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Dating the exhumation of a metamorphic dome: geological evidence for pre-Eocene unroofing of the Niğde Massif (Central Anatolia, Turkey)

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Abstract – The timing of exhumation of metamorphic rocks and granitoids of the Niğde metamorphic dome, at the southern tip of the Central Anatolian Crystalline Complex, is a matter of debate. According to some authors, the metamorphic rocks are overlain nonconformably by a sedimentary sequence of late Maastrichtian to Late Palaeocene age. In contrast, other authors recently argued that the Niğde dome represents an extensional core complex of Oligocene–Early Miocene age, finally unroofed during late Miocene times. On the one hand, the results of our study contradict the latter interpretation. A sedimentary sequence of earliest Eocene to early Middle Eocene age nonconformably overlies the high-grade rocks of the Niğde dome on its southeastern flank. Pebbles from the metamorphic rocks are ubiquitous in the conglomerates of this sequence. As a result, the Niğde metamorphic rocks must have reached the surface before Eocene times, or at the very beginning of the Eocene at the latest. The Üçkapılı granite, whose crystallization age has been inferred to be Early Miocene, has intruded the metamorphic complex during exhumation. The granite is also found as pebbles within the conglomerates of the Eocene sedimentary sequence and, thus, is actually older than the Eocene. Apatite fission track dates of 12–11 Ma across the Niğde dome do not indicate that the metamorphic rocks were still on their way to the surface at that time; instead, they must reflect a later event, which is most probably heating during late Neogene magmatism. Lastly, there is no ductile-then-brittle extensional detachment in the two areas where it has been invoked, that is, on the western and southern flanks of the dome. An extensional detachment nevertheless exists at the top of the Niğde dome, best documented in its northern part, where the detachment fault superposes a superficial unit made up of massive ophiolitic rocks onto the high-grade metamorphic sequence. Field evidence indicates that this detachment developed before Eocene times. On the other hand, our observations do not confirm the nonconformity of the sedimentary sequence dated as late Maastrichtian–Late Palaeocene onto the Niğde high-grade rocks. Field relations show either a tectonic contact between the two, or the direct nonconformity of the Eocene sediments onto the metamorphic rocks. The lack of coarse clasts originating from the Niğde high-grade rocks within the Maastrichtian–Palaeocene sequence further suggests that the metamorphic dome did not reach the surface before Late Palaeocene times. These results compare well with available data from the northwestern part of the Central Anatolian Crystalline Complex, suggesting that exhumation has been broadly synchronous on the scale of the massif, as a result of an episode of high magnitude extension that affected the region in Campanian to Palaeocene times.

Keywords: exhumation, extension tectonics, unconformities, Anatolia, Alpine Orogeny.

1. Introduction

Establishing the time at which a metamorphic terrain has been exhumed can provide major clues in the study of orogens. In a classical approach, this relies on the identification of sediments that nonconformably cover the metamorphic rocks (Fig. 1a). The oldest such sediments provide a minimum age of unroofing (in this paper, we use 'exhumation' to describe the motion of a rock toward the surface, whereas we restrict 'unroofing' to the stage where the rock reaches the surface). In some cases, however, the acquisition of radiometric data implying later cooling and unroofing may prove the previous identification of a nonconformity to be erroneous. This holds true especially for the case of extensional metamorphic core complexes, where the presence of unmetamorphosed sediments on top of the metamorphic rocks may be suggestive of a nonconformity, whereas careful examination of the contact between the two often reveals the presence of a major tectonic boundary (the extensional detachment, Fig. 1b). In such an example, the detritic sediments

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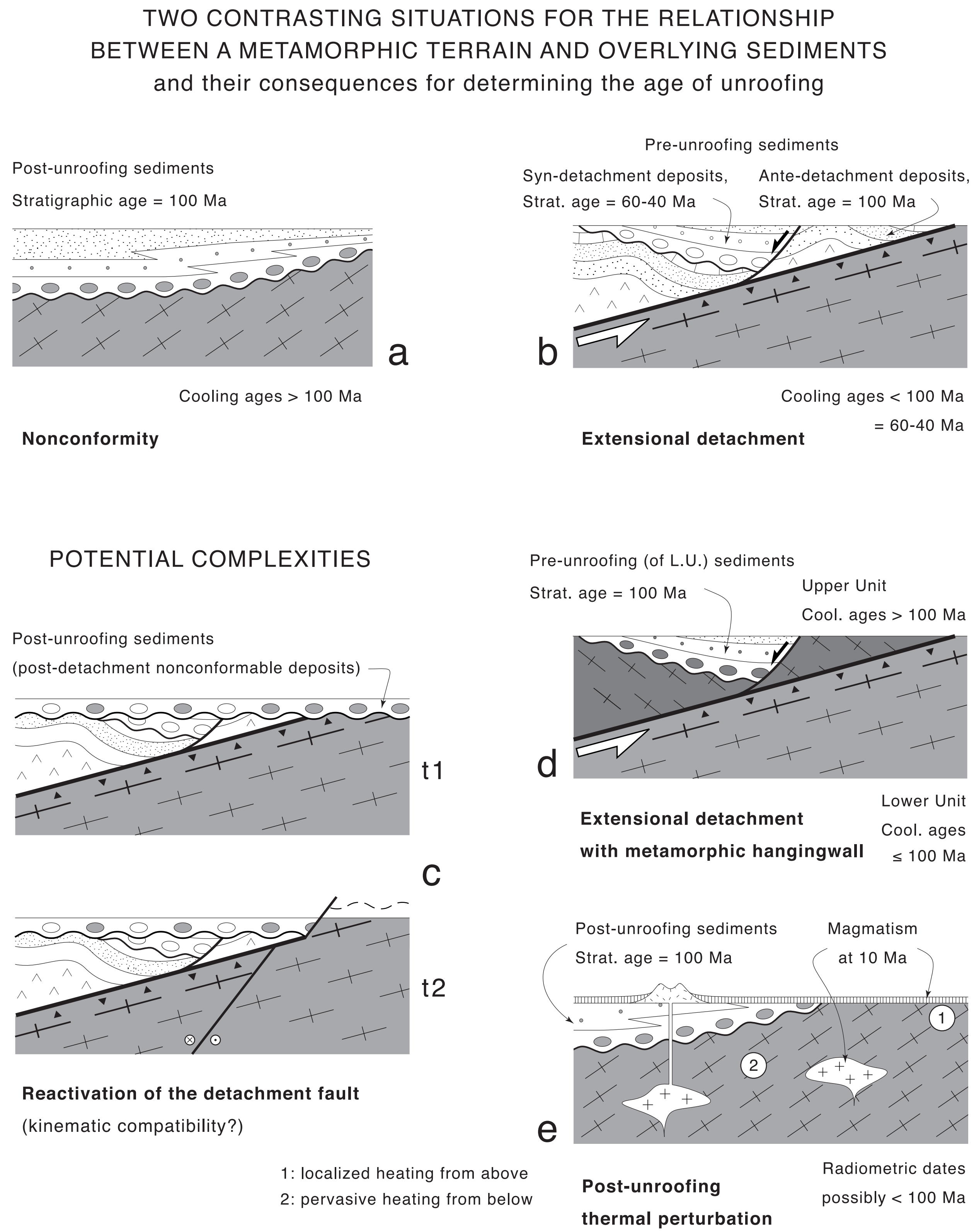

Figure 1. Schematic cross-sections illustrating a variety of situations for the relationship between a metamorphic terrain and overlying sediments, and their consequences for constraining the timing of exhumation of the metamorphic rocks. See text for details.

above the contact are normally devoid of pebbles derived from the underlying metamorphic sequence, highlighting the fact that sedimentation occurred *before* unroofing. However, some problems may arise when trying to decipher these two drastically different situations.

First, as a metamorphic core complex is ultimately unroofed from beneath a detachment, it starts to be eroded, and a new layer of sediments may be deposited nonconformably over it (Fig. 1c, step t1). The detachment might then be reactivated, either because of ongoing regional extension or due to a distinct tectonic event (Fig. 1c, step t2). As a result, the new layer of sediments may look like syn-detachment, pre-unroofing deposits, yet the presence of pebbles derived from the metamorphic rocks attests to its deposition *after* unroofing.

Second, in a case where the hangingwall unit of a detachment is made of metamorphic rocks, as well as the footwall unit, metamorphic pebbles in the sediments might be erroneously taken as evidence that the whole metamorphic pile has been unroofed before the sediments were deposited. Eventually, the metamorphic grade, and the dominant lithologies, can be quite similar in both the hangingwall and footwall units (Fig. 1d), obscuring the origin of the pebbles (and, to a lesser extent, the identification of the detachment itself). In such a case, the acquisition of radiometric data in both metamorphic units may ultimately be the only way to establish their contrasting exhumation histories.

Third, radiometric data can be misleading in cases where a significant thermal event occurs after unroofing (Fig. 1e). This holds true especially for low-temperature chronometers, such as fission track dating of apatites, which are easily reset. As a result, the obtained radiometric dates have no bearing on the timing of exhumation (that is, ages are underestimated). Eventually, the radiometric data may seem to conflict with the minimum age of unroofing indicated by older nonconformable sediments.

The general problem depicted above, which addresses the question of the time relationship between a sedimentary cover and an underlying metamorphic terrain, is commonly met in collision belts. In the present paper, we discuss it with the example of the Niğde Massif, a high-grade metamorphic dome located in southern Central Anatolia (Fig. 2). We show that careful examination of the field relations between the metamorphic rocks and overlying sediments provides a solid basis for constraining the timing of exhumation of the metamorphic dome, and illustrate how recently published radiometric data have been misinterpreted to infer a much younger unroofing.

2. Regional context

In central Anatolia, the Alpine belt comprises a large domain made up of metamorphic rocks, ophiolites and granitoids, known as the Kirşehir Massif (e.g. Görür *et al.* 1984) or Central Anatolian Crystalline Complex (Göncüoğlu *et al.* 1991; Floyd *et al.* 2000)

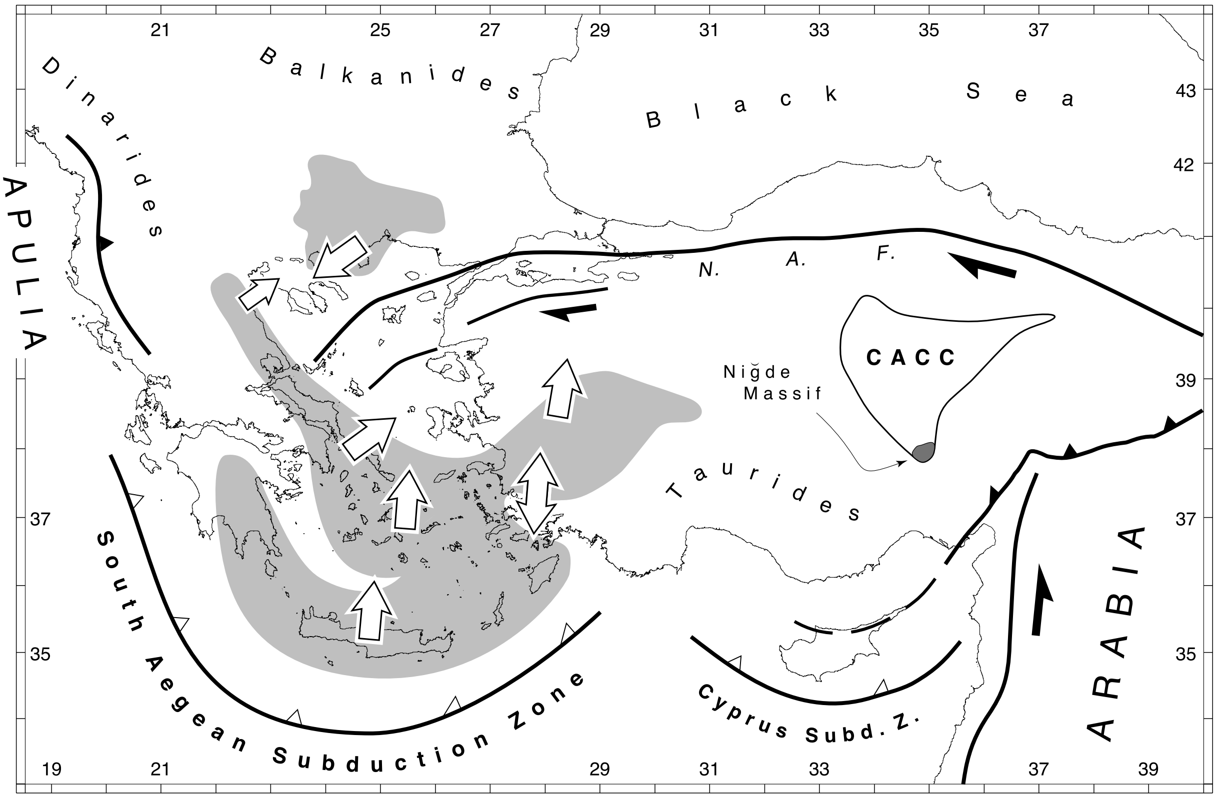

Figure 2. Simplified structural map of the Eastern Mediterranean area. Grey shading indicates the envelope of the main metamorphic complexes of Cenozoic age. 'CACC' is the Central Anatolian Crystalline Complex. Large white arrows summarize the sense of shear associated with ductile-then-brittle extensional detachments and décollements in the metamorphic complexes of the Aegean (Gautier *et al.* 1999). This core complex-type extension was active from at least 21 Ma until around 11 Ma. The North Anatolian Fault ('N.A.F.') has developed more recently.

(Fig. 2). Late Miocene to Quaternary volcanic rocks and sediments cover a large part of this complex, isolating the Niğde Massif, in the extreme south, from other exposures further north. According to most authors, the metamorphic rocks of the whole Central Anatolian Crystalline Complex were exhumed in the course of latest Cretaceous times, reaching the surface before the end of Maastrichtian times (Görür *et al.* 1984; Göncüoğlu *et al.* 1991; Floyd *et al.* 2000). In contrast, Whitney & Dilek (1997) recently argued that the Niğde Massif experienced a distinct evolution, as it represents an extensional core complex of Oligocene–Early Miocene age finally unroofed during the Middle or Late Miocene period. According to this hypothesis, southern Central Anatolia experienced core complex-type extension at the same time as the Aegean region, more than 600 km further west, although the two regions were involved in different geodynamic environments.

In the Aegean, the development of core complexes during Neogene times has been suggested to relate to 'back-arc' extension following Alpine thickening, due to southward retreat of the South Aegean Subduction Zone (Lister, Banga & Feenstra, 1984; Gautier *et al.* 1999) (Fig. 2). In contrast, Central Anatolia is commonly considered to have evolved in a pure orogenic setting since at least Late Eocene times (e.g. Görür *et al.* 1984; Dirik, Göncüoğlu & Kozlu, 1999). According to Whitney & Dilek (1997), the Niğde Massif evolved as an extensional core complex during orogenesis because of its location in the immediate hangingwall of the suture zone of an earlier oceanic domain, the Inner Tauride Ocean (Görür *et al.* 1984), the existence of which, however, is debated (Dirik, Göncüoğlu & Kozlu, 1999).

More recently, Whitney *et al.* (2001) and Fayon *et al.* (2001) have modified their interpretation on the basis of new apatite fission track data. According to this interpretation, northern parts of the Central Anatolian Crystalline Complex were exhumed earlier (apatite FT dates at 47–32 Ma), through erosion, in a context of frontal collision, whereas the Niğde Massif was exhumed later, through tectonic denudation, in a context of oblique collision. The Niğde Massif is described as a core complex developed within a zone of wrenching paralleling the Central Anatolian Fault Zone, a NE–SW-trending fault zone bounding the Central Anatolian Crystalline Complex on its eastern side (Koçyiğit & Beyhan, 1999). One of the main segments of the Central Anatolian Fault Zone is the Ecemiş Fault Zone, which runs NNE–SSW along the eastern margin of the Niğde Massif (Fig. 3). The Ecemiş Fault Zone has accommodated about 60 km of sinistral displacement (Jaffey & Robertson, 2001), which may support the view that exhumation in the Niğde Massif was wrench-controlled.

Alternatively, Oligocene–Miocene core complex development in the Niğde area could represent the northernmost expression of another domain of back-arc extension, at the rear of the present Cyprus Subduction Zone and/or in the hangingwall of a slightly earlier subduction zone running along the northern coast of Cyprus (see Robertson, 1998) (Fig. 2). Verifying the reality of Oligocene–Miocene core complex development in the Niğde area is therefore an important goal, for constraining the tectonic evolution of southern Central Anatolia during Cenozoic times, and more generally for determining the geodynamic conditions required for this type of extension to develop within an orogen.

3. Geological setting

3.a. The Niğde metamorphic dome

Metamorphic rocks forming the mountainous Niğde Massif are arranged in a broad irregular dome defined by gently sloping foliation surfaces. The dome is centred on the northwestern part of the area (Fig. 3). Although lithological contours display a complex pattern, a synthetic log can be established (Göncüoğlu *et al.* 1991). The lower part of the metamorphic series is mostly made of paragneiss and micaschists which experienced various degrees of partial melting. Higher in the series, pervasively recrystallized quartzites and marbles dominate. Peak P–T conditions are estimated at around 5–6 kbar and > 700 °C in the paragneiss (Whitney & Dilek, 1998). Granitoids are abundant and display various degrees of deformation. The main intrusion is represented by the Üçkapılı granite and its associated dyke swarm (Göncüoğlu, 1986). The granite is mostly exposed from the centre of the massif to the northeast, whereas smaller exposures are found to the south and to the west (Fig. 3), although it is not fully clear whether they all correspond to the same generation of intrusions. The state of deformation of the Üçkapılı granite is discussed in Section 5.c. In addition, ophiolitic rocks are present. Since the literature is ambiguous on this point (Göncüoğlu *et al.* 1991; Whitney & Dilek, 1998), it must be stressed that there are actually two types of such rocks (see also Floyd *et al.* 2000). In the southern part of the massif, 'ophiolites' are found as thin slices belonging to higher levels of the high-grade metamorphic unit. This is documented by the intense amphibolite facies deformation seen in the metabasites, showing a fabric paralleling the one in underlying and overlying marbles and quartzites. In contrast, a massive ophiolite is exposed to the north and to the extreme east, made up of gabbros with minor tonalitic intrusions and ultramafic rocks. The rocks show pure magmatic fabrics and mineralogical assemblages, except at the contact with the high-grade metamorphic rocks. There, greenschist facies deformation within narrow shear zones is observed across a thickness of about 10 m. The massive ophiolite is systematically found on top of the high-grade metamorphic sequence, therefore it constitutes a

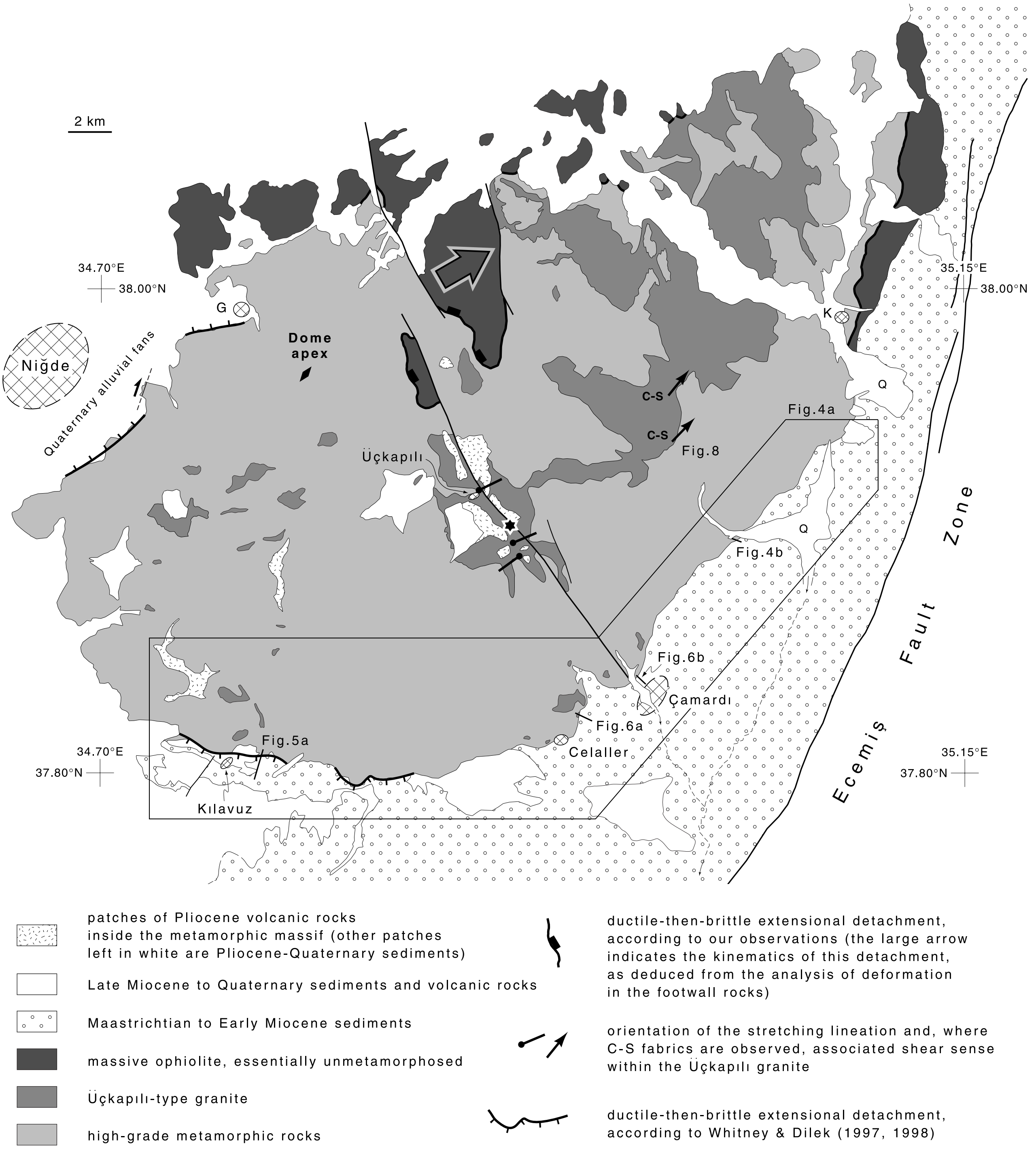

Figure 3. Geological map of the Niğde massif, simplified after Göncüoğlu *et al.* (1991), with slight modifications. The black star 2 km southeast of Üçkapılı indicates the location (D. Whitney, pers. comm.) of the sample used by Whitney & Dilek (1997) for U–Pb monazite dating of the Üçkapılı granite. Quaternary alluvial terraces along the trace of the Ecemiş Fault Zone are omitted for clarity. G: Gümüşler; K: Kavlaktepe. Q: Quaternary.

distinct upper unit having experienced significantly lower peak *P*–*T* conditions (Fig. 3).

3.b. Current interpretations of the relationship between the Niğde dome and its sedimentary cover

The Niğde dome is surrounded by sediments and volcanic rocks of variable age. To the north, Late Miocene–Pliocene ignimbrites and younger sediments nonconformably cover the metamorphic rocks, resulting in a loose definition of the northern boundary of the dome. Isolated outcrops of ignimbrite are also found within the massif (Fig. 3). To the south and southeast, most of the sediments are older, and their contact relationship with the underlying high-grade rocks forms the basis for contrasting interpretations in

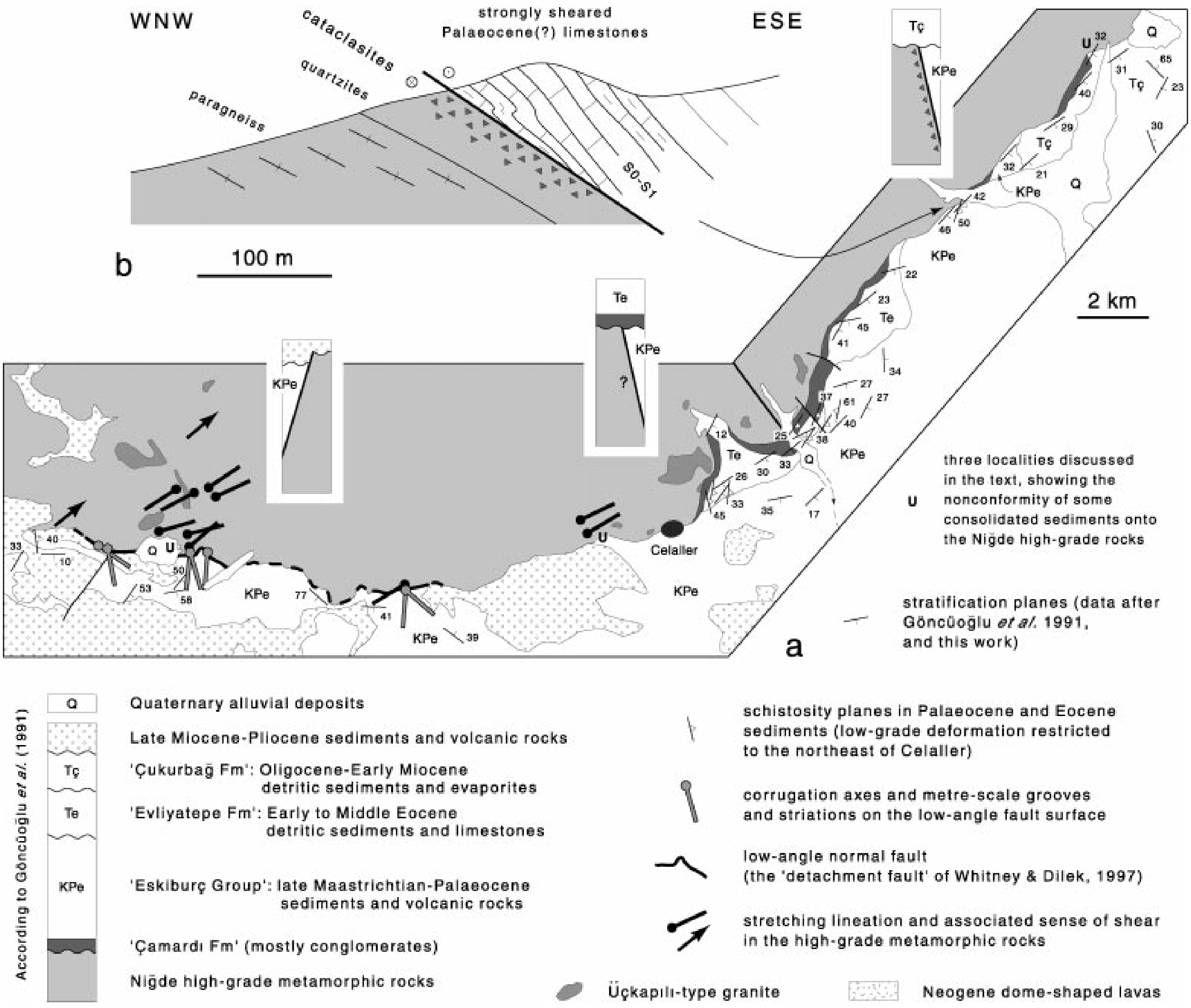

Figure 4. (a) Structural map of the southern and southeastern flanks of the Niğde dome. Geological contours slightly modified after Göncüoğlu *et al.* (1991). The column at bottom left shows a synthetic log of the sedimentary cover according to Göncüoğlu *et al.* (1991, their figure 14). The other columns show the field relations in three different subareas, according to our observations. (b) Cross-section in the area of Bademdere (location on Fig. 3), modified after Göncüoğlu *et al.* (1991, their figure 15). Our observations indicate that the 'Çamardı conglomerate' there corresponds to thick cataclasites developed at the expense of high-grade quartzites.

the literature. According to most authors, the overall sedimentary sequence lies nonconformably on the metamorphic complex. According to the early work of Blumenthal (1941), this sequence starts with deposits of early Middle Eocene age. The more detailed map of Blumenthal (1952) shows a narrow ridge of Palaeocene limestones to the east of Çamardı, but the sediments which directly cover the metamorphic rocks further west are still attributed to the Middle Eocene. According to more recent authors, the nonconformable sequence starts in the Late Palaeocene (Yetiş, 1978; Yetiş *et al.* 1995), or even in the late Maastrichtian (Göncüoğlu *et al.* 1991). A synthetic log of the sequence (Göncüoğlu *et al.* 1991, fig. 14) indicates that the 'Eskiburç group', made up of detritic and volcanic rocks with minor limestones, begins with a basal conglomerate nonconformably overlying the metamorphic complex ('Çamardı formation'), whereas clastic rocks and limestones of the 'Evliyatepe formation' overlie the Eskiburç group with an angular unconformity (Fig. 4a, bottom left column). Fossils typical of late Maastrichtian and of Early and Late Palaeocene times are reported from flysch layers of the Eskiburç group in the area between west of Kılavuz and Celaller (Göncüoğlu, 1986; Göncüoğlu *et al.* 1991, pp. 60–1). The age of the Evliyatepe formation, which is broadly Early to Middle Eocene, is discussed in detail in Section 4.b.2. Although the formations are given different names, Yetiş (1978) and Yetiş *et al.* (1995) come to a quite similar conclusion about the sequence. As a result, the high-grade rocks of the Niğde dome are believed to have reached the surface before the end of Maastrichtian times (Göncüoğlu *et al.* 1991).

In contrast, Whitney & Dilek (1997) have recently reinterpreted the contact between the metamorphic rocks and the overlying Maastrichtian–Palaeogene sequence as a shallow-dipping extensional detachment fault, along which the footwall rocks have been progressively exhumed, first in ductile, then in brittle conditions (see also Fayon *et al.* 2001). The Niğde dome as a whole is considered as an extensional metamorphic core complex. According to Whitney & Dilek (1997, 1998), the detachment fault can be traced along the southern and western margins of the dome (Fig. 3). The kinematics of the extensional ductile deformation are inferred to be top-to-the-NE in the northern part of the dome, and top-to-the-SW in the south. Two lines of evidence are given in favour of an Oligocene–Early Miocene age for the extensional denudation of the metamorphic complex (Whitney & Dilek, 1997). Firstly, within the sedimentary sequence covering the dome to the southeast, pebbles from the high-grade rocks are supposedly found for the first time in Middle to Upper Miocene strata. Secondly, Whitney & Dilek (1997, 1998) report a monazite U–Pb date in the range of 13.7 to 20 Ma for the Üçkapılı granite, which they consider as the age of crystallization of the intrusion (see also Fayon *et al.* 2001, fig. 6b). The pluton is assumed to have been emplaced during the extensional denudation of the metamorphic complex. As a result, the detachment is thought to have been active during Early Miocene, and possibly during Oligocene times. However, the analytical results of the monazite U–Pb dating have not been published so far, and the inferred Early Miocene crystallization age conflicts with several dates previously published by Göncüoğlu (1986). A four-point whole rock Rb–Sr isochron gives '95 ± 11' Ma (the error is probably underestimated), whereas K–Ar dates on muscovite and biotite give 78.5 and 76–75 Ma, respectively, for samples of the Üçkapılı granite taken from small exposures in the western part of the dome. Rb–Sr dating of mica-whole rock pairs gives 78.7 Ma for muscovite and 78.2–77.5 Ma for biotite (recalculated from the analytical data in Göncüoğlu, 1986). Biotite Rb–Sr and K–Ar dates obtained from the paragneiss near the core of the dome give similar results. As a whole, these mica dates suggest cooling of both the granite and the metamorphic rocks from about 500 °C to 300 °C at *c.* 79–75 Ma.

Eleven apatite fission track dates recently obtained by Fayon *et al.* (2001) from samples of paragneiss and granite taken along a NW–SE transect across the Niğde dome are in the range of 9.4 ± 2.2 to 16.6 ± 3.8 Ma, with a pronounced cluster around 12–11 Ma. Fayon *et al.* (2001) and Whitney *et al.* (2001) take these dates as an indication that the metamorphic rocks were still on their way to the surface at around 10 Ma, thus seemingly supporting the hypothesis of Oligocene–Miocene extensional denudation of the metamorphic complex.

4. New observations and interpretation

4.a. No detachment fault where previously inferred

The extensional detachment fault of Whitney & Dilek (1997, 1998) lies along the western and southern margins of the Niğde dome (Fig. 3). To the west, the sediments in the hangingwall of the inferred detachment are Quaternary unconsolidated alluvial fan deposits (e.g. Göncüoğlu *et al.* 1991), implying that the fault should have been active very recently. Seen from a distance, the topographic slope lowers rather abruptly near the transition from the metamorphic rocks to the sediments, which might suggest the presence of an active fault there. However, our observations along this boundary indicate that the marbles of the Niğde dome plunge westwards below the sediments via a ubiquitous nonconformity. The marbles remain coarse-grained and display no evidence of tectonic brecciation, at variance with the report in Whitney & Dilek (1997). A limited area shows a series of steep faults within the marbles, the larger of which trends N015°. These faults bear subhorizontal striations (pitch less than 15°), and sense-of-slip criteria indicate that the main fault is dextral (Fig. 3). Thus, there is no evidence for a extensional detachment fault along the western margin of the Niğde dome.

To the south, our observations confirm the existence of a low-dipping fault between the sedimentary cover and the underlying high-grade rocks (Figs 4a, 5a, b). The fault surface, which dips in the range of 20 to 50°, displays 10 to 100 m-scale corrugations and metre-scale grooves and striations associated with centimetre-thick microbreccias (Fig. 5b). Locally, brecciation extends for a few metres into the footwall. This large fault therefore resembles a typical extensional detachment fault at the top of a metamorphic core complex. However, two lines of evidence argue against such an interpretation. Firstly, the trend of corrugation axes, grooves and striations measured at several places along the fault surface lies between N–S and NW–SE, whereas the trend of the stretching lineation in the highly strained marbles and quartzites of the footwall is NE–SW to ENE–WSW (Fig. 4a). Although clear evidence is lacking, the sense of slip of the fault is most probably normal (the pitch of grooves and striations is always greater than 56°), that is, top-to-the-S or SE. Limited shear sense criteria within the metamorphic sequence indicate top-to-the-NE shearing during the high-grade ductile deformation (Fig. 4a). These differences in trend and kinematics conflict with the picture of a continuum of deformation during the development of a single ductile-then-brittle extensional detachment (cf. Whitney & Dilek, 1997, and Fayon *et al.* 2001). Secondly, on the cross-section east of Kılavuz (Fig. 5a), sediments immediately above the fault include pebbles made up of coarse-grained marble similar to the marbles in the immediate footwall of the fault (Fig. 5c). This indicates that these deposits

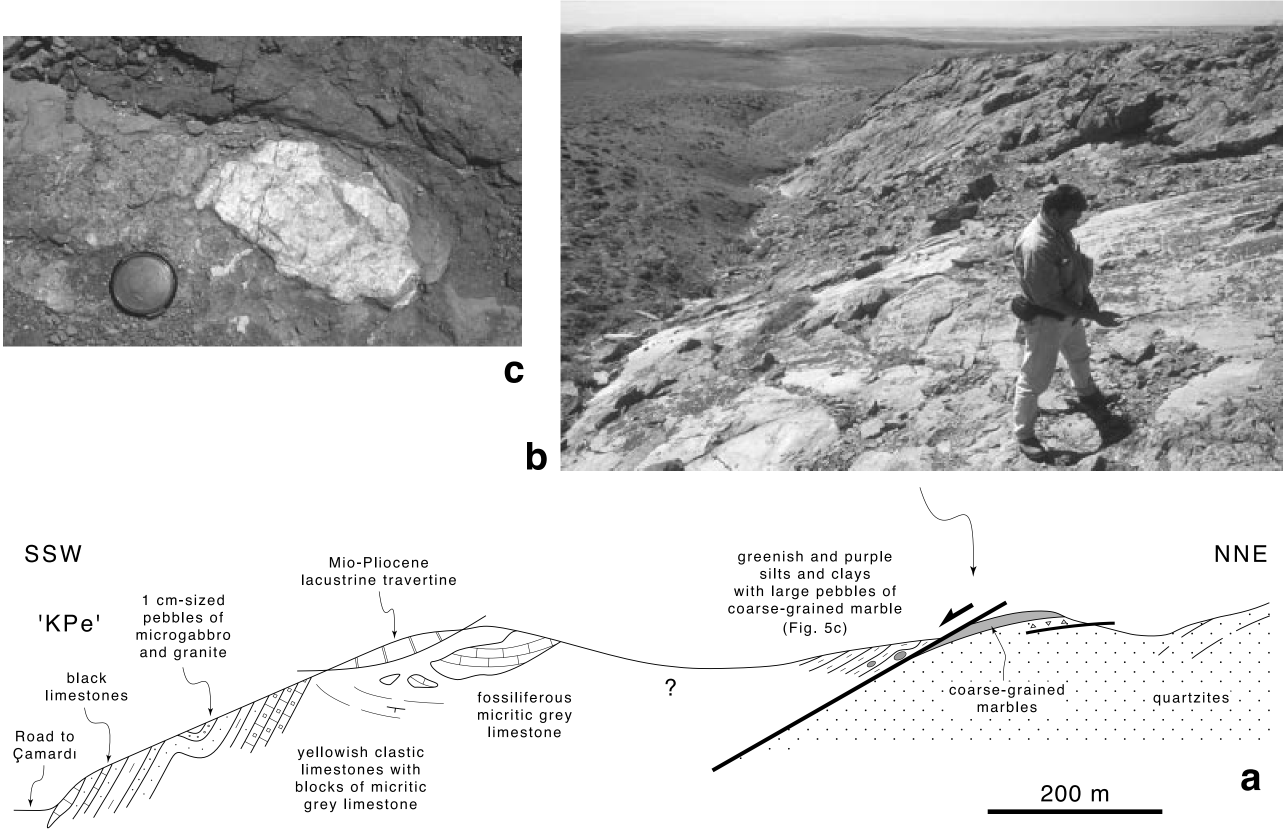

Figure 5. (a) Cross-section in the area of Kılavuz (location on Fig. 3). The sediments at the southern end of the section probably belong to the 'turbiditic flysh sequence' in which late Maastrichtian fossils have been found (Göncüoğlu, 1986; Göncüoğlu *et al.* 1991). (b) Field view of the low-angle normal fault shown on the cross-section. The fault surface is corrugated on the 50 m scale and shows metre-scale nearly dip-slip grooves and striations associated with a thin coat of microbreccia. (c) Field view of a pebble of marble inside the fine-grained sediments in the immediate hangingwall of the low-angle fault. The irregular contour of the pebble is due to fractures developed in the sediments during scraping against the fault surface. Lens cap is 5 cm in diameter.

originate from nearby erosion of the metamorphic unit now occuring below the fault. The sediments have suffered faulting together with minor folding and are scraped against the main fault, which indicates that they are not late deposits overlapping onto the fault surface. Therefore, the metamorphic rocks were already at the surface when the fault developed, which indicates that this fault did not accommodate any significant exhumation. This challenges the interpretation of the fault as an extensional detachment, as proposed by Whitney & Dilek (1997). The fault running along the southern margin of the Niğde dome is better seen as a late normal fault cross-cutting, or slipping along, an older nonconformity (as illustrated in Fig. 1c). In the same area, unconsolidated Mio-Pliocene detritic and lacustrine deposits overlie older sediments with a pronounced angular unconformity. Immediately west of Kılavuz, the Mio-Pliocene sediments are gently folded on a 100 metre scale and rest against the normal fault (Fig. 4a), suggesting that the fault developed during Neogene times.

As a whole, there is therefore no evidence for an extensional detachment fault in the two key areas invoked by Whitney & Dilek (1997).

4.b. Nonconformity of the Eocene sediments on the Niğde metamorphic rocks

4.b.1. Observations along two cross-sections

Two cross-sections (Fig. 6) allow discussion of the relation between the metamorphic rocks of the Niğde dome and the sediments older than the Miocene. The section across the hill immediately north of the village of Kavaklıgöl (Fig. 6a) documents the following points, from WNW to ESE. The high-grade rock sequence of the Niğde dome here includes paragneiss and quartzites. The foliation of the highly strained rocks is cross-cut by dykes of fine-grained light-coloured granite showing a weak foliation (Fig. 7a, b). Both the metamorphic rocks and the granitic dykes are in turn truncated by a rugged erosional surface. The first sediment above this surface is an unsorted coarse conglomerate consisting of subangular pebbles of granite, quartzite and paragneiss (Fig. 7b). The conglomerate reaches several metres in thickness and grades upward into sandstones (Fig. 7a). This layer is succeeded by alternating sandstones, siltstones, and conglomerates which also contain rounded pebbles of marble (Fig. 6a). Higher in the section, the fine-

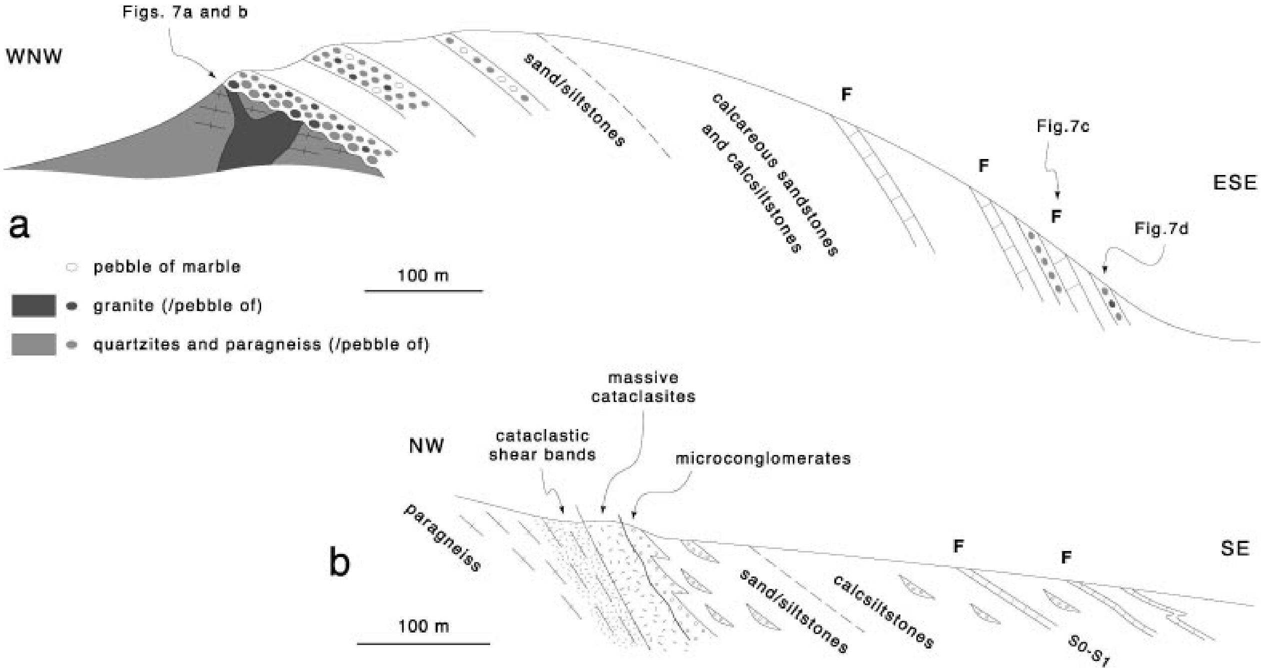

Figure 6. Cross-sections immediately north of Kavaklıgöl village (a) and northwest of Çamardı (b) (locations in Fig. 3). F: fossiliferous limestones with benthic foraminifera ('Evliyatepe formation' of earliest Eocene to early Middle Eocene age).

grained sediments become dominant, then they grade into calcareous sandstones and calc-siltstones. Finally, on the eastern flank of the hill, yellowish limestone layers containing abundant large benthic foraminifera (Fig. 7c) are intercalated in the series at three different horizons. The highest layer is intercalated between layers of conglomerates that contain pebbles of metamorphic rocks and granite (Fig. 7d). The rocks along this section are variably deformed. At the base, the quartzites have locally suffered cataclasis. Higher up, the development of a low-grade shistosity is pervasive in the fine-grained layers, and more crude in the conglomerates (Fig. 7d). A few metre-scale recumbent folds with axial plane schistosity have been observed in the fine-grained layers from the lower part of the section. Nevertheless, this does not contradict the general picture of a way-up younging of the sedimentary pile (Fig. 6a), which is confirmed by the presence of an erosional surface at the base of the conglomeratic layers. The limestones are also deformed, showing sharp changes in the type of shistosity developed, from pressure-solution along discrete planes (Fig. 7c) to penetrative recrystallization during flattening. Despite this deformation, the layers of limestone are continuous for several tens of metres, whereas their maximum thickness is about 2 m. This excludes an interpretation that the limestones are clasts incorporated into the series during the dominantly detritic sedimentation. This view is supported by the first appearance of impure calcareous sediments slightly below in the section, and by the absence of limestone pebbles in the conglomerates (they only contain pebbles of metamorphic rocks and granite). The characteristics and habitus of the numerous fossils inside the limestones (no broken test, foraminifera of variable size, from 1 mm to > 1 cm, coexistence of forms corresponding to successive growing stages of individuals, homogeneous micritic matrix) also preclude their interpretation as a reworked fauna. Some levels within the limestones have a coarser-grained matrix and contain rounded grains of quartz, which makes sense in the context of terrigenous sedimentation recorded by the remainder of the sequence.

The second section (Fig. 6b), immediately west of Çamardı, at the entrance of the steep valley toward Üçkapılı, displays similar features, except for the contact between the sedimentary pile and the high-grade metamorphic rocks, which appears to be more complex. A layer of massive cataclasites developed at the expense of the underlying paragneiss constitutes a prominent ridge in the slope. Microconglomerates of variable thickness rest against this ridge and wedge laterally into sandstones and siltstones. The fine-grained sediments and, to a lesser extent, the microconglomerates are pervasively schistosed. Most pebbles in the microconglomerates are made of quartz. On the opposite flank of the valley, along strike, granite is also present as angular pebbles within coarser-grained conglomerates, and as rounded isolated blocks, as large as 50 cm in diameter, within the schistosed fine-grained sediments. Higher in the section (Fig. 6b), the siltstones grade into calc-siltstones, then thin layers of fossiliferous limestone are intercalated in the series. The limestones are grey, marly and strongly schistosed or, locally, dark grey, more pure and better preserved, containing abundant benthic foraminifera. Despite the deformation, conglomeratic

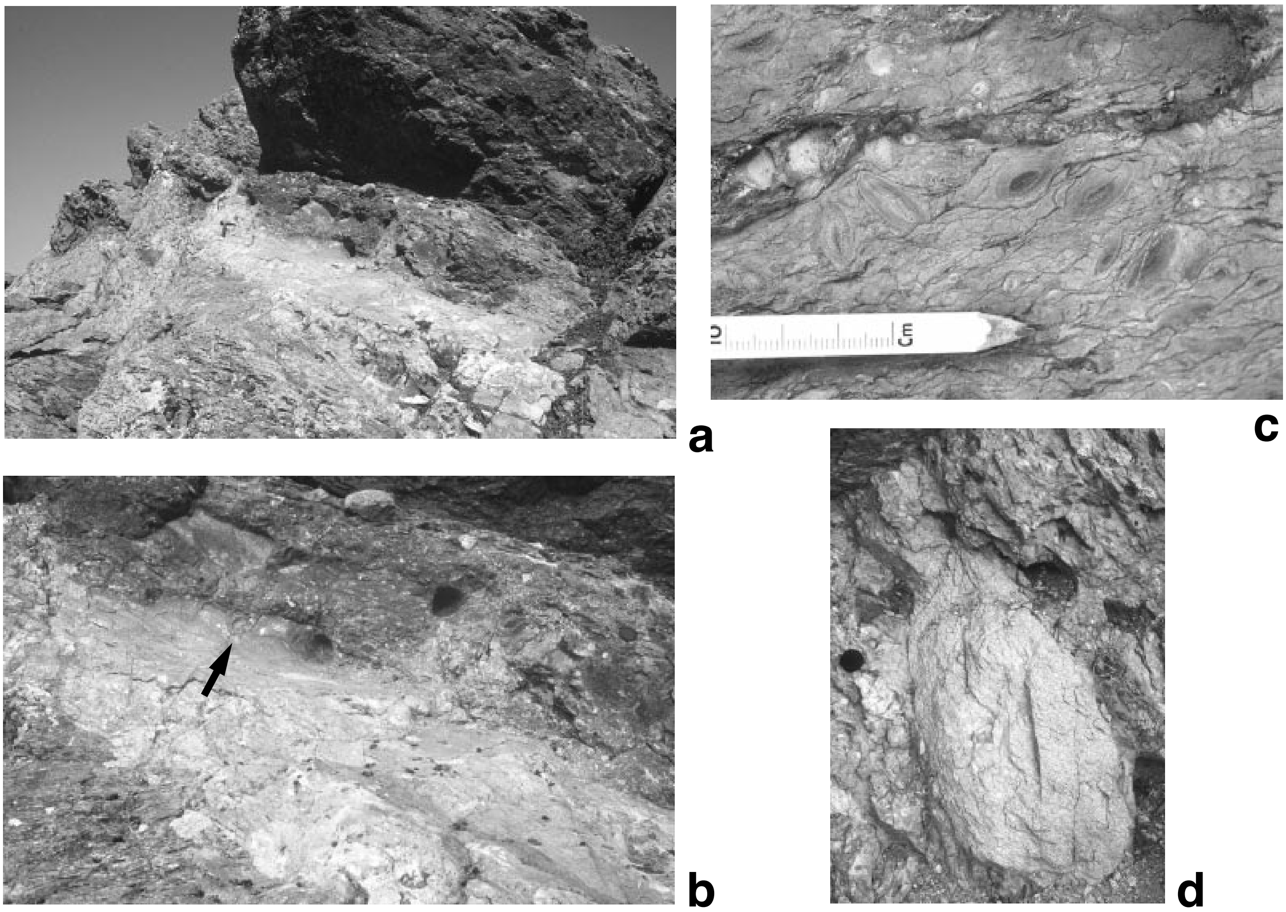

Figure 7. Field views along the cross-section of Figure 6a. (a) General view of the nonconformity at the base of the sedimentary sequence. From bottom left to top right, one observes pervasively foliated dark paragneiss and quartzites (the foliation dips at a moderate angle to the right), a dyke of light-coloured granite cross-cutting the foliation of the quartzites (with the hammer on it), then a *c.* 4 m thick layer of dark conglomerate dipping at about 30° to the right. (b) Detailed view of the central part of the previous view. From bottom left to top right, one observes the foliated dark quartzites (on the plane of this view, the foliation is subhorizontal), the light-coloured granitic dyke, then the bottom part of the dark conglomerate containing pebbles and a subangular block (top left) of the granite. The contact between the granite and the conglomerate is a rugged erosional surface. The arrow shows one of the sharp irregularities of this surface (U-shaped). Lens cap at the right end is 5 cm in diameter. (c) Close view of one of the layers of limestone in the upper part of the sedimentary sequence. The limestone has a micritic matrix and contains benthic foraminifera of variable size. A spaced pressure-solution cleavage is developed, along which some of the fossils are partially dissolved. (d) View of a large pebble of fine-grained granite within a layer of conglomerate immediately above the limestone of the previous view. A crude schistosity is developed in the conglomerate, corresponding to the surfaces which dip steeply to the right. Lens cap is 5 cm in diameter.

bodies within the fine-grained sediments still display the hull-shape and the upward fining of clasts that are typical of channel infills, documenting a way-up younging for the sedimentary pile.

4.b.2. Interpretation

The first section (Fig. 6a) documents the presence of a nonconformity between the sedimentary pile and the high-grade rocks of the Niğde dome (Fig. 7a, b). Pebbles within the basal conglomerates are derived from these metamorphic rocks and from the Üçkapılı-type granite observed below the nonconformity. The pebbles in the conglomerates between and above the fossiliferous limestones are derived from the same lithologies (e.g. Fig. 7d). Most probably, the contact between the high-grade rocks and the sediments in the second section (Fig. 6b) also coincides with a nonconformity, although the original sedimentary contact has been disturbed by later shearing deformation. This agrees with the presence of large pebbles of Üçkapılı-type granite in the schistosed sediments. Despite the deformation, both sections show a gradual upward transition from purely terrigenous to mixed terrigenous–carbonate sedimentation, indicating a continuum of sedimentation, that is, there is no major tectonic break within the studied sedimentary piles. Altogether, these features demonstrate that at the time of the deposition of the fossiliferous limestones, the high-grade rocks of the Niğde dome were already at the surface, providing clasts for the terrigenous part of the sedimentary sequence.

According to the map of Göncüoğlu *et al.* (1991), the conglomeratic lower part in both sections of Figure 6 belongs to the Çamardı formation, whereas the limestone-bearing upper part belongs to the Evliyatepe formation (Fig. 4a). Among the large benthic foraminifera reported by Göncüoğlu *et al.* (1991) in the Evliyatepe formation from the large exposure north–northeast of Çamardı (Fig. 4a), some are characteristic of the earliest Eocene (Ilerdian), such as *Nummulites globulus, N. pernotus* and *Alveolina globosa* (SBZ 7 to 9 in Serra-Kiel *et al.* 1998), whereas *Alveolina oblonga* is characteristic of the late Early Eocene (Cuisian, SBZ 10–11 in Serra-Kiel *et al.* 1998). The same exposure has been studied by Yetiş (1984) who describes a log which closely resembles the one given above for the two sections of Figure 6. Yetiş (1984) mentions that the conglomeratic layers in the lower part of the sequence contain pebbles derived from the Niğde high-grade rocks. He also reports *Nummulites* aff. *uranensis* in the sandy limestones and pure limestones from the upper part of the sequence, while Blumenthal (1941, 1952) mentions *Nummulites laevigatus* from the wedge-shaped exposure of Evliyatepe formation in which the two sections of Figure 6 are located. These two species are characteristic of the earliest Middle Eocene (early Lutetian, SBZ 13 in Serra-Kiel *et al.* 1998). As a whole, the palaeontological evidence constrains a period from the earliest Eocene to the early Middle Eocene for the sedimentation of the Evliyatepe formation, that is, from *c.* 54 Ma to *c.* 46 Ma (see Serra-Kiel *et al.* 1998). This, in turn, indicates that the high-grade rocks of the Niğde dome must have reached the surface before the Eocene, or at the very beginning of Eocene times at the latest.

5. Discussion

5.a. No Oligocene–Miocene extensional detachment around the Niğde dome

The results presented above are inconsistent with the existence of an extensional detachment having accommodated the exhumation of the Niğde metamorphic dome during Oligocene–Early Miocene times (Whitney & Dilek, 1997, 1998). Pebbles from the Niğde high-grade rocks are ubiquitous in the conglomerates of the Evliyatepe formation of proven Eocene age, which contradicts the assertion that such pebbles are found for the first time in Middle to Upper Miocene strata (Whitney & Dilek, 1997). Where drawn, the extensional detachment fault of Whitney & Dilek (1997, 1998) does not exist (western margin of the dome) or corresponds to a normal fault which acted once the metamorphic rocks were already unroofed (southern margin).

5.b. A newly defined pre-Eocene extensional detachment

To clarify our position, we note that an extensional detachment does exist at the top of the Niğde dome, but not where Whitney & Dilek (1997, 1998) have shown. The structures associated with this ductile-then-brittle detachment zone are best documented in the northern part of the dome, where the fault separates the Niğde high-grade rocks from the overlying massive ophiolitic unit of much lower grade (see Section 3.a) (Fig. 3). Traces of the detachment are also found over a restricted area located west of Celaller, on the southern flank of the dome (central 'U' in Fig. 4a). There, cataclasites and ultracataclastic faults corresponding to higher levels of the detachment zone are truncated nonconformably by a series of conglomerates and microconglomerates of Eocene age (or possibly late Maastrichtian–Palaeocene age; see Section 5.e.2). The rugged erosional surface defining the nonconformity and the overlying sediments are tilted but not strained. On the section of Figure 6b, further east, low-grade shearing deformation that post-dates the deposition of the Eocene sediments may account for only a part of the huge cataclasis seen in the underlying ridge of massive cataclasites and ultracataclasites. Therefore, this ridge could also represent higher levels of the detachment zone. The outcrop west of Celaller and, more generally, the fact that the Niğde metamorphic rocks reached the surface before the Eocene, indicate that this newly defined extensional detachment developed before Eocene times.

5.c. State of deformation and age of the Üçkapılı granite

The recognition that the Niğde metamorphic rocks reached the surface before the Eocene conflicts with the 13.7–20 Ma monazite U–Pb date, interpreted as the age of crystallization of the intrusion, reported by Whitney & Dilek (1997, 1998) for the Üçkapılı granite. The conflict is striking when considering that small bodies of 'Üçkapılı-type' granite are also found along the southern margin of the metamorphic dome (Figs 3, 4a), just below the nonconformable Eocene sediments (Figs 6a, 7a) and as pebbles within the conglomerates of the Eocene series (Fig. 7b, d). A solution to this contradiction could be that these bodies belong to a first generation of intrusions of pre-Eocene age, whereas a later generation has given rise to the main body of granite, closer to the centre of the dome, where the U–Pb date has been obtained (see location of the sample in Fig. 3). According to this hypothesis, the granite around Üçkapılı would have intruded the central and northeastern parts of the metamorphic dome during the Early Miocene, long after the southern and southeastern parts reached the surface. This would imply that the granite emplaced at very shallow depths (less than about 3 km) and subsequent to pre-Eocene extensional shearing. The Üçkapılı granite generally shows only a weak to very weak ductile fabric and is associated with dykes of variable orientation which cross-cut the foliation of the metamorphic

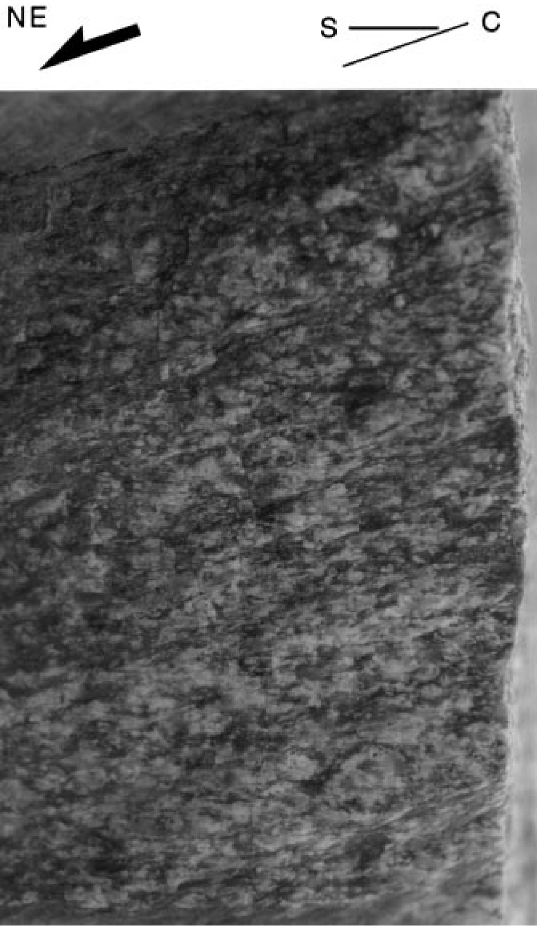

Figure 8. Close view (height around 5 cm) of C–S fabrics within the Üçkapılı granite (main central body, see Fig. 3). The foliation is horizontal, while discrete C planes dip at about 20° to the left, indicating a top-to-the-left sense of shear in the plane of this view (top-to-the-NE in the field).

rocks at a high angle (see, for example, the cross-sections in Blumenthal, 1941, and Whitney & Dilek, 1997). These features could suggest that the Üçkapılı granite is a post-tectonic intrusion, lending support to the above hypothesis.

However, more detailed field observations reveal that the Üçkapılı pluton is actually a late-kinematic intrusion. In the area around Üçkapılı, the granite shows a weak linear/planar to linear ductile fabric with a stretching lineation trending NE–SW (Fig. 3). Further northeast, still within the main central body of granite, the ductile deformation becomes more intense near the contact with the overlying host marbles, resulting in the development of typical C–S fabrics (Fig. 8). These fabrics document a top-to-the-NE sense of shear. The NE–SW-trending stretching lineation and the top-to-the-NE shear fabric are also characteristic of the ductile deformation within the high-grade host rocks, although associated with much higher strain intensities. The maximum intensity of ductile top-to-the-NE shear strain is recorded within the extensional detachment zone, just below the contact with the overlying massive ophiolitic unit. This contact is locally underlined by thick cataclasites. In the area where the C–S structures are observed, the ductile fabric of the Üçkapılı granite is reworked by flat-lying several centimetres-thick ultracataclastic faults. Altogether, these features indicate that the Üçkapılı granite was emplaced during extensional shearing and unroofing of the Niğde metamorphic dome (Fig. 9). As a result, the whole of the Üçkapılı granite must be older than the Eocene.

This pre-Eocene age for the emplacement of the Üçkapılı granite is in agreement with radiometric data suggesting cooling of both the granite and the host metamorphic rocks from about 500 °C to 300 °C at *c.* 79–75 Ma (Göncüoğlu, 1986; see Section 3.b). In contrast, it disproves an Early Miocene age of crystallization for the pluton (Whitney & Dilek, 1997, 1998). Therefore, the meaning of the 13.7–20 Ma monazite U–Pb date needs to be reassessed. Where it has been sampled (on the roadside 2 km southeast of Üçkapılı: D. Whitney, pers. comm.), the granite lies along a steep fault zone that cross-cuts the Niğde Massif (Fig. 3). The granite is cut by a dense array of subvertical chlorite-bearing cataclastic faults paralleling the main fault trace. In addition, exposures of granite lie at a maximum of 20 m below a flat-lying cover of late Neogene ignimbrites (Fig. 3; see next Section). We therefore suspect that fluid infiltration during cataclasis and/or heating during the emplacement of the ignimbrites resulted in recrystallization of the monazites, or disturbed the U–Pb system to the point that the obtained date significantly underestimates the age of crystallization of the granite.

5.d. Significance of the apatite fission track dates

According to Fayon *et al.* (2001) and Whitney *et al.* (2001), apatite fission track dates clustering around 12–11 Ma throughout the Niğde dome indicate that the metamorphic rocks were still on their way to the surface at this time, lending support to the Oligocene–Miocene core complex hypothesis. Here again, the recognition that the Niğde metamorphic rocks were already unroofed in Eocene times conflicts with this view. Therefore, an alternative interpretation needs to be found for the fission track data. As for the U–Pb system of monazites at Üçkapılı, the distribution of fission tracks in apatites is likely to have been disturbed during the thermal event associated with Neogene magmatism. The Niğde dome lies immediately south of Cappadocia, an area which experienced intense volcanism during the last 11 Ma (e.g. Pasquarè *et al.* 1988; Le Pennec *et al.* 1994). In contrast, northern parts of the Central Anatolian Crystalline Complex, in which Fayon *et al.* (2001) obtained older fission track dates (47–32 Ma), lie away from this area of intense volcanism.

Ignimbrite layers with ages between 8 and 5 Ma (Le Pennec *et al.* 1994) surround a large part of the Niğde dome, from Kılavuz to Kavlaktepe (Göncüoğlu *et al.* 1991). At least one of them, presumably the 5 Ma old Incesu–Kızılkaya ignimbrite, is also found as patches within the massif (Fig. 3). All the samples of Fayon *et al.* (2001) except one come from either close to Gümüşler, where ignimbrites are exposed, or close to the volcanic patches around Üçkapılı, or in between. One sample comes from further east (close to the section of Fig. 4b), apparently away from any Neogene volcanic rock. In this area, however, Late Miocene–Early Pliocene sediments are missing, and Late Pliocene(?)–Quaternary alluvial deposits rest directly onto tilted strata of the 'Çukurbağ Formation' (Fig. 4a; see also Koçyiğit & Beyhan, 1999), the age of which is Oligocene (Yetiş *et al.* 1995) or Oligocene–Early Miocene (Jaffey & Robertson, 2001). Thus, the Neogene ignimbrite(s) may well have extended over the southeastern flank of the Niğde dome, being subsequently eroded before the deposition of the Quaternary sediments. As a result, the whole set of samples of Fayon *et al.* (2001) likely lies close beneath one or several layers of ignimbrite, the temperature of which was certainly ≥ 400 °C at the time of spreading. The 'partial annealing zone' of fission tracks in apatites coincides with a much lower temperature range (60–120 °C), therefore fission track data at around 12–11 Ma may well reflect partial resetting of the apatites during the spreading of ignimbrites between 8 and 5 Ma (as illustrated in Fig. 1e).

Alternatively, the apatite fission track data of Fayon *et al.* (2001) may reflect more pervasive heating from below (as also illustrated in Fig. 1e), sometime between 12–11 Ma and *c.* 8.5 Ma, that is, during the earliest known stage of Neogene magmatism in the region. The aerial distribution of this early magmatism is not well defined but seems to have involved a large domain north and northwest of the Niğde Massif (Pasquarè *et al.* 1988; Toprak, 1998). It is not known whether the Niğde Massif itself was part of this domain, however, the presence of dome-shaped thick lavas intruding the sediments of the 'Eskiburç group' on the southern margin of the metamorphic dome (Fig. 4a) may suggest this. In order to experience ambient temperatures around 80 °C (well into the partial annealing zone) at this time, the metamorphic rocks would have to have lain at some depth. The nonconformable sequence of Eocene to Early Miocene sediments overlying the Niğde high-grade complex may account for this burial. According to Jaffey & Robertson (2001), within this sequence, the Oligocene–Early Miocene Cükürbag formation reaches 1400 m in thickness immediately east of the Niğde Massif. The direction of palaeocurrents in this formation trends parallel to the margin of the dome (Jaffey & Robertson, 2001, fig. 4b), which suggests that the Niğde Massif was not an elevated area at this time. Therefore, the nonconformable sequence probably covered the whole massif, with a thickness in excess of 1400 m. Taking 15 °C for the mean temperature at the surface, a geothermal gradient of 46 °C/km would be required for the underlying metamorphic rocks to reach 80 °C. Adopting 20 °C for the temperature at the surface (Fayon *et al.* 2001 apparently take an even higher temperature; cf. their fig. 5) and a depth of 1600 m for the metamorphic rocks (given that most samples lie well beneath the Eocene nonconformity), the geotherm should be 37.5 °C/km. The rather high geothermal gradients suggested by this calculation may well result from regional magmatism, as discussed above.

The two proposed mechanisms for the resetting of the apatite fission track dates (localized heating from above, between 8 and 5 Ma, or pervasive heating from below, between 12–11 and *c.* 8.5 Ma) are not mutually exclusive. They may have combined if an important phase of erosion took place between the two events, that is, during the early Late Miocene, removing about 1600 m of rocks at a minimum rate of 0.5 mm/year. This phase of erosion may coincide with the initiation of uplift of the Niğde Massif as a new mountainous area. Whatever the details of the story, the important point to stress here is that the initial unroofing of the Niğde metamorphic dome is pre-Eocene, as shown by the geological evidence. The apatite fission track data thus reflect a later event, and cannot be used to evaluate the time at which the metamorphic rocks first reached the surface, in contrast to the contention of Fayon *et al.* (2001) and Whitney *et al.* (2001). This illustrates the necessity of being cautious when interpreting low-temperature chronometers in metamorphic terrains, especially in areas known to have suffered a widespread thermal perturbation at a late stage (Fig. 1e).

5.e. When did the Niğde metamorphic rocks first reach the surface?

Our analysis has shown that the Niğde metamorphic rocks reached the surface before Eocene times, because a sedimentary sequence of earliest Eocene to early Middle Eocene age nonconformably overlies the high-grade rocks, and reworks them as clasts. According to some authors (Yetiş, 1978; Göncüoğlu *et al.* 1991; Yetiş *et al.* 1995), the relation between the metamorphic dome and older sediments (late Maastrichtian to Late Palaeocene) also corresponds to a nonconformity, suggesting that unroofing was already achieved by that time. We discuss below the evidence for this interpretation.

5.e.1. Kılavuz area

For Göncüoğlu *et al.* (1991), the late Maastrichtian–Palaeocene sediments of the 'Eskiburç group' nonconformably overlie the Niğde metamorphic rocks (Fig. 4a, bottom left column). In the area of Kılavuz, where the late Maastrichtian fossils were found, we have shown that a late normal fault, corresponding to the ‘detachment’ of Whitney & Dilek (1997), separates the high-grade rocks from the sediments. On the section in Figure 5a, the sediments immediately above the fault contain large pebbles derived from the footwall marbles (Fig. 5c). This might suggest that the remainder of the sedimentary sequence, which lies further south as a part of the Eskiburç group sequence, has accumulated once the metamorphic rocks were already unroofed. However, the stratigraphic position of the silts and clays above the low-angle fault is difficult to ascertain, as they are separated from the sediments of the Eskiburç group by a shallow depression filled with recent alluvial deposits (indicated with a question mark in Fig. 5a). Further east, the low-angle fault curves southeastwards (Fig. 4a) and yellowish clastic limestones lie directly against the fault. Within the sediments of the Eskiburç group, the coarsest detritic deposits are sandstones which occasionally contain centimetric pebbles of microgabbro and granite (Fig. 5a). These lithologies are not typically representative of the Niğde metamorphic sequence. In the same area, the only outcrop displaying the nonconformity of some ‘old’ consolidated sediments onto the Niğde high-grade rocks is a small (50 × 30 m) isolated exposure of conglomerates and sandstones lying to the north of the low-angle fault (western ‘U’ in Fig. 4a). These sediments differ significantly from those to the south of the fault and resemble more the conglomeratic ‘Çamardı formation’. Since the stratigraphic position of the Çamardı formation needs also to be reassessed (see next Section), this eventual correlation does not ensure that these isolated conglomerates and sandstones belong to the Eskiburç group. We conclude that the nonconformity of the late Maastrichtian–Palaeocene sediments on the Niğde dome is not documented so far in the area of Kılavuz (Fig. 4a, left column on the map).

5.e.2. *Çamardı area*

Northeast of Celaller, Göncüoğlu *et al.* (1991) have mapped the ‘Çamardı formation’ as a subcontinuous layer bounding the Niğde dome (Fig. 4a). This conglomeratic formation is reported to overlie the Niğde metamorphic rocks nonconformably and to constitute the basal layers of the Eskiburç group (Fig. 4a, bottom left column). However, on the map of Figure 4a, the Eocene Evliyatepe formation is commonly sandwiched between the Çamardı formation and the sediments of the Eskiburç group, an unexpected feature if the Çamardı formation was to lie at the base of the Eskiburç group. Moreover, our observations in the area between Celaller and Çamardı (Fig. 6) have shown that there is a gradual upward transition from coarse terrigenous sediments lying directly on the metamorphic rocks (mapped as the Çamardı formation) to mixed terrigenous–calcareous sediments containing the Eocene microfauna (mapped as the Evliyatepe formation). This indicates that the two formations belong to the same sedimentary sequence. Therefore, in its type locality, the Çamardı formation forms the base of the Eocene Evliyatepe formation (Fig. 4a, central column on the map) and does not belong to the Eskiburç group as previously suggested (Göncüoğlu *et al.* 1991). In the area around Çamardı, Celaller and surroundings is the only locality where a direct contact between the Niğde metamorphic sequence and the sediments of the Eskiburç group might in principle be observed (Fig. 4a). Our investigations in this area have led to the identification of a limited exposure (central ‘U’ in Fig. 4a) of consolidated conglomerates and microconglomerates, tilted at about 25° to the south and nonconformably overlying the Niğde high-grade rocks (the top of which includes cataclasites and ultracataclastic faults; see Section 5.b). This outcrop lies on the eastern flank of a large steep valley entering the Niğde dome. The conglomerates, which resemble the Çamardı formation, plunge southwards below Quaternary alluvial sediments, so that, here again, their relation with the sediments of the Eskiburç group further south remains unclear.

5.e.3. *Northeastern area*

About 6 km northeast of Çamardı and beyond, the sedimentary sequence of the Eskiburç group is reported to begin locally with a layer of conglomerates nonconformably overlying the Niğde dome (Göncüoğlu *et al.* 1991). This layer of irregular thickness is considered as a lateral extension of the Çamardı formation (Fig. 4a). On a 100 m scale cross-section (Göncüoğlu *et al.* 1991, fig. 15), the nonconformable conglomerates are reported to grade upwards into a sequence of Palaeocene impure limestones. However, on the same exposure, we observed no conglomerate but thick cataclasites developed at the expense of the underlying quartzites (Fig. 4b). The top of the cataclasites is marked by a fault dipping at 35° to the southeast and bearing N–S-trending striations. The impure limestones lie directly above the fault and are themselves strongly foliated, bearing a NNE–SSW-trending stretching lineation. Therefore, on this section, the contact between the Niğde high-grade rocks and the Eskiburç group is tectonic, not sedimentary. We suspect that the ‘Çamardı formation’ shown further northeast along the margin of the Niğde dome also corresponds to massive cataclasites developed at the expense of the high-grade rocks (Fig. 4a, upper right column on the map). Along this boundary, at the single locality where we did observe the nonconformity of some ‘old’ sediments on the Niğde dome, the sequence corresponds to moderately consolidated basal conglomerates, sandstones and lacustrine limestones of the post-Middle Eocene Çukurbağ formation (upper right ‘U’ in Fig. 4a).

5.e.4. 'Late Palaeocene' sediments

According to Yetiş (1978) and Yetiş *et al.* (1995), the high-grade rocks of the Niğde dome are overlain nonconformably by Late Palaeocene sediments. We have argued before that the nonconformable Evliyatepe formation is as old as the earliest Eocene, so the difference in age may not appear significant. However, the Late Palaeocene sedimentary sequence of Yetiş (1978) is equivalent to the Eskiburç group of Göncüoğlu *et al.* (1991), so its actual age is rather late Maastrichtian to Late Palaeocene (see Section 3.b). The main difference between the two stratigraphic logs (Yetiş, 1978; Göncüoğlu *et al.* 1991) is the lack of a layer of conglomerates at the base of the nonconformable Palaeocene flysch sequence in the log of Yetiş (1978) (see also Yetiş *et al.* 1995). According to Yetiş (1978), conglomerates appear for the first time at the base of the unconformable Eocene sequence. This agrees with our inference that the conglomeratic Çamardı formation of Göncüoğlu *et al.* (1991) should be displaced from the base of the Eskiburç group to the base of the Eocene Evliyatepe formation (see Section 5.e.2). The lack of coarse clastic deposits as the first sediments deposited onto the metamorphic rocks, in the log of Yetiş (1978), casts doubt on the fact that these sediments overlie the metamorphic complex with a sedimentary contact. Yetiş (1978) does not mention where the nonconformity of Late Palaeocene sediments on the Niğde dome can be seen in the field. Moreover, according to the map of Yetiş *et al.* (1995), Eocene sediments are restricted to the main exposure lying north–northeast of Çamardı (Fig. 4a). Elsewhere along the Niğde dome, the sediments are shown as parts of the Late Palaeocene sequence, whereas the maps of Blumenthal (1952) and Göncüoğlu *et al.* (1991), together with our observations (Figs 6, 7c), show that there is another large exposure of Eocene sediments to the west of Çamardı. Minor outcrops of conglomerates resembling the Çamardı formation are also present further west (western and central 'U' in Fig. 4a). Therefore, it is possible that the nonconformity reported by Yetiş (1978) and Yetiş *et al.* (1995) actually lies between the Niğde dome and Eocene sediments.

5.e.5. Synthesis

As a whole, our investigations do not confirm the nonconformity of late Maastrichtian to Late Palaeocene sediments of the 'Eskiburç group' on the Niğde high-grade rocks. Field evidence shows either a tectonic contact between the two (a late normal fault in the area of Kılavuz, and a low-grade ductile to brittle strike-slip shear zone in the northeastern area), or the direct nonconformity of the Eocene Evliyatepe formation, with the conglomeratic Çamardı formation at its base, on the Niğde metamorphic rocks (Çamardı area). These relations are summarized in the three columns on the map of Figure 4a, casting doubt on the validity of the synthetic log proposed so far (bottom left column).

According to Göncüoğlu *et al.* (1991), the lower part of the Eskiburç group sequence (from which we exclude the Çamardı formation) is made up of an olistostromal complex. The blocks in this complex consist of limestone, basic to intermediate volcanic rocks, and serpentinite. No block of the Niğde high-grade sequence is mentioned, which strongly suggests that at the time the sediments of the Eskiburç group accumulated, the Niğde metamorphic rocks were not yet unroofed. An easy way to explain this feature is to infer a tectonic contact between the Niğde dome and the Eskiburç group sequence, along which the metamorphic rocks have been exhumed until they reached the surface, at about the end of the Palaeocene (Fig. 9). For this reason, we suspect that a fault systematically exists between the Niğde high-grade rocks and the sediments of the Eskiburç group, even in the areas where the contact between the two is hidden by the overlap of the Eocene sediments (central column in Fig. 4a). As shown on Figure 9, this suspected fault probably corresponds to the extensional detachment seen in the northern part of the dome (Fig. 3) and to the west of Celaller (central 'U' in Fig. 4a).

6. Regional implications

The results of this study indicate that the metamorphic rocks of the Niğde Massif were unroofed before Eocene times. This contradicts the hypothesis of core complex development in southern Central Anatolia during Oligocene–Early Miocene times (Whitney & Dilek, 1997, 1998). As a consequence, Neogene core complex-type extension in the Eastern Mediterranean seems restricted to the Aegean domain (Fig. 2). This probably results from the greater amplitude of southward retreat of the South Aegean Subduction Zone, compared with that of the Cyprus Subduction Zone, and/or from the fact that the Aegean domain experienced greater crustal thickening (and consequent thermal weakening) soon before the onset of extension (Gautier *et al.* 1999).

On the scale of the Central Anatolian Crystalline Complex, Whitney *et al.* (2001) and Fayon *et al.* (2001) recently argued that northern parts have been exhumed earlier (apatite fission track dates at 47–32 Ma), through erosion, in a context of frontal collision, whereas the Niğde Massif has been exhumed later, through tectonic denudation, in a context of oblique collision. Our results show that the Niğde high-grade rocks were already unroofed at 54 Ma, but probably not before *c.* 60 Ma (Fig. 9). In so far as the fission track dates at 47–32 Ma represent simple cooling ages during exhumation (no partial resetting occurred during Neogene magmatism), the opposite chronology is actually indicated, that is, the Niğde

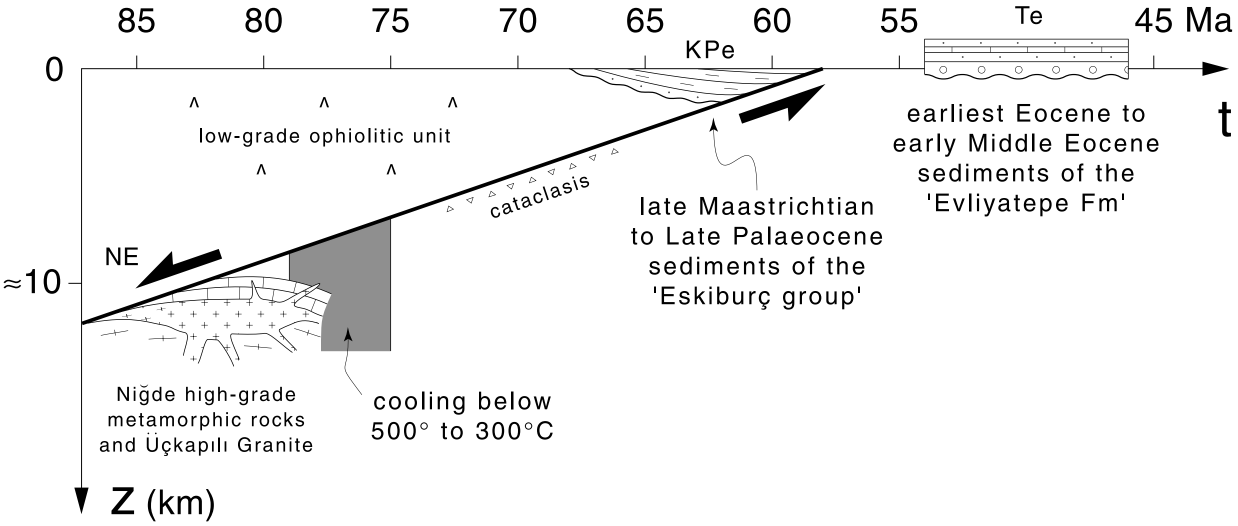

Figure 9. Schematic time–depth diagram illustrating the exhumation history of the Niğde high-grade metamorphic rocks and granitoids.

dome has been exhumed slightly earlier than northern parts of the Central Anatolian Crystalline Complex.

Whitney *et al.* (2001) and Fayon *et al.* (2001) consider that northern parts of the complex were exhumed primarily by erosion because the metamorphic rocks are overlain nonconformably by 'Tertiary' sediments. However, the observation of a nonconformity is not enough to state this. As illustrated by Figure 1c (step 1) and by the case of the Niğde dome itself (Fig. 9), exhumation may result primarily from extension, whereas minor erosion is sufficient to account for the ultimate development of a nonconformity. As a fact, in the northwestern Central Anatolian Crystalline Complex, Okay & Tüysüz (1999) recently suggested that a low-dipping fault previously mapped by Seymen (1981, 1984) as a major thrust should be reinterpreted as an extensional detachment, juxtaposing an unmetamorphosed ophiolitic complex onto high-grade rocks with similar lithologies to those in the Niğde Massif. According to Seymen (1981, 1984), Late Maastrichtian to Early Palaeocene sediments and volcanic rocks are found atop the hangingwall unit only, whereas Early–Middle Eocene sediments cover both the hangingwall and footwall units. Therefore, the situation in this northwestern area closely resembles the one in the Niğde Massif (Fig. 9). This coincidence suggests that exhumation has been broadly synchronous on the scale of the Central Anatolian Crystalline Complex, as a result of an episode of high magnitude extension that affected the whole region. However, more work is needed in northern parts of the complex to test this hypothesis.

Finally, the recognition that the Niğde high-grade rocks were unroofed before the Eocene also casts doubt on the interpretation of the Niğde dome as a core complex developed within a zone of wrenching (Whitney *et al.* 2001; Fayon *et al.* 2001). This interpretation is implicitly based on the hypothesis that the Ecemiş Fault Zone (Fig. 3) accommodated at least part of its total displacement (about 60 km of sinistral offset) during the exhumation of the metamorphic complex. Following Yetiş (1978, 1984), most authors consider that the main displacement on the Ecemiş Fault Zone pre-dates the Middle Eocene (in fact, the deposition of sediments of the Evliyatepe formation). Recently, however, Jaffey & Robertson (2001) convincingly argued that the offset of 60 km across the fault zone was accommodated after the Late Eocene. Thus, the Niğde high-grade rocks were already unroofed at the time the Ecemiş Fault Zone started to slip. As a result, there is no clear indication that the Niğde dome developed as a wrench-type core complex. Instead, we think that the Niğde dome is better seen as a classical core complex that developed during an episode of pre-Eocene extension. As discussed above, this episode of high magnitude extension may well have affected the whole Central Anatolian Crystalline Complex.

7. Conclusions

The results of this study allow reassessment of the timing of exhumation of the metamorphic rocks and granitoids of the Niğde metamorphic dome. They contradict the main arguments of Whitney & Dilek (1997, 1998), Whitney *et al.* (2001) and Fayon *et al.* (2001) in favour of an interpretation of the Niğde dome as a core complex of Oligocene–Miocene age:

(1) Where invoked, the associated extensional detachment does not exist (western margin of the dome) or corresponds to a normal fault which acted once the metamorphic rocks were already at the surface (southern margin).

(2) The high-grade rocks of the Niğde dome reached the surface before Eocene times, or at the very begin-

ning of the Eocene at the latest, since they are overlain nonconformably by a sedimentary sequence of earliest Eocene to early Middle Eocene age. Pebbles from the metamorphic rocks are ubiquitous in the conglomerates of this sequence, which contradicts the assertion that such pebbles are found for the first time in Middle to Upper Miocene strata.

(3) The Üçkapılı granite is a late-kinematic intrusion which was emplaced during progressive exhumation of the metamorphic complex. Like the high-grade rocks, the granite is found as pebbles within the conglomerates of the Eocene sedimentary sequence. Thus, the Üçkapılı granite is older than the Eocene. This contradicts an Early Miocene age of crystallization for the intrusion, casting doubt on the meaning of the 13.7–20 Ma U–Pb monazite date reported in Whitney & Dilek (1997, 1998).

(4) Since the initial unroofing of the Niğde dome is pre-Eocene, apatite fission track dates around 12–11 Ma cannot be used to infer that the metamorphic rocks were still on their way to the surface at that time. The fission track dates necessarily reflect a later event, which is most probably heating during the late Neogene magmatism that typifies the region.

An extensional detachment nevertheless exists at the top of the Niğde dome, best documented in its northern part, where the detachment fault superposes a superficial unit made up of massive ophiolitic rocks onto the high-grade metamorphic sequence. Field evidence indicates that this extensional detachment developed before Eocene times.

At variance with Yetiş (1978), Yetiş *et al.* (1995) and Göncüoğlu *et al.* (1991), we do not confirm the nonconformity of sediments older than the Eocene (late Maastrichtian to Late Palaeocene deposits of the ‘Eskiburç group’) on the Niğde dome. Field evidence shows either a tectonic contact between the two, or the direct nonconformity of the Eocene sedimentary sequence onto the high-grade rocks. As a result, the Niğde metamorphic rocks may have reached the surface at any time between late Campanian (cooling ages at 79–75 Ma, Göncüoğlu, 1986) and earliest Eocene times. Nevertheless, the lack of coarse clasts originating from the Niğde dome within the sedimentary sequence of the Eskiburç group suggests that the metamorphic rocks did not reach the surface before Late Palaeocene times. Compared with available data from the northwestern part of the Central Anatolian Crystalline Complex, these time constraints further suggest that exhumation has been broadly synchronous on the scale of the massif, as a result of an episode of high magnitude extension that affected the region in Campanian (and possibly earlier) to Palaeocene times.

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