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Zircon age constraints on sediment provenance in the Caspian region

MARK B. ALLEN[1,2], ANDY C. MORTON[3,4], C. MARK FANNING[5], ARIF J. ISMAIL-ZADEH[6] & SALOMON B. KROONENBERG[7]

[1]*CASP, Department of Earth Sciences, University of Cambridge, 181A Huntingdon Road, Cambridge CB3 0DH, UK*
[2]*Present address: Department of Earth Sciences, University of Durham, Durham DH1 3LE, UK*
(e-mail: m.b.allen@durham.ac.uk)
[3]*HM Research Associates, 2 Clive Road, Balsall Common CV7 7DW, UK*
[4]*University of Aberdeen, Department of Geology and Petroleum Geology, Aberdeen AB24 3UE, UK*
[5]*Australian National University, Research School of Earth Sciences, Canberra, A.C.T. 0200, Australia*
[6]*Geology Institute of the Azerbaijan Academy of Sciences, 29A H. Javid Prospect, Baku, Azerbaijan*
[7]*Delft University of Technology, Department of Applied Earth Sciences, Mijnbouwstr. 120, NL-2628 RX Delft, Netherlands*

Abstract: Sensitive high-resolution ion microprobe (SHRIMP) U–Pb ages for detrital zircons from the Caspian region reveal the age ranges of basement terrains that supplied the sediment. One sample from the modern Volga river has groupings at *c.* 340–370 Ma, *c.* 900–1300 Ma and *c.* 1450–1800 Ma, with a small number of older zircons. This is consistent with derivation from the Precambrian basement of the East European Craton, and Palaeozoic arcs in the Urals. Mid- and Late Proterozoic components may be derived from beyond the present Volga drainage basin, such as the Sveconorwegian orogen. A Bajocian sandstone from the Greater Caucasus has 73% zircons that post-date 350 Ma. Ages cluster at *c.* 165–185 Ma, *c.* 220–260 Ma, *c.* 280–360 Ma and *c.* 440–460 Ma. This pattern suggests derivation from Palaeozoic basement of the Greater Caucasus itself and/or the Scythian Platform, and igneous rocks generated at a Jurassic arc in the Lesser Caucasus. Four samples from the Lower Pliocene Productive Series of the South Caspian Basin have common Phanerozoic grains, and groups between *c.* 900–1300 Ma and 1500–2000 Ma. Each sample contains zircons dated to *c.* 2700 Ma. The overall age patterns in the Productive Series samples suggest a combination of East European Craton and Greater Caucasus source components.

This paper presents the first detrital zircon provenance data for one of the world's major rivers (Volga), mountain belts (Greater Caucasus) and thickest sedimentary basins (South Caspian). These data help define the sediment provenance patterns of the modern Volga and its Pliocene forerunner, the Palaeo-Volga. They also help understand the crustal evolution of the sediment source regions: the East European Craton and neighbouring orogenic belts of the Urals and Greater Caucasus.

U–Pb ages of detrital zircons provide insights into the provenance of clastic successions in sedimentary basins. In ancient basins, this gives information on sediment pathways that may not be available by other means, such as palaeocurrent studies (Berry *et al.* 2001). In modern river systems, the age data improve understanding of the basement terrains that directly or indirectly supplied the sediment (Cawood *et al.* 2003). This paper uses both approaches, by presenting U–Pb ages for detrital zircons from: (1) a sample of modern river sand from the Volga river; (2) a Mesozoic (Bajocian) sandstone from the eastern Greater Caucasus; (3) four sandstones from the Pliocene Productive Series of the Apsheron Peninsula, Azerbaijan (two from the Kirmaky Suite and two from the Balakhany Suite; Figs 1 and 2). These analyses characterize the provenance of sediment in the modern Volga and the Pliocene Palaeo-Volga, which terminated several hundred kilometres south of the modern Volga delta, in the interior of the South Caspian Basin (e.g. Reynolds *et al.* 1998). No 'exotic' age ranges are identified in the age spectra that cannot be matched to one or more of the known basement provinces around the East European Craton. There are also known crustal segments that are not represented in our data, such as the *c.* 3.5 Ga crust of Sarmatia. The Greater Caucasus zircons reveal the age and nature of the sediment sources for the Mesozoic depocentre in this region: there is little evidence for involvement of the Precambrian basement of the East European Craton. The Greater Caucasus data also reinforce the idea that this range was a sediment source for the South Caspian Basin during its rapid Pliocene–Quaternary subsidence.

Geological background

The modern Volga river delivers sediment into the Caspian Sea from a drainage basin *c.* 1.38×10^6 km^2 in area (Kroonenberg *et al.* 1997; Fig. 1). Most of the bedrock across this area consists of Phanerozoic sediments that form the cover to the East European Craton. The basement to this succession belongs to three main blocks that accreted to each other to form the craton in the Early Proterozoic: Fennoscandia, Sarmatia and Volgo-Uralia (Bogdanova 1993; Gorbatschev & Bogdanova 1993; Claesson *et al.* 2001; Fig. 1). Basement is exposed in the Baltic and Ukrainian shields (Fig. 1), which contain large areas of late Archaean crust. The Sarmatian province is distinctive for Archaean crust of *c.* 3.5–3.6 Ga, which is not found in Fennoscandia or Volgo-Uralia (Bibikova & Williams 1990; Shchipansky & Bogdanova 1996). Most of the Volga drainage basin lies within the Volgo-Uralia segment, but the only exposures of Precambrian rocks in this region are along the western side of the Urals (Puchkov 1997). Here there is structural and geochronological evidence for both Mid- and Late Proterozoic orogeny, affecting a thick sedimentary succession at the craton margin (Glasmacher *et al.* 2001). At the

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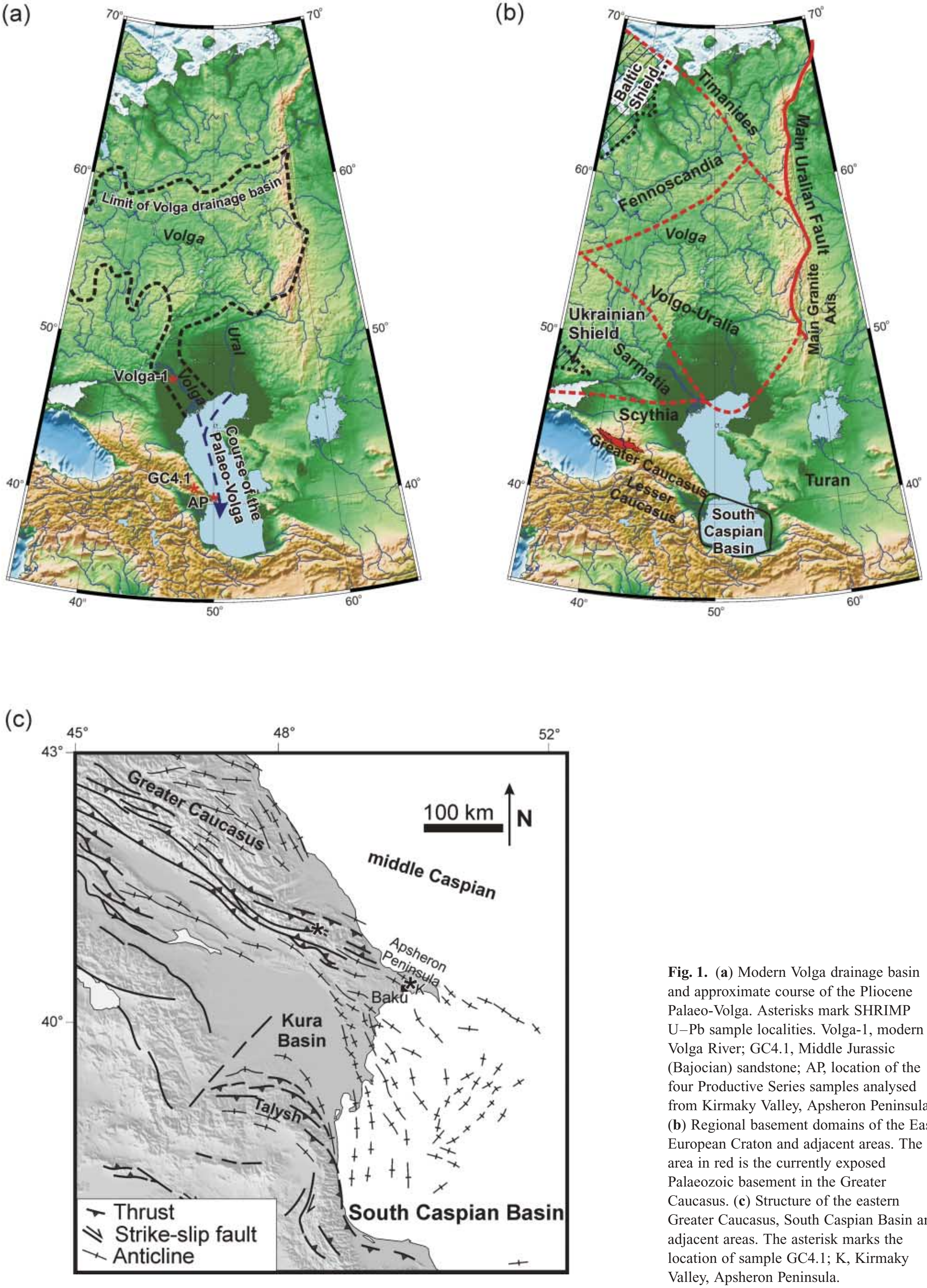

Fig. 1. (**a**) Modern Volga drainage basin and approximate course of the Pliocene Palaeo-Volga. Asterisks mark SHRIMP U–Pb sample localities. Volga-1, modern Volga River; GC4.1, Middle Jurassic (Bajocian) sandstone; AP, location of the four Productive Series samples analysed from Kirmaky Valley, Apsheron Peninsula. (**b**) Regional basement domains of the East European Craton and adjacent areas. The area in red is the currently exposed Palaeozoic basement in the Greater Caucasus. (**c**) Structure of the eastern Greater Caucasus, South Caspian Basin and adjacent areas. The asterisk marks the location of sample GC4.1; K, Kirmaky Valley, Apsheron Peninsula.

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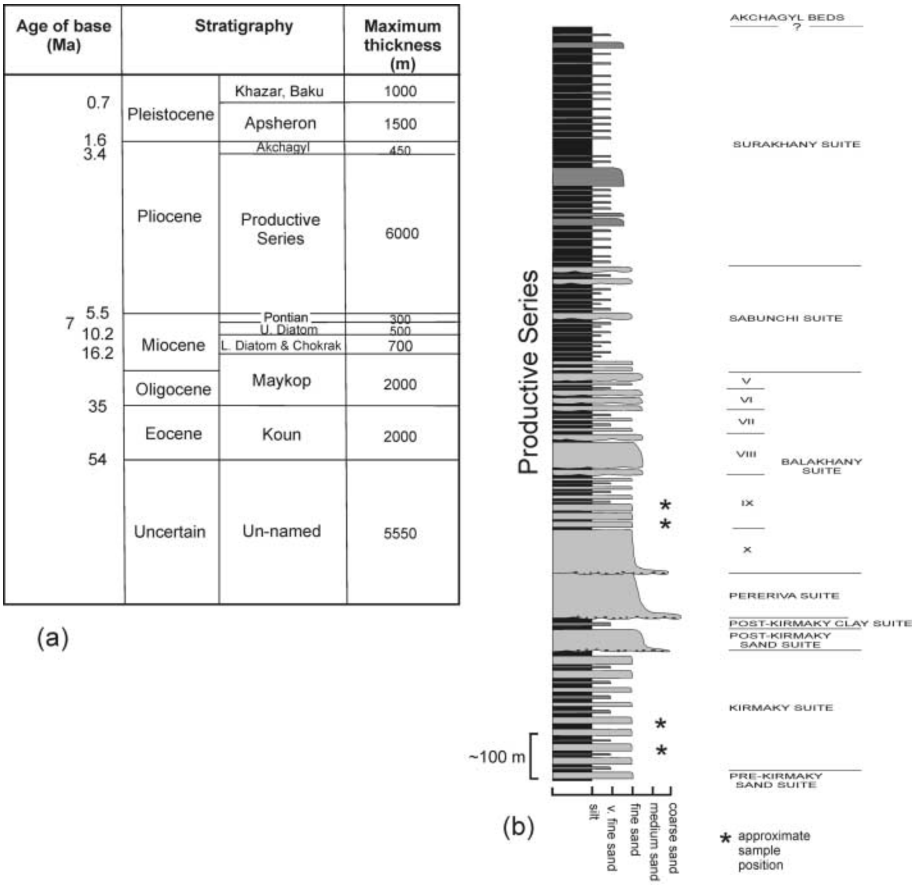

Age of base (Ma)	Stratigraphy		Maximum thickness (m)
0.7	Pleistocene	Khazar, Baku	1000
1.6		Apsheron	1500
3.4	Pliocene	Akchagyl	450
5.5		Productive Series	6000
7	Miocene	Pontian	300
10.2		U. Diatom	500
16.2		L. Diatom & Chokrak	700
35	Oligocene	Maykop	2000
54	Eocene	Koun	2000
	Uncertain	Un-named	5550

Fig. 2. (**a**) Stratigraphic summary of the South Caspian Basin. From Allen *et al.* (2002). (**b**) Stratigraphy of the Productive Series, showing the stratigraphic position of samples analysed in this study. From Hinds *et al.* (2004).

eastern side of the craton, Palaeozoic volcanic rocks, granitoids, ophiolites and metasediments of the Urals, east of the Main Uralian Fault, record the accretion of arcs to the craton in the late Palaeozoic. Phanerozoic sediments deposited across the craton are presumably derived from a combination of the Precambrian basement blocks and the Uralian orogenic belt, but there are few provenance details based on radiometric age dating. Tectonic subsidence across the craton was generated by a combination of episodic rifting events, such as the late Palaeozoic Dneiper–Donets rift, and subsequent regional thermal subsidence (Nikishin *et al*. 1996).

To the south of the East European Craton, the Scythian Platform extends to the northern side of the Greater Caucasus. The geology of the Scythian Platform includes a stable, mixed clastic and carbonate succession deposited in the Mesozoic over basement that is poorly known, but apparently largely juvenile Palaeozoic crust (Şengör & Natal'in 1996). This geology continues across the Central Caspian Basin into the Turan Platform to its east (Garzanti & Gaetani 2002). Jurassic extension in the Greater Caucasus took place in a back-arc setting, north of one or more north-dipping subduction zones. Magmatism associated with subduction is principally located in the Lesser Caucasus, but there are also Jurassic volcanic rocks within parts of the Greater Caucasus, associated with the thick clastic sequences deposited during extension (Nalivkin 1983; Hess *et al*. 1995). Parts of the Greater Caucasus remained as depocentres until the late Cenozoic, when compressional deformation created by the Arabia–Eurasia collision uplifted the range. At present, basement (gneisses and granitoids) is exposed in the interior of the west of the mountain belt (Fig. 1). This basement is supposed to have been largely generated and deformed during the late Palaeozoic, during events grouped as 'Variscan'. There are few precise age constraints in the international literature; late Carboniferous (*c*. 298 Ma) two-mica granites, tonalites and granodiorites (Hanel *et al*. 1992), are dated by a combination of Rb/Sr, K/Ar and ^{40}Ar/^{39}Ar methods.

The South Caspian Basin is adjacent to the eastern end of the Greater Caucasus, and underlies roughly the southern third of the present Caspian Sea (Fig. 1). It has basement with the geophysical properties of either unusually thick oceanic crust or thin, high-velocity continental basement (Mangino & Priestley 1998). This basement is overlain by as much as *c*. 20 km of sediments. The age and origin of the basement is not certain, although there is a general consensus that it formed by back-arc extension to a Neotethyan subduction zone at some time between the Jurassic and early Tertiary (Brunet *et al*. 2003). Roughly half of the sediment thickness has accumulated in the last *c*. 5.5 Ma, i.e. in one-tenth or less of the lifespan of the basin (Fig. 2). This is interpreted to be the result of incipient subduction of the basement beneath the northern and western basin margins (Allen *et al*. 2002; Jackson *et al*. 2002), possibly combined with overthrusting from the southern and eastern margins (Axen *et al*. 2001; Allen *et al*. 2003). As much as 6 km of sediment was deposited in the basin in the early Pliocene alone, in the Productive Series and its lateral equivalents. These clastic rocks were deposited in a mixture of fluvial, lacustrine and deltaic environments (Reynolds *et al*. 1998; Hinds *et al*. 2004), after the Messinian salinity crisis isolated the basin from the open ocean system (Jones & Simmons 1997). The Productive Series is divided into suites in the Russian/former Soviet Union terminol-

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ogy, each of which is roughly equivalent to a formation in international usage (Fig. 2).

Conventional and geochemical heavy mineral studies of Productive Series sandstones from outcrops in the Aspheron Peninsula area of Azerbaijan have indicated the involvement of two provenance components. One of these components is characterized by high garnet:zircon ratios (GZi), high rutile:zircon ratios (RuZi) and high chrome spinel:zircon ratios (CZi), the other being characterized by low GZi, RuZi and CZi (Morton *et al*. 2003). Interplay of these two provenance components has generated the range of mineralogies shown in Figure 3. Data from sediment transported by rivers at present draining the Greater Caucasus, and from Mesozoic sandstones that crop out in the Greater Caucasus, fall at the low GZi, low RuZi and low CZi end of this mixing trend, suggesting that the Greater Caucasus was the source of the low GZi, low RuZi, low CZi component. Although modern Volga sand has relatively high GZi, RuZi and CZi, the Volga samples fall within the Productive Series data array, rather than the extreme high end of the mixing trend. The modern Volga sediments have garnet geochemical populations that are comparable with those of the Productive Series (Morton *et al*. 2003). The available information is interpreted as indicating that the high GZi, high RuZi, high CZi end-member was supplied by the Palaeo-Volga. The Palaeo-Volga had subtly different provenance characteristics from the modern Volga, possibly because of unroofing or reworking of glacial deposits, or input from rivers such as the Ural (Fig. 1), which presumably joined the Palaeo-Volga but remains distinct from the modern Volga. Our study does not include Productive Series or equivalents from region of the South Caspian Basin supplied by rivers other than the Palaeo-Volga, such as the Palaeo-Kura and Palaeo-Amu Darya, which were the predecessors of the modern Kura and Amu Darya rivers, respectively.

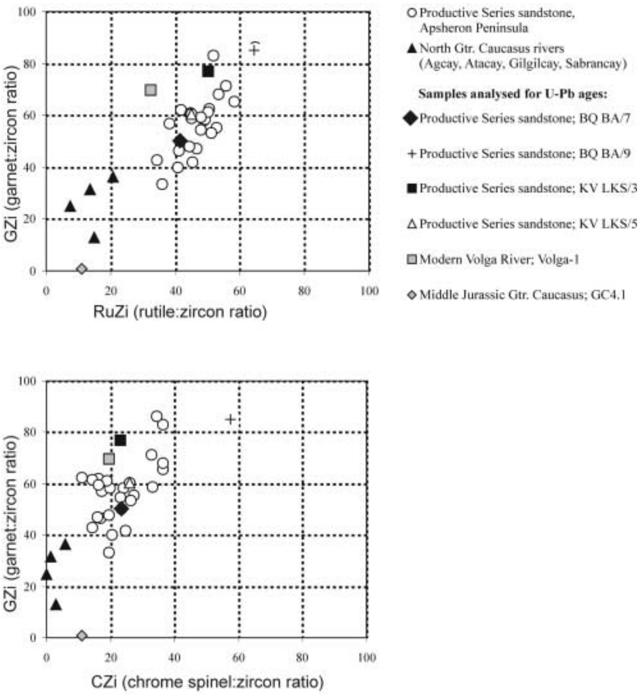

Fig. 3. Heavy mineral ratio–ratio plots of the Kirmaky and Balakhany Suite sandstones of the Productive Series of the Aspheron Peninsula, highlighting the samples chosen for zircon age dating, compared with sand transported by rivers draining north from the Greater Caucasus, the Mesozoic sandstone sample GC4.1 (Greater Caucasus) and a sample of modern Volga River sand (Volga-1). Data from Morton *et al*. (2003).

Zircon age dating analytical methods

Where necessary, samples were disaggregated using mortar and pestle, and then washed and cleaned using an ultrasonic probe. Very fine sand (63–125 µm) fractions were separated using standard sieving techniques. Heavy mineral fractions, consisting dominantly of zircon, were obtained using standard density and magnetic separation techniques. Arbitrary, and as far as possible representative, fractions for each sample were poured onto double-sided tape, cast into an epoxy disc, sectioned and polished. Transmitted- and reflected-light photomicrographs, together with cathodoluminescence (CL) images, were prepared for all grains. Examples of zircons from sample GC4.1 are shown in Figure 4.

The U–Pb analyses were undertaken by sensitive high-resolution ion microprobe (SHRIMP) using SHRIMP I and SHRIMP RG at the Australian National University in Canberra. The procedures employed for zircon U–Pb dating followed Williams (1998) and references therein, each analysis consisting of four scans through the mass spectrum, as is the norm for detrital zircon studies. Subjectivity in zircon dating was avoided by analysing all zircons encountered during the traverse of the mount, unless the grain showed evidence of being metamict (i.e. amorphous) or otherwise structurally compromised (i.e. with a core and rim(s) that cannot be separated with the 20 µm diameter spot used). These determinations were made from examination of the reflected- and transmitted-light photomicrographs and CL images. Where a core and rim were present, the rim was analysed. Normalization of Pb/U isotopic ratios was achieved by reference to analyses of the AS3 and FC1 reference zircons (both 1099 Ma: ^{206}Pb/^{238}U $= 0.1589$: Paces & Miller 1993). The raw SHRIMP data were processed using SQUID (Ludwig 2001), with plots generated using Isoplot/Ex (Ludwig 1999). For zircon areas that are older than *c*. 800 Ma, the measured ^{206}Pb/^{204}Pb ratios have been used to correct for common Pb and the radiogenic ^{207}Pb/^{206}Pb ratio used to calculate the preferred age. For zircon areas that are younger than *c*. 800 Ma, correction for common Pb was made using the measured ^{207}Pb/^{206}Pb and ^{238}U/^{206}Pb ratios, giving a radiogenic ^{206}Pb/^{238}U ratio and age following Tera & Wasserburg (1972) as described by Williams (1998). For Neoproterozoic and older zircons, when an analysis is more than 20% discordant it has been excluded from the relative probability plots. For the younger zircons, the validity of the radiogenic ^{206}Pb/^{238}U age has been determined on the basis of a number of factors, including the amount of common Pb (that is, if the total ^{207}Pb/^{206}Pb ratio deviates

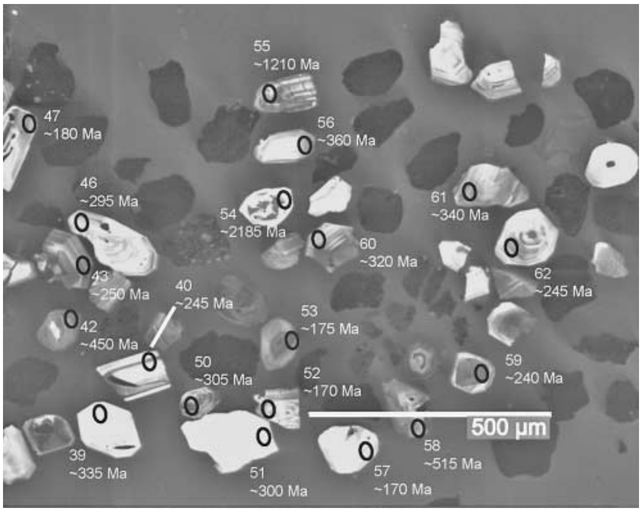

Fig. 4. Cathodoluminesence image of zircons analysed from sample GC4.1 (Jurassic, Greater Caucasus).

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significantly from concordance on the Tera & Wasserburg plot), the relative concentrations of U and Th, the nature of the area analysed when examined post-analysis and the abundance of a particular age grouping. The data are available online at http://www.geolsoc.org.uk/SUP18241 (a hard copy can be obtained from the Society Library), and are presented using combined histogram–relative probability plots (Figs 5 and 6). The data are also plotted on concordia diagrams (Fig. 7) to display the degree of concordance shown by individual zircons.

The U–Pb system in zircons is very stable, and is not affected by processes that operate during the sedimentation cycle or most metamorphism. Consequently, the age of a detrital zircon obtained by SHRIMP represents the original crystallization age, and does not imply that the zircon was derived directly from basement of that age, as it could have been recycled many times. The vast majority of zircons are of intermediate–acidic igneous parentage (Deer *et al*. 1997), although they do also occur rarely in basic igneous rocks and can form during very high grade (granulite- or upper amphibolite-facies) metamorphism.

Zircon age data

Volga river sample (Volga-1)

Volga-1 comes from the present floodplain near Chorny Yar, about 150 km downstream from Volgograd (48°05′N, 46°07′E; Fig. 1). Given the vast area of the Volga drainage basin the age spectrum is predictably wide and diverse, covering the Mesozoic

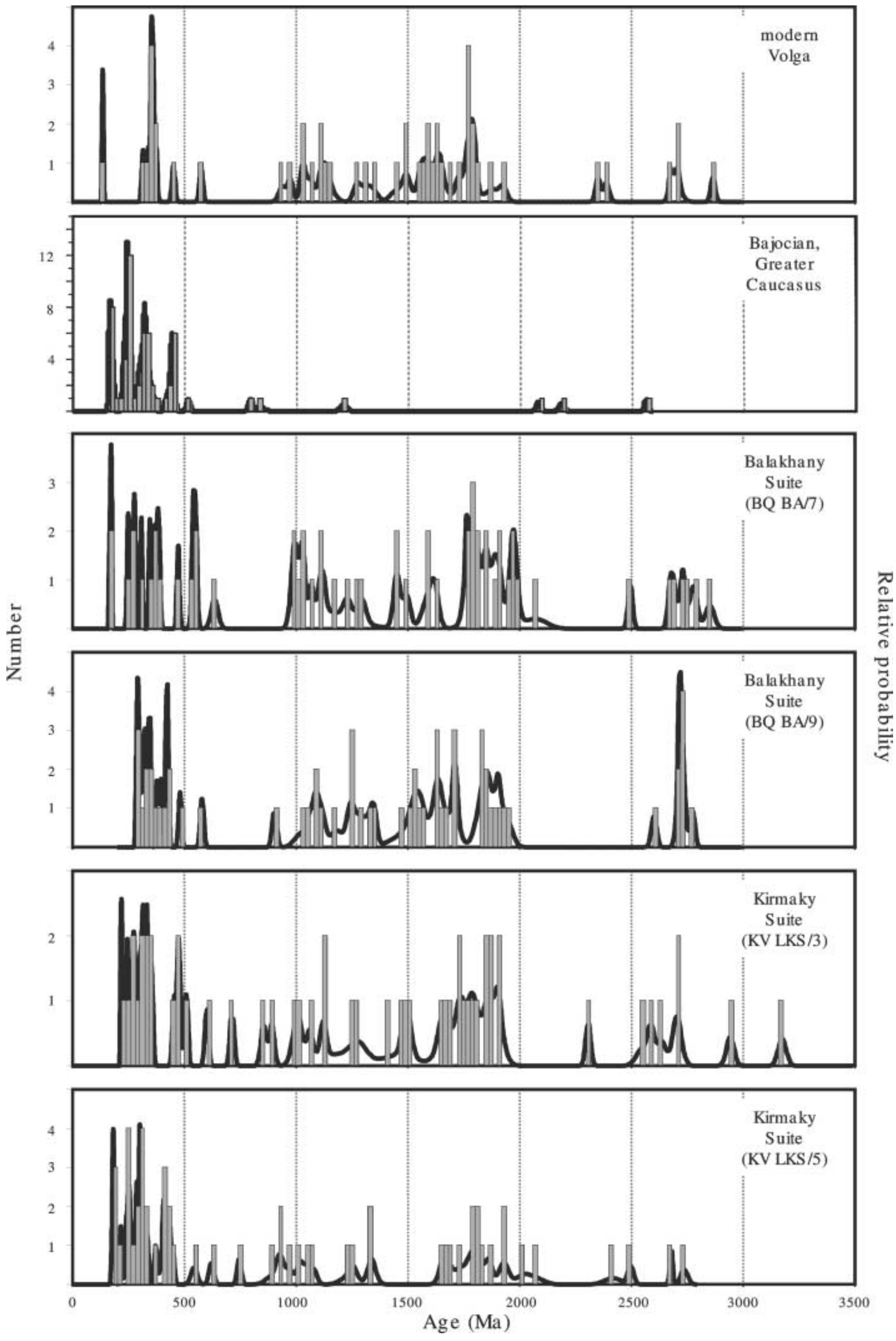

Fig. 5. Combined histogram–relative probability plots showing zircon age spectra for Productive Series samples, Volga river sand and a Mesozoic sandstone from the Greater Caucasus. Histogram bars in the foreground are the absolute number of samples in 20 Ma intervals. Cumulative relative probability is shown in the background.

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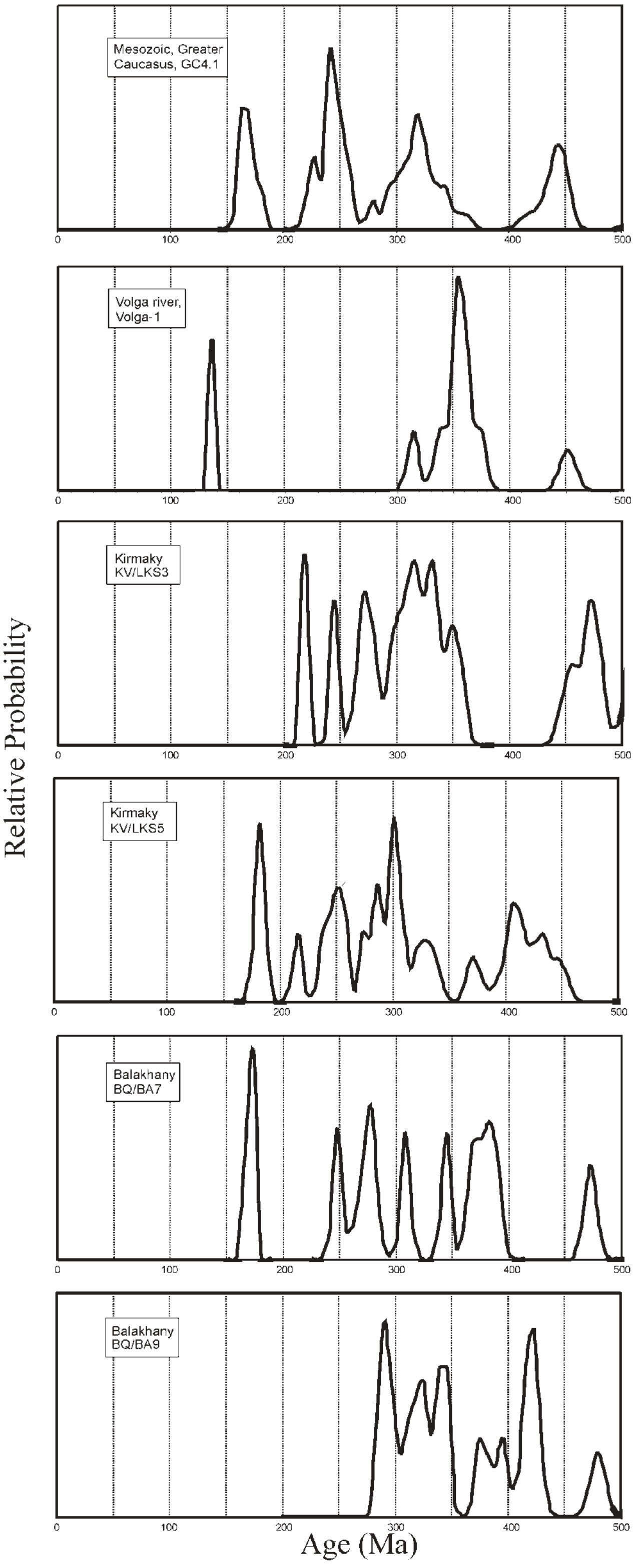

Fig. 6. Relative probability plots for analysed samples, for zircons younger than 500 Ma.

(youngest zircon dated as 135 Ma, Early Cretaceous) to the Archaean (oldest zircon dated as 2865 Ma).

The spectrum contains three main groups of zircon ages (Figs 5 and 6). There is a well-defined group of eight zircons dated between *c*. 340 and 370 Ma (Late Devonian–Early Carboniferous), and two broad groups in the Proterozoic, one between *c*. 900 Ma and *c*. 1300 Ma and another between *c*. 1450 Ma and 1800 Ma. It could be argued that the older of these two groups comprises two separate clusters, but because the age spectrum is wide and diverse and only 53 zircons were analysed, caution against over-interpretation is advisable. There are also some Early Proterozoic and Archaean zircons (six between 2350 Ma and 2865 Ma, with no well-defined structure) together with occasional zircons in the period between *c*. 370 Ma and 900 Ma. Only four of the zircons are dated as younger than 350 Ma.

Greater Caucasus sandstone (GC4.1)

Sample GC4.1 is a Middle Jurassic (Bajocian) sandstone from the eastern Greater Caucasus, Azerbaijan. It was collected at 41°03.21′N, 48°34.81′E (Fig. 1), from a marine turbidite succession. The zircon age spectrum of sample GC4.1 is entirely different from that of the Volga (Figs 5 and 6). The vast majority of the zircons are Phanerozoic, with four distinct clusters being identified. There are nine zircons defining a sharp peak at *c*. 165–185 Ma (Early–Mid-Jurassic), 17 in the range between *c*. 220 and 260 Ma (Late Permian–Triassic), 19 forming the somewhat broader peak between *c*. 280 and 360 Ma (Carboniferous–Early Permian), and seven in the peak between *c*. 440 and 460 Ma (Late Ordovician). There are only five reliably dated older zircons (910 Ma, 1194 Ma, 2082 Ma, 2185 Ma and 2565 Ma). Over 70% of the zircons are younger than 350 Ma, in marked contrast to the Volga sample, which has only 8%.

Productive Series data

All four Productive Series samples come from the Kirmaky Anticline, on the Apsheron Peninsula, at the northwestern side of the South Caspian Basin (Fig. 1). The samples were chosen to investigate whether low GZi and high GZi sandstones have different zircon age spectra, and also to identify any stratigraphic evolution in zircon provenance. The Productive Series samples analysed in the study are KV LKS/3 (Kirmaky Suite, high GZi), KV LKS/5 (Kirmaky Suite, low GZi), BQ BA/7 (Balakhany Suite, low GZi) and BQ BA/9 (Balakhany Suite, high GZi). Heavy mineral data from these samples were presented by Morton *et al*. (2003), and are shown in Figure 3.

The zircon age spectra for the four Productive Series samples have closely comparable patterns (Figs 5 and 6). All four samples have common Phanerozoic grains, an interval between *c*. 500 Ma and *c*. 900 Ma with scarce zircons, a broad group between *c*. 900 Ma and *c*. 1300 Ma, an interval between *c*. 1300 Ma and *c*. 1500 Ma with relatively few zircons, another broad group from *c*. 1500 Ma and *c*. 2000 Ma, and scattered Archaean grains, each sample notably containing zircons dated as *c*. 2700 Ma. There are differences in appearance of the four spectra, mainly in the relative height of the Phanerozoic and Precambrian groups. This is partly an effect caused by the presence of young grains with low error bars. For example, the peak at *c*. 170 Ma in the BQ BA/7 spectrum comprises two zircons dated at 170 ± 3 Ma. However, it is also partly due to variations in abundance of zircons within the different clusters identified above. The significance of these differences is uncertain, as the spectra are complex and defined on the basis of relatively few zircons (maximum of 63).

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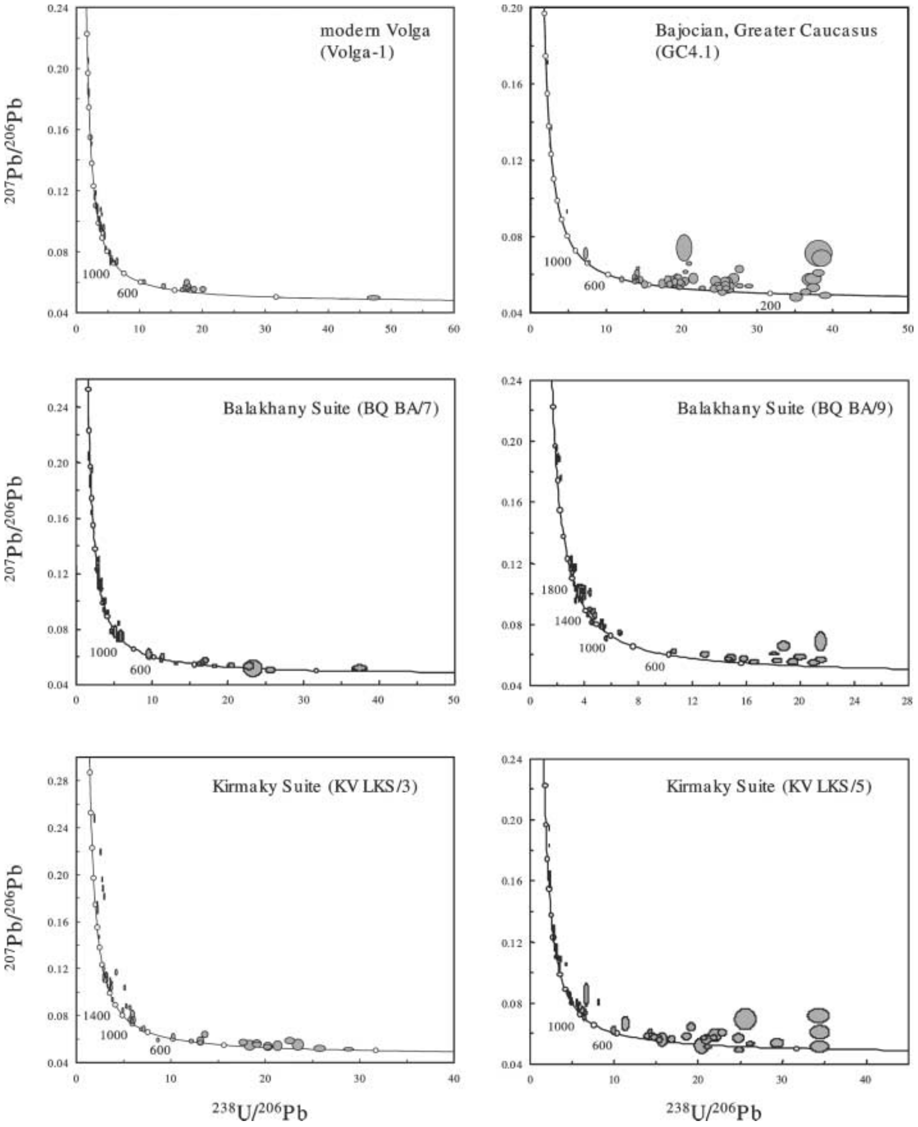

Fig. 7. Concordia diagrams showing zircon isotopic compositions in Productive Series samples, Volga river sand, and a Mesozoic (Bajocian) sandstone from the Greater Caucasus; 1σ error ellipses.

Discussion

Volga

The wide range of Precambrian ages in the Volga river sample is consistent with the polyphase evolution of the East European Craton. No zircons are older than 2865 Ma, which matches the scarcity of Archaean crust of >3 Ga age in Fennoscandia (Gorbatschev & Bogdanova 1993; Puchtel *et al*. 1998). Older crust is present in Sarmatia (e.g. Samsonov *et al*. 1996). The exposed Archaean of Sarmatia lies in the Ukrainian Shield (Fig. 1), and outside the drainage basin of the modern Volga. It does not appear to have contributed significantly to the Phanerozoic deposits of the East European Craton within the drainage basin, although this is a tentative extrapolation, given the relatively low number of samples analysed in this study and the many stratigraphic intervals not covered.

The cluster of ages between *c*. 1450 Ma and 1800 Ma largely post-dates the Svecofennian orogeny between 1.9 and 1.8 Ga (Beunk & Page 2001), but it coincides well with the age ranges of rapakivi and related granitoids around the margins of the Baltic Sea (1.8–1.45 Ga; Claesson *et al*. 2001) and the older parts of the Transscandinavian Igneous Belt along the western side of Fennoscandia (1.86–1.65 Ga; Ahall & Larson 2000; Ahall *et al*. 2000). However, present exposures of such basement are far beyond the present limits of the Volga drainage basin. The cluster of ages in the Volga samples between 900 and 1300 Ma correlates reasonably well with the crust generated during the Sveconorwegian orogeny (Bingen *et al*. 2003), which forms part of the Grenville orogeny. Again, exposed basement with such characteristics lies far from the modern drainage basin. One source of detrital zircons with these various Precambrian age ranges in the Volga river sand is via the Phanerozoic cover of the East European craton. Also, Scandinavian ice sheets repeatedly penetrated well into the Volga drainage basin during the Pleistocene, and would have transported sediment southwards.

It is noteworthy that there are no zircons in the sample Volga-1 dated as mid-Carboniferous to Late Permian. This is the age range of the granites that form the Main Granite Axis of the Urals, generated during the late stages of the Uralian orogeny (Fershtater *et al*. 1997; Puchkov 1997). The late Devonian–early Carboniferous group of zircons (*c*. 340–370 Ma) could have

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been derived from the intermediate–acidic rocks of this age that are widespread in the Urals, formed during subduction along the East European margin prior to the main collision events (Puchkov 1997), but these rocks are juxtaposed against the Main Granite Axis to their east, and the lack of mid-Carboniferous–Permian zircons is therefore surprising. It is possible that this is an effect of drainage patterns, as the rivers that at present drain the Main Granite Axis flow eastwards, rather than into the drainage basin of the Volga. If so, it implies that there has been little or no late Palaeozoic and post-Palaeozoic contribution from these granites to the cover of the East European Craton, otherwise they would be expected to be present in the modern Volga sediment via recycling.

Greater Caucasus, Mid-Jurassic

The rarity of Precambrian zircons in sample GC4.1 is inconsistent with derivation from the Precambrian shields that crop out at the margins of the East European Craton, or the Precambrian belts covered by younger rocks in the craton interior. Although there are peaks in the Palaeozoic, these do not coincide with the spectrum of the Volga sample. The frequency of Mesozoic grains is totally unlike the Volga spectrum. We think it is more likely that the Palaeozoic zircons in the Greater Caucasus sample were derived from the basement of the same region (Hanel *et al.* 1992), exposed during the extension that created the Mesozoic basin (Brunet *et al.* 2003). The Mesozoic zircons in the sample could have been derived from the volcanic rocks in the Greater Caucasus, or volcanic rocks and granites in the Lesser Caucasus.

South Caspian Basin, Productive Series

The patterns identified in the Precambrian of the four Productive Series samples are closely comparable with those seen in the Volga river sand sample, and the zircon data therefore support the heavy mineral evidence for a East European Craton source component in the Productive Series (Morton *et al.* 2003). However, all the Productive Series samples contain a large number of Phanerozoic grains, and in particular they have a large number of zircons younger than 350 Ma. The Kirmaky Suite samples KV LKS/3 and KV LKS/5 have 13/58 zircons (22%) and 19/60 (32%) younger than 350 Ma, respectively, and the Balakhany Suite samples BQ BA/7 and BQ BA/9 have 7/60 (12%) and 9/63 (14%), respectively. These samples therefore have considerably more young zircons than the Volga sample, in which only 4/53 (8%) of the zircons are younger than 350 Ma. By contrast, 44/60 (73%) of the zircons in the Greater Caucasus Mesozoic sandstone GC4.1 are younger than 350 Ma. This strongly suggests that the Greater Caucasus also contributed to the Productive Series throughout its deposition in the Apsheron area, a conclusion also made on the basis of the heavy mineral data (Morton *et al.* 2003). However, there is no correlation between GZi and the proportion of zircons younger than 350 Ma, which would be expected if there was a simple relationship between these parameters and the proportion of sediment derived from the Greater Caucasus.

Conclusions

The Volga zircon population has strong groupings at *c.* 340–370 Ma, *c.* 900–1300 Ma and *c.* 1450–1800 Ma, with a small number of Early Proterozoic and Archaean zircons. These groupings match the ages of Precambrian basement blocks exposed at the margins of the East European Craton and Devonian–Carboniferous magmatic arcs in the Urals. There is little or no obvious contribution from the *c.* 3.5–3.6 Ga Archaean rocks of the Ukrainian Shield or the Carboniferous–Permian Main Granite Axis of the Urals. There are no 'exotic' age groupings that would imply an unknown basement terrain, although it is likely that mid- and late Proterozoic zircons come from beyond the present Volga drainage basin, from orogenic belts exposed on the Baltic Shield, such as the Sveconorwegian.

The Greater Caucasus sample is distinctive in that 73% of the zircons post-date 350 Ma, compared with only 8% in the Volga sample. The great differences in the age spectra for the Greater Caucasus and modern Volga samples suggest that the Mesozoic sandstone of the Greater Caucasus was not derived from the basement or cover of the East European Craton or the Urals, but probably from juvenile Palaeozoic basement of the same range or the adjacent Scythian Platform, with a contribution from Mesozoic magmatism of the Lesser Caucasus arc(s).

The four Productive Series samples from the South Caspian Basin have similar age distributions to each other, although there are some variations in relative abundance of the different components. All four have Precambrian profiles that are closely comparable with that of modern Volga sand, confirming that the Palaeo-Volga was an important supplier of Productive Series sediment. However, they also have higher abundances of post-350 Ma zircons than the modern Volga, which indicates that the Greater Caucasus also supplied sand throughout Productive Series deposition.

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