Constraints on Variscan and Cimmerian magmatism and metamorphism in the Pontides (Yusufeli–Artvin area), NE Turkey from U–Pb dating and granite geochemistry

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Abstract: Metamorphic and igneous rocks exposed in NW-vergent thrust sheets and their autochthonous basement in the NE Pontides were dated by the U–Pb method using zircons, supported by geochemical data for granitic rocks. Two meta-sedimentary units (Narlık schist and Karadag˘ paragneiss) yielded detrital zircon populations of 0.50–0.65 and 0.9–1.1 Ga, suggesting an affinity with NE Africa (part of Gondwana). The youngest concordant zircon age is Ediacaran for the schist but Devonian for the paragneiss, bracketing the paragneiss depositional age as Mid-Devonian to Early Carboniferous. Metamorphic rims of zircon cores in the paragneiss gave Carboniferous ages (345–310 Ma). The zircon rim data indicate two Variscan metamorphic events (334 and 314 Ma) separated by a hiatus (320–325 Ma). Granite emplacement took place during early Carboniferous phases. The crystallization age of the early Carboniferous granites (c. 325 Ma) corresponds to a hiatus in the zircon age data that could reflect subduction slab break-off. The Variscan granitic rocks intruded a Gondwana-derived continental terrane that was loosely accreted to Eurasia during early–late Carboniferous time but remained isolated from Eurasian-derived terrigenous sediment. In contrast, the Jurassic granitic magmatism relates to later back-arc extension along the southern margin of Eurasia.

Supplementary material: Full isotope data (8 tables) are available at www.geolsoc.org.uk/SUP18558

In this study we report the results of U–Pb laser ablation sector field inductively coupled mass spectrometry (LA-SF-ICP-MS), LA-ICP-MS and ion probe dating of zircons that were separated from two meta-sedimentary units and several granitic units in NE Turkey. The northeasternmost Pontide region (Figs 1 & 2), specifically the Yusufeli area of Artvin region (Fig. 3), exposes an unusually complete tectono-stratigraphy and is thus a key area for the study and interpretation of geological settings and processes during Palaeozoic to Cenozoic time. The region is characterized by a relatively autochthonous basement, overlain by a stack of NW-vergent thrust sheets that were finally emplaced after Mid-Eocene time. Ophiolites and ophiolitic melanges occur at the top of the thrust stack, for example in the Olta–Narman area (Fig. 3) and mark the location of the Late Mesozoic–Early Cenozoic İzmir–Ankara–Erzincan suture zone that bounds the Pontides to the north. The suture zone continues to the E–SE into the Caucasus, within Armenia, where it is termed the Sevan–Akera suture zone (Fig. 1). Recent radiometric dating indicates that ophiolites there were created during Early–Middle Jurassic time (155–180 Ma; Galoyan et al. 2009; Rolland et al. 2009, 2010; Çelik et al.)

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followed by southward emplacement onto Tauride-related units and the South Armenian Block during latest Cretaceous time.

Pre-Jurassic to Early Jurassic basement units in the northeasternmost Pontides are exposed in both the relatively autochthonous basement and in the overlying thrust sheets. Several granitic plutons have been dated and chemically analysed to help constrain the timing and tectonic setting of magma emplacement. In addition, zircons were extracted from variably metamorphosed, mainly meta-sedimentary units and dated to determine their source ages, provenance and tectonic affinities. The age data shed light on the timing of burial and exhumation. We also combine existing geological information and age data from the Pontides–Transcaucasus region to test several alternative hypotheses for Variscan orogeny in this region. We infer that Gondwana-derived terranes were dispersed northwards to a location adjacent to Eurasia and later intruded by Early Carboniferous granites. This setting was isolated from identifiable Eurasian-derived terrigenous sediment.

**Geological setting**

The regional tectono-stratigraphy is summarized in Figures 3 and 4 (Ustaömer & Robertson 2010). Current knowledge of the region owes much to regional mapping by MTA (Mineral Exploration and Research Institute; Baydar et al. 1969, 1977; Konak & Hakyemez 1996, 2001) and to several specific studies (e.g. Şengör et al. 1980; Yılmaz & Şengör 1985; Ustaömer 1998; Adamia et al. 1995, 2001; Dokuz 2000; Yılmaz et al. 2001; Dokuz et al. 2006, 2010, 2011; Ustaömer & Robertson 2010). Here, we focus on several key lithologies that we have dated and chemically analysed from the eastern Pontide autochthon and the lower slice complex of the overlying thrust sheets (Figs 3 & 4).

Within the autochthon a granitic intrusion named the Çamlıkaya pluton is cut by younger granitic dykes, both lithologies being located beneath an Early Jurassic unconformity (Figs 3 & 4a). The first allochthonous unit above the autochthon is known as slice 1 of the lower slice complex (Figs 3 & 4; Ustaömer & Robertson 2010). The pre-Liassic

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Fig. 1. Tectonic map of the Pontides, the Caucasus and adjacent regions. The study area in the far NE of Turkey is marked by a red box. The black box shows the location of Figure 2. Several additional units that are mentioned in the paper are too small to show at the scale of this map. CUZ, Chortchana–Utslevi unit; S, Svanetia Uplift; DZ, Dzirula Salient; KH, Khrami Salient; LS, Loki Salient; RD, Rhioni Depression (all in the Caucasus); PCF, Peceneaga–Camena Fault.
basement of slice 1 is made up of a meta-sedimentary unit, termed the Narlık schist, which is cut by the Narlık granite (Fig. 4b). Two granite bodies in slice 1 intrude Early Jurassic terrigenous sediments and Mid-Jurassic volcaniclastic sediments; these were recently dated using the \(^{39}\text{Ar} - {^{40}}\text{Ar}\) method (Dokuz et al. 2010). One of these, the Dutlupınar granite, yielded an age of 188.3 \pm 4.3\text{ Ma} while the other, the Kecikaya granite, yielded an age of 153 \pm 3.4\text{ Ma} (Fig. 3).

Slice 2 of the lower slice complex comprises igneous and meta-igneous rocks known as the Demirkent Intrusive Complex (Ustãoemer 1998; Fig. 4c). The oldest rocks are banded amphibolites cut by granitic veins. The host rocks are intruded by swarms of dykes ranging in composition from gabbro to granite. Two granites, termed the Kölik and Sinevrat granites, cut the dyke complex and its host rocks. Slice 3 (Fig. 4d) exposes a metamorphic basement named the Karadağ metamorphics that is made up of migmatitic garnet cordierite gneiss, amphibolite and micaschist, indicating high-temperature metamorphism under upper amphibolite to granulite facies conditions. Geothermobarometric studies on the Karadağ metamorphics have revealed temperatures of 550–810 °C and pressures of 0.4–0.8 GPa (Dokuz 2000). Basaltic dykes intrude all of the metamorphic lithologies. Early Jurassic sediments and younger sedimentary and igneous units unconformably overlie the metamorphic rocks.

Analytical methods

Zircons were extracted for U–Pb dating from eight samples. The analysis was carried out at three different laboratories using LA-SF-ICP-MS, SIMS and
LA-ICP-MS. LA-SF-ICP-MS at Goethe University (Frankfurt) was used for the U–Pb isotope analysis of zircon separates from two meta-sedimentary and three igneous samples, following the method described in Gerdes & Zeh (2006, 2009). One igneous sample was dated using SIMS at the University of Edinburgh Ion Probe Unit (UK) as explained in Ustaömer et al. (2011) and Ustaömer et al. (2012a). Finally, two igneous samples were dated using LA-ICP-MS at the Geological Institute of the Bulgarian Academy of Sciences (Sofia), as described in Aysal et al. (2012). In addition, five samples of the

Fig. 3. Regional geological map of the area studied (modified from the 1:500 000 geological map of Turkey; MTA 2002). Dated sample locations are marked with a black star. The ages of two granitic rocks dated by Dokuz et al. (2010) by $^{39}$Ar–$^{40}$Ar method are also plotted.
Narlık granite were analysed for major, trace and rare earth elements by ICP-MS at the ACME laboratories in Canada (see http://acmelabs.com).

The time scale of Gradstein et al. (2004) is used here. The geochemical plots were produced using the software GCDKit (Janousek et al. 2006).

U–Pb geochronology

**Dating of meta-sedimentary rocks**

Most of the zircon grains from the sample of Karadağ paragneiss are rounded or sub-rounded, although some are sub-idiomorphic. The rounded zircons are characteristic of metamorphic zircons (Corfu et al. 2003). Cathodoluminescence (CL) images (Fig. 5) reveal a clear core v. mantle structure in all of the grains analysed. Even the most rounded and homogeneous-looking zircons exhibit small protolith cores (<40 μm) with faint internal zoning. These zircons exhibit swirly patterns or sector zoning. The rims of the zircons (<40 μm thick) are pale grey and weakly zoned.

Some of zircon rims illustrate three growth stages, marked by alternations of darker and paler zones. Sector zoning is common in the rims, whereas the cores commonly display oscillatory zoning. On the other hand, some cores are structureless, with darker zones compared with the rims. Some of the sub-rounded zircons do not show any core–mantle structure but instead resemble the rims of the core–mantle-type zircons in their internal patterns and pale grey colour.

Spot analysis (196 points) was carried out on 132 individual zircon grains (Fig. 6). The age span ranges from 2630 Ma (Neoarchean) to 303 Ma (Late Carboniferous). Ninety-two percent of the ages (173 out of 196 spot analyses) are 90–110% concordant. The ages of well-rounded zircons and the core–mantle-type rims (86 spot analyses) form a well-clustered population yielding a Carboniferous age. The second largest zircon population is of Ediacaran–Chryogenian (Neoproterozoic) age (552–683 Ma), which was obtained from 40 core analyses. The third largest population is from the cores of 19 zircons clustering between 904 and 1035 Ma (Tonian–Stenian; here termed Grenvillian).

Small zircon populations (90–110% concordance levels) are indicative of Palaeozoic ages (i.e. Devonian, six spot analyses; Silurian, one spot analysis; Ordovician, five spot analyses; Cambrian, ten spot analyses). Early Neoproterozoic ages are also evident (i.e. Chryogenian; 774–843 Ma; seven spot analyses). In addition, 13 spot analyses yielded Mesoproterozoic (1263–1600 Ma; seven spot analyses), Palaeoproterozoic (1600–2500 Ma; seven spot analyses) and Neoarchean ages (>2500 Ma; two spot analyses). Apart from the Carboniferous rim ages,
the youngest 100% concordant zircon age obtained is 565 Ma (Ediacaran). One zircon grain with typical oscillatory zoning yielded an age of 396 Ma that is 99% concordant.

The Th–U ratios of the rims or the well-rounded zircons (84 grains) range from 0.01 to 0.66. No correlation of Th–U ratio with age is observed. For example, the Th–U ratios of 36 rims are covering the whole range of rim ages (345–303 Ma).

The zircons from the Narlık schists are dominated by sub-idiomorphic and rounded zircons (Fig. 7). Most of the zircons display oscillatory zoning in the cores and rims, typical of igneous zircons. Some of the zircons exhibit core–mantle structures with a great variety of internal patterns and colour. Several of the zircons resemble those in the paragneiss as they have pale grey rims surrounding protolith cores. Where present, the rounding appears to have resulted from abrasion and sedimentary transport.

Spot analysis (162 points) was carried out on 79 zircon grains from the Narlık schist (Fig. 8). The ages range from 306 Ma (Late Carboniferous) to 2668 Ma (Neoarchean). Ninety-six percent of the ages (154 out of 162 spot analyses) are 90–110% concordant. Three prominent zircon populations are identified: 555–638 Ma (59 data; 36%); 656–839 Ma (28 data; 17%) and 892–1083 Ma (34 data, 21%). Smaller groupings occur at 1806–2042 (12 data; 7%) and 2340–2577 Ma (11 data; 7%). Eleven spot analyses yielded 90–110% concordant Palaeozoic ages; of these, eight that are from the rims of six zircon grains have Carboniferous ages (306–345 Ma). One zircon grain has a Devonian age (95% concordant) and two zircon grains have a Cambrian (c. 95% concordant) age. The youngest 100% concordant age is 568 Ma (Ediacaran). Th–U ratios are <0.1 for 27 zircon rims and cores (16% of the data set), typical of metamorphic zircons (Rubatto 2002; Teipel et al. 2004). Of these,
the Th–U ratios of eight Carboniferous rims are <0.05, while three are near zero (c. 0.002). Other 100% concordant zircons with Th–U <0.1 give ages of 588, 669, 938 and 2018 Ma. The remainder of the data (135 spot analyses) have a Th–U ratio >0.1 (0.1–1.8).

**Dating of igneous rocks**

Zircons crystals that were separated from the Çamlıkaya pluton (Fig. 9) are typically acicular (needle-like) with some stubby varieties (elongation ratio 2.5–6). Acicular zircons are characteristic of rapidly crystallized, high-level intrusions (Corfu et al. 2003). Fluid-assisted chemical alteration is present along fractures, while metamictization is present within most of the zircon crystals (e.g. Fig. 9; grains 1–5). Unaltered parts of some zircon grains exhibit oscillatory and rhythmic zoning.

U–Pb dating of zircons from the Çamlıkaya pluton mostly yielded discordant ages. The Concordia plot indicates a lower intercept age of 17 ± 13 Ma (Early Miocene) and an upper intercept age of 319 ± 19 Ma (Early Carboniferous–Serpukhovian). The most concordant ages are 330.4 ± 4.2 Ma (Early Carboniferous–Visean; Fig. 10a).

Zircons from the crosscutting granitic dykes display dominantly oscillatory zoning, characteristic...
of igneous zircon, together with sector zoning (Fig. 9). The crosscutting dykes are dated at 156.3 ± 2 Ma (Oxfordian–Late Jurassic) (Fig. 10b).

Zircons that were separated from the granitic vein within the amphibolite of the Demirkent Intrusive Complex are characterized by relatively large sector-zoned cores and rhythmically zoned narrow rims. Fluid-related alteration is visible on the CL images of some zircons (Fig. 9; grains 12, 16, 17). Th–U ratios of the analysed spots are high (0.53–0.92) compared with those of the Çamlıkaya pluton (0.08–0.92). The zircons from the granitic vein yielded discordant ages, as noted for the Çamlıkaya pluton. 206Pb–238U ages of 16 grains range from 317 to 332 Ma, except for one grain that gave a discordant age of 230 Ma. On the Concordia diagram the discordia intercepts the concordia curve at 0 and 320 ± 19 Ma. The most concordant result gave an age of 325 ± 11 Ma (Fig. 11a).

The Narlık granite at the stratigraphical base of slice 1 (lower slice complex) yielded discordant ages with an upper intercept age of 330 ± 19 Ma (Fig. 11b). One inherited core gave a Palaeoproterozoic age.

A small (<1 m) metagranitic intrusion within the paragneiss yielded a Concordia age of 357 ± 5 Ma (Tournasian–earliest Carboniferous; Fig. 11c). Three inherited cores gave ages of 545, 574 and 1017 Ma (at 90–110% concordant levels).

The Kölik (c. Sebzeciler) pluton that intrudes the Demirkent Intrusive Complex gave a Concordia age of 179 ± 1 Ma (Toarcian–late Early Jurassic; Fig. 12a). The Sinevrat granite that also intrudes the Demirkent Intrusive Complex yielded 206Pb–238U ages ranging from 163 to 181 Ma, with a weighted mean age of 173 ± 3 Ma (Aalenian to early Mid-Jurassic; Fig. 12b).

**Geochemistry of the 330 Ma granites**

Four samples of the Çamlıkaya granite and five from the Narlık granite were analysed for major, trace elements and rare earth elements. The Narlık granite is an S-type adamellite, whereas the Çamlıkaya granite is an I-type tonalite, as revealed by the A/CNK v. A/NK (i.e. Shand index; Shand 1943) and P-Q (Debon & Le Fort 1983) diagrams (Fig. 13a, b). The two Çamlıkaya and Narlık granites are classified as high K and medium K calc-alkaline granites, respectively, on the SiO2 v. K2O classification diagram of Peccerillo & Taylor (1976; not shown). The Çamlıkaya granite differs from the Narlık granite in its high concentrations of Sr and...
light rare earth elements (e.g. La), combined with low concentrations of Y and heavy rare earth elements (e.g. Yb).

The Çamlıkaya granite plots in the adakite field or in area of the adakite field overlapping with the classic island arc field on the Sr–Y v. Y and the (La–Yb)\textsubscript{n} v. Yb\textsubscript{n} discrimination diagrams (Defant & Drummond 1990). In contrast, the Narlık granite plots in the arc magmatic field (Fig. 13c, d). On ocean ridge granite (ORG)-normalized spidergrams, the Narlık granite displays Nb-depletion relative to Ce and Zr-depletion relative to Hf and Sm, whereas the Çamlıkaya granite is characterized by extreme depletion of Y and Yb but not Nb and Zr (Fig. 14a, b). On rare earth element-normalized spidergrams, the Narlık granite shows flat patterns from medium to heavy rare earth elements, enrichment by 10–25 times the chondrite value and a strong negative Eu anomaly. The Çamlıkaya pluton, on the other hand, displays spoon-shaped REE patterns, characteristic of adakite-like magmatic rocks. The absence of a negative Eu in the Çamlıkaya granite is compatible with an adakitic composition (Defant & Drummond 1990).
Discussion

Age relations

Three periods of igneous activity are identified: (1) Early Carboniferous (325–357 Ma) for the Çamlıkaya and Narlık granites and the granitic veins in both the amphibolite and the Karadag paragneiss; (2) Early Jurassic (c. 180 Ma) for the emplacement of the Kölik and Sinevrat granites; and (3) Late Jurassic (154 Ma) for the intrusion of the granitic dykes cutting the Çamlıkaya pluton. The ages for two meta-sedimentary samples range from late Carboniferous (300 Ma) to Neoarchean (2650 Ma).

Constraints on depositional age

The depositional age of the Narlık schist is bracketed by the 100% concordant, youngest zircon age (568 Ma) and the crystallization age of the crosscutting Narlık granite (330 ± 19). The low degree of concordance of the Devonian-aged core (109%) makes this potentially unreliable. The two Cambrian ages (c. 95% concordant) are, however, acceptable. This constrains the depositional ages of the Narlık schists as Ordovician to early Carboniferous.

The depositional age of the Karadağ paragneiss can be estimated from the youngest core age and the age of the crosscutting metagranitic intrusion,

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Fig. 9. Selected cathodoluminescence images of zircons analysed from the granitoids. Location of the LA-SF-ICP-MS analysis spots and the corresponding ages are also indicated. CN 36 Çamlıkaya granite; CN 39 Granitic dyke within the Çamlıkaya granite; DEM1 granitic vein in the amphibolite of the Demirkent Intrusive Complex; S14 Kölik granite.
while the age of the metagranitic intrusion is earliest Carboniferous (c. 357 Ma). The youngest, 100% concordant core age is Ediacaran (c. 565 Ma), while the oldest 100% concordant rim age is early Carboniferous (c. 337 Ma). Less concordant, younger, ages within the sample may be used to help constrain the depositional age. The ages of the small Palaeozoic zircon population (22 spot analyses) range from Cambrian to Devonian; 99–101% concordant ages are dated as Devonian (396 Ma; Th–U = 0.35–1 grain), Ordovician (473 Ma; Th–U = 0.03–1 grain) and Cambrian (510 to 532; Th–U = 0.04 to 1.20–3 grains). A Mid-Devonian and early Carboniferous depositional age is, therefore, likely.

Age and provenance of meta-sediments

The ages of the zircon populations (>400 Ma) from the Narlık schist and the Karadağ paragneiss are plotted in Figure 15, together with the known source ages of the major cratons and several peri-Gondwanan terranes. Late Neoproterozoic and Grenvillian zircon ages predominate in both samples. The age ranges of the significant zircon populations of the Narlık schist are 0.53–0.64 Ga (39%), 0.66–0.79 Ga (8%) and 0.9–1.1 Ga (22%), while those for the Karadağ paragneiss are 0.53–0.68 Ga (35%), 0.69–0.81 Ga (8%) and 0.9–1.1 Ga (18%).

The Narlık schist sample lacks zircons of the age ranges 1.08–1.8 Ga (with one exception) and
2.04–2.34 Ga. The paragneiss sample exhibits a large age gap from 2.04 to 2.5 Ga. Only 11 zircons fall within 1.08–2.04 Ga, of which only two are 99–101% concordant (1.63 and 2.04 Ga). Zircons of 1.1 Ga do not form significant zircon populations.

The dominance of the Late Neoproterozoic zircons in the samples studied is inconsistent with an origin in either Baltica or Siberia because these areas are known to be magmatically inactive during this time interval (Meert & van der Voo 1997; Greiling et al. 1999; Hartz & Torsvik 2002; Meert & Torsvik 2003; Linnemann et al. 2004; Murphy et al. 2004a, b). An exception is the Timanide belt in the polar Urals and NW Russia (Siedlecka et al. 2004), although this is not considered as a possible source terrane as it is bordered by a wide continent to the SW. Peri-Gondwanan terranes (Fig. 15) are characterized by zircon populations of Late Neoproterozoic age for which the source is generally considered to be a Cadomian–Avalonian arc terrane (Nance et al. 2008). Three different types of peri-Gondwanan terranes are recognized in the European and Eastern Mediterranean regions, namely the Avalonian terranes (including those of Ganderian type), the Cadomian terranes and the Minoan terranes. These have affinities, respectively, with the Amazon Craton, NW Africa and the NE Africa/Arabian–Nubian Shield.

The zircons of Amazonian affinity are characterized by Grenvillian (0.9–1.3 Ga), Mesoproterozoic (c. 1.5 Ga) and Palaeoproterozoic (1.9–2.2 Ga)-aged zircon populations (Tassinari & Macambira 1999; Linnemann et al. 2004; Winchester et al. 2006; Nance et al. 2008; Drost et al. 2011). The 0.9–1.1 Ga zircon population in the samples studied is at first sight compatible with an Amazonian Craton origin. However, c. 1.5 Ga age (two zircon cores) and 1.9–2.2 Ga ages (two zircon cores) are rare, which does not support an Amazonian origin. Derivation from a successor Avalonian terrane is thus also unlikely.

The West African Craton and the terranes that are related to the adjacent northern margin of Gondwana margin (i.e. Cadomian terranes) are characterized by magmatic quiescence from 0.8 to 1.7 Ga (Linnemann et al. 2004). In contrast, the prominent Grenvillian-aged zircon populations in our metasediments are inconsistent with a NW African (and hence Cadomian) origin.

Grenvillian-age zircon populations characterize terranes that were derived from NE Africa and the Arabian–Nubian Shield (Avigad et al. 2003; Kolodner et al. 2006; Be’eri-Shlevin et al. 2009). These terranes, termed the Minoan terranes (Zulauf et al. 2007), have been documented from the Eastern Mediterranean area (Romano et al. 2006; Zulauf et al. 2007; Ustaömer et al. 2012a, b) and Romania (Balintoni et al. 2009, 2010). Magmatic and metamorphic events of Grenvillian age are known from the Saharan Metacraton (Abdelsalam et al. 2002; DeWit et al. 2005) and the East African (Kibaran) Orogen (Cahen et al. 1984; Kolodner et al. 2006; Tack et al. 2010). Detrital zircons of 1 Ga also form a significant population within Palaeozoic and Mesozoic sediments that are transgressive on the Saharan Craton in southern Libya (Meinhold et al. 2011).

The detrital zircon populations of our two metasedimentary samples are comparable to those of the Cambrian and Ordovician sandstones at the periphery of the Arabian–Nubian shield in Jordan and Israel. They are also comparable with sillimanite–garnet schist of the Central Sakarya Basement of the Western Pontides (Fig. 16; Ustaömer et al. 2012a). A striking similarity exists in the density–probability diagrams of the detrital zircon populations for all three of these areas. The sources of the Grenvillian-aged zircon populations in the Early Palaeozoic sediments of Jordan and Israel have been considered to be the Kibaran orogen in Central Africa (Cahen et al. 1984; Kolodner et al.

**Fig. 12.** U–Pb ages of granitic intrusions in the study area. (a) Concordia diagram for the Kölik granite; (b) $^{238}\text{U} - ^{206}\text{Pb}$ weighted average diagram of the Sinevrat granite.
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2006), although more local sources (e.g. Sinai Peninsula) have also been suggested (Be’eri Shlevin et al. 2009). An Arabian–Nubian Shield origin has been proposed for zircons from the Sakarya basement of NW Turkey (Ustao¨mer et al. 2012a) and is also favoured here for our meta-sedimentary samples from the Artvin–Yusufelli area.

Occasional Palaeozoic-aged zircons (>350 Ma) are found in the Karadağ paragneiss (20 grains), five of which are 99–101% concordant: 396 Ma (Mid-Devonian), 473 Ma (Mid-Ordovician), 510, 519 and 532 Ma (Early Cambrian). The Th–U ratio of 0.03 suggests a metamorphic origin for the 473 and 510 Ma zircons, while the remainder of the grains have Th–U ratios >0.25 compatible with an igneous origin. The >350 Ma ages of three zircon grains in the Narlık schist are c. 95 or 109% concordant and, are therefore, discounted.

The only known Devonian magmatism in the Pontides is in the Biga Peninsula, NW Turkey (Okay et al. 1996, 2006; Aysal et al. 2012). Granitic stocks there intrude a meta-clastic succession, dated at 401–396 Ma. The granites and their host meta-clastics (Kalabak Unit) are unconformably overlain by Late Triassic clastic sediments and are in tectonic contact with the Permo-Triassic Karakaya Complex (Pickett & Robertson 1996; Aysal et al. 2012; Robertson & Ustao¨mer 2012).

Early Cambrian granitic magmatism (c. 530 Ma) is known from the Bitlis Massif, SE Turkey (Ustao¨mer et al. 2009). Zircons separated from a Precambrian (572 Ma) granite there have metamorphic rims dated at c. 520 Ma (Ustao¨mer et al. 2012b). A small number of detrital zircons from the host paragneiss have yielded Late Neoproterozoic and Grenvillian ages, similar to our dominant population. The

Fig. 13. Geochemical plots for the Early Carboniferous Čamlıkaya and Narlık granites. (a) P–Q diagram of Debon & Le Fort (1983); (b) A/CNK v. A/NK diagram (Shand 1943); (c) Y v. Sr–Y and (d) Yb, v. (La–Yb), diagram of Defant & Drummond (1990).
source of the Cambrian igneous and metamorphic zircons could thus be equated with the pre-Devonian units of the Bitlis Massif, which has affinities with the Arabian–Nubian Shield (Üstao¨mer et al. 2009, 2012). Early Cambrian granitic magmatism has also been described from the Variscan basement of eastern Crete (Romano et al. 2004, 2006) and the Sandıklı region of the western Turkey (Gürsu et al. 2004).

Mid-Ordovician (c. 473 Ma) magmatism is known in the Armutlu Peninsula and the Tavsınlı Zone (Okay et al. 2008a, b; Özbey Üçtaş et al. 2010; Özbey et al. 2013), part of the HP/LT-metamorphosed Anatolides (Okay 2002). However, Ordovician metamorphism is so far unknown in Turkey.

**Constraints on Variscan metamorphism**

Zircons from the Karadag paragneiss as a whole and a few grains from the Narlık schist exhibit inherited cores with pale grey rims. The Th–U ratios of rims (97 rim analyses) range from 0.0 to 0.66, of which nearly half (45 rim analyses) exhibit ratios of

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**Fig. 14.** (a) ORG-normalized spidergram of the Narlık and Çamlıkaya granites. The normalizing factors are from Pearce et al. (1984). (b) Chondrite-normalized REE spidergram of the Narlık and Çamlıkaya granites. The normalizing factors are from Boynton (1984).
<0.10, which is compatible with a metamorphic origin (Rubatto 2002). The concentrations of Th and U in zircons are influenced by element availability and also by the partitioning of Th and U between zircon, co-existing minerals, fluids and melts (Harley et al. 2007). High Th–U ratios (0.15–3.2) in metamorphic zircons occur in some high-temperature metamorphic units (Carson et al. 2002; Kelly & Harley 2005; Harley et al. 2007).

We, therefore, envisage that our rim ages should record the duration of regional, high-temperature (i.e. upper amphibolite to granulite facies) Variscan metamorphism (c. 42 Ma).

Was Variscan metamorphism continuous or episodic? To address this question, all of the rim ages are plotted in Figure 17. Each yellow circle represents one rim age. Fully concordant (100%) ages are marked by a red circle, while 1σ errors of these concordant ages are shown as red bars. CL images of 100% concordant-aged zircons are also shown. Using the most concordant age data, two periods of metamorphism (grey bands) can be distinguished, separated by a long time gap. The most concordant age data from each period yields concordia ages of 334 ± 3.2 and 314.8 ± 3.9 Ma, respectively. The ‘earlier metamorphism’ could record peak Variscan metamorphism, whereas the ‘later metamorphism’ may reflect exhumation.

The age of the adakite-like Çamlıkaya pluton lies in an apparent time gap within the ‘earlier metamorphism’ field. This granite might relate to delamination of a subducting slab following peak Variscan high-temperature metamorphism (c. 334 Ma).

For comparison, the age of the Sakarya Zone Carboniferous magmatism is plotted as black rectangles, with the black bars representing 1σ errors (Fig. 17). The ages of these granites (325–320 Ma) lie in a gap between the ‘earlier metamorphism’ and the ‘later metamorphism’. Zircon growth apparently stopped during this period of melt...
emplacement into the crust, possibly owing to changes in pressure and temperature conditions during exhumation. The Late Carboniferous shallow-marine and continental sediments in the Demirizü area of the central Eastern Pontides (Fig. 18) contain granitic pebbles and metamorphic detritus (Okay & Şahintürk 1997; Okay et al. 1997; our unpublished data) that could have been derived from partially exhumed Variscan granites and their host metamorphic rocks.

**Age of amphibolites and gabbro-diabase dykes**

The amphibolites of the Demirkent Intrusive Complex (Ustaömer & Robertson 2010) are older than the 325 U–Pb age of the crosscutting granitic veins. The gabbro-diabase dykes, intruding the amphibolites and crosscutting granitic veins, on the other hand, are older than the U–Pb age (179 Ma) of the intruding Kölik granite. The emplacement age of the extension-related gabbro-diabase dykes is, therefore, bracketed between 325 and 179 Ma (post-Visean to pre-Toarcian).

**Regional comparisons**

**Variscan magmatism and metamorphism in the eastern Pontides**

Metamorphic units and early Carboniferous granites are exposed elsewhere in the central eastern Pontides, specifically the Gümüşhané area, as shown in Figure 18 (Okay & Şahintürk; 1997; Topuz & Altherr 2004; Topuz et al. 2004a, b, 2007, 2010; Dokuz 2011; Dokuz et al. 2011). Two different types of metamorphic units are exposed in the Gümüşhané area. First, high-temperature metamorphics (Pulur metamorphics; ≥820 °C, 0.7–0.8 GPa) are exposed above a sole thrust that can be traced northeastwards as far as the Yusufeli area, where high-temperature metamorphics rocks are exposed in a similar structural position. Low-temperature metamorphics (Kurtog˘lu metamorphic complex; 650 °C, 0.4 GPa; Topuz et al. 2007; Topuz & Okay 2009) in the Gümüşhané area are mainly confined to the margins of the large Gümüşhané and Köse composite plutons that are exposed in the eastern Pontide autochthon to the north. Low-temperature metamorphics also occur in a small tectonic window beneath the Pulur metamorphics. Small ultramafic blocks or slices are associated with these low-temperature metamorphics (Dokuz et al. 2011). A tectonic sliver of phyllite and meta-sandstone, plus blocks of meta-diabase and serpentinite, occur at the structurally lowest position of the Kurtog˘lu metamorphic complex (Topuz et al. 2007, 2009). The presence of blueschist facies metamorphism is
indicated by the high silica content of mica in the phyllites and the pumpellyite–blueschist facies mineral assemblage of an associated meta-diabase. Similarly, the low-temperature metamorphic rocks of the Yusufeli area are confined to the margins of the Narlık granite, which is exposed within the Lower Slice Complex (above the eastern Pontide autochthon).

The early Carboniferous ages of the granites in both the Gümuşhane and Yusufeli areas are similar when analytical errors are taken into account. The large granitic plutons are exposed in the eastern Pontide autochthon, whereas only small granitic veins of this age are known within the overlying thrust sheets in the Yusufeli area.

U–Pb protolith zircon age data are not yet available for the low-temperature metamorphic units of the Gümuşhane area. Preliminary detrital zircon ages for the metaclastics of the blueschist unit have been reported. The youngest detrital zircon age is 560 Ma (Topuz et al. 2009), similar to the youngest detrital zircon age (568 Ma) from the meta-clastic Narlık schists. However, insufficient lithological and chemical information exists to correlate the Narlık schists of the Yusufeli area with the blueschist unit of the Gümuşhane area.

The age of peak metamorphism of the Pulur metamorphics is c. 330 Ma, based on $^{40}$Ar–$^{39}$Ar dating of high-temperature metamorphic rocks, with exhumation following at c. 310 Ma (Topuz & Altherr 2004; Topuz et al. 2004a, b). These ages are identical (within analytical uncertainty) to ours (334 and 314 Ma) based on U–Pb zircon dating of zircons from the high-temperature metamorphic rocks of the Yusufeli area.

**Variscan magmatism and metamorphism of the Transcaucasus**

Several pre-Early Jurassic metamorphic and igneous units include the Dzirula, Khrami and Loki crustal units in the Transcaucus (Fig. 1). These units record Late Neoproterozoic–Cambrian and Variscan tectono-thermal events (Zakariadze et al. 2007; Somin 2011; Adamia et al. 2011a). The oldest units, dated at 750–540 Ma by the Sm–Nd isochron method (Zakariadze et al. 2007), are basic...
meta-igneous and meta-sedimentary rocks that are intruded by arc-type gabbro-diorite-quartzdiorite plutons. U–Pb dating of the rims of 540 Ma zircons from a granodiorite in the Dzirula massif gave ages clustering around 330 Ma (Treloar et al. 2009). High-temperature metamorphism was dated at 330 Ma using zircon and monazite from a paragneiss. High-K, I-type calc-alkaline plutons also gave U–Pb ages of 330 Ma. The high-temperature metamorphism was driven by the emplacement of the above granites, according to Treloar et al. (2009). 40Ar–39Ar dating of various metamorphic and igneous units in the Transcaucasian massifs has yielded similar results (Rolland et al. 2011). Variscan metamorphism in the Transcaucasian massifs is dated at 329–337 Ma, followed by igneous activity of late Carboniferous to Mid-Permian age (303–265 Ma) and some Early Jurassic migmatite ages (183 Ma). In summary, the ages of the Variscan metamorphism and magmatism elsewhere in the Eastern Pontides and in the Transcaucasus are similar to our results from the easternmost Pontides (Yusufeli area).

Any regional interpretation needs to take account of the fact that our new detrital zircon age data for both the low- and the high-temperature metamorphic rocks do not indicate the existence of any detrital source from a known Eurasian-derived terrane.

**Tectonic setting of Variscan metamorphism and magmatism**

In one interpretation the Variscan metamorphism and magmatism in the Pontides, Transcaucasus and the Balkan regions took place along the southern margin of Eurasia, with Palaeotethys to the south (Stocklin 1974; Adamia et al. 1977, 1981, 1995; Robertson & Dixon 1984; Dercourt et al. 1986, 1993; Robertson et al. 1996, 2004; Stampfli et al. 2001, 2002; Stampfli & Borel 2002; Stampfli...
The rifting of continental fragments from Gondwana took place in response to plume activity or slab pull, followed by northward drifting until these fragments finally accreted to Eurasia. Specifically, an elongate ‘ribbon continent’, encompassing the Pontides and the Trana- Caucasus, rifted from Gondwana during the Early Palaeozoic and drifted northwards until it accreted to Eurasia during Late Palaeozoic time (Carboniferous). In one scenario the collision was associated with the partial closure of a related backarc marginal basin (Dizi basin), although this is not believed by some to have finally closed until Cenozoic time (Adamia et al. 2011b). In another, the Variscan high-temperature metamorphism can be explained by rifting of a magmatic arc that was located adjacent to the Eurasian margin (Rolland et al. 2011). In this case high-temperature metamorphism could, in principle, have been achieved without a collisional event.

In a more complex interpretation, also involving northward subduction, several different Gondwana-derived continental blocks accreted to the southern margin of Eurasia, represented by the East European Platform. The accretion took place during the Carboniferous–Permian closure of the Rheic ocean to create a Cordilleran-type orogen (Euxinus Orogen). Granitic magmatism along the south-Eurasian continental margin was again related to subduction (without continental collision) in this interpretation (Nikishin et al. 2011). The concept of the Pontides as being made up of different continental blocks or terranes is indeed supported by the existence of several contrasting tectonic units, including the İstanbul terrane and the combined Central Sakarya–Yusufeli terrane (Göncüoğlu et al. 1997, 2000; Okay & Tüysüz 1999; Ustaömer et al. 2011, 2012a; Aysal et al. 2012).

In a different interpretation, subduction was exclusively southwards (Şengör & Yılmaz 1981; Şengör 1984; Şengör et al. 1984; Göncüoğlu et al. 1997, 2000). The absence of a Eurasian signature in the detrital zircon ages is indeed consistent with a southward subduction model, as suggested for the wider region by several authors (Romano et al. 2004, 2006; Zulauf et al. 2007; von Raumer & Stampfli 2008; Robertson & Ustaömer 2009a, b; see Robertson 2012). In this case the Late Palaeozoic arc and its continental basement rifted from Gondwana and drifted northwards related to continuing southward subduction until collision with Eurasia took place prior to Permian time. Against this, there is no evidence of a Palaeotethyan suture to the north of the East Pontide arc.

A further published model for the area studied postulates a combination of northward and southward subduction of the Rheic ocean in the NE Pontides region (Dokuz et al. 2011). The authors provide an explanation for the low-temperature metamorphism in the north v. the high-temperature metamorphism in the south of the area and also for the intrusion of the granitic batholiths exclusively into low-temperature metamorphic rocks. The Variscan orogeny is seen as taking place along the northern margin of Gondwana during Early to Late Carboniferous time in response to collision with a Eurasian-derived continental fragment. The crustal fragment supposedly rifted from Eurasia during the early Devonian, opening a Palaeotethyan ocean in its wake. The fragment driftedsouthwards to collide with an inferred intra-oceanic trench during the early Carboniferous, resulting in low-temperature metamorphism, followed finally by collision with Gondwana. The Carboniferous granitic magmatism was triggered by delamination and slab-breakoff in this interpretation. Palaeotethys was necessarily located to the north of the Variscan orogen in this interpretation.

There are three main problems with the above interpretation of Dokuz et al. (2011). First, the main provenance of the meta-sediments should be their inferred Eurasian rifted fragment. However, a Eurasian (e.g. Baltican) signature is absent from our data set. As noted above, the zircon populations of our two meta-sedimentary samples are also incompatible with an Avalonian origin. The data are, however, consistent with an origin in north-eastern Gondwana. Secondly, there is no evidence for the existence of the two implied amalgamated crustal units in the eastern Pontides. Thirdly, there is no evidence of Palaeotethys having been located to the north of the Variscan orogen, as noted above.

Finally, Topuz et al. (2010) view Early to Late Carboniferous magmatism in the Sakarya Zone and Caucasus generally as a late-stage phase of Variscan orogeny in the Eastern Mediterranean region, although without giving further details.

Our present working hypothesis is that the continental fragment represented by our study area in the easternmost Pontides rifted from NE Gondwana during the Early Palaeozoic and drifted northwards towards the Eurasian margin during Early–Late Carboniferous time.

**Variscan tectono-thermal processes**

Any viable interpretation needs to explain the origin of the arc-type granitic magmatic rocks and the process by which the intruded terrigenous country rocks were metamorphosed. In principle, the metamorphism could have taken place in the roots of an Andean-type magmatic arc unrelated to continental collision, for example during back-arc rifting. For the Caucasus, Rolland et al. (2011) envisage a long-lived active margin history related to
northward subduction along the southern margin of Eurasia (without continental collision). Comparable high-temperature metamorphic rocks are, for example, known in the roots of emplaced active margin magmatic arcs, as reported from the Karakorum Mountains in Pakistan (Rolland et al. 2001; Petterson & Michael 2011), the intra-oceanic Kohistan arc, also in Pakistan (Rolland et al. 2000; Garrido et al. 2006) and Hokkaido, in Japan (Kemp et al. 2007).

Alternatively, the metamorphism could reflect a collisional setting, followed by exhumation, partial melting and granite intrusion. A continental collision setting has been suggested for the Variscan metamorphism and magmatism in the eastern Pontides (Topuz & Okay 2009), and is also suggested for the Carboniferous granitic rocks of northern Greece (Kotopouli et al. 2000) and the Balkans generally (see Pe-Piper & Piper 2002; Robertson 2012). The apparent onset of metamorphism (c. 350 Ma) prior to granitic magmatism (c. 330 Ma) is consistent with the collision-related hypothesis. In this case, the inferred continental fragment rifted from Gondwana, drifted northwards and collided with the Eurasian margin, where it was deeply buried and regionally metamorphosed. The granitic melts were generated during exhumation. The main argument against this interpretation is the absence of a Eurasian signature in our paragneiss samples. However, a collided continental fragment could have remained topographically isolated from Eurasian-derived detritus. It is interesting to note that the intra-oceanic Kohistan arc in Pakistan is known to have docked with Eurasia during Late Cretaceous time yet its Cenozoic sedimentary cover contains locally derived, rather than Eurasian, arc detritus (Sullivan et al. 1993).

In addition, the timing of Variscan metamorphism reported here is similar to that given for the Internal Variscides of central Europe (e.g. Moldanubian domain; see Dörr & Zulauf 2010). It is thus possible that the Variscides from Central Europe in the west to the Caucasus in the east were formed more or less simultaneously by processes involving subduction and collision of peri-Gondwana terranes with the southern margin of Eurasia.

**Jurassic magmatism**

Three different Jurassic granites were dated during this study. The first is a granitic dyke (156.3 ± 2 Ma) intruding the early Carboniferous Çamlıkaya pluton. The other two are the Kölik (179 ± 1.2 Ma) granite and the Sinevrat (173.6 ± 2.6 Ma) granite that intrude the Demirkent Intrusive Complex. Similar ages have been reported from granitic rocks in the Yusufeli area (Dokuz et al. 2010).

The Jurassic granitic rocks have been explained according to either southward or northward subduction models. The Dutlupınar granite (188.3 ± 4.3 Ma) has been interpreted as a rift-related intrusion above a southward-subducting Palaeotethys. In contrast, the Jurassic Keçikaya pluton (153 ± 3.4 Ma) has been suggested to relate to Late Jurassic slab-breakoff following Mid-Jurassic suturing of Palaeotethys (Dokuz et al. 2010). Problems with the southward subduction model include palaeomagnetic data that positions the eastern Pontides at c. 40° N palaeolatitudes; that is, within the south Eurasian continental margin during the Jurassic (Channell et al. 1996). There is no reported evidence of Mid-Jurassic collisional orogeny from the eastern Pontides (Okay & Şahin-türk 1997; Koçyiğit & Altın 2002; Ustaömer & Robertson 2010). The geological evidence is instead indicative of extension-related regional subsidence during the Late Jurassic. The extension relates to the opening of a narrow intra-continental margin basin along the southern margin of Eurasia (İrmakyanı basin; Ustaömer & Robertson 2010). This basin closed owing to some still unknown event during Late Jurassic (pre-Oxfordian) time (e.g. collision of a seamount or continental fragment). This was followed by the re-establishment of a northward-dipping subduction beneath the active continental margin of Eurasia until the Mesozoic ocean (c. İzmir-Ankara-Erzincan ocean) finally closed during the Early Cenozoic.

**Conclusions**

U–Pb dating of zircon separated from the six granitic intrusions and two meta-sedimentary units sheds light on the timing and processes of sedimentation, magmatism and metamorphism in the classic, well-exposed easternmost Pontide region (Yusufeli-Artvin). Two meta-sedimentary units (Narlık schist and Karadag paragneiss) yielded detrital zircon populations of 0.50–0.65 and 0.9–1.1 Ga, suggesting an affinity with the NE African part of Gondwana.

The depositional age of the paragneiss is bracketed as Mid-Devonian to early Carboniferous based on the youngest concordant zircon age in the paragneiss and the age of the cross-cutting metagranite.

The metamorphic rims of zircon cores in the paragneiss are Carboniferous (345–310 Ma).

The age data from the zircon rims indicate two Variscan metamorphic events (334 and 314 Ma), separated by a hiatus (320–325 Ma).

The crystallization age of the early Carboniferous granites (c. 325 Ma) corresponds to a hiatus in the zircon age data that could reflect subduction slab-breakoff.
Granite emplacement again took place during Early Jurassic and Late Jurassic phases.

In our tectonic interpretation the study area in the NE Pontides originated as a Gondwana-derived terrane that drifted northwards to a position near Eurasia where this crustal unit was intruded by Carboniferous (c. 330 Ma) granites. High-temperature metamorphism is likely to have taken place in the roots of the magmatic arc rather than related to continental collision. The Jurassic granitic magmatism then relates to the formation of an extensional intra-continental marginal basin along the south Eurasian margin during northward subduction of the Izmir–Ankara–Erzincan ocean.

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