Late Neoproterozoic granulite facies metamorphism in the Menderes Massif, Western Anatolia/Turkey: implication for the assembly of Gondwana

O. Ersin Koralay*

Mühendislik Fakültesi, Jeoloji Mühendisliği Bölümü, Dokuz Eylül Üniversitesi, Tınaztepe Yerleşkesi, 35160, Buca, İzmir, Turkey

(Received 3 November 2014)

The Menderes Massif is a major polymetamorphic complex in Western Turkey. The late Neoproterozoic basement consists of partially migmatized paragneisses and metapelites in association with orthogneiss intrusions. Pelitic granulite, paragneiss and orthopyroxene-bearing orthogneiss (charnockite) of the basement series form the main granulite-facies lithologies. Charnockitic metagranodiorite and metatonalite are magnesian in composition and show calc-alkaline to alkali-calcic affinities. Nd and Sr isotope systematics indicate homogeneous crustal contamination. The zircons in charnockites contain featureless overgrowth and rim textures representing metamorphic growth on magmatic cores and inherited grains. Charnockites yield crystallization age of ~590 Ma for protoliths and they record granulite-facies overprint at ~ 580 Ma. These data indicate that the Menderes Massif records late Neoproterozoic magmatic and granulite-facies metamorphic events. Furthermore, the basement rocks have been overprinted by Eocene Barrovian-type Alpine metamorphism at ~42 Ma. The geochronological data and inferred latest Neoproterozoic–early Cambrian palaeogeographic setting for the Menderes Massif to the north of present-day Arabia indicate that the granulite-facies metamorphism in the Menderes Massif can be attributed to the Kuunga Orogen (600–500 Ma) causing the final amalgamation processes for northern part of the Gondwana.

Keywords: SHRIMP/LA-ICP-MS U-Pb dating; granulites; Menderes Massif; Gondwana; Kuunga Orogen

1. Introduction

Gondwana (-land) (Du Toit, 1937) was by far the largest continent for more than two hundred million years since its formation in the late Neoproterozoic. The assembly of Gondwana was originally perceived as a single large-scale collision between two Neoproterozoic continental masses, East Gondwana (India–Australia–Antarctica) and West Gondwana (Africa–South America), along the Mozambique Ocean during the interval 800–650 Ma (Dalziel, 1992; Hoffman, 1991; McWilliams, 1981; Stern, 1994; Windley, Razatiniparany, Razakamanana, & Ackermand, 1994). However, new palaeomagnetic, geochronological and geological data have revealed that both East and West Gondwana have never existed as separate Neoproterozoic supercontinents, but their constituents came together during Neoproterozoic (Collins & Pisarevsky, 2005; Fitzsimons, 2000; Fritz et al., 2013; Johnson et al., 2011; Meert, 2003; Meert & Van Der Voo, 1997; Meert, Van der Voo, & Ayub, 1995; Torsvik et al., 2012 and references therein). A multiphase assembly of Gondwana is suggested in these studies.

Within the amalgamation history of Gondwana, the term ‘Pan-African’ was originally used to describe a widespread ~500 Ma intracraton tectono-thermal event in Africa and adjacent Gondwana elements by Kennedy (1964). Later, Kröner (1984) broadened this term for orogenic events between 950 and 450 Ma in Africa. Recently, four distinctive episodes are suggested for the amalgamation history of Gondwana; (i) West African-Brasiliano, (ii) Damara-Zambesi-Irumide, (iii) East African and (iv) Kuunga orogenies (Fritz et al., 2013) (Figure 1(b)). Especially, the East African Orogen (650–620 Ma) and Kuunga Orogen (600–500 Ma) have played an important role in the final configuration of supercontinent Gondwana. The East African Orogen (Stern, 1994) resulted from the amalgamation of arc terranes in the northern Arabian-Nubian Shield and continental collision between East African fragments in the south, Saharan–Congo–Tanzania–Bangweulu Cratons, parts of the Azania terrane comprising of Madagascar–Somalia–Ethiopia–Arabia, India, Sri Lanka and East Antarctica (Collins & Pisarevsky, 2005; Fritz et al., 2013). This tectonic episode formed the Mozambique Belt, which extends from southern Israel, Sinai and Jordan in the north to Mozambique and Madagascar with continuation to Antarctica in the south (Jacobs & Thomas, 2004). The second major orogenic episode, which was termed as the Kuunga Orogeny by Meert et al. (1995) resulted from the collision between Australia and East Antarctica with the tectonic units assembled earlier during the older East African Orogen. However, Fritz et al. (2013) broadened this term including the common ~600 and 500 Ma tectonothermal events characterising the final assembly of Gondwana.

A general tectonic division consisting of Pontides with Laurasian affinity to the north and Anatolite-Tauride

*Email: ersin.koralay@deu.edu.tr

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Block to the south, which are separated by İzmir–Ankara–Erzincan suture zone representing the Late Cretaceous to Eocene closure of the northern branch of Neotethys (Candan et al., 2005; Collins & Robertson, 1998; Okay et al., 1996, 2001; Pourteau et al., 2013). Prior to the Permo–Triassic the tectonic zones south of the İzmir–Ankara–Erzincan suture zone, e.g. Anatolide-Tauride Block and Central Anatolian Crystalline Complex, constituted a part of the northern margin of Gondwana, probably in a position close to that of Arabia (Candan et al., in press; Gessner, Collins, Ring, & Güngör, 2004; Kröner & Stern, 2004; Linnemann, D’Lemos et al., 2009; Linnemann, McNaughton et al., 2014).
2004; Monod et al., 2003; Murphy, Eguiluz, & Zulauf, 2002; Sengör, Satir, & Akkök, 1984; Şengör & Yilmaz, 1981; Stampfl & Borel, 2002; Stern, 1994; Torsvik & Cocks, 2013; Ustaömer, Ustaömer, Collins, & Robertson, 2009). Within this general tectonic framework, the Menderes Massif forms the largest crystalline basement of the Anatolides. In addition to Alpine overprint, petrological, petrographical and geochronological data indicate that the basement of the massif has experienced late Neoproterozoic poly-phase metamorphic events under granulite-, eclogite- and amphibolite-facies conditions (Candan, 1995; Candan & Dora, 1998; Candan, Dora, Dürr, & Oberhännli, 1994; Candan et al., 2001; Candan, Oberhännli et al., 2011; Oberhännli, Candan, Dora, & Dürr, 1997; Oberhännli, Candan, & Wilke, 2010) and was intruded by late Neoproterozoic basic and acidic magmas (Candan, 1996; Candan et al., in press; Candan, Koralay et al., 2011; Gessner et al., 2004; Hasözbek, Akay, Erdoğan, Satir, and Siebel 2011; Hetzel & Reischmann, 1996; Koralay et al., 2011, 2012, 2004; Loos & Reischmann, 1999).

In the previous studies, based on geological relationships, an age between Cambrian-Ordovician has been assumed for granulite facies metamorphism (Candan, 1995). P-T conditions for this high-T event were estimated at about 730–760 °C and .6 GPa (Candan & Dora, 1998; Candan, Oberhännli et al., 2011). In many papers, the poly-metamorphic evolution of the Precambrian basement series of the Menderes Massif has been attributed to the Pan-African Orogeny and was related to the closure of the Mozambique Ocean during the assembly of Gondwana (Candan, Dora, & Oberhännli et al., 2001; Candan et al., in press; Candan, Oberhännli et al., 2011; Dora, Candan, Kaya, Koralay, & Akal, 2005; Koralay 2011, 2012).

Considering the late Neoproterozoic-early Cambrian palaeogeographic position of the Anatolides to the north of present-day Arabia, the granulite-facies metamorphism documented in the Precambrian basement of the Menderes Massif can provide crucial evidence on the latest stage of the amalgamation history for this part of Gondwana. In this paper, new geochemical, isotopic and geochronological data on the granulite-facies rocks of Precambrian basement of the Menderes Massif are reported. Furthermore, these geochronological data are discussed in terms of the possible genetic relationships with the late Neoproterozoic orogenic events, East African Orogeny and Kuunga Orogeny, leading to the final amalgamation of Gondwana.

2. General stratigraphy of the late Neoproterozoic basement of the Menderes Massif

The Menderes Massif is made up of a latest Neoproterozoic–early Cambrian basement (core series) and an unconformably overlying Palaeozoic–Early Tertiary cover series (Figure 2(b); Candan, Dora et al., 2011; Candan, Koralay et al., 2011; Dürr, 1975; Koralay et al., 2012). A generalised lithostratigraphy for the basement consisting of a thick metaclastic sequence and numerous syn- to post-metamorphic basic to acidic intrusions is suggested. The metaclastic sequence, with a minimum thickness of 10 kms, forms the oldest unit of the basement. It can be divided into two subunits: a paragneiss unit and a schist unit (Candan, Dora et al., 2011; Candan, Koralay et al., 2011; Dora, Candan, Kaya, Koralay, & Dürr, 2001; Koralay et al., 2012). The partly migmatized paragneiss unit, up to 8 km in thickness, occurs at the lower levels of the sequence and contains mica schist interlayers, up to 200 m in thickness. Over 85% of the paragneiss unit was derived from medium-grained sandstones of litharenitic composition (Dora et al., 2001), while the schist horizons represent former siltstone-subarkosic sandstone intercalations. The schist unit conformably overlies the paragneiss unit with a transitional contact representing a primary facies change. Over 70% of the schist unit is made up of garnet mica schist and mica schist, which represents primary mudstone-siltstone intercalation. The schists contain subordinate biotite-albite schist layers (~30%) representing former subarkosic sandstones. Based on the geochronological data, the depositional age of the protoliths of the paragneiss-schist sequence is constrained between 600 and 590 Ma, i.e., Ediacaran (Koralay et al., 2012).

The metaclastic sequence was intruded by the protoliths of voluminous orthogneisses. Based on the mineralogical compositions and textural properties, several different types of orthogneisses have been distinguished: biotite orthogneiss, leucocratic tourmaline orthogneiss and amphibole orthogneiss (Bozkurt, Winchester, Mittwede, & Ottley, 2006; Candan, Dora et al., 2011; Koralay, Candan, Chen et al., 2012). U/Pb and Pb/Pb zircon ages cluster at around ~ 550 Ma and are interpreted as intrusion ages of the precursors of the orthogneisses (Candan, Koralay et al., 2011; Gessner et al., 2004; Hasözbek et al., 2011; Hetzel & Reischmann, 1996; Koralay et al., 2011, 2012, 2004; Loos & Reischmann, 1999). The orthogneisses are interpreted as syn- to post Pan-African intrusions, related to the latest Neoproterozoic final amalgamation of the Gondwana (Candan, Dora et al., 2011; Candan, Oberhännli et al., 2011; Hetzel & Reischmann, 1996; Koralay et al., 2011, 2012, 2004; Loos & Reischmann, 1999). The orthogneisses are interpreted as syn- to post Pan-African intrusions, related to the latest Neoproterozoic final amalgamation of the Gondwana (Candan, Dora et al., 2011; Candan, Oberhännli et al., 2011; Hetzel & Reischmann, 1996; Koralay et al., 2011, 2012, 2004; Loos & Reischmann, 1999). The orthogneisses are interpreted as syn- to post Pan-African intrusions, related to the latest Neoproterozoic final amalgamation of the Gondwana (Candan, Dora et al., 2011; Candan, Oberhännli et al., 2011; Hetzel & Reischmann, 1996; Koralay et al., 2011, 2012, 2004; Loos & Reischmann, 1999). The orthogneisses are interpreted as syn- to post Pan-African intrusions, related to the latest Neoproterozoic final amalgamation of the Gondwana (Candan, Dora et al., 2011; Candan, Oberhännli et al., 2011; Hetzel & Reischmann, 1996; Koralay et al., 2011, 2012, 2004; Loos & Reischmann, 1999).

3. Geology of granulite-facies rocks

Eocene Alpine metamorphism has erased most of the mineralogical and textural evidence for the former
granulite-facies metamorphism in the basement of the Menderes Massif. The Neoproterozoic metamorphism is mainly recognised by rare orthopyroxene relics and porphyroblastic black spots (Figure 3(a)–(d)). These spots, up to 2 cm in size, consist of sillimanite, biotite, garnet and quartz, and are thought to represent pseudomorphs after cordierite porphyroblasts (Figure 3(b)), which were stable during the granulite-facies metamorphism (Candan, 1995; Candan & Dora, 1998; Candan, Oberhänslı et al., 2011; Dora et al., 2001). Two types of granulitic rocks can be defined. These are (i) paragneisses with orthopyroxene which is replaced commonly by biotite and (ii) charnockitic orthogneisses. Based on the protolith, textural characteristic and mineralogical composition, the charnockitic orthogneisses can be divided into three groups (type-1: massive, medium-grained granodiorite, type-2: granodiorite with gneissose texture and type-3: coarse-grained metatonalite). Granulite facies relics are best preserved in Tire and Birgi areas (Figure 2(b)).

In Tire area, high-T rocks occur as a klippe, 5 × 6 km in size, resting on late Neoproterozoic biotite schist-garnet mica schist intercalation (Figure 4, Candan, 1995; Candan & Dora, 1998). The klippe is made up of metaclastic rocks and numerous granitoid and metagabbro-metanorite intrusions. The metaclastic rocks consist of an intercalation of sillimanite-paragneiss and sillimanite-kyanite-staurolite schist. Paragneisses contain rarely orthopyroxene partly consumed by biotite. They are partially migmatized and are cut by numerous small sillimanite- and garnet-bearing anatectic metagranite bodies. The metaclastic sequence is intruded by charnockitic orthogneisses with a granodioritic composition. The medium-grained metagranodiorites (type 1) are sillimanite-rich, medium- to coarse-grained massive rocks with orthopyroxene crystals, up to 3 mm in size (Figure 3(c)). Whereas, coarse-grained metagranodiorites (type-2) are characterised by a gneissose texture with bluish orthoclase porphyroblasts, up to 5 cm in diameter, (Figure 3(d)). They include partly assimilated paragneisses bodies, up to 100 m, representing a primary intrusive contact relationship with the metaclastics. Additionally, these high-grade rocks are intruded by numerous basic meta-igneous sill-like bodies, several metres in thickness and stocks up to 500 × 1000 m in size. These late Neoproterozoic (ca. 565 Ma, Candan et al., in press) intrusions are made up of predominantly olivine-gabbros with minor amount of gabbro-norite and norites. They are converted to eclogitic metagabbros along their margins (Candan, Dora, & Dürr et al., 1994; Candan, Dora, & Oberhänslı et al., 2001; Oberhänslı et al., 1997; Oberhänslı et al., 2010), whereas the primary igneous texture and mineralogy are well preserved in the undeformed cores. The eclogites were extensively retrogressed to garnet amphibolites by a medium-P Barrovian overprint.

In Birgi area, high-T rocks are represented by paragneisses and orthopyroxene-bearing metatonalite (type-3) and sillimanite metagranodiorite (type-2) intrusions. Similar to Tire area, they are intruded by gabbroic stocks/veins with eclogitic marginal zones. Metatonalites are coarse-grained, dark and massive rocks with orthopyroxene crystals, up to 1 cm (Figure 3(e)). Sillimanite metagranodiorite with gneissose texture is strongly sheared and were transformed to mylonites along the high-strain zones.

4. Petrography and mineral chemistry

Four samples from charnockitic orthogneisses, metagranodiorite (type-1, samples 05-2 and 05-9), metagranodiorite (type-2, sample 371) and metatonalite (type-3, sample 12-28) were analysed by electron microprobe. Analytical method is listed in Appendix A (supplementary data). A representative electron microprobe data-set is summarised in Table 1. Orthopyroxene paragneisses are massive to weakly foliated rocks with fine-grained granoblastic texture. The granulite-facies mineral assemblage is quartz, plagioclase, orthoclase, orthopyroxene, garnet, biotite and rutile. Garnet corona developments and replacement of orthopyroxene by biotite are typical retrograde textures. During the amphibolite-facies overprint, the porphyroblasts that are interpreted as former cordierite (Candan, Oberhänslı et al., 2011; Dora et al., 2001) have been completely replaced by fine-grained aggregates of sillimanite, garnet, quartz and biotite (Figures 3(a)–(b) and 5(a)–(b)).

Metagranodiorites (type-1) form the best-preserved high-T rocks. They are massive and medium- to coarse-grained rocks with a granoblastic to polygonal texture. Their granulite-facies assemblage is quartz, plagioclase, orthoclase, orthopyroxene, garnet, sillimanite and biotite. Zircon, rutile and ilmenite are accessory phases. Orthopyroxenes are hypersthene in composition (43–53 mol % En) and Al₂O₃ contents reach up to 3.67 wt% (Table 1 and Figure 6(a)). Garnet occurs as xenoblastic porphyroblasts with quartz inclusions. As a consequence of complete volume diffusion under high temperature conditions, it has chemically a homogeneous composition. Garnets are essentially almandine-pyrope solid solutions with minor grossular and spessartine components (<5 mol %); a typical composition is Al₉₅₂₋₇₂ – Prp₂₁₋₃₂ – Sps₁₋₃ – Sps₂ – Grs₁₋₃ – And₁ (Figure 6(c)). Sillimanite is closely associated with biotite and occurs as fibrolite and small prismatic crystals. Plagioclases display a narrow compositional variation from oligoclase (An₂₅) to andesine (An₃₃) (Figure 6(b)). They show common antiperthitic texture. Albite contents of orthoclase range from 10 to 20 (Figure 6(b)).

Replacements and corona textures, which can be interpreted as the isobaric cooling during the retrogression under upper amphibolite-facies conditions, are common in this type of charnockitic orthogneisses. They are characterised by the common development of secondary garnet and/or biotite coronas/reaction rims between plagioclase and the mafic phases (orthopyroxene, biotite, ilmenite and garnet) or complete replacement of
Table 1. Representative mineral chemistry of orthopyroxene, garnet, orthoclase and plagioclase from the charnockitic orthogneisses.

| Orthopyroxene | Granulitic garnet | Garnet coronas | Orthoclase Metagranodiorite-Tire 05-2/type-1 | Plagioclase | Orthoclase Metagranodiorite-Tire 05-2/type-1 | Plagioclase Metatonalite-Birgi 12-28/type-3 |
|---------------|------------------|---------------|------------------------------------------|------------|------------------------------------------|------------------------------------------|
| **SiO₂**      | 49.10            | 49.82         | 50.19                                    | 49.89      | 49.63                                    | 52.79                                    |
| **TiO₂**      | 0.10             | 0.18          | 0.18                                     | 0.21       | 0.08                                     | 0.05                                     |
| **Al₂O₃**     | 3.11             | 3.38          | 3.50                                     | 3.62       | 3.42                                     | 3.60                                     |
| **FeO**       | 30.94            | 28.78         | 31.92                                    | 31.93      | 31.05                                    | 23.76                                    |
| **MnO**       | 0.51             | 0.24          | 0.96                                     | 0.84       | 0.60                                     | 0.42                                     |
| **MgO**       | 0.15             | 0.16          | 0.18                                     | 0.16       | 0.16                                     | 0.16                                     |
| **CaO**       | 0.94             | 0.85          | 0.86                                     | 0.84       | 0.80                                     | 0.80                                     |
| **Na₂O**      | 0.01             | 0.01          | 0.00                                     | 0.00       | 0.00                                     | 0.00                                     |
| **K₂O**       | 0.00             | 0.00          | 0.01                                     | 0.01       | 0.00                                     | 0.00                                     |
| **Cr₂O₃**     | 0.08             | 0.08          | 0.09                                     | 0.11       | 0.11                                     | 0.11                                     |
| **Total**     | 99.49            | 99.44         | 10.14                                    | 99.85      | 10.00                                    | 99.88                                    |

**Note:** Values are in weight percent (wt%) for minerals.
porphyroblasts, probable after cordierite. Garnet corona enclosing biotite can be divided into two continuous zones in terms of quartz inclusions, an inner inclusion-free and an outer inclusion-rich zone (Figure 5(c)). They are almandine-rich garnets and show a regular increase of Grs content toward the plagioclase from Grs_{10} to Grs_{22}. The grossular content of garnet coronas (Grs_{22}) is distinctly higher than granulite-facies garnets (Grs_{5-3}). Orthopyroxene and granulitic garnet are enclosed by the same secondary garnet coronas (Figure 5(d)). The garnet coronas with an outer shell of fine-grained biotite aggregates are commonly observed between rutile/ilmenite and plagioclase.

Metagranodiorites (type-2) show a variation of gneissose texture from granoblastic to blasto-mylonite representing ductile deformation under amphibolite-facies conditions (Figure 5(e)). The mineral assemblage is quartz, plagioclase, orthoclase, orthopyroxene, garnet and biotite. During the amphibolite-facies overprint, orthopyroxenes (En_{45-45}) are widely replaced by fine-grained biotite. Similarly, biotite porphyroblasts are recrystallized to fine-grained biotite aggregates or are partially broken down to plagioclase-biotite symplectite.

Metatonalites (type-3) are massive and coarse-grained rocks with granoblastic texture (Figure 5(f)). Their granulite-facies assemblage is quartz, plagioclase, orthopyroxene, biotite, rutile and ilmenite. Retrograde mineral assemblage consists of amphibole, biotite, garnet and quartz. Garnet-corona textures surrounding the orthopyroxene are also very common. They are almandine-rich garnets and show high Grs_{19-21} content similar to garnet coronas of metagranodiorite (type-1). Furthermore, orthopyroxenes (En_{40-60}) are replaced towards the centre by an outer shell of green hornblende and an inner shell of irregularly distributed cummingtonite, biotite, iron oxide and quartz. Plagioclases display a wide compositional variation from andesine (An_{33}) to labradorite (An_{60}) (Figure 6(c)). Orthoclase has narrow compositional variation of albite component between 14 and 16.

5. Geochemistry and isotopic results

Eleven charnockitic orthogneiss samples were selected for whole rock Rb-Sr and Sm-Nd isotopic and geochemical analysis. A list of the analysed samples, including geochemical classification, mineralogy, type of analyses and their locations is given in Table 2. Analytical methods are listed in Appendix A. Representative geochemical and isotopic data are given in Table A (Appendix B, supplementary data) and Table 3, respectively.

Both type-1 (SiO_2 63–67 wt %) and type-2 (SiO_2 63–64 wt %) charnockitic orthognesses have similar composition and plot into granodiorite field on normative An-Ab-Or diagram (Figure 7(a)). But, one sample (05-2) of type-1 falls into the quartz-monzonite field. On the other hand, type-3 (SiO_2 54–58 wt %) charnockitic orthognesses are mainly tonalitic in composition. Metagranodiorites (type-1 and type-2) are characterised higher SiO_2, TiO_2, Rb, Y and Rb/Sr and lower Al_2O_3 and CaO than the metatonic (type-3). The Fe_2O_3 and MnO content of Metagranodiorite (type-1) is higher than that of metagranodiorite (type-2) and metatonalite. In terms of Fe-number (Frost et al., 2001), all types of charnockitic orthognesses are magnesian (Figure 7(b)). Although metagranodiorite samples show calc-alkalic affinity on the basis of modified alkali-lime index (Frost et al., 2001), metatonalite samples show variations from calc-alkalic to alkaline-calcic (Figure 7(c)).

6. Geochronological results

6.1. U-Pb SHRIMP and LA-ICP-MS zircon ages

Four charnockitic orthognesses samples, metagranodiorite (type-1, sample 05-2), metagranodiorite (type-2, samples 371 and 05-3/1) and metatonalite (type-3, sample 12-28) from basement of the Menderes Massif were selected for U-Pb geochronology using SHRIMP and LA-ICP-MS (Figures 2 and 4). Zircon morphologies and age interpretations are given in Table 4.

6.1.1. Sample 05-2 (type 1: metagranodiorite)

This sample (Tire area; Figures 3 and 4, Table 2) is massive, medium- to coarse-grained rock locally cut by shear zones. A granulite-facies assemblage (plagioclase, orthoclase, quartz, garnet, orthopyroxene and biotite) is well preserved with minor amphibolite facies overprint (garnet coronas and second generation of biotites). Thirty-four points from 28 zircon grains were analysed with the SHRIMP (Table B).

The main zircon population spreads along the concordia curve from 550 to 950 Ma. Featureless, bright luminescent rims on zircons (Figure 8) are interpreted as...
having formed during the granulite-facies metamorphism. They have U contents of 162–647 ppm and Th/U ratio ranging from 0.05 to 0.14. Seven analyses including two >10 discordant data (spots 1r and 6r) yield a concordia age of 580 ± 6 Ma (spots: 1–7, MSWD = 2.6, Figures 9(a)–(b)). They yield a \(^{206}\text{Pb}^{238}\text{U}\) weighted mean age of 584 ± 8 Ma (2σ, 95% confidence, MSWD = 1.2). This weighted mean age is interpreted as the age of granulite-facies metamorphism in this sample. Inherited zircon ages range from 2530 to 940 Ma.

Table 2. Geochemical classification, mineralogy, completed analyses and locations of samples. Mineral abbreviations as defined by Whitney and Evans (2010).

| Sample | Description | Mineralogy | Analyses done | Location |
|--------|-------------|------------|---------------|----------|
| 05-2   | Granodiorite (type-1) | qtz + pl + kfs + opx + grt + sil + bt | - Major and trace element geochemistry - SHRIMP U-Pb geochronology - LA-ICPMS monazite - Whole rock Sm–Nd, Sr isotope analysis - Mineral chemistry - Whole rock Sm–Nd, Sr isotope analysis | 35S 0584700/4213380 |
| 05-4   | Granodiorite (type-1) | qtz + pl + kfs + opx + grt + bt | - Major and trace element geochemistry - Whole rock Sm–Nd, Sr isotope analysis | 35S 0584500/4214360 |
| 05-9   | Granodiorite (type-1) | qtz + pl + kfs + opx + grt + sil + bt | - Major and trace element geochemistry - Whole rock Sm–Nd, Sr isotope analysis - Rb-Sr biotite age determination - Whole rock Sm–Nd, Sr isotope analysis - Mineral chemistry | 35S 0584500/4214000 |
| 05-10  | Granodiorite (type-1) | qtz + pl + kfs + opx + grt + sil + bt | - Whole rock Sm–Nd, Sr isotope analysis | 35S 0584500/4213870 |
| 05-2/3 | Granodiorite (type-2) | qtz + pl + kfs + opx + grt + bt | - Major and trace element geochemistry - SHRIMP U-Pb geochronology - Whole rock Sm–Nd, Sr isotope analysis - Mineral chemistry - Whole rock Sm–Nd, Sr isotope analysis | 35S 0582300/4214775 |
| 05-2/8 | Granodiorite (type-2) | qtz + pl + kfs + opx + grt + bt | - Major and trace element geochemistry - Whole rock Sm–Nd, Sr isotope analysis | 35S 0582650/4215 125 |
| 05-3/1 | Granodiorite (type-2) | qtz + pl + kfs + opx + grt + bt | - Major and trace element geochemistry - Whole rock Sm–Nd, Sr isotope analysis | 35S 0582000/4213415 |
| 12-28  | Metatonalite (type-3) | qtz + pl + kfs + opx ± grt + bt ± sil | - Major and trace element geochemistry - LA-ICPMS U-Pb geochronology - Whole rock Sm–Nd, Sr isotope analysis - Mineral chemistry - Whole rock Sm–Nd, Sr isotope analysis | 35S 0596390/4234940 |
| 12-29  | Metatonalite (type-3) | qtz + pl + kfs + opx ± grt + bt±sil | - Major and trace element geochemistry - LA-ICPMS U-Pb geochronology - Whole rock Sm–Nd, Sr isotope analysis - Mineral chemistry - Whole rock Sm–Nd, Sr isotope analysis | 35S 0596375/4234880 |
| 12-30  | Metatonalite (type-3) | qtz + pl + kfs + opx ± grt + bt±sil | - Major and trace element geochemistry - Whole rock Sm–Nd, Sr isotope analysis | 35S 0596410/4234815 |
Table 3. Analytical data of whole-rock Rb-Sr and Sm–Nd isotopic compositions. Initial isotopic ratios (I) have been recalculated for the crystallization ages obtained in this study.

| Sample No | Rock type    | Rb (ppm) | Sr (ppm) | $^{87}$Rb/$^{86}$Sr | $^{87}$Sr/$^{86}$Sr (t) | $^{143}$Nd/$^{144}$Nd (i) | $^{147}$Sm/$^{144}$Nd | $^{143}$Nd/$^{144}$Nd (t) | TDM (Ma) |
|-----------|--------------|----------|----------|---------------------|--------------------------|------------------------|------------------------|----------------------------|
| 05-2      | Metagranodiorite | 46.6     | 2000.0   | 0.06705             | 0.71452                  | 5.71395                | 0.10776                | 0.71395                   | 8.10776 | 0.71395 | 1.10776 | 0.71395 | 12     | 9.73 | 3.13 | 1450 |
| 05-4      | Metagranodiorite | 45.4     | 263.0    | 0.50216             | 0.71104                  | 7.0677                 | 3.75                   | 0.11657                  | 0.70677 | 3.75   | 0.11657 | 0.70677 | 14     | 9.55 | 3.61 | 1566 |
| 05-9      | Metagranodiorite | 57.4     | 252.9    | 0.65373             | 0.71331                  | 7.0771                 | 5.43                   | 0.11720                  | 0.70771 | 5.43   | 0.11720 | 0.70771 | 14     | 9.69 | 3.13 | 1587 |
| 05-9      | Metagranodiorite | 449.0    | 5.4      | 242.76              | 85803                    | 7.1292                 | 5.71292                | 0.51214                  | 0.51214 | 5.71292 | 0.51214 | 0.51214 | 14     | 9.69 | 3.13 | 1587 |
| 05-10     | Metagranodiorite | 78.0     | 244.7    | 0.92091             | 0.71482                  | 7.0693                 | 7.40                   | 0.11710                  | 0.70693 | 7.40   | 0.11710 | 0.70693 | 13     | 9.48 | 6.3  | 1570 |
| 05-2/3    | Metagranodiorite | 57.2     | 247.6    | 0.65875             | 0.71310                  | 7.0753                 | 11.03                  | 0.10977                  | 0.70753 | 11.03  | 0.10977 | 0.70753 | 13     | 9.25 | 1.44 | 1343 |
| 05-3/1    | Metagranodiorite | 80.5     | 1265.1   | 1.84444             | 0.71975                  | 7.1822                 | 29.83                  | 0.11017                  | 0.71822 | 29.83  | 0.11017 | 0.71822 | 15     | 8.80 | 2.08 | 1301 |
| 05-3/1    | Metagranodiorite | 58.4     | 241.4    | 0.69659             | 0.71297                  | 7.0714                 | 10.07                  | 0.10953                  | 0.70714 | 10.07  | 0.10953 | 0.70714 | 13     | 8.92 | 2.41 | 1414 |
| 12-28     | Metatonalite    | 21.7     | 362.3    | 0.17331             | 0.70892                  | 7.0746                 | 5.07                   | 0.11611                  | 0.70746 | 5.07   | 0.11611 | 0.70746 | 4      | 8.80 | 3.13 | 1502 |
| 12-29     | Metatonalite    | 28.2     | 304.1    | 0.26835             | 0.70978                  | 7.0752                 | 3.00                   | 0.08937                  | 0.70752 | 3.00   | 0.08937 | 0.70752 | 3      | 8.85 | 1.93 | 1194 |
| 12-30     | Metatonalite    | 20.2     | 306.8    | 0.19050             | 0.70796                  | 7.0636                 | 4.89                   | 0.11284                  | 0.70636 | 4.89   | 0.11284 | 0.70636 | 2      | 7.92 | 2.02 | 1386 |
This sample (Tire area; Figures 3 and 4, Table 2) with gneissose texture is characterised by the presence of large orthopyroxene (.5 cm) and orthoclase (4 cm) crystals. It has a mineral assemblage of quartz, plagioclase, orthoclase, orthopyroxene, garnet and biotite and was dated using both SHRIMP and LA-ICP-MS. Twenty-one points from 18 zircon grains were analysed with the SHRIMP (Table B). The main age data spreads along the concordia curve from 540 to 600 Ma with two major populations (Figure 9(c)).

The zircons showing ghost zoning (relict of primary oscillatory zoning) form the oldest group. Three of the more concordant analyses (between 109 and 116%
concordant) yield a $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age of $582 \pm 9$ Ma (spots: 3–5, $2\sigma$, 95% confidence, MSWD = .72, Figure 9(c)). They show moderate U contents of 321–624 ppm and low Th/U ratios ranging from .05 to .12. Therefore, the mean age of $582 \pm 9$ Ma for such zircon domains are interpreted as dating recrystal-

ization during granulite-facies metamorphism. In particular, twelve 90–110% concordant analyses yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 550 ± 4 Ma (2\(\sigma\), 95% confidence, MSWD = .8, Figure 9(e)). This second group age was obtained from planar-zoned overgrowths and bright, weak fine-oscillatory zoned rims with U contents of 127–481 ppm and Th/U ratios of .09–.56. Two featureless dark cores (spots 11 and 18) yield Early Palaeo-

proterozoic $^{207}\text{Pb}/^{206}\text{Pb}$ ages, 2473 ± 53 Ma and 2329 ± 47 Ma, respectively.

6.1.3. Sample 05-3/1 (type-2, metagranodiorite)

This sample (Tire area; Figures 2 and 3, Table 2) shows similar textural characteristics as sample 371. It has a mineral assemblage of quartz, plagioclase, orthoclase, orthopyroxene, garnet and biotite. Sixteen rims from this sample were analysed using a LA-ICP-MS (Table C, Appendix B, supplementary data). The main zircon pop-

ulation in this sample spreads along the concordia curve between 550 and 650 Ma (Figure 9(d)). The eight concordant analyses of featureless, bright luminescent rims indicating granulite-facies metamorphism yield a $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age of 589 ± 14 Ma (spots: 1–8, MSWD = 6.2, Figure 9(d)). This age is consistent with the U-Pb zircon SHRIMP age of 582 ± 9 Ma, obtained from featureless rims of the sample 371. The rims have moderate abundances of U (193–826 ppm), with Th/U ratios of .06–.12. There are five older rim analyses that range from 626 to 1611 Ma. The young age data from three zircon rims (spots: 14–16) range from 541 to 552 Ma (97–101% concordant). They have relatively low Th/U ratios (.05–.11).

6.1.4. Sample 12-28 (type-3, Metatonalite)

This sample (Birgi area; Figures 2 and 3, Table 2) is a massive and coarse-grained rock with a high amount of orthopy-

roxene. Granulite-facies assemblage is quartz, plagi-

oclase, orthoclase, orthopyroxene and biotite. Thirty-one mineral assemblage of quartz, plagioclase, orthoclase, orthopy-

roxene. Granulite-facies assemblage is quartz, plagio-

oclase, orthoclase and biotite. Sixteen rims from this sample were analysed using a LA-ICP-MS (Table C, Appendix B, supplementary data). The main zircon pop-

ulation in this sample spreads along the concordia curve between 550 and 650 Ma (Figure 9(d)). The eight concordant analyses of featureless, bright luminescent rims indicating granulite-facies metamorphism yield a $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age of 589 ± 14 Ma (spots: 1–8, MSWD = 6.2, Figure 9(d)). This age is consistent with the U-Pb zircon SHRIMP age of 582 ± 9 Ma, obtained from featureless rims of the sample 371. The rims have moderate abundances of U (193–826 ppm), with Th/U ratios of .06–.12. There are five older rim analyses that range from 626 to 1611 Ma. The young age data from three zircon rims (spots: 14–16) range from 541 to 552 Ma (97–101% concordant). They have relatively low Th/U ratios (.05–.11).

6.2. U-Pb LA-ICP-MS monazite ages

One grain of monazite was dated by LA-ICP-MS from metagranodiorite (type-1, sample 05-2; Table D). The monazite is stubby with rounded margins and back-

scattered electron (BSE) images, revealing a homogenous grain without internal structure (Figure 10(a)). The anal-

ysed spots are shown in Figure 10(a). The monazite yield a weighted mean age of 577.7 ± 2.7 Ma (Figure 10(b–

c)). Although the total number of analyses is relatively small (n = 24), the data show a well-defined age pop-

ulation with a normal distribution. This age is consistent with the U-Pb zircon SHRIMP age, 584 ± 8 Ma, obtained from featureless rims of this sample.

6.3. Rb-Sr biotite age

Biotites were separated from metagranodiorite (type-1, sample 05-9) for Rb-Sr analyses (Table 3) to identify the age of the Alpine overprint on the basement rocks. Biotite and whole-rock values of this sample define an isochron and yield Rb-Sr age of 42.1 ± .8 Ma for the bio-

tile-whole-rock pair (Figure 11). This age is interpreted as the cooling age of the Alpine overprint on the basement.

7. Discussion

7.1. Interpretation of age data

Prior to the Eocene Alpine metamorphism, the basement of the Menderes Massif has undergone a complex meta-

morphic history during the latest Neoproterozoic, which is ascribed to the assembly of Gondwana (Candan, Oberhänslil et al., 2011 and references therein). As described in Table 4, zircons show complex recrystal-

lization and overgrowth textures verifying these multi-stage metamorphic events. The textural characteristics of the metamorphic rocks and their geochronology suggest five intervals, which can be correlated with significant events; 590, 585–580, 570–560 and 550–540 Ma and the scattered ages between 600 and 2543 Ma. The inter-

pretation of these ages is discussed below.
Figure 2. (a) Tectonic map of Turkey showing the major terranes and bounding sutures. The filled triangles indicate the polarity of subduction (modified after Okay & Tüysüz, 1999; Candan et al., 2005; Pourteau et al., 2013). Unit abbreviations are the following: AS: Assyrian Suture; AZ: Afyon Zone; BFZ: Bornova Flysch Zone; BZS: Bitlis-Zagros Suture; CACC: Central Anatolian Crystalline Complex; CM: Cycladic Massif; D-Z-I: Damara-Zambezi-Irumide Orogen; IPS: Intra-Pontide Suture; ITS: Inner-Tauride Suture; İZ: İstanbul Zone; İAES: İzmir-Ankara-Erzincan Suture; LN: Lycian Nappes; MM: Menderes Massif; PS: Pamphylian Suture; RSM: Rhodope-Strandja Massif; SZ: Sakarya Zone. (Okay & Tuysuz, 1999); (b) Simplified geological map of the Menderes Massif and distribution of granulite facies relics in late Neoproterozoic–early Cambrian basement.
7.1.1. Age of magmatism and granulite-facies metamorphism and comparison with magmatic-metamorphic evolution of the basement

The LA-ICP-MS zircon U-Pb data from the metatonalite (type-3), sample 12–28, from the Birgi region yields an age of 591 ± 6 Ma (Figure 9(e)). Based on well-defined oscillatory zoning and high Th/U ratios of zircons, this age is interpreted as the protolith age of the metatonalite. However, the metagranodiorite (type-2), sample 371 and 05-3/1 from Tire area yielded weighted mean ages of 582 ± 9 and 589 ± 14 Ma, respectively, which are interpreted as the age of granulite-facies metamorphism. Although the zircons in these samples show ghost zoning (weak magmatic zoning), they have low Th/U ratio indicating that they were completely recrystallized during the high-T metamorphism. Considering the youngest inherited zircon age (600 Ma, Koralay et al., 2012) and the protolith age of metatonalite with intrusive contact relationship (590–582 Ma), a primary depositional age between 600 and 590 Ma for paragneisses affected by granulite-facies metamorphism, forming the host rocks of the metagranodiorites can be suggested. Furthermore, these syn-orogenic granodiorite intrusions are cut by the gabbroic stocks dated at ~565 Ma (Candan et al., in press). Considering these radiometric age constrictions, a crystallization age between 600 and 582 Ma can be envisaged for the precursor rocks of the type-2 metagranodiorites. Similarly, crystallization age of the type-1 granodiorites, which is typified by sample 052 could not be dated directly. The ages obtained from inherited magmatic zircons and cores are scattered between 599 and 2543 Ma. This scattering on the ages may indicate that the metagranodiorites were derived from a sedimentary source rock by partial melting. Furthermore, the consistency between the ages of inherited zircons of the granodiorites and detrital zircon population in the paragneisses verifies this possibility (Koralay et al., 2002). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of metagranodiorite (type-1) samples range between 0.70677 and 0.70771 and indicate a magmatic origin as other charnockitic orthogneisses.

Figure 3. (a) Fine grained orthopyroxene bearing paragneiss. Dark layers are composed of biotite, garnet, orthopyroxene and sillimanite. White layers consist of quartz, k-feldspar and plagioclase. Length of photograph is 5 cm; (b) Black spots after former cor-dierite porphyroblasts. They prefer clay rich layer of primary sediment. Length of photograph is 1 metre; (c) Massive, medium- to coarse-grained metagranodiorite (type-1); (d) Coarse-grained metagranodiorite (type-2) with gneissose texture. Length of photograph is 18 cm; (e) Coarse-grained, massive metatonalite (type-3). Length of photograph is 14 cm.
(type 2 and 3). However, sample 052 has higher \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio (.71395) suggesting a probable sedimentary origin. Considering these data, similar to type-2 metagranodiorites, a time interval between 600 and 582 Ma can be envisaged for the crystallization age of the igneous protoliths of the type-1 metagranodiorites.

Only a few age data have been obtained from the high-T rocks of the basement. Based on U-Th-Pb EMS monazite ages from orthopyroxene-bearing rocks in Birgi region, an age of \(660 \pm 61/63\) Ma has been suggested for the high-T event by Oelsner, Candan, and Oberhänsli (1997). Additionally, using ion microprobe method, Th–Pb monazite ages of \(563 \pm 7\) Ma and \(571 \pm 9\) Ma indicating a Pan-African event have been reported by Catlos and Çemen (2005). Zircons separated from metagranodiorite (type-1) by this study show featureless rims with bright luminescence that cut across primary oscillatory zones and metamorphic zircons showing “ghost zoning” (Hoskin & Black, 2000). All these features are interpreted to represent crystallization of rims and recrystallization of magmatic zircon domains under high-grade thermal events (Corfu, Hanchar, Hoskin, and Kinny, 2003; Hoskin & Black, 2000; Pidgeon, 1992; Vavra, Gebauer, & Schmid, 1996; Vavra et al., 1999; Wu & Zheng, 2004). The analyses obtained from these metamorphic domains yield ages of \(584 \pm 8\) Ma (sample 05-2), \(582 \pm 9\) (sample 371), \(589 \pm 14\) Ma (sample 05-3/1) and \(580 \pm 5\) Ma (sample 12-28) (Tables B and C). The age data form a statistically robust population, when combined, they yield a mean age of \(582 \pm 4\) Ma (2\(\sigma\), MSWD = .63). In addition to zircon ages, monazite (sample 05-2) yields an age of \(578 \pm 3\) Ma. As a result, the age of \(580\) Ma has been interpreted the age of granulite-facies metamorphism affected the basement of the Menderes Massif.

The sedimentation age of the metasedimentary rocks in the Menderes Massif has been the focus of interest for many years, and it was estimated as Late Palaeozoic by Dora et al. (2001) considering the ca. 550 Ma intrusion age of the orthogneisses (Koralay et al., 2012 and references therein). Based on the age relations between youngest detrital zircon age, 610 Ma (Koralay Dora, Candan, Chen, and Satır, 2003) and 600 Ma (Koralay et al., 2012) using Pb/Pb evaporation, and the intrusion ages of the plutonic rocks, the deposition age for paragneiss between 590 and 550 Ma (Koralay et al., 2002) and 600 and 590 Ma (Koralay et al., 2012) were suggested. In addition, Zlatkin, Avigad, and Gerdes (2013) reported
that weighted average ages of the youngest zircon population are 568 ± 4 Ma from the upper part of paragneiss unit (including “purple paragneiss” of Dora et al., 2001 and Zlatkin et al., 2013) and 571 ± 7 Ma from the top of overlying schist unit (core schist of Şengün, Candan, Dora, & Koralay, 2006 and Zlatkin et al., 2013). Thus, the deposition age of metasediments (core schists) between 570 and 550 Ma was suggested by the authors. Furthermore, some samples including ages between 556 and 526 Ma which are younger than this time interval.
were reported in metaclastics of the basement by Loos and Reischmann (1999). However, these metaclastics are included into lower level of the cover series by Dora et al. (2005). Only one sample (93T35 of Loos & Reischman, 1999) with a time interval between 638 and 620 Ma taken from 100 m south of gneiss-schist boundary can be included into the core series and the ages. The age of granulite-facies metamorphism conflicts with inferred primary deposition age of the metaclastic sequence of the basement (Zlatkin et al., 2013; 570 and 550 Ma). The metaclastics generally occur as big-sized xenolites in the huge orthogneiss intrusions, especially in southern submassif (Candan, Dora et al., 2011). Only in Kula area, some preserved continuous sections of this sequence can be observed. But, the poly-phased metamorphic latest Neoproterozoic–early Cambrian events (Kuunga Orogeny) and Alpine overprint has almost completely obscured their primary stratigraphical and sedimentological characteristics. Furthermore, there is no detailed stratigraphical study to reveal a possible unconformity which is supported by detrital zircon ages. Although in some papers it is suggested that the whole basement was subjected to granulite facies metamorphism (Candan et al. 2011 and references therein), there is not also any detailed study considering both geochronological and petrological data to find out a possible discontinuity in the series. Based on the petrological and geochronological data, a hitherto unrecognized discontinuity, unconformity or a tectonic contact within the metaclastic sequence can also be envisaged.

7.1.2. Interpretations of the other ages
The relative order of the polymetamorphic history and associated acidic, basic and alkaline igneous activities in the basement, which are supported by some radiometric age data is given by Koralay et al. (2012). These previous data are combined with new radiometric ages in this study. In addition to the age data, geological relationships and replacement textures among the minerals (Candan, Oberhänslí et al., 2011) clearly indicate that the granulite-facies metamorphism represents the oldest metamorphic event and is overprinted by medium and high-P events and was followed by migmatization and the intrusions of gabbro, granite and syenite during the latest Neoproterozoic to Cambrian. The possible relationships between the ages of these magmatic-metamorphic events and the new geochronological data obtained by this study are discussed below:

- **570–560 Ma events**: the presence of gabbroic stocks in the basement series has been documented for a long time (Candan, Dora, & Oberhänslí et al., 2001 and references therein). Recently, the intrusion of these basic rocks has been dated clearly at ~565 Ma (Candan et al., in press). The analyses obtained from some rims and overgrowths yield ages of 567–562 Ma (sample 05–2) and 566–561 Ma (sample 12–28) (Tables B and C). Therefore, the ages between 570 and 560 Ma, third group, are assigned to gabbroic intrusions of the basement.

Candan et al. (2001) and Oberhänslí et al. (2010) suggested that the metagabbros have experienced an early prograde amphibolite- to granulite-facies metamorphism characterised by coronitic texture. This view conflicts with the intrusion age of gabbros. However, the origin of such coronitic microstructures between olivine-plagioclase described commonly in basic rocks is still controversial (De Haas et al., 2002 and references therein). This type of corona texture has been documented in high-P terranes (Indares, 1993; Indares & Rivers, 1995; Mørk, 1985; Mørk & Mearns, 1986) as a medium stage of...
gabbro-eclogite transformation and in medium- to high-pressure amphibolite- to granulite-facies rocks (Grant, 1988; McLelland & Whitney, 1977; Whitney & McLelland, 1973). Furthermore, they can be observed even in non-metamorphic gabbros as reactions during magmatic cooling (Joesten, 1986; Turner & Stuewe, 1992).

- 550–540 Ma events: in this study, the textural relationships of the zircons clearly reveal that granulite-facies featureless rims are surrounded by planar-zoned overgrowths reflecting crystallization from anatectic melt (Wu & Zheng, 2004). Widespread migmatization of the paragneisses has been well documented in many studies (Candan, Oberhänsli et al., 2011). Based on the intrusive contact relationship between migmatites and post-granulitic orthogneisses dated at ca. 550 Ma, a pre-550 Ma age is postulated for the partial melting of basement (Candan, Koralay et al., 2011). Additionally, the basement series of the Menderes Massif is characterised by the existence of widespread post-granulitic orthogneisses, which were derived from voluminous granitoid intrusions (Bozkurt, 2004; Bozkurt, Winchester, & Park, 1995; Bozkurt et al., 2006; Gessner et al., 2004; Hetzel & Reischmann, 1996; Loos & Reischmann, 1999; Koralay, 2004, 2011, 2012). Recent studies have revealed that the main peak of this acidic magmatic activity can be constrained between 550 and 540 Ma (Candan, Koralay et al., 2011; Koralay, 2012). Considering these metamorphic and magmatic events, the fourth age group, 550–540 Ma, is ascribed to these thermal events characterised by migmatization and phase of granitoid intrusions.

The other ages scattered between 599 and 2543 Ma represent the inherited zircon grains from the protoliths of the charnockitic orthogneisses. These ages are consistent with the detrital zircon population of the paragneiss-schist sequence of the basement (Koralay et al., 2012).

7.1.3. Interpretations of Rb-Sr biotite age

The age and P/T conditions of the Alpine metamorphism have not yet been well documented. This event has been considered to reach upper amphibolite-facies conditions and has affected the whole Massif; it is called as the “main Menderes metamorphism” (Bozkurt & Satr, 2000; Satr & Friedrichsen, 1986; Sengör et al., 1984) or the “main Alpine metamorphism” (Brinkmann, 1976). Satr and Friedrichsen (1986) have reported Rb-Sr mica ages of this Alpine event. The crystallization ages of muscovites range from 63 to 48 Ma with an average age of 56 ± 1 Ma, which was interpreted as the age of Alpine metamorphism. Biotite Rb-Sr ages range between 50 and 27 Ma with a mean age of 37 ± 1 Ma. This age has been interpreted as the cooling following the Alpine metamorphism (Satr & Friedrichsen, 1986). Later, Bozkurt and Satr (2000) reported Rb-Sr mica ages, ranging from 62 to 43 Ma. They are attributed to the Alpine deformation and Barrovian-type HT/MP metamorphism in the Menderes Massif. When compared with these ages, the new biotite age at 42 ± 1 Ma is in good agreement with these Rb-Sr ages and can be interpreted as the cooling age of Barrovian-type Alpine overprint on the late Neoproterozoic basement.

7.2. Relationship of the granulite-facies metamorphisms with the latest Neoproterozoic assembly of Gondwana

As it is emphasised in the previous chapters, two tectonothermal events, ~650–620 Ma East African
Orogeny and ~600–500 Ma Kuunga Orogeny, play crucial role in the final configuration of the Neoproterozoic to Early Palaeozoic supercontinent Gondwana (Figure 1). Both orogenic events are characterised by the existence of widespread granulite-facies metamorphism (Figure 1).

In the Mozambique Belt of the East African Orogen, granulite-facies rocks have been documented well in Tanzania (652 ± 10 Ma, Coolen et al., 1982), Tanzania-Uluguru (633 ± 7 and 618 ± 16 Ma, Maboko & Nakamura, 1996; 642 ± 9, 642 ± 5 and 638 ± 1 Ma, Muhongo et al., 2001), Mugeba klippe - northeastern Mozambique (~615 Ma, Kröner et al., 1997), Monapo Klippe in Mozambique (634 ± 8, Macey et al., 2013), Usambara (625–630 Ma, Möller et al., 2000), Madagascar (630–600 Ma, Jöns & Schenk, 2008), Kenya (630–645 Ma, Hauzenberger et al., 2004; Hauzenberger, Sommer et al., 2007), in the Buur region of southern Somalia (between ~600 and 530 Ma, Küster et al., 1990; Lenoir et al., 1994), in central Madagascar (~570–520 Ma, Berger et al., 2006; Collins, 2006; Giese et al., 2011; Goodenough et al., 2010; Grégoire et al., 2009), in southern Madagascar (580–560 Ma, Markl, Bäuerle, and Grujic, 2000 and references therein), in Namibia (570–520 Ma, Jung et al., 2007), in Sri Lanka (580 Ma, Sajeev et al., 2007) and in India (600–540 Ma, Fonarev et al., 2000; 590–520 Ma, Santosh et al., 2006; ~620–550 Ma, Collins et al., 2014; Figure 1).

Figure 8. Cathodoluminescence (CL) images of the representative internal textures of typical zircon populations for metagranodiorite (type-1; 05-2), metagranodiorite (type-2; 371 and 05-3/1) and metatonalite (type-3; 12-28).
The age of granulite-facies metamorphism (~ 580 Ma) in the Menderes Massif rules out a possible genetic relationship to the East African Orogeny. Whereas, there is a close correspondence between the timing of the granulite-facies metamorphism in the Menderes Massif and high-T metamorphism occurred during the second period orogenic events (600–500 Ma).

In the Madagascar, this orogenic event termed as Malagasy orogeny by Collins and Pisarevsky (2005) is attributed to the collision between India and the previously amalgamated Congo/Tanzania/Bangweulu-Azania Block. Northward continuity of this orogen and related suture zone (Palghat-Cauvery Suture in India and Bet-simisaraka Suture in Madagascar) into Arabia are inferred by several researchers (Collins, 2006; Collins & Pisarevsky, 2005; Cox et al., 2012; Robinson, Foden, Collins, & Payne, 2014). Considering the inferred latest Neoproterozoic–early Cambrian palaeogeographic setting.

Figure 9. Zircon U-Pb concordia diagrams of metagranodiorite (type-1; 05-2), metagranodiorite sample (type-2; 371 and 05-3/1) and metatonalite sample (type-3; 12-28).
of the Anatolide-Tauride Block, the granulite-facies metamorphism in the Menderes Massif can be attributed to the northward continuity of such second period (600–500 Ma) orogenic events hidden mostly by the deep Phanerozoic cover sequence in the eastern Arabian Peninsula (Figure 1).

8. Conclusions

The Menderes Massif is made up of a latest Neoproterozoic–early Cambrian basement (core series) and unconformably overlying Palaeozoic–Early Tertiary cover series. Mineralogical and textural evidence indicate the presence of a former high-T metamorphism under granulite-facies conditions in the poly-metamorphic basement of the Menderes Massif, which was overprinted strongly by both later stages of Neoproterozoic events and by Alpine (Eocene; 42 Ma) metamorphism. Granulite-facies rocks in the Menderes Massif include orthopyroxene-bearing metapelitic sequence and charnockitic orthogneiss intrusions. Whole-rock geochemical data indicate that charnockitic orthogneisses are magnesian and show calc-alkalic to alkali-calcic affinities. Nd and Sr isotope ratios of charnockitic rocks are similar, reflecting homogeneous crustal contamination. U/Pb SHRIMP and LA-ICP-MS zircon and monazite ages from granulitic rocks yield ages of 582 ± 4 and 578 ± 3 Ma, respectively, which can be interpreted as the time of granulite-facies metamorphism in the basement of the Menderes Massif. Additionally, crystallization age of the protolith of the metatonalite, which has experienced the granulite-facies metamorphism, has been determined as 591 ± 6 Ma. Considering the poly-metamorphic history and multistage of magmatic events in the basement, the ages between 570–560 and 550–540 Ma obtained from the rims and overgrowths of the zircons can be assigned to the post-granulitic gabbroic intrusions and migmatization/granitoid magmatism of the basement, respectively. Based on the inferred latest Neoproterozoic–early Cambrian palaeogeographic setting of the Anatolide-Tauride Block to the north of present-day Arabia, the granulite-facies metamorphism in the Menderes Massif can be attributed to the orogenic event (600–500 Ma; Kuunga Orogeny), causing the final amalgamation processes for this part of the Gondwana.
Supplemental material
The supplemental material for this paper is available at http://dx.doi.org/10.1080/09853111.2015.1014987.

Acknowledgements
This research was supported by Dokuz Eylul University research fund (BAP, project no: 04KBFE0088). Detailed reviews by two anonymous reviewers were much appreciated and helped improve the manuscript. I gratefully acknowledge Osman Candan for his constructive and insightful comments on the preliminary version of this manuscript. Thanks are due to Yusheng Wan and Fukun Chen for the friendly access to SHRIMP and LA-ICP-MS facility, respectively. Special thanks to Aral Okay, Alan S. Collins and Yalcin Ersoy for their constructive comments. Thanks are also due to Quili Li and Zhenhui Hou for help during the SHRIMP and LA-ICP-MS measurements, respectively. The author thanks Aoife McFadden and Adelaide Microscopy team for helping during monazite measurement by LA-ICP-MS.

Funding
This research was supported by Dokuz Eylul University research fund [BAP, grant number 04KBFE0088].

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