The Büyük Menderes River: Origin of Meandering Phenomenon

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Abstract

The Büyük Menderes River is the longest river that discharges into the Aegean Sea, with a length of 615 km. It is one of the main rivers dominating in the geomorphology of western Turkey, with its drainage basin that reaches to 24,000 km^2. The river is also very important because of its meandering channel patterns. The term 'meandering' in geomorphology, architecture and art originates from the ancient name of this river: *Maiandros*. Its catchment area mainly consists of three courses located in the main grabens of the region. The upper course of the Büyük Menderes River is located in the Baklan-Dinar Graben, while the middle and lower courses are in the Denizli and Büyük Menderes grabens, respectively. The aim of this study is to describe the meandering channel features of this river in its current course from its source to its mouth, and related landforms and landscapes.

Keywords

Fluvial geomorphology • Sinuosity ratio • Maiandros • Ulubey Canyon • Western Anatolia • Turkey

29.1 Introduction

A meandering river is one of the most common river types in nature, but also, it is formidable by its morphodynamics. It is encumbered with neither the sterile order of its straight cousin, nor the undecipherable disorder of its braided relative (Ikeda and Parker 1989). However, it is the most mysterious type due to its esthetical elegance and richness in pattern diversity. Albert Einstein was one of the scientists concerned about dynamics of this physical phenomenon as he published a theory explaining meandering on the basis of physical laws (Einstein 1926). The process has ever since been an interesting subject in different platforms, from simple physics to complex mathematical models. In geosciences, it has been one of the most interesting topics for decades, especially in geomorphology and sedimentology (e.g., Leopold and Wolman 1960; Langbein and Leopold 1966; Xu et al. 2011). Outside terrestrial rivers, meandering patterns are also observed in submarine fans (e.g., Babonneau et al. 2010) and in other planetary environments (e.g., Weihaupt 1974; Howard 2009). An interest in meandering river patterns is not limited to research in fundamental sciences. The topic includes concerns related to applied sciences such as river engineering and management (e.g., Jansen et al. 1979), petroleum engineering (e.g., Swanson 1993) and landscape ecology and river restoration (e.g., Kondolf 2006).

The name of the 'meandering' phenomenon originates from the Büyük Menderes River, which flows in western Turkey (Fig. 29.1). Its spring is located in west-central Turkey and it flows into the Aegean Sea on the western coast of Anatolia. This river was known as the *Maíandros* River during Antiquity (e.g., Strabo). However, the attracting channel pattern of the Büyük Menderes River has subsequently evolved to describe any winding form as 'meandering', including decorative patterns in art and architecture (Güneralp et al. 2012; Fig. 29.2).

Although there are several geomorphic, morphometric, sedimentological and hydrodynamic studies in the literature that have been carried out on the physical bases of this channel pattern, the meandering features of the eponymous Büyük Menderes River are not widely known. The aim of this study is to delineate the meandering pattern and related landscape and landform features of this ancient Anatolian River.

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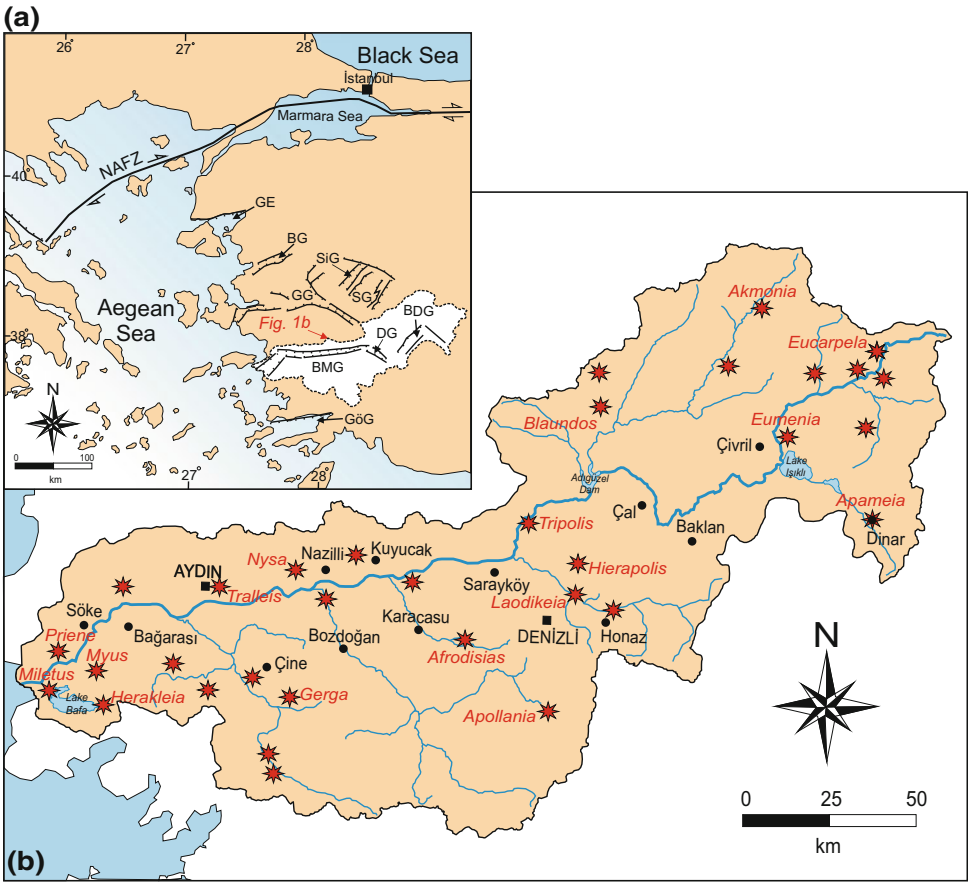

Fig. 29.1 **a** Location of the Büyük Menderes River basin in the Aegean extensional province. BMG—Büyük Menderes Graben, DG—Denizli Graben, BDG—Baklan-Dinar Graben, GE—Gulf of Edremit, BG—Bakırçay Graben, SiG—Simav Graben, GG—Gediz Graben, GöG—Gökova Graben, NAFZ—North Anatolian Fault Zone. **b** Ancient cities in the drainage basin of the Büyük Menderes River are shown with stars. Only major city names are written here

29.2 Historical Background

The drainage basin of the Büyük Menderes River (*Maiandros*) hosted several civilizations and their important settlements within the cultural wealth of ancient Anatolia (Fig. 29.1b). Phrygia, Caria, Lydia, Ionia and other kingdoms that date back to second millennium BC were hosted in the fertile lands of the river. Therefore, there are numerous descriptions in the ancient documents about historical geography, and there is a wealth of archaeological data from these lands. Here, we present some ancient arguments directly related to the Büyük Menderes River and its meandering character. Additionally, several historical and geoarchaeological data focusing on the lowest course of the river around the ancient city of Miletus will be discussed below.

One of the oldest written documents related to the mythological character and meandering geometry of the Büyük Menderes River could be found in the *Theogony* of Hesiod. Hesiod (also known as Hesiodos) was a poet who lived between 750 and 650 BCE (there is no consensus between scholars about his exact dates of birth and death). The Theogony is considered as his earliest work. The poem describes the origins and family tree of the Greek Gods. In this work, Maiandros is referred to as one of the many sons of Tethys and Okeanos and the God of the winding river in Phrygia and Caria. According to ancient Greek mythology, the Gods of the rivers and streams of the Earth were depicted in three forms: as a man-headed bull; or as a bull-horned man with the body of serpentine-fish from the waist down; or as a man reclining with an arm resting upon an amphora jug pouring water. Maiandros was usually personified by the last one (Fig. 29.3).

Herodotus (484–425 BC) mentions the attractive meandering features of the Nile River through citing the winding character of the Büyük Menderes River (i.e. IInd Book, 29). He points out that due to this geometric feature the total length of the river course is much longer than its length due to this geometric feature.

In another famous historical source, *Geographica*, Strabo (64/63 BC–AD 24) presents the most detailed descriptions of the historical geography of the Büyük Menderes River. About the origin of the term *meandering* and ancient physiographic features of the Büyük Menderes River Strabo gives some important details in the XIIth Book of Geographica:

Fig. 29.2 Examples of 'meandering' patterns in the details of different art and architectural works. A tondo of a kylix from Altes Museum Berlin (a kind of drinking cup in ancient Greece) on the top, a pillar on the left and a mosaic floor on the right

Fig. 29.3 'Maiandros' as represented on a coin of Tripolis (an ancient city of Lydia, see Fig. 29.1b for location) on the left (ancients.info). A 'Maiandros' statue from ancient city Miletus on the right (livius.org). On both depictions, Maiandros is represented as in mythology; reclining left, holding reed and cornucopia, resting on an overturned amphora from which water flows

"…Apameia is situated near the outlets of the Marsyas River, which flows through the middle of the city and has its sources in the city; it flows down to the suburbs, and then with violent and precipitate current joins the Maeander. The latter receives also another river, the Orgas, and traverses a level country with an easy-going and sluggish stream; and then, having by now become a large river, the Maeander flows for a time through Phrygia and then forms the boundary between Caria and Lydia at the Plain of Maeander, as it is called, where its course is so exceedingly winding that everything winding is called "meandering." And at last it flows through Caria itself, which is now occupied by the Ionians, and then empties between Miletus and Prienê. It rises in a hill called Celaenae, on which there is a city which bears the same name as the hill…" "…In fact, the soil is not only friable and crumbly but is also full of salts and easy to burn out. And perhaps the Maeander is winding for this reason,

> because the stream often changes its course and, carrying down much silt, adds the silt at different times to different parts of the shore; however, it forcibly thrusts a part of the silt out to the high sea. And, in fact, by its deposits of silt, extending forty stadia, it has made Prienê, which in earlier times was on the sea, an inland city."

In his Elegie poetry book, Propertius (c. 50–15 BC) describes the Büyük Menderes River with its salient channel form that obscures the direction of its flow. Similarly, both Publius Ovidius Naso (better known as Ovid; 43 BC–AD 17/18) in his *Metamorphoses* and Nonnus of Panopolis (ca. end of the fourth or fifth century AD) in his epic poem *Dionysiaca* mention the mythological role and meandering features of the river.

29.3 Geological Setting

Western Turkey is one of the most seismically active extensional provinces in the world. Pervasive crustal extension since the Neogene led to the development of grabens trending E-W and N-S (e.g., Şengör 1987; Sözbilir and Emre 1990; Seyitoğlu and Scott 1992; Yılmaz et al. 2000; Gürer et al. 2001, 2009; Bozkurt 2003; Koçyiğit 2005; Purvis and Robertson 2005; Rojay et al. 2005; Kaymakçı 2006; ten Veen et al. 2009; Gürbüz et al. 2012; Ocakoğlu et al. 2014). These grabens are parts of a broad complex of horsts and grabens (Fig. 29.1a). The Büyük Menderes River drainage basin hosts some of these grabens. The Baklan-Dinar Graben is located in the upper course, the Denizli Graben in the middle course and the Büyük Menderes Graben in the lower course of the river (e.g., Kazancı et al. 2009, 2011). The sedimentary basins (grabens) along the path of the Büyük Menderes River generally contain similar Neogene sequences dominated by fluvio-lacustrine deposits intercalated with volcanoclastics. Also, their Quaternary evolution involved similar erosional and depositional processes along the Büyük Menderes River on a large scale, except small temporal and palaeoenvironmental differences.

The Neogene units and other bedrock, which belongs to the Menderes Massive and Muğla Nappes within the drainage basin, are well exposed, particularly on the sides of the incised valleys (Fig. 29.4). The regional stratigraphy is confidently defined by palaeontological, palynological, magnetostratigraphic and radiochronological data (e.g., Ünay et al. 1995; Akgün and Akyol 1999; Sarıca 2000; Saraç 2003; Şen and Seyitoğlu 2009).

Quaternary formations within the Büyük Menderes River Basin are so similar that it is sometimes difficult to differentiate them visually. Remote sensing studies from satellite images and/or air photographs are useful for mapping and also for differentiating fluvial and lacustrine deposits (e.g., Erol 1996). Another way to understand the spatial and lithological variations of Quaternary deposits can be subsurface seismic imagery and coring campaigns. According to facies analyses of the Quaternary successions using the latter approaches, the upstream part of the river basin contains a well-developed fluvio-lacustrine sequence, while the downstream part shows a sequential infilling of the graben basin induced jointly by both sea level changes and tectonism (e.g., Kazancı et al. 2009, 2011). However, the sediment thicknesses of the Quaternary formations are not so much in contrast with the underlying Neogene units. On the other hand, the Büyük Menderes River has discharged a considerable amount of clastic load into the graben infill and to the sea, continuing to do so even today (Kazancı et al. 2009).

29.4 The Büyük Menderes River: Physiography and Sediment Load

With a length of 615 km, the Büyük Menderes River is the longest river that discharges into the Aegean Sea (Fig. 29.5). The river originates from near the Sandıklı town (Afyon province) in central-western Anatolia. The mean gradient of the streamline is 2‰. Its channel meanders during most of the river course except for some short discontinuities caused by 5–10 m high steep steps when crossing graben-connections (Kazancı et al. 2011). The drainage basin of the river covers about 24,300 km^2 in which two lakes are present. With the construction of two major dams, the area drained into the main riverbed has recently decreased to 11,900 km^2 (Kazancı et al. 2009).

In the upper course, the major tributaries are the Küfi, Dinarsuyu, Banaz and Ulubey streams. The Çürüksu stream that flows in the Denizli Graben constitutes the middle course. The Akçay, Çine and Vandalaz streams are the main tributaries located in the lower course of the Büyük Menderes River (Fig. 29.5). Interestingly, a large part of these streams also presents meandering channels, as they drain local depressions. With the number of artificial small dams and ponds on streams increasing in recent years, the water discharge of the main river has gradually decreased in the last 25 years, also because of increases in intensive use of water for irrigation purposes and temperature rise between 1998 and 2005. As a result, annual discharges were 154, 90 and 40 m^3/s in 1984, 1990 and 2005, respectively (e.g., EİE 2006; Kazancı et al. 2009). Meanwhile, the sediment load has also decreased. According to the records at the monitoring station near Söke district, the suspended sediment load of the river was 13,046.45 ton/day in the late 1960s,

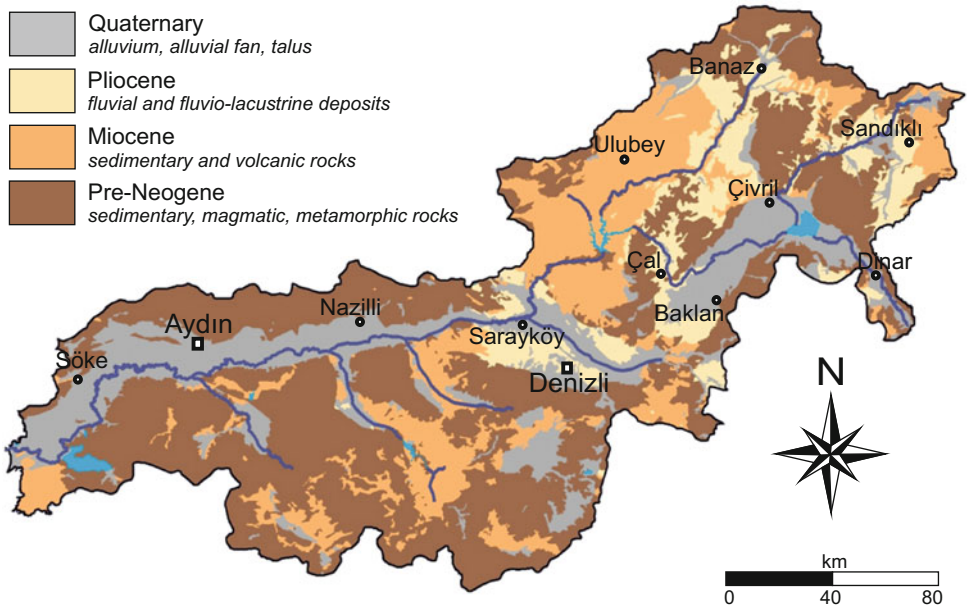

Fig. 29.4 Simplified geological map of the catchment area of Büyük Menderes River. See text for further explanations about the units (modified from Kazancı et al. 2011)

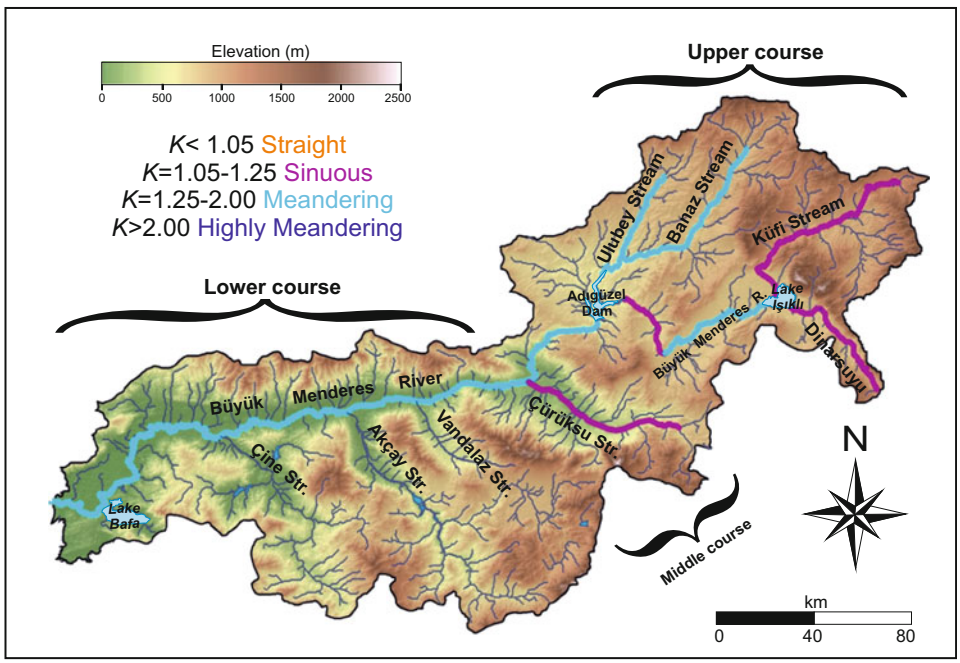

Fig. 29.5 Drainage network map of the Büyük Menderes River basin and the meandering ratios of the main streams forming the upper catchment. K —Sinuosity ratio

decreased to 7671.24 ton/day in the late 1970s (at station 707; EİE 1986). In 1990, this station had to move closer to the Aydın city because water discharge decreased too much (Kazancı et al. 2009).

According to three sediment monitoring stations of the EİE (Electric Works of Turkey) which have been operating on the river recently, the mean sediment load of the Büyük Menderes River in sediment observation station near Aydın city (station 706), reached a value of about 1089 ton/day with a mean water discharge of only 59.9 m^3/s between 1950 and 1996 (Kazancı et al. 2009).

29.5 Meandering Channel Features of the Büyük Menderes River

Meandering rivers generally consist of a single, highly sinuous channel responding to erosion sedimentation processes. The channels are smooth in plan view, and stream velocity is relatively high (e.g., Twidale 2004). When the sinuosity becomes too large, the river intersects itself leading to the formation of a 'short cut' and forming a cut-off lake or oxbow. This is one of the most characteristic features of a

meandering river (Meakin et al. 1996). There are some sophisticated approaches to analyse meandering phenomenon that use mathematical functions (i.e. sine-generated curves, parabolas, Van Shelling, Fargue spirals and piecewise linear interpolation to represent the form of bends (see Güneralp and Rhoads (2008) for a detailed review of these methods and further contributions). These approaches are generally based on some geometric parameters (Fig. 29.6) of the arcuate forms of meandering belts. However, the simplest method for defining the winding feature of a river is its meandering ratio. The meandering ratio (i.e. sinuosity ratio or index) reports the length of the sinuous channel between two points to the straight distance between these same points. A straight river, which has the same length as its valley, has a meandering ratio of 1, while this ratio is higher than 1 when the river meanders more (Fig. 29.5).

According to our measurements using Landsat and Quickbird images (Fig. 29.7), the Büyük Menderes River presents a mean sinuosity ratio (K) of 1.42 in its upper course, 1.34 in its middle course and 1.71 in its lower course. However, from the source (Sandıklı town) of the main course to the mouth (Aegean Sea), the average sinuosity is 1.42. Along the whole length, the highest meandering values are found in the Baklan-Dinar (K = 1.74) and in the Büyük Menderes Grabens (K = 1.71) (Fig. 29.5). But these measurements are calculated for today's river channel, which has many artificial channels along the river course, to prevent flood events and save space for farming, and cannot represent the natural meandering ratio of the river. Especially in the middle course and in some parts of the upper and lower courses, it is remarkable to see the smoothed line of the river course through the satellite images. However, due to the aforementioned artificial channelization processes in some reaches of the river course discrepancies between these two parameters can be seen. According to the traceable meander belts of the abandoned river channels, it is clear that the 'natural' meandering ratio of the Büyük Menderes River should be higher than the currently measured values. Because of these recent modifications of riverbeds, any measurement attempts should thus be checked by field-based studies using trenching and drilling in key areas.

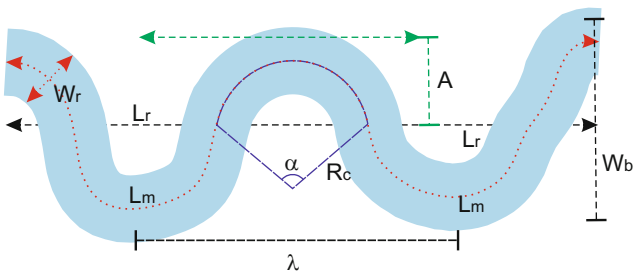

Fig. 29.6 Geometric elements of a meandering channel pattern that are generally used in mathematical calculations and formulations of the meandering ratio, curvature or other approaches (modified from Güneralp and Marston 2012). Lr—Straight length, Lm—Sinuous channel length, α—Arc angle, Rc—Radius of curvature, Wr—Width of river, λ—Linear wavelength, A—Meander amplitude, Wb—Belt width (2A)

29.6 The Büyük Menderes Delta

The Büyük Menderes River has a large, wave-dominated delta with a surface area of 530 km^2 and a 35 km progradation during the last 4 millennia. This area is ornamented by abandoned meandering channels and ancient floodplains of the lowest course of the river (Fig. 29.8). The shoreline is formed by a coastal barrier island system, which extends over the entire width of the delta. It is developed by the reworking of channel mouth coarse clastics by waves and longshore currents (Aksu et al. 1987). Eastward from this island system, there are extensive lagoons, lakes, swamps and marshes. Although the current delta is made up of one lobe, fed by a single channel, several abandoned channels on the delta backplain record the development of several sub-deltas (Aksu et al. 1987).

According to seismic studies performed offshore, the Büyük Menderes River has developed a complex delta formed by four superimposed delta formations built during the Late Pleistocene; a fifth one, dated post-Last Glacial is still developing (Aksu et al. 1987). During this last delta stage, the Aegean coast of the Büyük Menderes Graben has gained its present morphology and landscape which result from the combined effects of tectonism, climate and sea level changes (e.g., Göney 1973; Erol 1976; Erinç 1978; Özgür 1982–83; Schröder and Bay 1996; Brückner 1997; Hakyemez et al. 1999; Kayan 1999; Brückner et al. 2002; Ergin et al. 2007; Kazancı et al. 2009, 2011; Yönlü et al. 2010; Sümer et al. 2013), with the additional factor of continental erosion and sedimentation processes driven by the hydrodynamics and morphodynamics of the Büyük Menderes River.

As previously mentioned, several historical and geoarchaeological data concern the ancient geography of the Büyük Menderes Delta plain and its progradation. Strabo, in his Geographica's XIVth Book, describes geographical features related to the relationships between many ancient cities (Fig. 29.8) and meandering channels (Fig. 29.9) on the plain: *"The island Ladê lies close in front of Miletus, as do also the isles in the neighbourhood of the Tragaeae, which afford anchorage for pirates… Next comes the Latmian Gulf, on which is situated "Heracleia below Latmus," as it is called, a small town that has an anchoring-place."… of the gulfs, is a little more and one hundred stadia, though that from Miletus to Pyrrha, in a straight course, is only*

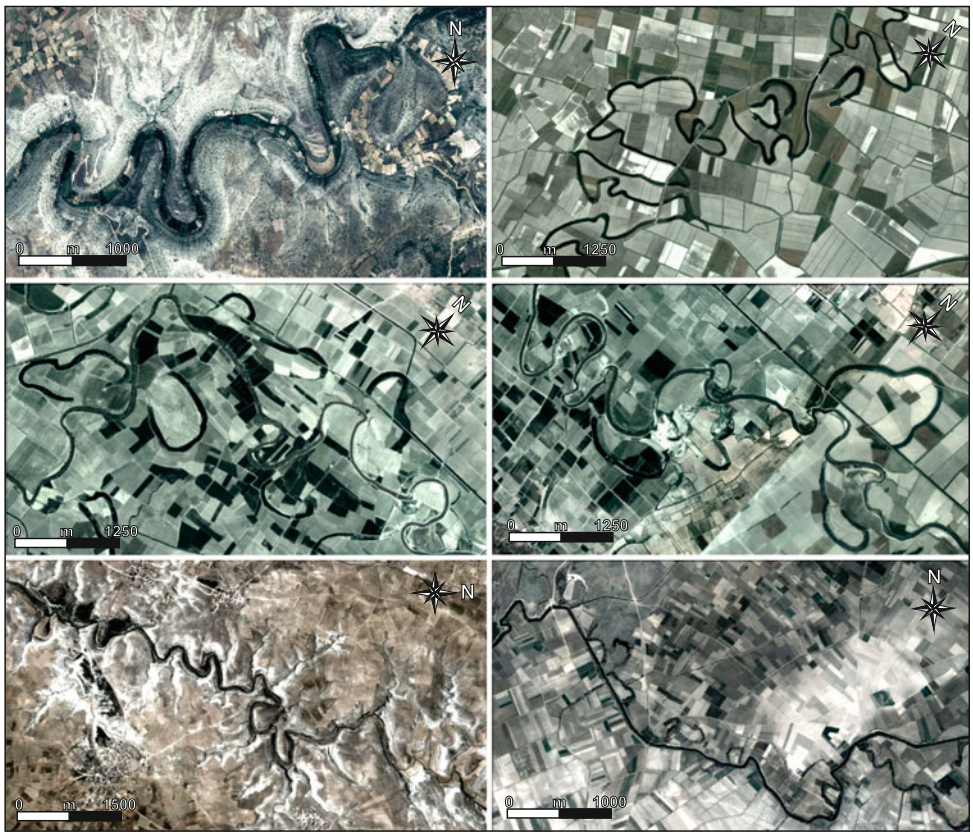

Fig. 29.7 Examples of meandering channel features along the Büyük Menderes River

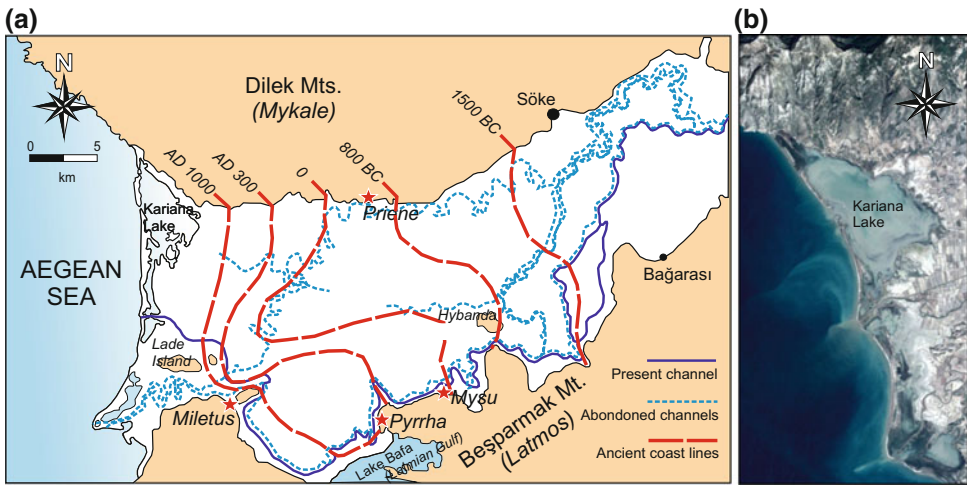

Fig. 29.8 **a** Present and abandoned channels of the Büyük Menderes River and ancient coastlines in the delta plain. Dates of ancient coasts are from Göney (1973) and Müllenhoff et al. (2004). **b** Two mouths of the river on the prograding coastline, with sediment input into the Aegean Sea (visible on the satellite image dated 10/19/2013)

thirty—so much longer is the journey along the coast."... "After the outlets of the Maeander comes the shore of Prienê, above which lies Prienê, and also the mountain Mycalê ...".

Possible former positions of the Aegean shoreline are presented in Fig. 29.8 after Göney (1973) and Müllenhoff et al. (2004). At 1500 BC, the coastline was located 30 km inland. By the beginning of Common Era, it had prograded 5 km, to a line near Mysu. About AD 1000 westward progradation of the shoreline pushed the harbour around Miletus, which was one of the most important ancient cities in western Anatolia and became a cradle for natural philosophy and mathematics by the contributions of Thales, his pupil Anaximander and again the pupil of the latter, Anaximenes (Strabo, Geographica, Book XIV). Lake Bafa was a marine embayment formerly known as Latmian Gulf during the Hellenistic and Roman times, the western part of which has been infilled by sediments of the Büyük Menderes

Fig. 29.9 Engraving dated 1782 in the ruins of Miletus and the meandering channels of the Büyük Menderes River (J.B. Hiliard, J.B. Tilliard)

River. As a result of this process, the Latmian Gulf finally lost its connection to the open sea and turned into today's Lake Bafa at around AD 1500 (Knipping et al. 2008).

29.7 The Ulubey Canyon

The Ulubey Canyon is one of the most impressive landscapes formed by the meandering dynamics of the Büyük Menderes River (Fig. 29.10). This canyon is an incised fluvial landform 100 km long, 1000 m wide, with a mean depth of 180 m. However, the depth on the final 25 km of the upper course of the Büyük Menderes River reaches 700 m after the Adıgüzel Dam, before it enters to the Denizli Graben (Fig. 29.5).

As noted above, the main course of the Büyük Menderes River is located within graben floors, which are filled by Quaternary fluvial and fluvio-lacustrine deposits (Fig. 29.4). In the upper part of the drainage basin, the Banaz and Ulubey tributaries drain the Neogene (and partially

Fig. 29.10 Ulubey Canyon formed by the incision of the meandering channel of the Büyük Menderes River

Palaeozoic) units isolating the Baklan-Dinar Graben from the Denizli Graben. The region drained by these streams is a plateau topped by an erosional surface representing an unconformity between the Neogene and Quaternary sedimentary formations. Between the Baklan-Dinar and Denizli sedimentary basins, the river is confined in a canyon, which gives place only to a narrow floodplain and follows deeply incised meanders imprinted in the landscape. The occurrence of this landscape is related to the base level of erosion, the river downcutting into its channel faster than it can change its course. The Ulubey Canyon was formed concurrently with the differential tectonic movements, which resulted in the subsidence of graben floors and uplift of horsts, in the context of the extensional tectonic regime in western Anatolia. Also, the Aegean Sea level changes during Quaternary and stream captures have effectively driven the incision process.

29.8 Conclusions

The *Maiandros* of ancient times, called today the Büyük Menderes River, is characterized by fascinating features regarding its geomorphologic, morphodynamic and historical backgrounds. It is the longest influent river of the Aegean Sea with a course of 615 km. The river originates in the east, around the Sandıklı district of Afyon in central-west Turkey, outflowing on the western coasts of the country. During its trip, the river draws a complex winding route from the upper course to the lower course. The river's name is the same as one of the River-Gods in mythology; *Maiandros*. This name is the eponym of the term 'meandering' pattern, which is used particularly in geomorphology, art and architecture. In this study, the meandering channel pattern of the Büyük Menderes River is analysed through its geometric forms. The results indicate a mean sinuosity ratio (K) of 1.42 for the main bed of the river from spring to mouth, while the thalweg profile presents a 1.90‰ gradient. The most winding parts of the river are located in the Baklan-Dinar (K = 1.74) and in the Büyük Menderes (K = 1.71) Grabens (Fig. 29.5). The floor of these basins also has the lowest gradient values with 0.41‰ and 0.51‰, respectively. It is, however, surprising to evidence a low sinuosity ratio (1.29) on the Dinarsuyu stream part of the river, in contrast to its low gradient value (1.3‰). As expected, this is related to the rectification of the geometry of the original meandering belt, which has been implemented to reduce the flood risk in the basin.

The lowest course of the river developed a wave-dominated delta, which progradated approximately 35 km since the first millennia BCE (e.g., Müllenhoff et al. 2004) and 60–80 km since the late Pleistocene (e.g., Kazancı et al. 2009). This progradation results both from sediment input by the Büyük Menderes River and from sea level changes in the Aegean Sea. As a matter of fact, the Aegean region is known as one of the most rapidly prograding delta complexes, which have buried several ancient cities and their harbours (e.g., Marriner and Morhange 2007). In the upper course of the river, the Ulubey Canyon is an impressive landscape feature formed by the incision of the meandering channel patterns. The canyon is approximately 100 km long and 1000 m wide. It has a mean depth of ~180 m, with a maximum valley depth of 700 m in the downstream part of the upper course. Further studies should focus on the understanding of the meandering features of the Büyük Menderes River using more quantitative means (i.e. morphometric) to demonstrate the forces (hydrodynamic, sedimentation, tectonic, etc.) that drive its channel patterns.

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