted with big red plus (Figure 41). As seen in the schematic map and mentioned in above sections, dominant T-vector along the eastern side of Büyük Menderes fault, indicating the movement of river segment with respect to the basin midline as a result of possible tilting originated from tectonic activity of Bozdoğan fault, are pointing towards south west direction as opposite to uplifted area. Additionally, this map contains lithologies exposed in the study area. The lithology data, given as a base layer in the relevant map, is composed of Quaternary units (grey) , Neogene sedimentary units (orange), Palaeozoic schist (green) and Precambrian gneiss and metagranitoid adopted from 1/25000 scaled MTA geological map. Although the study area has been selected as characterized with homogeneous lithology consisting of Metamorphics of Menderes Massif, the variations of units in Metamorphic Massif are evaluated in terms of correlation with the anomalies of morphometric parameters. The map shows that the Palaeozoic schist, exposed in the south eastern sector of study area, is highly correlated with the anomalies of DEM-Isobase values.

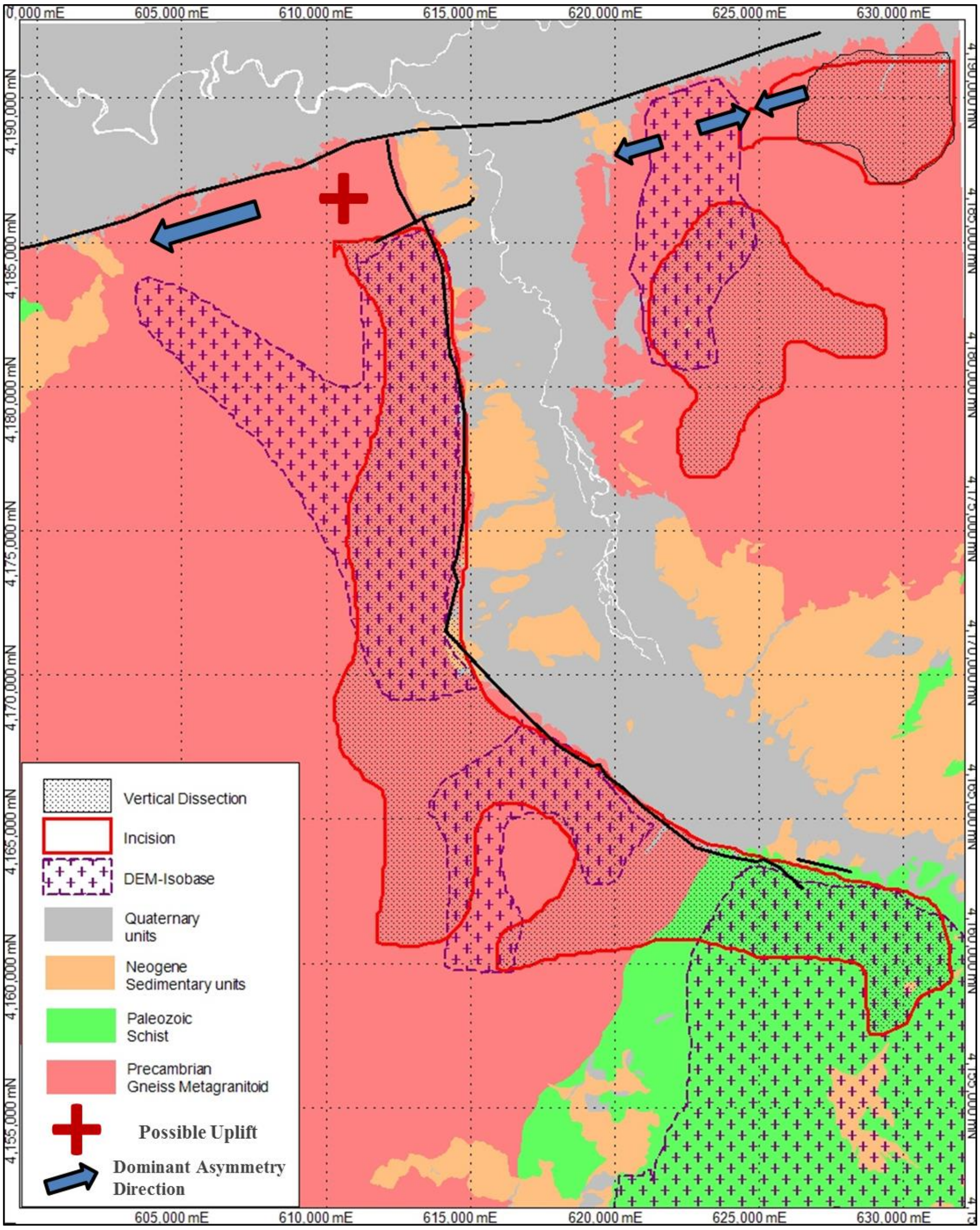


Figure 41 Summary map showing anomalous patterns of Incision, Vertical Dissection values and DEM- Isobase values, their relations with lithological variation and stream asymmetries

Isobase, Incision, Vertical Dissection and DEM-Isobase values show distinctive anomalies on the upthrown blocks of Bozdoğan and Kamışlar normal faults and the values are relatively lower inside the graben compared with these high anomalies. The differences in Isobase, Incision, Vertical Dissection and DEM-Isobase between footwall and hanging wall blocks are remarkable. However along Büyük Menderes fault this contrast is not noticed. It can be concluded that Bozdoğan and Kamışlar faults are more active on tectonic control and differential uplift compared to Büyük Menderes fault. But we should also consider that the watersheds inside the Büyük Menderes graben have not been analysed in this study. Therefore, fault based asymmetry maps are studied together and fault based Stream Asymmetry Maps, given in Section 5.3, support this idea in terms of existence of regional anomalies characterized with southwest directed asymmetries related with the tectonic activity of nearly N-S orientated Bozdoğan fault.

Two morphological models are suggested for the formation of Bozdoğan Graben in the literature. Alçiçek and Jimenez-Moreno (2013) defines the Bozdoğan Graben as a arcuate half graben structure bordered by a fault along one side of its boundaries and Ocakoğlu et al. (2014) states that Bozdoğan Graben is a symmetrical graben i.e. full graben where the depression is bounded by two parallel faults dipping towards the center of the graben. Figure 42 A and B show the schematic cross sections of full (symmetrical) and half graben structures, respectively.

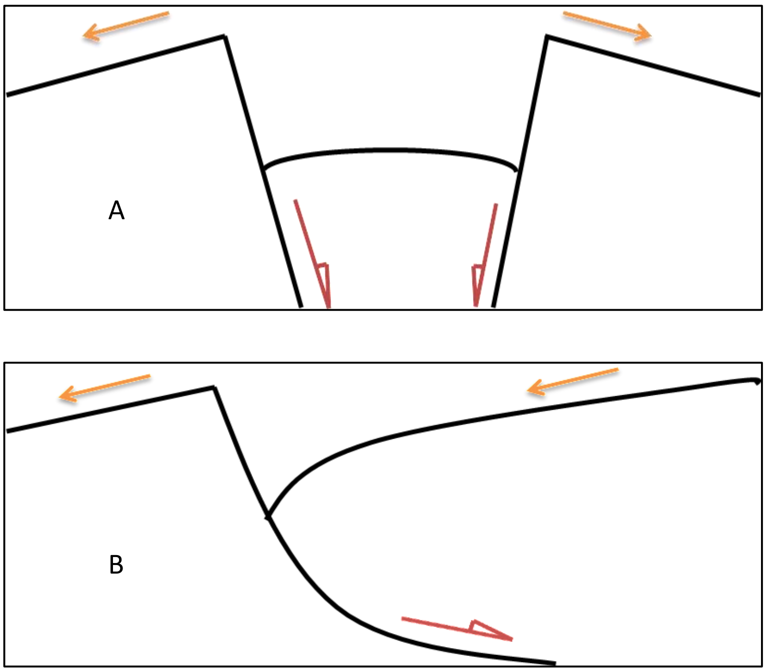


Figure 42 Schematic cross sections of (a) full (symmetrical) and (b) half graben structures

Watersheds with anomalous DEM – Isobase values distinct at the eastern margin of Bozdoğan graben can give an idea about the presence of a normal fault parallel to the Bozdoğan fault mentioned in the study carried out by Ocakoğlu et al. (2014). However, when we compare this anomaly with asymmetry directions of western part of Büyük Menderes fault, T-vector data does not support the indication of existence of full graben structure. Because at the eastern of Bozdoğan Graben the direction of asymmetry has not changed that is towards southwest which is similar with the western margin of the graben, unlike that is expected if there exists any tectonic activity originating from a fault at the eastern margin of Bozdoğan Graben.

As mentioned in Section 4.1 the fault lines were adapted from 1/500000 scaled geological map of Turkey, generated by MTA and modified in 2002. Based on the MTA faults, we can interpret that Büyük Menderes faults is younger than Bozdoğan fault by using the cross cutting relationship. Since Büyük Menderes fault seems to cut and results in an N-S displacement on the Bozdoğan fault. Also Büyük Menderes fault is assumed to be continuous in the Quaternary unit based on MTA data although there is no elevation difference observed in the Quaternary related with the part of Büyük Menderes fault located in Quaternary units. Therefore accuracy of

MTA fault data is controversial. This morphometric study cannot give any conclusion about the relative ages of faults or continuity of Büyük Menderes fault in the Quaternary units. Field observations, which are out of scope of this thesis study, are required to confirm the accuracy of fault data.

The Büyük Menderes and Akçay Rivers are tectonically controlled streams. Their stream course is controlled by fault plane. Thus drainage network is developed perpendicular to the active faults and accordingly watershed delineation is also perpendicular around these normal faults. Therefore we cannot observe any movement recorded by the stream of the watershed around the relevant fault related with its activity. To give en example, we cannot give comment on the activity of Bozdoğan fault using the watersheds around the Bozdoğan fault because watersheds are mostly E-W oriented which is perpendicular to the fault orientation. Along Büyük Menderes fault, the similar condition is valid, the orientation of watersheds around this fault are mostly NW-SE which is suitable to record SW or NE activity. To overcome this limitation, an area characterized by active conjugate faulting has been selected for this study.

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