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Meaning of the Küçük Menderes graben in the tectonic framework of the central Menderes metamorphic core complex (western Turkey)

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ABSTRACT

Unusually steep, high-angle south-dipping normal faults, that separate the metamorphic rocks of the Menderes massif from the Neogene sedimentary deposits, occur in the northern Küçük Menderes graben in western Turkey. These faults probably reached their current position as a result of the special tectonic framework of the central Menderes metamorphic core complex. This area experienced further exhumation along with the rolling hinges of faults limiting Alaşehir and Büyük Menderes grabens, giving rise to a huge syncline in the region. This regional structure would be most likely responsible for the present position of the high-angle graben bounding normal faults that rotated along a horizontal axis. However, recent studies in the same area claim for the development of reverse faulting between the metamorphic basement and the Neogene sedimentary units, and present this observation as evidence for a supposed Miocene–Pliocene regional contractional regime in western Turkey. Even if these reverse faults or other post-Miocene contractional structures existed in the central Menderes massif, they would not afford evidence of regional contraction since its generation could be related to the contractional area that would have developed along the axial zone of the huge syncline in the central Menderes massif, in its turn resulting from a regional extensional process that took place during the further exhumation stage.

KEYWORDS **Aegean. Turkey. Extension. Tectonics. Menderes Massif.**

INTRODUCTION

Western Turkey has experienced extensional tectonics since Oligocene times and this region includes a well developed metamorphic core complex, the so-called Menderes massif (Bozkurt and Park, 1994; Hetzel et al., 1995; Gessner et al., 2001; Işık and Tekeli, 2001) (Fig. 1). Ring et al. (2003) suggested that the Menderes massif was exhumed as a symmetrical core complex along the south-dipping Lycian and north-dipping Simav detachments (Işık and Tekeli, 2001; Işık et al., 2004). However, an asymmetrical core complex formation along the north-dipping Datça-Kale main breakaway fault and its northern continuation, the Simav detachment, has been proposed as an alternative hypothesis for the Menderes massif structure (Seyitoğlu et al., 2004). Both models are in agreement that the central Menderes massif has been exhumed further due to the rolling hinges of the faults bordering the Alaşehir and Büyük Menderes grabens (Ring et al., 2003; Seyitoğlu et al., 2004). The footwall and hanging wall evidences of the rolling hinge model in these grabens have been presented by Gessner et al. (2001), Seyitoğlu and Şen (1998) and Seyitoğlu et al. (2002a) respectively. Further symmetrical exhumation of the central Menderes massif created a special tectonic position (see discussion) in which the Küçük Menderes graben is located. More recent field observations (Bozkurt and Rojay, 2005; Rojay et al., 2005) from the central Menderes massif in the Küçük Menderes graben (Fig. 1) support the view of a two-stage Neogene extension, separated by a compressional phase. The field evidence of the two-stage extension model (Koçyiğit et al., 1999) is based on the folding in the Alaşehir graben fill. On the other hand, there are two important issues against this model; first, the undeformed nature of the early-Middle Miocene İnay group on the north of Alaşehir graben (Seyitoğlu, 1999; Seyitoğlu et al., 2007); and secondly the extensional nature of folding in the Alaşehir graben (Seyitoğlu et al., 2000). Discussion about this subject is currently developing within the literature (see Bozkurt, 2002; Yusufoğlu, 2002; Seyitoğlu et al., 2002b; Kaya et al., 2004; Bozkurt and Sözbilir, 2004). Therefore, the confirmation or refusal of the existence of a reverse fault between the metamorphic rocks of the Menderes massif and the Neogene deposits in the Küçük Menderes graben (Bozkurt and Rojay, 2005) deserves a detailed study. This paper summarises the observations made in this critical location and evaluates the graben bounding faults of the Küçük Menderes graben in light of the special tectonic position of the central Menderes massif.

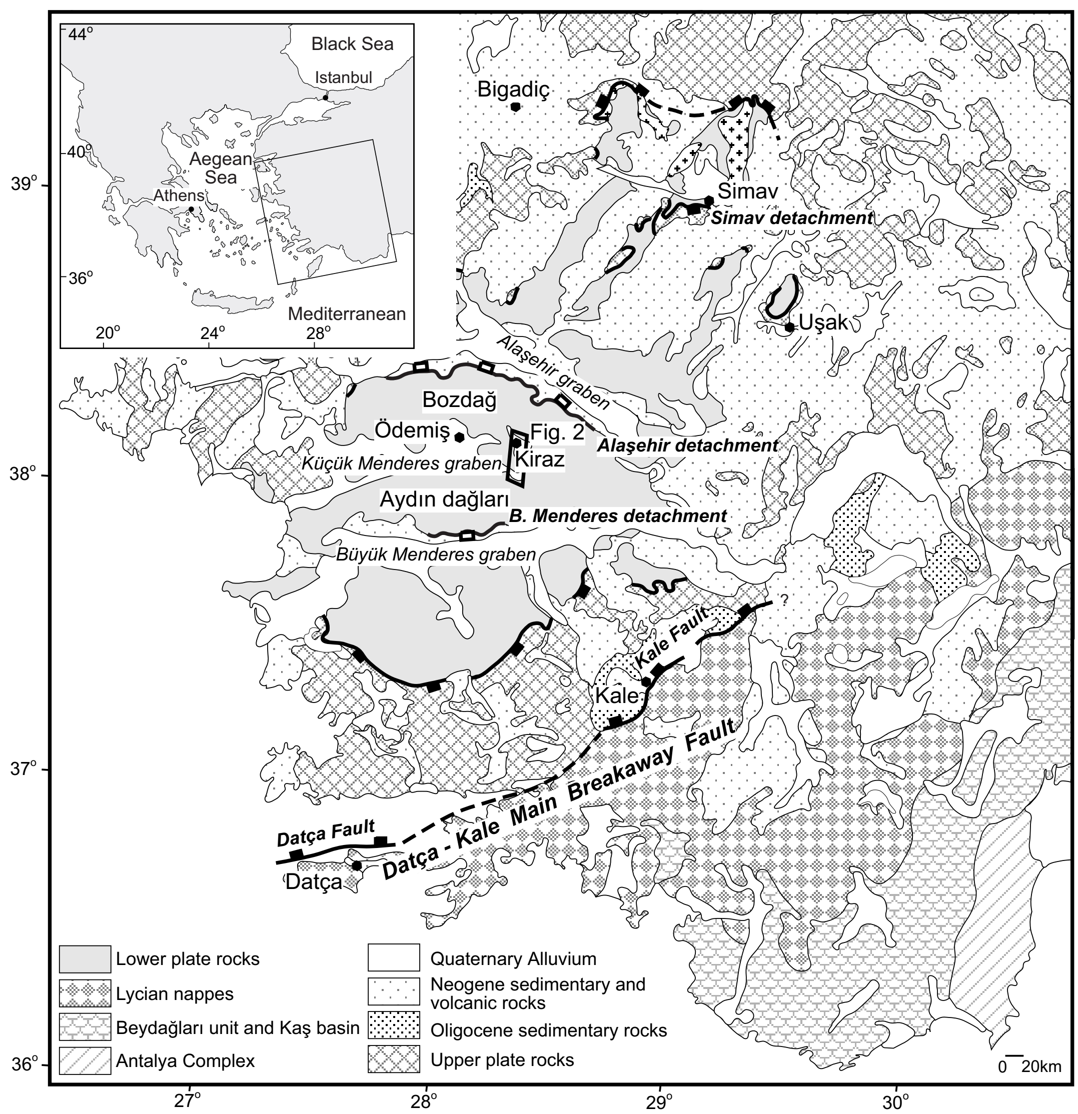

FIGURE 1 | **The main tectonic elements in western Turkey (after Seyitoğlu et al., 2004).**

THE KÜÇÜK MENDERES GRABEN: GEOLOGICAL FEATURES

The Menderes massif (Bozkurt and Park, 1994; Hetzel et al., 1995; Gessner et al., 2001; and Tekeli, 2001; Fig. 1) is a well developed metamorphic core complex located in Western Turkey, a region submitted to extension since the Oligocene. The Küçük Menderes graben stretches between Bozdağ to the north and Aydın Dağları to the south in the central Menderes massif (Figs. 1 and 2) in western Turkey. It is a less prominent east-west trending structure relative to the Alaşehir and Büyük Menderes grabens.

The graben fill

The Neogene fill of the Küçük Menderes graben started with the Suludere Formation (Fm.) that unconformably overlies meta-sedimentary and meta-igneous rocks of the Menderes massif and the Başova andesites (14.3 - 14.7 Ma: Emre et al., 2006). This formation consists mainly of conglomerates, sandstones, mudstones and lacustrine limestones. It is suggested that the Suludere Fm. accumulated as a stream-influenced alluvial fan and lake deposits (Emre et al., 2006).

The Suludere Fm. is unconformably overlain by the Aydoğdu Fm. That is mainly made up by light brown, reddish brown poorly lithified conglomerates with sandstone and mudstone interbeds. This unit is interpreted as deposited on alluvial fan systems. All of these sedimentary units are covered by recent alluvium deposits (Emre et al., 2006).

Basement rocks of the Menderes massif along the northern side of the Küçük Menderes graben

The basement rocks exposed along the northern side of the Küçük Menderes graben near Suludure (Fig. 3) consist of meta-sedimentary and meta-igneous rocks (e.g. Ashworth and Evirgen, 1984; Candan and Dora, 1998; Hetzel et al., 1998; Koralay et al., 2001; Bozkurt, 2000; Işık et al., 2003). The meta-sedimentary rocks are made up of mica gneisses, mica schists, garnet mica schists, calc-schists, quartztic schists and marbles. A meta-igneous rock, orthogneisses, is exposed further to the north of the study area. During Tertiary extension these rocks were converted into changing mylonitic rocks ranging from protomylonite to blastomylonite. Recently, Bozkurt and Rojay (2005) have documented the structural features of these rocks.

Structural contact between the Menderes massif and Küçük Menderes graben fill

There have been controversial observations on the geological contact between basement rocks of the central

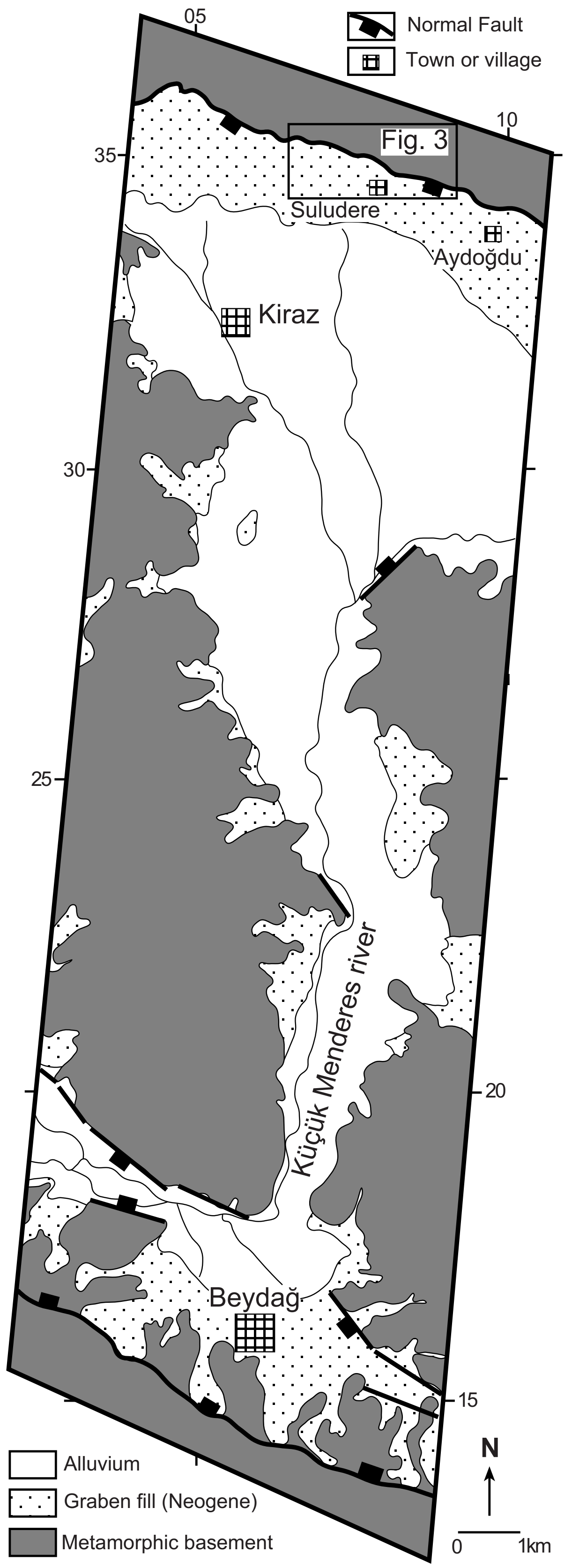

FIGURE 2 | **Geological sketch along a north–south transect in the Küçük Menderes graben (after Emre and Sözbilir, 2007).**

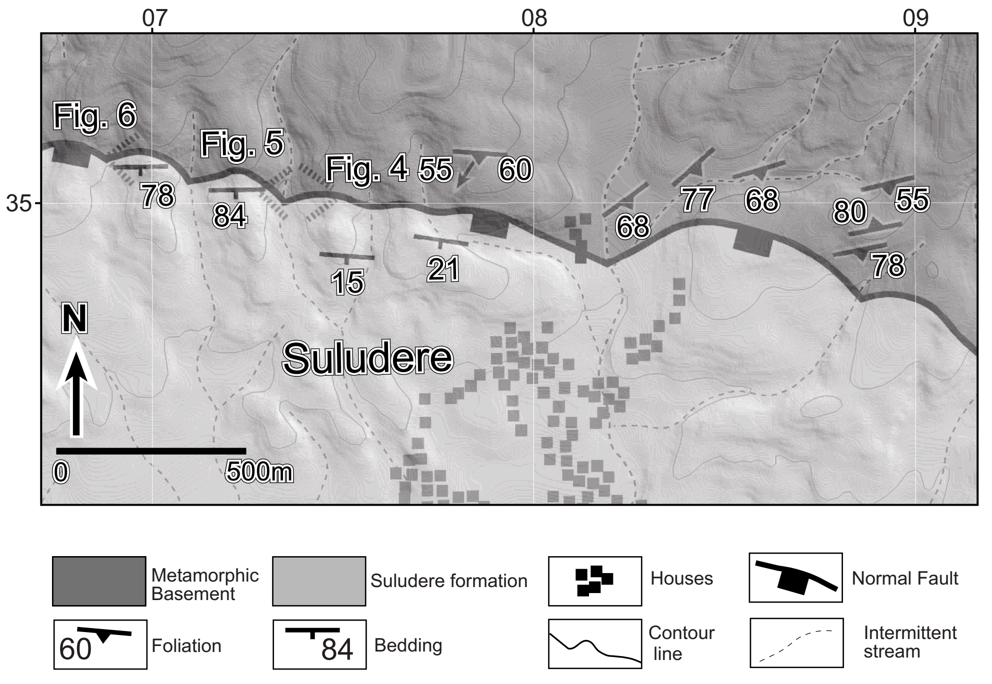

FIGURE 3 | **Geological map of the northern Küçük Menderes Graben around Suludere.**

Menderes massif and the Küçük Menderes graben fill. Bozkurt and Rojay (2005) mapped the area to the north of Suludere as a reverse fault in which rocks of the Menderes massif were thrust onto Neogene sediments. The bedding of the basin fill in this location is reported to be overturned as a result of reverse faulting. However, the same contact has been mapped as a normal fault by Emre et al. (2006), but later, pre-extensional reverse faulting is also reported (Emre and Sözbilir, 2007). The authors have carried out many detailed observations in the same area and the contact between rocks of the Menderes massif and the Suludere formation has been carefully mapped (Figs. 3 to 5).

This tectonic contact is mainly characterized by a brittle shear zone without apparent fault surface. The fault surface has only been measured in one location (surface: N53W, 60SW; slickenline: N18E, 58SW). The brittle shear zone between metamorphic and sedimentary rocks is 10 to 40 metres wide. Foliation planes of metamorphic rocks and bedding of sedimentary rocks of the graben fill along the contact zone lie at high angles (Fig. 4). Foliation planes dip to the north and south but the bedding of the Suludere formation dips to the south. Outside the zone, these planar structures display normal orientations. The effect of brittle deformation gradually increases through the contact. The brittle deformation in metamorphic rocks is characterized by the formation of a brittle zone with variably fracturing (e.g., joints, shear fractures), breccias and gouges (Fig. 6). The fracturing sub-zone is commonly associated with steeply dipping fractures with small displacement to the southwest and is developed adjacent to the metamorphic host rock. These fractures in the brittle zone only just cross-cut the foliations of metamorphic rocks and have gouges developed along them, being a few millimetres thick. Within the zone, fractured-metamorphic rocks are transitional into the sub-zone of breccias and gouges, indicating that the intensity of brittle deformation increases toward the contact between metamorphic rocks and rocks of the Suludere Fm. Breccias are incohesive rocks which, texturally are either clast-supported or matrix-supported and have derived from metamorphic rocks. Pre-existing metamorphic fabrics are destroyed. In clast-supported breccias, metamorphic lenses are preserved and surrounded by intensively deformed materials of metamorphic rocks. The boundary between clast-supported and matrix-supported breccias is arbitrary in the field. Matrix-supported breccia is defined by angular and sub-angular clasts up to 8 cm, which occur embedded in matrix material. Gouges occur in breccias, especially in closer proximity to Neogene sediments.

The intersection between the tectonic contact and topography suggests a high-angle normal fault surface dipping towards the south (dip >45 degrees) and no overturned bedding was observed, except in one location due to the downslope creep. The asymmetric syncline, with its axis parallel to the tectonic border, can be explained as a drag fold syncline in the hanging wall of the normal fault (Figs. 3 and 4).

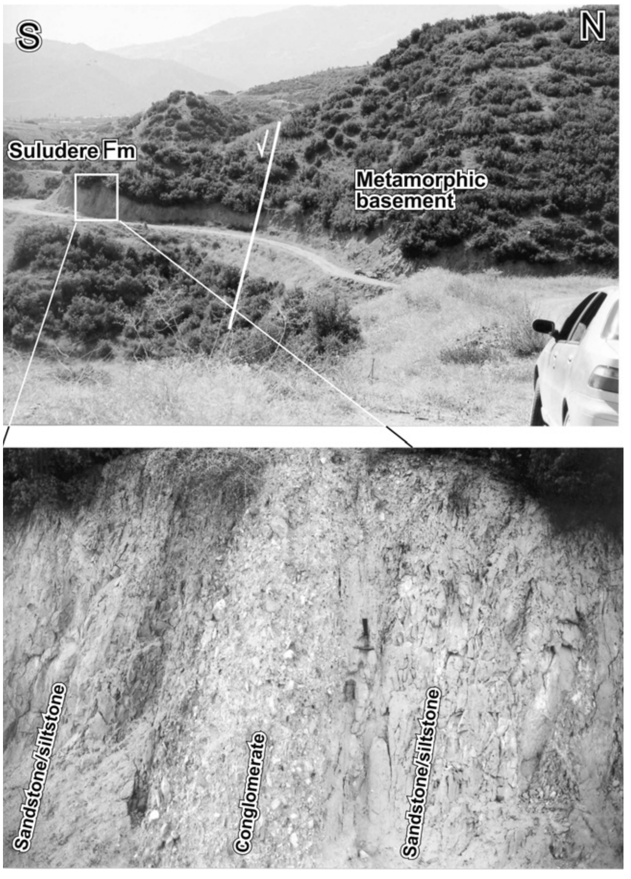

FIGURE 4 | **The high angle normal fault between the metamorphic rocks and Neogene deposits at the north of Suludere; the picture is taken towards the west. For location see Figure 3.**

DISCUSSION

In contrast to the proposal of Bozkurt and Rojay (2005), no reverse or thrust fault was observed at the north of the Küçük Menderes graben around Suludere village. The main question is whether, due to the special tectonic position of this area, this or any other potential contractional structure observed at the central Menderes massif would record a region-wide contraction.

Special tectonic position of the central Menderes massif

The central Menderes massif was exhumed along the north-dipping Alaşehir (Kuzey) and south-dipping Büyük Menderes (Güney) detachments. Although fragmentation of a dome -shaped massif occurred during the Early Miocene due to the activity of east–west trending graben bounding faults, their rotation to low angle faults occurred in Pliocene times, after activation of the second fault system in their hanging wall (Seyitoğlu et al., 2002a). This process is similar to the rolling hinge model presented by Gessner et al. (2001). This study demonstrates that the central Menderes massif is a huge syncline with a wavelength of 45 km and amplitude of 10 km that developed as a result of rolling hinges of two opposite-facing detachments (Gessner et al., 2001) (Fig. 7A). The possibility that this syncline was formed by extensional processes is supported both by the field observations and by general numerical models (Wijns et al., 2005).

Fold kinematical analyses indicate that shortening occurs in the inner arc and that this creates reverse or thrust faults parallel to the axis of folding (Ramsay and Huber, 1987; Davis and Reynolds, 1996) (Fig. 7B). If this basic kinematical rule was applied to the syncline created by extensional processes in the central Menderes massif, it would be theoretically possible to see some local contractional structures around the Küçük Menderes graben (i.e. the claim of reverse faults in the research of Bozkurt and Rojay, 2005; Emre and Sözbilir, 2007). However, we observed only unusually high-angle normal faults in the north of Suludere. It is probable that these high-angle normal faults in the northern border of Küçük Menderes

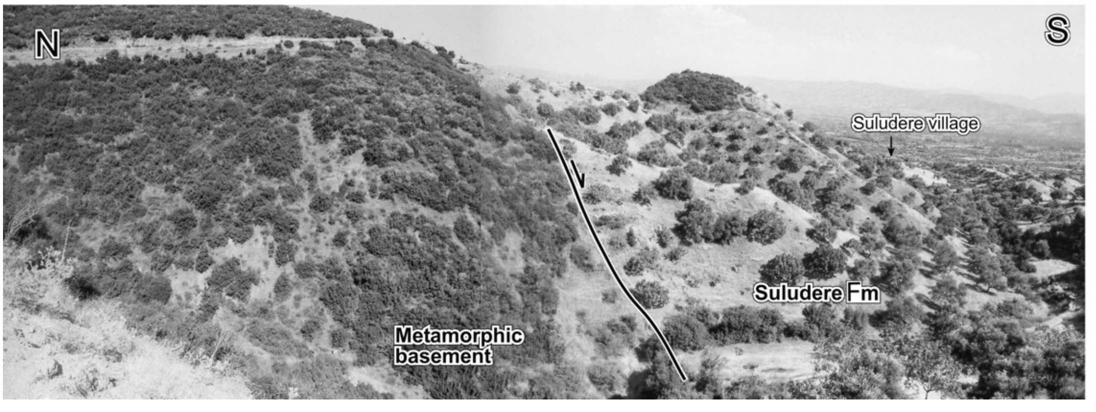

FIGURE 5 | **The high angle normal fault between the metamorphic rocks and Neogene deposits at the north of Suludere. Photograph is taken towards the east. Note that the border of a fig garden corresponds to the tectonic contact. For location see Figure 3.**

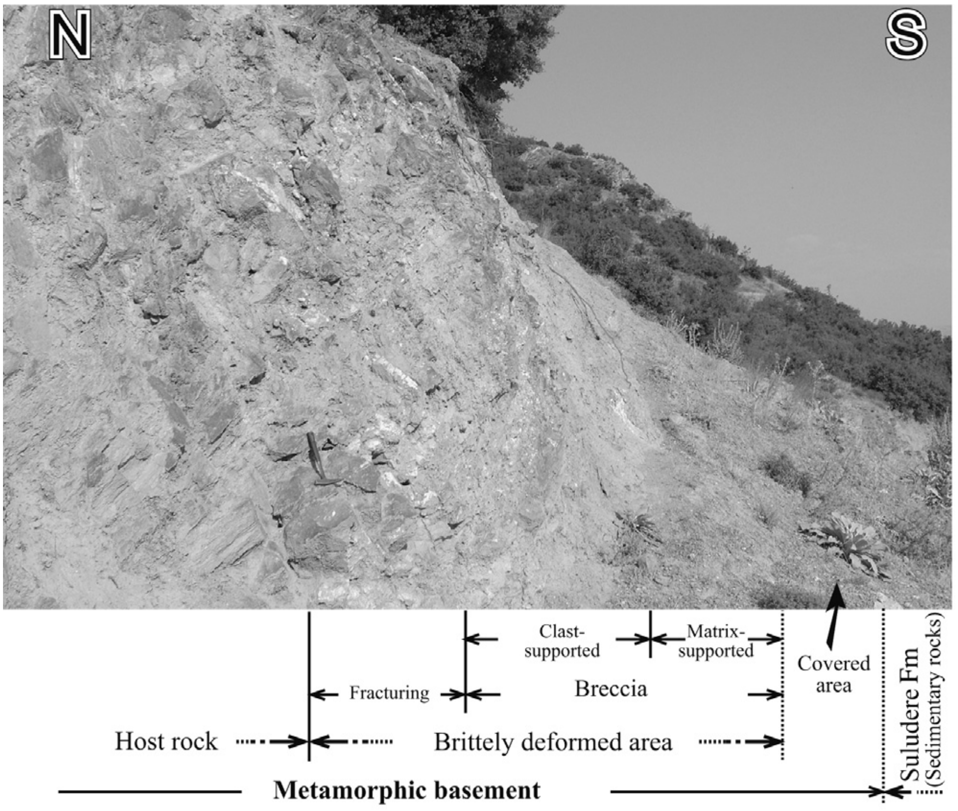

FIGURE 6 | **Details of the brittle shear zone at the north of Suludere, the northern Küçük Menderes graben. For location see Figure 3.**

graben might have relatively lower angles (such as 45 degree) at the beginning. These structures reached their present arrangement along with the rotation of a horizontal axis. Initial fault surfaces having a 45 degree dip angle became nearly vertical normal faults. In the central Menderes massif, during the Pliocene, this rotation occurred in the limb of a huge syncline created by the extensional processes explained above. Therefore, if any post-Miocene contractional structures were successfully identified in the area, they would not be regarded as representative of a region wide (i.e. western Turkey) contraction as previously claimed by Bozkurt and Rojay (2005) in order to support a two-stage extension model of Koçyiğit et al. (1999). Furthermore, this model still does not explain the undeformed nature of the early-Middle Miocene Ìnay group in the Selendi and Uşak-Güre basins (Seyitoğlu, 1997, 1999; Seyitoğlu et al., 2007).

It may also be argued that the rolling hinge model is not applicable to the east-west trending Alaşehir and Büyük Menderes grabens because presently low-angle graben bounding faults are cut and displaced by high-angle normal faults (i.e. Bozkurt and Sözbilir, 2004). Therefore, a huge syncline could not be created by extensional processes in the central Menderes massif. When the research by Seyitoğlu et al. (2002a) presenting hanging wall evidence of the rolling hinge model in the Alaşehir graben is carefully examined, it can easily be seen in their fig. 10d that the faults marked "IV" are very young, high-angle normal faults which cut and displaced earlier structures. This relationship does not affect the earlier (Early Miocene-Quaternary) history of the rolling hinge process. In order to disprove the rolling hinge model in

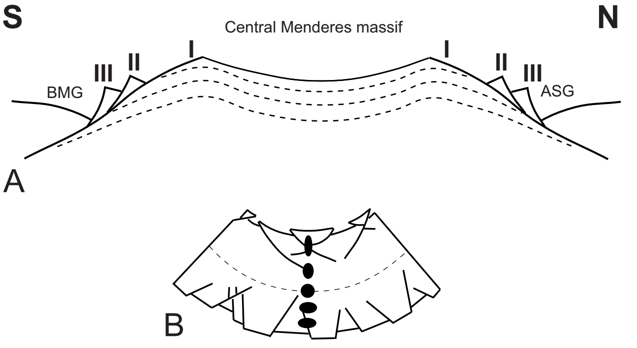

FIGURE 7 | **A) The overall syncline structure in the central Menderes massif developed due to the rolling hinge of the graben bounding fault system of the Alaşehir and Büyük Menderes grabens (after Gessner et al., 2001). ASG: Alaşehir graben, BMG: Büyük Menderes graben, I: First fault system, II: Second fault system, III: Third fault system. B) Kinematical analysis of a syncline (after Ramsay and Huber, 1987; Davis and Reynolds, 1996).**

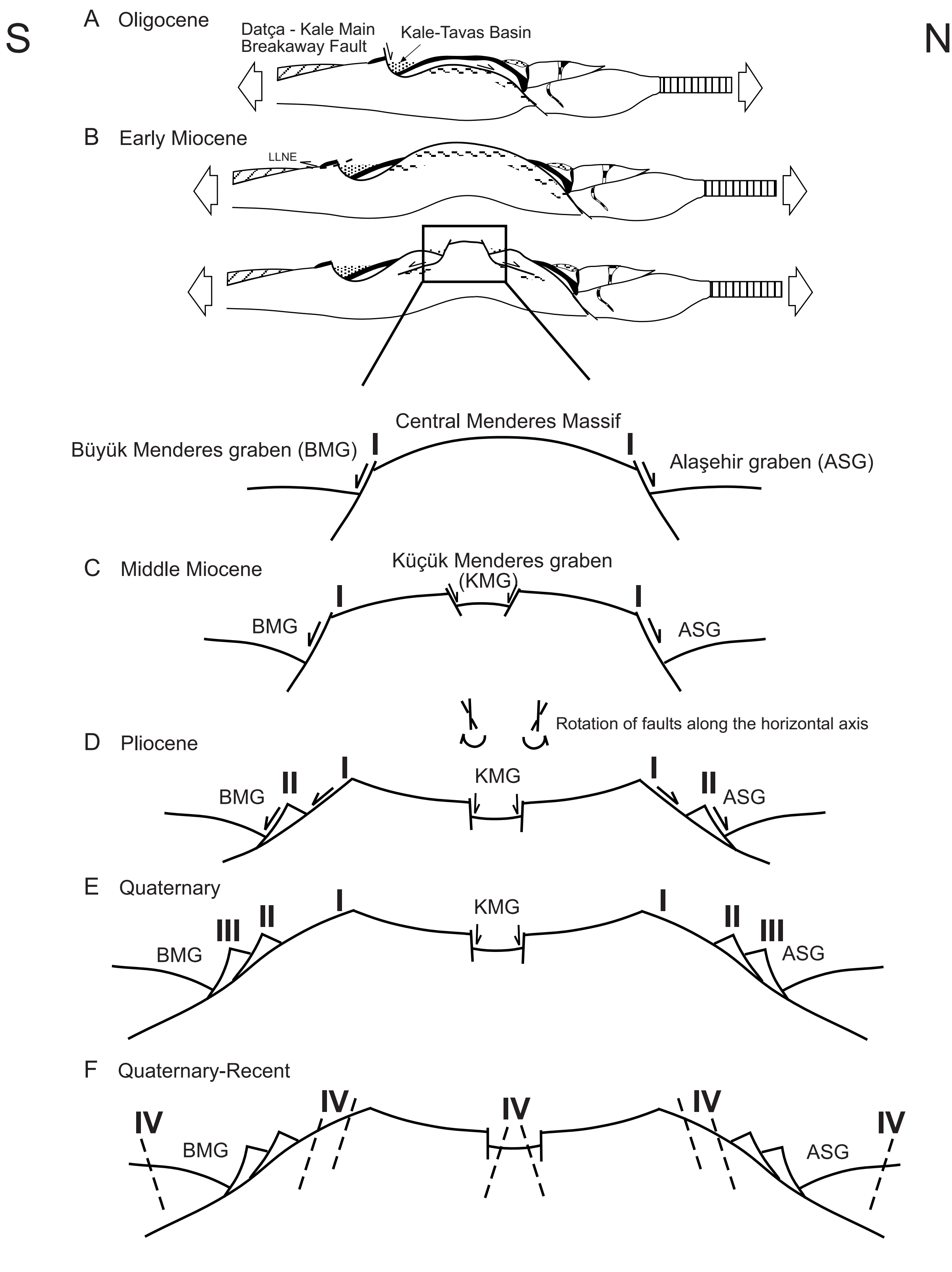

FIGURE 8 **Tectonic evolution of the Central Menderes massif. A) In the Oligocene Datça-Kale Main breakaway controls the sediment accumulation in the Datça and Kale basin. B) In the Early Miocene the Menderes massif reached the surface and the E-W trending Alaşehir and Büyük Menderes half-grabens fragments the dome shaped massif (after Seyitoğlu et al., 2004). C) In the Middle Miocene Küçük Menderes graben started developing, see Emre et al. (2006). D) In the Pliocene, second fault system of the Alaşehir and Büyük Menderes grabens developed and first fault systems rotated to the low angle and a huge syncline was created in the central Menderes massif by extensional processes. Note the rotation on the faults bordering the Küçük Menderes graben. E) In the Quaternary, the third fault system is operational and both first and second systems are further rotated. F) Recently a fourth fault system cut and displaced all earlier structures.**

the Alaşehir graben, it should be demonstrated that the second fault system cuts the first fault system. All of the cross-cutting relationships documented in Bozkurt and Sözbilir (2004) belong to the "very young high-angle normal faults." They describe in detail what is shown at fig. 10d in Seyitoğlu et al. (2002a) but fail to disprove the existence of a rolling hinge model in the Alaşehir graben.

Extensional evolution of the Küçük Menderes graben

The Late Cenozoic extensional history of western Turkey started in the Oligocene by a north-dipping Datça-Kale main breakaway fault that controlled the accumulation of basin fill in the Gökova and Kale basins (Seyitoğlu et al., 2004) (Fig. 8A). After upward bending of the Datça-Kale main breakaway, the dome-shaped Menderes massif reached the surface during the Early Miocene, as indicated by thermo-chronological data presented by Gessner et al. (2001). This dome-shaped massif is fragmented by east-west trending Alaşehir and Büyük Menderes grabens (Seyitoğlu et al., 2004) (Fig. 8B) and, in the Middle–Late Miocene, the Küçük Menderes graben started to develop (Emre et al., 2006) (Fig. 8C). During the Pliocene, the second fault system occurred in the hanging wall of the major graben bounding faults in the Alaşehir and Büyük Menderes grabens and these faults rotated to low angles similar to the rolling hinge model (Seyitoğlu et al., 2002a). The central Menderes massif was further exhumed and a huge syncline developed with rotated limbs (Gessner et al., 2001 and Wijns et al., 2005). This process resulted in rotated, steep high-angle normal faults in the borders of the Küçük Menderes graben (Fig. 8D). Following the Pliocene, younger normal faults developed in the Küçük Menderes graben due to the continuing extension (Fig. 8E, F).

CONCLUSIONS

The evolution of the Küçük Menderes graben did not require region wide short term contraction. Reverse faulting reported between the Menderes massif and the Neogene basin fill in the north of the Küçük Menderes graben (Bozkurt and Rojay, 2005) is not confirmed by our field observations, which instead of reverse faults indicated high-angle normal faults in the same area. These high angle normal faults developed as a result of rotation along a horizontal axis in the limbs of a huge syncline. This regional syncline was created by extensional processes following the Pliocene, during the further exhumation of the central Menderes massif along with the rolling hinges of normal major faults bordering the Alaşehir and Büyük Menderes grabens.

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REFERENCES

Ashworth, J.R., Evirgen, M.M., 1984. Garnet and associated minerals in the southern margin of the Menderes Massif, southwest Turkey. Geological Magazine, 121, 323-337.

Bozkurt, E., 2000. Timing of extension on the Büyük Menderes graben, western Turkey, and its tectonic implications. In: Bozkurt, E., Winchester, J.A., and Piper, J.D.A. (eds.). Tectonics and magmatism in Turkey and the surrounding area. Geological Society of London, Special Publication, 173, 385-403.

Bozkurt, E., 2002. Discussion on the extensional folding in the Alaşehir (Gediz) Graben, western Turkey. London, Journal of the Geological Society, 159, 105-109.

Bozkurt, E., and Park, R.G., 1994. Southern Menderes massif: an incipient metamorphic core complex in western Anatolia, Turkey. London, Journal of the Geological Society, 151, 213-216.

Bozkurt, E., Sözbilir, H., 2004. Tectonic evolution of the Gediz Graben: field evidence for an episodic, two-stage extension in western Turkey. Geological Magazine, 141, 63-79.

Bozkurt, E., Rojay, B., 2005. Episodic two-stage Neogene extension and short-term intervening compression in Western Turkey: field evidence from the Kiraz Basin and Bozdağ Horst. Geodinamica Acta, 18, 299-316.

Candan, O., Dora, O., 1998. Granulite, eclogite and blueschist relics in the Menderes Massif: An approach to Pan-African and Tertiary metamorphic evolution. Geological Bulletin of Turkey, 41, 1-36.

Davis, G.H., Reynolds, S.J., 1996. Structural Geology of Rocks and Regions. New York, John Wiley and Sons, 776 pp.

Emre, T., Sözbilir, H., Gökçen, N., 2006. Neogene-Quaternary stratigraphy of Kiraz - Beydağ vicinity, Küçük Menderes graben, west Anatolia. Bulletin of the Mineral Research and Exploration, 132, 1-32.

Emre, T., Sözbilir, H., 2007. Tectonic evolution of the Kiraz basin, Küçük Menderes graben: Evidence for compression/uplift-related basin formation overprinted by extensional tectonics in west Anatolia. Turkish Journal of Earth Sciences, 16, 441-470.

Gessner, K., Ring, U., Johnson, C., Hetzel, R., Passchier, C.W., Güngör, T., 2001. An active bivergent rolling-hinge detachment system. Central Menderes metamorphic core complex in western Turkey. Geology, 29, 611-614.

Hetzel, R., Ring, U., Akal, C., Troesch, M., 1995. Miocene NNE-directed extensional unroofing in the Menderes massif, southwestern Turkey. London, Journal of the Geological Society, 152, 639-654.

Hetzel, R., Romer, R.L., Candan, O., Passchier, C.W., 1998. Geology of the Bozdağ area, central Menderes massif, SW Turkey: Pan-African basement and Alpine deformation. Geologische Rundschau, 87, 394-406.

Işık, V., Tekeli, O., 2001. Late orogenic crustal extension in the northern Menderes massif (western Turkey): evidence for metamorphic core complex formation. International Journal of Earth Sciences, 89, 757-765.

Işık, V., Seyitoğlu, G., Çemen, Ì., 2003. Ductile-brittle transition along the Alaşehir shear zone and its structural relationship with the Simav detachment, Menderes massif, western Turkey. Tectonophysics, 374, 1-18.

Işık, V., Tekeli, O., Seyitoğlu, G., 2004. The $^{40}Ar/^{39}Ar$ age of extensional ductile deformation and granitoid intrusion in the northern Menderes core complex: implications for the initiation of extensional tectonics in western Turkey. Journal of Asian Earth Sciences, 23, 555-566.

Kaya, O., Ünay, E., Saraç, G., Eichhorn, S., Hassenrück, S., Knappe, A., Pekdeğer, A., Mayda, S., 2004. Halitpaşa transpressive zone: Implications for an Early Pliocene compressional phase in central western Anatolia, Turkey. Turkish Journal of Earth Sciences, 13, 1-13.

Koçyiğit, A., Yusufoğlu, H., Bozkurt, E., 1999. Evidence from the Gediz graben for episodic two-stage extension in western Turkey. London, Journal of the Geological Society, 156, 605-616.

Koralay, E., Satır, M., Dora, O., 2001. Geochemical and geochronological evidence for Early Triassic calc-alkaline magmatism in the Menderes Massif, western Turkey. International Journal Earth Sciences, 89, 822-835.

Ramsay, J.G., Huber, M.I., 1987. The techniques of modern structural geology (Volume 2: Folds and Fractures). London, Academic Press, 700 pp.

Ring, U., Johnson, C., Hetzel, R., Gessner, K., 2003. Tectonic denudation of a Late Cretaceous - Tertiary collisional belt: regionally symmetric cooling patterns and their relation to extensional faults in the Anatolide belt of western Turkey. Geological Magazine, 140, 421-441.

Rojay, B., Toprak, V., Demirci, C., Süzen, L., 2005. Plio-Quaternary evolution of the Küçük Menderes Graben southwestern Anatolia, Turkey. Geodinamica Acta, 18(3-4), 317-331.

Seyitoğlu, G., 1997. Late Cenozoic tectono-sedimentary development of Selendi and Uşak-Güre basins: a contribution to the discussion on the development of east-west and north- trending basins in western Turkey. Geological Magazine, 134, 163-175.

Seyitoğlu, G., 1999. Discussion on evidence from the Gediz Graben for episodic two-stage extension in western Turkey. London, Journal of the Geological Society, 156, 1240.

Seyitoğlu, G., Şen, Ş., 1998. The contribution of first magnetostratigraphical data from E-W trending grabens fill to the style of late Cenozoic extensional tectonics in western Turkey. Third International Turkish Geology Symposium Abstracts, 188.

Seyitoğlu, G., Çemen, Ì., Tekeli, O., 2000. Extensional folding in the Alaşehir (Gediz) graben, western Turkey. London, Journal of the Geological Society, 157, 1097-1100.

Seyitoğlu, G., Tekeli, O., Çemen, Ì., Şen, Ş., Işık, V., 2002a. The role of the flexural rotation / rolling hinge model in the tectonic evolution of the Alaşehir graben, western Turkey. Geological Magazine, 139, 15-26.

Seyitoğlu, G., Çemen, Ì., Tekeli, O., 2002b. Discussion on the extensional folding in the Alaşehir (Gediz) Graben, western Turkey (reply). London, Journal of the Geological Society, 159, 105-109.

Seyitoğlu, G., Işık, V., Çemen, Ì., 2004. Complete Tertiary exhumation history of the Menderes massif, western Turkey: an alternative working hypothesis. Terra Nova, 16, 358-364.

Seyitoğlu, G., Işık, V., Yılmaz, Ì., Alçiçek, M.C., Alçiçek, H., Varol, B., Esat, K., 2007. Re-evaluation of the stratigraphic position of Kemiklitepe fossil locality (Uşak-Eşme) and its implications on the Neogene tectonosedimentary basin development in western Turkey. 60th Geological Congress of Türkiye, Abstracts, 457-459.

Wijns, C., Weinberg, R., Gessner, K., Moresi, L., 2005. Mode of crustal extension determined by rheological layering. Earth and Planetary Science Letters, 236, 120-134.

Yusufoğlu, H., 2002. Discussion on the extensional folding in the Alaşehir (Gediz) Graben, western Turkey. London, Journal of the Geological Society, 159, 105-109.

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