Along-strike variations in the composition of sandstones derived from the uplifting western Greater Caucasus: causes and implications for reservoir quality prediction in the Eastern Black Sea

STEPHEN J. VINCENT1*, FIONA HYDEN2 & WILLIAM BRAHAM3

1CASP, University of Cambridge, 181a Huntingdon Road, Cambridge, CB3 0DH, UK
2Oil Quest, 12 Abbey Court, Cerne Abbas, Dorchester, Dorset DT2 7JH, UK
311 Corner Hall, Hemel Hempstead, Hertfordshire HP3 9HN, UK

*Corresponding author (e-mail: stephen.vincent@casp.cam.ac.uk)

Abstract: Oligo-Miocene outcrops along the southern margin of the western Greater Caucasus preserve a record of sediments shed from the range into the northern and central parts of the Eastern Black Sea. Sandstones in the Russian western Caucasus are significantly more quartz-rich than those located farther SE in western Georgia. The latter contain appreciably more mudstone and volcanic rock fragments. Oligo-Miocene turbidite systems derived from the Russian western Caucasus in the Tuapse Trough and central Eastern Black Sea may therefore form better-quality reservoirs at shallow to moderate depths than sediments derived from west Georgian volcaniclastic sources in the easternmost part of the basin. Palynomorph analysis indicates sediment derivation predominantly from Jurassic and Cretaceous strata in the Russian western Caucasus and from Eocene strata, and an increasing proportion of Cretaceous strata upsection, in western Georgia. An Eocene volcaniclastic source is proposed for the increased rock fragment component in west Georgian sandstones. Eocene volcaniclastic rocks are no longer exposed in the Greater Caucasus, but similar rocks form the inverted fill of the Adjara–Trialet Basin farther south in the Lesser Caucasus. The former presence of a northern strand of this basin in the west Georgian Caucasus is supported by earlier thermochronological work.

Supplementary material: A sample data table, petrographic data table, petrographic key, QFL sandstone compositional plot and palynomorph reworking Stratabugs™ charts are available at www.geolsoc.org.uk/SUP18662

The Eastern Black Sea is one of the few remaining underexplored hydrocarbon basins in Europe. Two deep-water wells, Hopa-1 and Sırmene-1, have been drilled in Turkish waters (Fig. 1). Water depths typically in excess of 2 km hamper exploration efforts. The basin contains up to 8 km of Cenozoic sedimentary rocks (Minshull et al. 2005). These include a world-class source rock interval, the Oligocene to Early Miocene Maykop Series (Robinson et al. 1996), and turbiditic sandstones that, in the Oligocene and younger part of the succession, form important potential reservoir targets (e.g. Meisner et al. 2009). This paper documents along-strike variations in the composition, and therefore likely reservoir potential, of Oligo-Miocene sandstones shed from the evolving Greater Caucasus mountain belt into the Eastern Black Sea. It proposes that variations in the age and composition of earlier sedimentary rocks reworked during the inversion of the Greater Caucasus Basin are the principal control on the observed variations in composition and potential reservoir quality.

Geological background

The Eastern Black Sea, Greater Caucasus and Adjara–Trialet basins formed as a result of Mesozoic to earliest Cenozoic extension to transtension at the southern margin of Eurasia during the northern subduction and closure of the Tethys Ocean to the south (Dercourt et al. 1986, 2000; Şengör & Natal’in 1996; Nikishin et al. 1998, 2001; Golonka 2004; Kaz’min & Tikonova 2006a, b; Saintot et al. 2006; Barrier & Vrielynck 2008). Collision of the Arabian promontory with the assembled Tethyside orogenic collage resulted in the inversion of the Greater Caucasus and Adjara–Trialet basin from the Late Eocene–earliest Oligocene onwards to form the southern slope of the Greater Caucasus and the Adjara–Trialet Belt (Saintot et al. 2006; Vincent et al. 2007, 2011; Allen & Armstrong 2008, and references therein) (Fig. 1). These regions are major contributors to the fill of the Eastern Black Sea, while the Greater Caucasus also formed a barrier to more distantly from S:cott, R. A., Smyth, H. R., Morton, A. C. & Richardson, N. (eds) 2014. Sediment Provenance Studies in Hydrocarbon Exploration and Production. Geological Society, London, Special Publications, 386, 111–127. First published online September 17, 2013, http://dx.doi.org/10.1144/SP386.15 © The Geological Society of London 2014. Publishing disclaimer: www.geolsoc.org.uk/pub_ethics
Fig. 1. Simplified geological map of part of the western Greater Caucasus with sample locations marked. The inset shows the position of the study area in its wider geographical context.
sourced, Russian Platform-derived, sediment dispersal systems (Vincent et al. 2013). The oceanic nature of the Eastern Black Sea Basin (Starostenko et al. 2004; Minshull et al. 2005) means that it has largely resisted deformation and inversion.

Outcrops along the southern margin of the western Greater Caucasus preserve a record of the sediments that fed into the northern and central parts of the Eastern Black Sea during the Oligo-Miocene. They were derived from two main rock units within the western Greater Caucasus: the crystalline core of the range, and along its southern slope, the Jurassic to Eocene fill of the Greater Caucasus Basin (Fig. 1). The crystalline core of the range comprises Gondwana-derived, predominantly Early to middle Palaeozoic crystalline protolith and middle Palaeozoic island-arc and ophiolitic rocks that were metamorphosed and intruded during their Variscan accretion to the southern margin of Laurasia (Zonenshain et al. 1990; Hanel et al. 1992, 1993; Somin et al. 2006, 2007; Zakariadze et al. 2007; Somin et al. 2009; Treloar et al. 2009). The crystalline core is unconformably overlain by either Late Carboniferous to Permian, Triassic or Jurassic sedimentary successions (Somin 2000; Lavrishchev et al. 2002), which would suggest that these crystalline rocks have been at or near the surface for much of the Late Palaeozoic to Cenozoic time. Fission track thermal modelling indicates a maximum of c. 2 km of post-Middle Jurassic burial (Vincent et al. 2011).

Jurassic to Eocene sedimentary rocks to the south of the crystalline core of the range were deposited in the western segment of an extensional, or more likely transtensional, basin termed the Greater Caucasus Basin (Nikishin et al. 1998, 2001; Saintot et al. 2004, 2006; Kaz'min & Tikhopanova 2006a; McCann et al. 2010). The crystalline core of the range formed the northern shoulder of this basin, whereas its southern margin is represented by the Shatskiy Ridge and its onshore equivalent, the Transcaucasus (including the Dziruli Massif, Rioni Basin, and outcrops in southern Abkhazia and the southern part of the Mzimta River catchment in Russia) (Fig. 1). The fill of the basin is characterized by turbidite, calciturbidite

---

**Fig. 2.** Schematic stratigraphies through the Russian and west Georgian sectors of the western Greater Caucasus Basin. Data are compiled from local 1:200 000 geological maps, with additional information from Adamia et al. (1992) and McCann et al. (2010). Selandian to Priabonian strata are not preserved in the west Georgian sector of the Greater Caucasus Basin, and its stratigraphy is inferred from the Adjara–Trialet Belt further south (see text for discussion). See Figure 3 for the lithological key. The main intervals reworked into Oligo-Miocene sedimentary rocks are shown by shaded grey boxes; these data are derived from Figure 3. The geological timescale is from Gradstein et al. (2004).
Fig. 3. Summary logs and palynological reworking data for latest Eocene to Middle Miocene strata in representative (a) Russian and (b) west Georgian sections on the southern side of the western Caucasus. The sections are located on Figure 1. The age range of reworked palynomorphs is shown by the horizontal lines, where the line thickness is proportional to their abundance. For each sample, the most likely ages of the rocks from which these forms...
Fig. 3. (Continued) are derived are shown by the boxes. The grey background shading indicates the age range of the minimum number of rock units needed to provide the range of reworked palynomorphs identified, based on their occurrence throughout each section; these are plotted on Figure 2. The geological timescale is from Gradstein et al. (2004).
and hemipelagic mudstone and marl deposits, although Early–Middle Jurassic and Cretaceous volcanic rocks are also present (Fig. 2).

Sample dataset

In this dataset we have only considered sandstone and associated mudstone samples derived from the western Greater Caucasus. For a wider discussion of the provenance of sandstones entering the Eastern Black Sea, see Vincent et al. (2013). Determining which samples have a western Greater Caucasus provenance was an iterative process combining multiple factors, including (1) the presence of plant remains and associated conglomeratic facies (indicating a local sediment source), (2) palaeocurrent indicators and proximal to distal facies trends (indicating the direction of the sediment source, broadly from the north and NE), and (3) evidence for contemporaneous depositional systems with divergent palaeocurrent patterns and similar heavy mineral compositions on either side of the range (indicating a subaerial proto-Caucasus sediment source area from Oligocene time onward) (Vincent et al. 2007). Samples derived from the Adjara–Trialet Belt to the south of the west Georgian Caucasus were easily identified and excluded from the study by their rock fragment-rich and unstable heavy mineral-rich compositions and northerly palaeocurrent indicators (Vincent et al. 2013).

Sandstone-bearing Oligocene and younger sedimentary rocks on the southern side of the Russian western Caucasus are restricted to the region between Sochi and Adler, close to the Abkhazian border. Russian samples analysed in this study (prefix WC) come principally from exposures close to the Mzimta River (Fig. 1) that are dominated by mudstones and thin-bedded sandstones deposited by low-density turbidites and hemipelagic settling (Fig. 3a). Thick, massive, cross-bedded and laminated sandstones, interpreted as high-density turbidites, are present in the Early Oligocene part of the section, as are a number of olistostrome (debris flow) intervals.

Sandstone-bearing Oligocene and younger sedimentary rocks crop out more widely in western Georgia; sandstone samples analysed in this study (prefix WG) come from the Chanis and Tskhensis river valleys on the southern slope of the Greater Caucasus and from the margins of the Rioni Basin (Fig. 1). Mudstone samples come exclusively from the Chanis River section. West Georgian sedimentary rocks represent a greater variety of facies and depositional environments than those from the Sochi–Adler region in Russia. A broadly coarsening- and shallowing-upward trend is typical. For instance, in the Chanis River section, the Early Oligocene interval consists of hemipelagic mudstones (Fig. 3b). Sandstones first occur in the Late Oligocene interval, are thin-bedded and were deposited by low-density turbidites. The section is capped by Early to Middle Miocene mudstones and thick deltaic sandstones (Fig. 3b). Shoreline sandstones and conglomerates are developed in Middle Miocene sedimentary rocks elsewhere (e.g. the Tskhensis River section). A single sample was analysed from the autonomous region of Abkhazia between Russia and Georgia (sample prefix ABK; Fig. 1); this was taken from an existing collection in Tbilisi due to a lack of field access.

Petrographic analyses were carried out on 27 sandstone samples in order to characterize the composition of sandstones derived from the Caucasus. Palynological analyses were carried out on 15 mudstone samples (one of which was barren) inter-bedded with these sandstones in order to determine the age range of earlier sedimentary rocks that were reworked into the Oligo-Miocene section. Sample preparation, analytical methodologies and results are reported below. Conventional heavy mineral and single mineral geochemical analysis, and SHRIMP U–Pb dating of zircons were carried out, but do not affect the conclusions of this study and so for brevity’s sake are not reported here (see Vincent et al. 2013 instead).

Sample preparation and analysis

Sandstones

Sandstone samples were thin-sectioned, vacuum-impregnated with blue-dyed epoxy resin and then etched and stained with hydrofluoric acid and sodium cobaltinitrite, respectively, to identify alkali feldspars. Further etching with dilute hydrochloric acid and the application of a combined Alizarin-Red S and potassium ferricyanide stain facilitated identification of carbonate minerals.

Thin sections were point counted (300 points per thin section) using a Nikon Optiphot 2 microscope and Prior point-count stage. Counts were recorded via a bespoke (Oil Quest) point-count programme (P2P) that used an iteratively developed series of 77 predetermined categories to take account of both the traditional QFR method, where R stands for ‘rock fragments’, and the ‘Gazzi-Dickinson’ QFL method, where L stands for ‘aphanitic lithic fragments’. The main difference between these methods is the procedure used for the classification of sand- and gravel-grade grains within rock fragments. The former method records these grains as rock fragments of a particular type (e.g. plutonic), whilst the latter records them as specific sand- or
gravel-grade mineral species (e.g. alkali feldspar). The QFR data are presented here, because of the additional rock fragment provenance information they contain. The point-count data and a QFL plot are available in the supplementary material. Mudstone rock fragments are aphanitic siliciclastic sediment; carbonate mudstones are included in the carbonate rock fragment category. All point-count percentages were expressed with reference to total rock volume, in other words, the sum of total detrital components, authigenic phases and visible porosity. The grain solid method was used, whereby intragranular voids, matrix or cement within grains were counted separately from the enclosing grains (see Fig. 4. (a) Quartz–feldspar–rock fragment (QFR) and (b) volcanic–metamorphic–sedimentary rock fragment (Rvolc–Rmet–Rsed) plots of Oligo-Miocene sandstone samples derived from the western Caucasus on the southern side of the range. Sample locations are shown on Figure 1. Note that all samples are rich in sedimentary rock fragments and only this part of the Rvolc–Rmet–Rsed plot is shown. Compositional fields are from Pettijohn et al. (1987).
Jaanusson 1972). The point-count distance selected for each sample was, where possible, always greater than the largest grain diameter. Reproducibility of data is dependent on the abundance of elements to be counted and heterogeneity of the sample. Errors of +4–5% are likely for 300 counts (van der Plas & Tobi 1965). Modal grain size and sorting data were based on an assessment of the whole of each thin section using industry-standard visual comparator charts (e.g. Harrell 1964).

**Mudstones**

Mudstone samples were processed by standard palynological techniques involving gentle crushing to c. 1 mm then successive HCl (35%) and HF (60%) treatments followed by sieving at 15 μm and a further treatment in hot HCl (36%) to remove neo-formed fluorides. No oxidation was performed. If amorphous organic matter (AOM) was present, a tunable ultrasonic probe was used to break up the AOM, which was then removed by sieving. The palynomorphs were mounted in Elvacite 2044 on a glass slide protected by a coverslip.

Microscopic examination was carried out on a single slide using a Leitz Dialux 20 transmitted light microscope. A series of traverses were made across the centre of the slide in order to count, where possible, a minimum of 200 palynomorphs. Once this count was reached the remainder of the slide was scanned for forms not encountered during the counting process and a note made of their presence. In instances where the preparation did not yield 200 palynomorphs, the whole slide was counted. The resulting palynomorph abundance data were then entered into Stratabugs\textsuperscript{TM}. Stratabugs charts are available as supplementary material.

The assemblages recovered comprise a mixture of in situ and reworked palynomorphs. In many

![Intergranular composition variability plot](image-url)

**Fig. 5.** Intergranular composition variability plot of Caucasus-derived Oligo-Miocene sandstone samples on the southern side of the range. Note the larger amounts of intergranular volume and minus cement porosity in the Russian samples and the larger amounts of secondary porosity in the Georgian samples.
instances, determination of whether a particular palynomorph was reworked was made on the basis of exotic presence (i.e., taxa typical of Eocene sedimentary rocks being recorded within the Miocene) or, in the case of long-ranging forms, such as bisaccate pollen or pteridophyte spores, by whether they display unusually high levels of physical abrasion or thermal maturity. The age range of reworked palynomorphs in this study is used as a direct proxy for the age of the eroded sedimentary rocks contributing sediment to the studied Oligo-Miocene samples. It was not possible to distinguish between palynomorphs that have undergone single or multiple cycles of reworking, such that the palynomorph ages provide a maximum sediment source age. However, the only major episode of inversion in the Greater Caucasus Basin prior to Late Eocene–earliest Oligocene Arabia–Eurasia collision was in the latest Aalenian to Bathonian (the Mid Cimmerian orogeny; Zonenshain & Le Pichon 1986; Nikishin et al. 1998; Saintot et al. 2006; Nikishin et al. 2012), so any forms that have been reworked more than once are likely to be Early to Middle Jurassic in age or older.

Analytical results

Sandstone petrography

Sandstone compositions range from subarkose and sublitharenite to lithic arenite (Fig. 4a). Rock fragments are dominated by sediment, with lesser volcanic and negligible metamorphic types (Fig. 4b). Authigenic phases are dominated by ferroan calcite (up to 31%) and minor limonite (up to 8%) (Fig. 5). Other authigenic phases make up, on average, less than 2% of the total rock volume. The majority of samples have undergone moderate to high levels of compaction, leading to concavo-convex grain contacts and a marked reduction in primary porosity. T_max values of adjacent mudstones indicate that they are thermally immature to
transitional early mature (415–435 °C). Limited spore colour and vitrinite reflectance analyses are consistent with these findings (SCI = 2–3–5–6; \( V_R \approx 0.24–0.40 \)). A lack of detrital apatite fission track annealing (Vincent et al. 2011) and limited or no (early) quartz cementation would suggest that the sandstones have not been heated beyond 80 °C during burial (Walderhaug 1994; Primmer et al. 1997; Worden & Morad 2000). Maximum recorded overburden thicknesses are c. 3 km. Feldspars have undergone varying degrees of dissolution and are typically replaced by calcite. In some instances dissolution at outcrop cannot be discounted and may result in a limited artificial reduction in the arkosic nature of the sandstones and an increase in secondary porosity. Visual porosity is up to 23% (average 8%). He porosity and permeability data were obtained for a subset of the samples. Visual porosity determinations underestimate measured porosity due to the presence, on average, of c. 10% microporosity (Fig. 6a). There is a good correlation between He porosity and log permeability (Fig. 6b).

Large-scale spatial differences in the composition of the sandstones occur along the length of the range. Those from the Russian western Caucasus are significantly more quartz-rich and rock fragment-poor than those farther SE in western Georgia (incl. Abkhazia) (Fig. 4a). The largest differences in provenance-diagnostic grain type between the regions occur in the mudstone and volcanic rock fragment categories (Fig. 7). Caucasus-derived Oligo-Miocene sandstones in western Georgia contain, on average, c. 10% more volcanic rock fragments and c. 19% more mudstone rock fragments (relative to total extrabasinal detrital grains) than those from the southern side of the Russian western Caucasus (Fig. 7). West Georgian samples also typically contain a higher proportion of volcanic rock fragments relative to other rock fragment types (Fig. 4b). In addition to differences in detrital grain composition, samples from the Russian

![Detrital grain variability plot of Caucasus-derived Oligo-Miocene sandstone samples on the southern side of the range. Totals do not reach 100% where unidentifiable grains were encountered. Note the higher proportion of quartz in the Russian samples and the larger amounts of mudstone and volcanic rock fragments in the Georgian samples.](image-url)
western Caucasus have larger intergranular volumes and minus cement porosities. This difference is mainly due to an increase in ferroan calcite cement (Fig. 5). Volumes of other intergranular components are typically similar between the regions, although some Russian western Caucasus samples contain minor amounts of quartz cement. West Georgian samples contain larger amounts of secondary porosity (Fig. 5). This is likely to reflect the larger quantities of unstable grains within these sandstones (Fig. 7).

**Palynology data**

The age range of palynomorphs contained in the mudstone samples from the Mzimta River section in the Russian western Caucasus and the Chanis River section in western Georgia are graphically presented in Figure 3. There are marked spatial differences in the age of the sedimentary rocks reworked during the uplift and erosion of the Greater Caucasus Basin. In the Russian Mzimta River section, Jurassic and Cretaceous forms are present throughout, with a lesser, variable contribution from Paleocene and Eocene sedimentary rocks. The age of the oldest sedimentary rocks being reworked increases through time and includes Late Palaeozoic forms in the youngest sample (Fig. 3a). In the west Georgian Chanis River section, reworked palynomorphs are dominated by Eocene forms, with Cretaceous forms becoming more abundant upsection (Fig. 3b).

![Fig. 8. Crossplots of (a) sorting v. grain size, and (b, c) quartz amount, as a proportion of total detrital grains, v. (b) grain size and (c) sorting. See Figure 4 for the key. Note that for any given grain size or sorting value, samples derived from the Russian western Caucasus (circles) typically have a higher proportion of quartz than those from west Georgia (crosses).](image)

![Fig. 9. Quartz–feldspar–rock fragment (QFR) plot of pre-Oligocene sandstones from the Caucasus region. Note the marked compositional difference between Paleocene–Eocene samples from the Russian western Caucasus and those from the Adjara–Trialet Belt (the compositional analogue for inferred sandstones from the west Georgian Caucasus).](image)
Controls on the along-strike variability of the composition of sandstones derived from the Caucasus

Surface process controls

Samples from the Russian western Caucasus were deposited by turbidity currents. As a consequence, they may have been transported farther by marine processes than samples from western Georgia that were deposited in a variety of shallow-marine shoreface and deltaic environments. However, the distance from the present-day Caucasus drainage divide to the sample sites would suggest that overall transport distances were broadly similar (up to 110 km; Fig. 1). The majority of sandstones are fine-grained and moderately to well sorted (Fig. 8a). Typically, where surface processes are an important factor in controlling sandstone composition, this is reflected in a correlation between...
physical and compositional maturity. This is not apparent in the Caucasus dataset (Fig. 8b, c). However, when sandstones with similar grain sizes or sorting parameters are compared, those from the Russian western Caucasus are almost always more quartz-rich than those from western Georgia (Fig. 8b, c). This instead demonstrates the overriding control of source area provenance on Oligo-Miocene sandstone composition, typical in situations like the western Greater Caucasus where sediment transport lengths are short, and relief and sedimentation rates are high (e.g. Suttner et al. 1981; Garzanti 1986).

**Sediment reworking controls**

Minor spatial differences in the amount of sediment derived from igneous and metamorphic rocks in the crystalline core of the Caucasus are apparent in the petrographic data (Fig. 7). Zircon U–Pb age dating is ongoing in an attempt to quantify the proportion of first-cycle sediment within the Oligo-Miocene sedimentary pile. The main along-strike variations in composition, however, occur in the amount of sedimentary and volcanic grains eroded during the inversion of the Greater Caucasus Basin (Fig. 7). Although mudstone rock fragments show the greatest variation, it is impossible to match these to specific mudstone intervals within the Greater Caucasus Basin stratigraphy. Constraining controls on volcanic rock fragment variability is more informative and is discussed in the following text.

Volcanic intervals are present in the Middle Jurassic, mid Cretaceous and Middle Eocene stratigraphy of the Greater Caucasus and Adjara–Trialet Belt (Fig. 2). A large contribution from a Middle Jurassic volcanic source in western Georgia is not supported by the palynological data. Although mid Cretaceous volcanic rocks are present in the Transcaucasus (and Russian western Caucasus), they are not present in the west Georgian sector of the Greater Caucasus Basin (Fig. 2; Adamia et al. 1992). Consequently, the reworking of Cretaceous strata cannot be the cause for the higher proportion of volcanic rock fragments in Oligo-Miocene sandstones derived from the west Georgian Caucasus. The Eocene fill of the Greater Caucasus Basin is not exposed in western Georgia. (Thin accumulations of Eocene sediments in the west Georgian Caucasus represent shallow-water facies deposited to the south of the Greater Caucasus Basin on the northern margin of the Transcaucasus.) However, large volumes of volcanic and volcaniclastic rocks

---

**Fig. 11.** Map showing variations in the composition of sandstones deposited by Oligocene and younger sedimentary systems derived from the western Greater Caucasus in the Eastern Black Sea. Sediment dispersal routes are interpreted from unpublished seismic data. See Figure 1 for the key to the background geological map.
do occur in the Adjara–Trialet Belt to the south of the west Georgian Caucasus (Adamia et al. 1974; Lordkipanidze & Zakariadze 1974; Kazmin et al. 1986; Yilmaz et al. 1997) (Fig. 1). Similar rocks are also present farther east in the Talysh region of Azerbaijan (Kazmin et al. 1986; Vincent et al. 2005). Detailed mapping indicates that these narrow east–west elongated outcrops represent the fill of rapidly subsiding Middle Eocene transtensional basins (Vincent et al. 2005). Eocene volcanism is also common across large parts of Iran, Turkey and Armenia (Kazmin et al. 1986; Vincent et al. 2005; Keskin et al. 2008; Verdel et al. 2011).

Palaeocurrent and facies mapping indicate that Eocene volcanic rocks in the Adjara–Trialet Belt were not the source of the sandstones in the west Georgian Caucasus; they were derived from farther north within the Caucasus. We conclude therefore that a narrow volcanic and volcaniclastic-rich sub-basin, similar to the Adjara–Trialet Basin, may have previously existed in the west Georgian sector of the Greater Caucasus Basin and that this has subsequently been completely removed during basin inversion. This conclusion is supported by young detrital apatite fission track populations in western Georgia that have age profiles best explained by temporary storage within a transient Eocene Caucasus basin (Vincent et al. 2011, their fig. 7). The lithologies within this sub-basin would have been markedly different from those Eocene strata that still crop out farther to the NW in the Russian sector of the Greater Caucasus Basin that are non-volcanic in nature (Fig. 2) and include sub-arkosic, lithic arkosic and arkosic turbidite sandstones (Fig. 9). The presence of this former volcanic and volcaniclastic-rich sub-basin can be tested by dating mudstone and volcanic clasts in conglomerates within the Oligo-Miocene stratigraphy of the west Georgian Caucasus.

Implications for reservoir properties in the Eastern Black Sea

The limited He porosity and permeability data available in this study would suggest that reservoir performance at outcrop is linked to authigenic phase and matrix volume (Fig. 6c). This is because pervasive ferroan calcite cementation has filled much of the post-compactional minus cement porosity (Fig. 5); only four samples from the Russian western Caucasus and three samples from western Georgia have moderate to very good reservoir properties (Figs 6b & 10). It is unclear whether this will also be the case for equivalent sandstones in the subsurface, as the prediction of authigenic phase composition and volume is beyond the scope of this study. This requires a detailed understanding of the time-temperature history of the potential target interval. This uncertainty is reflected in the reservoir assessment methodology of Tobin (1997), which suggests that most of the samples in this study, if situated in the subsurface, would carry a moderate to high exploration risk (Fig. 10). That being said, numerous studies indicate that sandstone composition is a major control on reservoir quality (e.g. Nagtegaal 1978; Bloch 1991; Pittman & Larese 1991; Lundegard 1992; Dutton et al. 2012; Tobin & Schwarzer 2013). Data presented here provide clear evidence that lateral variations in sandstone composition will be present within the Oligo-Miocene fill of the Eastern Black Sea. The larger quantities of ductile grains derived from western Georgia will result in greater sandstone compactional volume loss, and a decrease in intergranular volume and minus cement porosity in sandstones in the subsurface relative to those derived from the Russian western Caucasus (Figs 5 & 10). Despite uncertainties over expected levels of carbonate cementation, it is reasonable to assume, therefore, that the quartz-rich depositional systems derived from the Russian western Caucasus will have the potential to form better-quality reservoirs at shallow and moderate burial depths than their lithic-rich counterparts derived from western Georgia (e.g. Tobin & Schwarzer 2013). At greater depths, the preferential development of quartz cements in quartz-rich sandstones may mitigate against this trend.

Conclusions

The most striking conclusion of this work is the possibility that an Eocene transtensional basin developed in western Georgia as part of the Greater Caucasus Basin for which no outcrop evidence remains. As in the Adjara–Trialet Basin to the south, it would appear that this basin was filled by volcanic and volcaniclastic rocks. Sediments derived from the inversion of these basins may significantly reduce the reservoir potential of Oligocene and younger sandstones within the easternmost part of the Black Sea (Fig. 11). Thus, although a crude estimate of potential sandstone compositions within young sedimentary basins may be made by an assessment of the current lithologies present within the river catchments of these basins, extreme caution needs to be taken when extrapolating these observations back in time, particularly in areas that have undergone recent episodes of rapid exhumation.

Oligo-Miocene sedimentary rocks derived from the inversion of the Greater Caucasus Basin in the Russian western Caucasus include sediment reworked from Jurassic strata, as well as the
Eocene and Cretaceous intervals also reworked into west Georgian samples. Jurassic, Early Cretaceous and Eocene sedimentary rocks in the Russian western Caucasus are relatively sandstone-rich (Fig. 2), with these sandstones being dominated by subarkoses and sublitharenites (Fig. 9). Sediment derivation from these relatively quartz-rich sandstones is likely to be a major reason why Oligo-Miocene sedimentary rocks on the southern margin of the Russian western Caucasus are also quartz-rich. These sedimentary rocks form the up-dip components of turbidite systems, which form potential hydrocarbon targets in the Tuapse Trough (e.g. Mityukov et al. 2011), and possibly in the central Eastern Black Sea (Fig. 11).

It is not possible to accurately constrain the boundary between the quartz- and rock fragment-rich depositional systems entering the Eastern Black Sea because of the paucity of data from the disputed Abkhazian region. It is possible that the Middle Jurassic granitoids that intrude the fill of the Greater Caucasus Basin north of Suchumi delimit the westward extent of the west Georgian volcanic- and volcanioclastic-rich Eocene Caucasus basin. Equally, the submarine Gudauta arch may have formed the bathymetric divide between litchic-rich, potentially poor-reservoir-quality depositional systems shed into the easternmost part of the Eastern Black Sea, and quartz-rich, potentially better-reservoir-quality depositional systems feeding the Tuapse Trough and, during lowstands, possibly the central part of the Eastern Black Sea (Fig. 11).

This work builds on over 12 years of research carried out by CASP and its collaborators in the Caucasus region. The research would not have been possible without the field assistance of M. Simmons, S. Inger and L. Voronova (all formerly CASP), T. Barabadze (Georgian Oil, Georgia), T. Pinchuk (Krasnodarneftgas, Russia) and V. Lavrishchev (Kavkazgeol’emka, Russia) or the funding of CASP’s industrial sponsors. The analytical assistance of A. Morton (HM Associates, UK), A. Carter (UCL, UK) and S. Gibbs (NOCS, UK) during earlier phases of this research is gratefully acknowledged. WB would like to thank S. Akbari for his palynological preparation and J. Marshall (both NOCS, UK) for his useful discussions. This paper has been improved by comments from J. Omma, reviewers R. Tobin and S. Andó, and editor H. Smyth. It is dedicated to the memories of R. Scott and T. Elliott. This is Cambridge Earth Science contribution esc:2676.

References

ADAMIA, S. A., GAMKRELIDZE, I. P., ZAKARIADZE, G. S. & LORDKIPANIDZE, M. B. 1974. Adjaria—Trialeti trough and problem of the Black Sea origin. Geotektonica, 1, 78–94 [in Russian].

ALLEN, M. B. & ARMSTRONG, H. A. 2008. Arabia–Eurasia collision and the forcing of mid-Cenozoic global cooling. Palaeogeography, Palaeoclimatology, Palaeoecology, 265, 52–58.

BARRIER, E. & VRIEYNCK, B. 2008. Palaeotectonic Maps of the Middle East. MEBE, Paris, 1:18 500 000.

BLOCH, S. 1991. Empirical prediction of porosity and permeability in sandstones. AAPG Bulletin, 75, 1145–1160.

DERCOURT, J., GAETANI, M. et al. 2000. Atlas Peri-Tethys, Palaeogeographical maps. CCGM, CGMW, Paris.

DERCOURT, J., ZONENSHAIN, L. P. et al. 1986. Geological evolution of the Tethys belt from the Atlantic to the Pамиrs since the Lias. Tectonophysics, 123, 241–315.

DUTTON, S. P., LOUCKS, R. G. & DAY-STIRRAT, R. J. 2012. Impact of regional variation in detrital mineral composition on reservoir quality in deep to ultradeep lower Miocene sandstones, western Gulf of Mexico. Marine and Petroleum Geology, 35, 139–153.

GARZANTI, E. 1986. Source rock versus sedimentary control on the mineralogy of deltaic volcanic arenites (Upper Triassic, northern Italy). Journal of Sedimentary Research, 56, 267–275.

GOLONKA, J. 2004. Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic. Tectonophysics, 381, 235–273.

GRADSTEIN, F. M., OGG, J. G. & SMITH, A. G. 2004. A Geologic Time Scale 2004. Cambridge University Press, Cambridge.

HANEL, M., GURIBANOV, A. G. & LIPPOLT, H. J. 1992. Age and genesis of granitoids from the Main-Range and Bechasy zones of the western Great Caucasus. Neues Jahrbuch Fur Mineralogie-Monatshefte, 1992, 529–544.

HANEL, M., LIPPOLT, H. J., KOBER, B., GURIBANOV, A. G. & BORSUK, A. M. 1993. On the Early Paleozoic age of metagranodiorites in the Early Range Zone of the Greater Caucasus. Petrology, 1, 487–498.

HARRELL, J. 1964. A visual comparator for degree of sorting in thin and plane section. Journal of Sedimentary Petrology, 54, 646–650.

JAANUSSON, V. 1972. Constituent analysis of an Ordovician limestone from Sweden. Lethaia, 5, 217–237.

KAZ’MIN, V. G. & TIKHONOVA, N. F. 2006a. Evolution of Early Mesozoic back-arc basins in the Black Sea–Caucasus segment of a Tethyan active margin. In: ROBERTSON, A. H. F. & MOUNTRAKIS, D. (eds) Tectonic Development of the Eastern Mediterranean Region. Geological Society, London, Special Publications, 260, 179–200.

KAZ’MIN, V. G. & TIKHONOVA, N. F. 2006b. Late Cretaceous–Eocene marginal seas in the Black Sea–Caspian region: paleotectonic reconstructions. Geotectonics, 40, 169–182.

KAZMIN, V. G., SBORTSHIKOV, I. M., RICOU, L.-E., ZONENSHAIN, L. P., BOULIN, J. & KNIPPER, A. L. 1986. Volcanic belts as markers of the Mesozoic–Cenozoic active margin of Eurasia. Tectonophysics, 123, 123–152.
Keskın, M., Genç, S. C. & Tuyşüz, O. 2008. Petrology and geochemistry of post-collisional Middle Eocene volcanic units in North-Central Turkey: evidence for magma generation by slab breakoff following the closure of the Northern Neotethys Ocean. *Lithos*, **104**, 267–305.

Lavrishchev, V. A., Prutskiy, N. I. & Semenov, V. M. 2002. National Geological Map of the Russian Federation, *Caucasus Series Sheet K-37-V (Krasnar Polyana)*. St. Petersburg Cartographic Enterprise of VSEGEI, Moscow. 1,200,000 [in Russian].

Lordkipanidze, M. B. & Zakariazade, G. S. 1974. Paleogene volcanism of Archara. Problems of geology of Archara—Trialeti. *Proceedings of Institute of Geology of GSSR*, **44**, 74–86 [in Russian].

Lundegard, P. D. 1992. Sandstone porosity loss: a ‘big picture’ view of the importance of compaction. *Journal of Sedimentary Research*, **62**, 250–260.

McCann, T., Chalot-Prat, F. & Saintot, A. 2010. The Early Mesozoic evolution of the Western Greater Caucasus (Russia): Triassic–Jurassic sedimentary and magmatic history. In: B. A., M., Kaymakci, N., Stephenson, R. A., Bergerat, F. & Starostenko, V. (eds) *Sedimentary Basin Tectonics from the Black Sea and Caucasus to the Arabian Platform*. Geological Society, London, Special Publications, **340**, 181–238.

Meisner, A., Krylov, O. & Nemcov, M. 2009. Develop- ment and structural architecture of the Eastern Black Sea. *The Leading Edge*, **28**, 1046–1055.

Minshull, T. A., White, N. J. et al. 2005. Seismic data reveal Eastern Black Sea Basin structure. *EOS*, **86**, 413, 419.

Mityukov, A., Al’mendinger, O., Myasoedov, N., Nikishin, A. & Gaiduk, V. 2011. The sedimentation model of the Tuapse Trough (Black Sea). *Doklady Earth Sciences*, **440**, 1245–1248.

Nagtegaal, P. J. C. 1978. Sandstone-framework instability as a function of burial diagenesis. *Journal of the Geological Society, London*, **135**, 101–105.

Nikishin, A. M., Cloetingh, S., Brunet, M.-F., Stephenson, R. A., Bolotov, S. N. & Ershov, A. V. 1998. Scythian Platform, Caucasus and Black Sea region: Mesozoic–Cenozoic tectonic history and dynamics. In: Crasquin-Soleau, S. & Barrier, E. (eds) *Péri-Tethys Memoir 3: Stratigraphy and Evolution of Peri-Tethyan Platforms*, Mémoire. Muséum national d’Histoire naturelle, Paris, **177**, 163–176.

Nikishin, A. M., Ziegler, P. A. et al. 2001. Mesozoic and Cenozoic evolution of the Scythian Platform–Black Sea–Caucasus domain. In: Ziegler, P. A., Cavazza, W., Robertson, A. H. F. & Crasquin-Soleau, S. (eds) *Péri-Tethys Memoir 6: Péri-Tethyan Rift/Wrench Basins and Passive Margins*, Mémoire. Muséum national d’Histoire naturelle, Paris, **186**, 295–346.

Nikishin, A. M., Ziegler, P. A., Bolotov, S. N. & Fokin, P. A. 2012. Late Palaeozoic to Cenozoic evolution of the Black Sea—southern Eastern European region: a view from the Russian Platform. *Turkish Journal of Earth Sciences*, **21**, 571–634.

Pettijohn, F. J., Potter, P. E. & Siever, R. 1987. *Sand and Sandstone*. New York, Springer Verlag.

Pittman, E. D. & Larese, R. E. 1991. Compaction of lithic sands; experimental results and applications. *AAPG Bulletin*, **75**, 1279–1299.

Primmer, T. J., Cade, C. A. et al. 1997. Global patterns in sandstone diagenesis: their application to reservoir quality prediction for petroleum exploration. In: Kucpe, J. A., Gluyas, J. & Bloch, S. (eds) *Reservoir Quality Prediction in Sandstones and Limestones*. American Association of Petroleum Geologists, Memoirs, **69**, 61–77.

Robinson, A. G., Rudat, J. H., Banks, C. J. & Wiles, R. L. F. 1996. Petroleum geology of the Black Sea. *Marine and Petroleum Geology*, **13**, 195–223.

Saintot, A., Chalot-Prat, F., McCann, T., Fokin, P., Korsakov, S. & Stephenson, R. 2004. The Early Middle Jurassic basins of the Western Greater Caucasus. In: *AAPG European Region Conference with GSA, Program & Abstracts*, Prague, 101–102.

Saintot, A., Brunet, M.-F. et al. 2006. The Mesozoic–Cenozoic tectonic evolution of the Greater Caucasus. In: Gee, D. & Stephenson, R. (eds) *European Lithosphere Dynamics*. Geological Society, London, Memoirs, **32**, 277–289.

Šengör, A. M. C. & Natal’ in, B. A. 1996. Palaeotectonics of Asia: fragments of a synthesis. In: Yin, A. & Harris- son, T. M. (eds) *The Tectonic Evolution of Asia*. Cambridge University Press, Cambridge, 486–640.

Somir, M. L. 2000. Structure of axial zones in the Central Caucasus. *Doklady Earth Sciences*, **375**, 1371–1374.

Somir, M. L., Kotov, A. B., Sal’nikova, E. B., Levchen- kov, O. A., Pismennyi, A. N. & Yakovleva, S. Z. 2006. Paleozoic rocks in infrastructure of the meta- morphic core, the Greater Caucasus Main Range Zone. *Stratigraphy and Geological Correlation*, **14**, 475–485.

Somir, M. L., Lepekhina, E. N. & Konilov, A. N. 2007. Age of the high-temperature gneiss core of the Central Caucasus. *Doklady Akademii Nauk*, **414**, 1–5 [in Russian].

Somir, M. L., Potapenko, Y. Y. & Smulk’aya, A. I. 2009. Chukchhur xenoliths and tectonic position of Middle Paleozoic volcano-sedimentary sequences in the Peredovoi Range, Northern Caucasus. *Doklady Earth Sciences*, **428**, 1097–1099.

Starostenko, V., Buryanov, V. et al. 2004. Topography of the crust–mantle boundary beneath the Black Sea Basin. *Tectonophysics*, **381**, 211–233.

Suttner, L. J., Basu, A. & Mack, G. H. 1981. Climate and the origin of quartz arenites. *Journal of Sedimentary Petrology*, **51**, 1235–1246.

Tobin, R. C. 1997. Porosity prediction in frontier basins: a systematic approach to estimating subsurface reservoir quality from outcrop samples. In: Kucpe, J. A., Gluyas, J. & Bloch, S. (eds) *Reservoir Quality Prediction in Sandstones and Limestones*. American Association of Petroleum Geologists, Memoirs, **69**, 1–18.

Tobin, R. C. & Schwarzer, D. 2013. Effects of sandstone provenance on reservoir quality preservation in the deep subsurface: experimental modeling of deep-water sand in the Gulf of Mexico. In: Scott, R. A., Smyth, H. R., Morton, A. C. & Richardson, N. (eds) *Sediment Provenance Studies in Hydrocarbon Exploration and Production*. Geological Society, London, Special
GREATER CAUCASUS SANDSTONE COMPOSITIONS

Publications, 386. First published online September 12, 2013, http://dx.doi.org/10.1144/SP386.17

Treloar, P. J., Mayringer, F., Finger, F., Gerdes, A. & Shengalia, D. 2009. New age data from the Dzirula Massif, Georgia: implications for Variscan evolution of the Caucasus. In: Dalkılıç, M. (ed.) 2nd International Symposium on the Geology of the Black Sea Region. General Directorate of Mineral Research and Exploration (MTA), Ankara, Turkey, Abstracts, 204–205.

Tugolesov, D. A. 1989. Album of Structural and Thickness Maps of Black Sea Basin Cenozoic Sediments; 1:1 500 000. Main Administration of Geodesy and Cartography under the Council of Ministers of the USSR, Moscow, 71 [in Russian].

Van der Plas, L. & Tobi, A. C. 1965. A chart for judging the reliability of point counting results. American Journal of Science, 263, 87–90.

Verdel, C., Wernicke, B. P., Hassanzadeh, J. & Guest, B. 2011. A Paleogene extensional arc flare-up in Iran. Tectonics, 30, 20.

Vincent, S. J., Allen, M. B., Ismail-Zadeh, A. D., Flecker, R., Folland, K. A. & Simmons, M. D. 2005. Insights from the Talysh of Azerbaijan into the Paleogene evolution of the South Caspian region. Geological Society of America Bulletin, 117, 1513–1533.

Vincent, S. J., Morton, A. C., Carter, A., Gibbs, S. & Barabadze, T. G. 2007. Oligocene uplift of the Western Greater Caucasus: an effect of initial Arabia–Eurasia collision. Terra Nova, 19, 160–166.

Vincent, S. J., Carter, A., Lavrishchev, V. A., Rice, S. P., Barabadze, T. G. & Hovius, N. 2011. The exhumation of the western Greater Caucasus: a thermochronometric study. Geological Magazine, 148, 1–21.

Vincent, S. J., Morton, A. C. & Hyden, F. 2013. The composition, provenance and reservoir potential of Cenozoic siliciclastic depositional systems supplying the northern margin of the eastern Black Sea. Marine and Petroleum Geology, 45, 331–348.

Walderhaug, O. 1994. Temperatures of quartz cementation in Jurassic sandstones from the Norwegian continental shelf – evidence from fluid inclusions. Journal of Sedimentary Research, A64, 311–323.

Worden, R. H. & Morad, S. 2000. Quartz cementation in oil field sandstones: a review of the key controversies. In: Worden, R. H. & Morad, S. (eds) Quartz Cementation in Sandstones. Wiley-Blackwell, Oxford, IAS Special Publication, 29, 1–20.

Yilmaz, A., Adamia, S., Engin, T. & Lazarashvili, T. 1997. Geoscientific Studies of the Area Along Turkish–Georgian Border. MTA-SDG-GIN, Ankara.

Zakariadze, G. S., Dilek, Y., Adamia, S. A., Oberhansli, R. E., Karpenko, S. F., Bazylev, B. A. & Sолов’ева, N. 2007. Geochemistry and geochronology of the Neoproterozoic Pan-African Transcaucasian Massif (Republic of Georgia) and implications for island arc evolution of the late Precambrian Arabian–Nubian Shield. Gondwana Research, 11, 92–108.

Zonenshain, L. P. & Le Pichon, X. 1986. Deep basins of the Black Sea and Caspian Sea as remnants of Mesozoic back-arc basins. Tectonophysics, 123, 181–211.

Zonenshain, L. P., Kuzmin, M. I. & Natapov, L. M. 1990. Geology of the USSR: A Plate Tectonic Synthesis. American Geophysical Union, Geodynamics Series, Washington, 21.