EOCENE VOLCANICLASTICS IN THE KARTLI BASIN, GEORGIA: A FRACTURED RESERVOIR SEQUENCE

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In the broader Caucasus region, multiple extrusive volcanic units are present within the Jurassic, Cretaceous, Eocene and Miocene sedimentary successions. Partial reworking of volcanic material from various provenance areas into Eocene, Oligocene and Miocene reservoir units is commonly observed in the Eastern Black Sea and in the Rioni, Kartli and Kura Basins of onshore Georgia. Reservoir quality has in general been negatively affected by volcanic rock fragments which may have undergone complex diagenetic alteration. However, despite concerns regarding reservoir quality, oil at the Samgori field, the largest field in Georgia (~200 MM brl recovered), is hosted in altered Middle Eocene volcaniclastic sandstones interbedded with deep-water turbidites. Previous studies of core material from numerous wells in this field showed that most of the oil is contained in altered, microfractured, laumontite-rich tuffs which have fracture and cavernous net porosities averaging 12% and average permeability of 15 mD. The laumontite tuffs comprise only up to 20% of a tuffaceous sandstone section and occur as isolated lenses or pods on a sub-seismic scale (i.e. 5-10 m thick), causing highly variable oil productivity from one well to another.

The petrographic analysis of samples of Middle Eocene volcaniclastic sandstones from outcrops in the central part of the Kartli Basin around Tbilisi broadly confirms the main conclusions of studies completed some 30 years ago which were based on the analysis of subsurface samples. However, the surface samples analysed show that zeolitization events typically did not improve, but actually reduced, reservoir quality due to extensive zeolite cementation. The poor reservoir properties of the plug samples, which are age-equivalent to the proven subsurface Middle Eocene reservoir interval, highlight fracturing as a key factor controlling the presence of exceptional producers (up to 9000 b/d) in the Samgori field complex. The study therefore underlines the critical role of fracturing of the Middle Eocene volcaniclastic reservoir sequence in the Kartli Basin.

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INTRODUCTION

In oil and gas exploration projects, the interplay between extrusive volcanic reservoir rocks and petroleum systems is typically considered, almost by default, as a risk element. However, a growing number of case studies from around the world show that volcanic and volcaniclastic reservoirs can deliver economic flow rates (Schutter, 2003; Zou et al., 2013; Bischoff et al., 2017; Senger et al., 2017; Mark et al., 2018). Many aspects of these unusual reservoirs are yet to be fully appreciated by the petroleum industry. In the context of petroleum systems, a key element is the pre-drill risking of reservoir presence and quality (e.g. Rohrman, 2007).

Porosity and permeability in volcanic rocks are the end-result of a sequence of primary and secondary processes spanning the entire period from eruption to cooling and subsequent alteration and tectonism (Sruoga and Rubinstein, 2007; Couves et al., 2016). Primary volcanic processes can lead to high total porosity and permeability (e.g. vesicles in non-welded ignimbrite with well-developed gas-pipe zones), while secondary processes may decrease primary total porosity (e.g. as a result of diagenetic processes and cementation). However, subsequent dissolution and hydraulic fracturing can enhance total porosity and permeability. In volcanic rocks, effective primary porosity dominantly consists of gas escape structures including vesicles and pipes, which are often not connected. Secondary mineral alteration processes and fracturing are generally required to generate connectivity. Therefore reservoir quality may be due to a combination of both primary and secondary processes (Sruoga and Rubinstein, 2007).

In addition, the depth of maximum burial is also an important factor which affects reservoir quality in volcanic reservoirs. A large number of case studies in China (e.g. Zou et al., 2013; Wang et al., 2018) show examples of critical depth ranges which should be taken into account in the exploration work flow. For example, in the Songliao Basin at burial depths shallower than 2000 m, sedimentary rocks (sandstones and conglomerates) are the preferred targets because of their higher porosity and permeability. Beyond 3000 m depth however, lavas and welded ignimbrites form better reservoirs because they maintain their poroperm characteristics better compared to siliciclastics (Wang and Chen, 2015).

The broader Caucasus region (Fig. 1) contains several examples of hydrocarbon fields producing from Upper Cretaceous and Middle Eocene volcaniclastic reservoirs. The most prominent of these fields is Samgori (Fig. 1), located in the Kartli (Upper Kura) Basin of central Georgia. Further east, in the middle Kura Trough (or Basin) of Azerbaijan, Levin (1995) reported that a total of about 300 MM brl oil and 70 bcf of gas is stored in volcanic and volcaniclastic
rocks at several fields including Muradkhanly, Zardob, Jafarly, Tarsdalliar and Gyzurzundag. The largest of these fields, Muradkhanly (Fig. 1), has an isometric 4-way closure (4.3 x 3.2 km) at the top of the Upper Cretaceous volcanic succession, with oil occurring in fractured basalts and andesites with cavernous porosity at depths of 3000-4000 m (Klosterman et al., 1997). Production is from the uppermost 25-30 m of the extrusive volcanics, an interval which is weathered and altered. These accumulations are characterised by overpressures (1.57 to 1.65 times hydrostatic), as well as high reservoir temperatures (up to 160°C) and low gas saturation (17-35 m³/t). The oil saturation and production rates are controlled by the extremely uneven fracture system; initial production rates may reach 1800-3000 b/d, but rates are less than 750 b/d in some 83% of the wells (Levin, 1995; Klosterman et al., 1997; Buryakovskyy et al., 2001; Blackbourn, 2007).

In the Rioni Basin of western Georgia (Fig. 1), the small-scale Supsa and Shromisubani oilfields produce from Upper Miocene and Pliocene sandstones, respectively, in the hangingwall and the footwall of a major north-vergent thrust fault (Robinson et al., 1997; Tari et al., 2018). Oil at the Supsa field is trapped at about 1000-2000 m depth in a number of stacked Sarmatian (Upper Miocene) clastic units deposited in a complex sedimentary setting that remains poorly understood. Petrographic analysis of outcrop samples of a fine-grained, argillaceous-rich volcanic litharenite along the Supsa River highlighted the relatively low quartz content in these sandstones (ca. 9%) which are overwhelming dominated by volcanic and schistoidal (metamorphic) rock fragments (Tari et al., 2018). The abundance of Eocene volcanogenic material suggests that the main provenance area was the Achara–Trialet volcanic region to the south of the basin (Blackbourn et al., 2021 this issue). The effective porosity and permeability of Sarmatian reservoir rocks in the Supsa field are 5-22% and 5-40 mD respectively, with typical production flow rates of 20 to 30 b/d.

In the adjacent Shromisubani field, the oil is reservoired in Pliocene (Maecotian) sandstones which are at a greater depth (about 3000-3500 m) than the reservoir at Supsa. The Maecotian sandstones are interpreted to have been deposited in a fluvial to shallow-marine environment (Robinson et al., 1997). Similar to the overlying Sarmatian sandstones of the Supsa field, the quality of the Maecotian sandstones limits reservoir productivity. The effective porosity and permeability values in the Shromisubani field reservoirs are 14-20% and 7-60 mD respectively, and typical initial flow rates range from 150 to 700 b/d. Outcrop samples of Maecotian sandstones from this area showed a highly macroporous (c. 17%) volcanic clast-rich litharenite lacking detrital clay or cementation (Tari et al., 2018). The abundant volcanic detritus, including volcanic glass, is prone to alteration processes such as chloritization and/or dissolution. The relatively abundant pyroxene content (ca. 14%) is consistent with the inferred volcanic provenance area. The petrographic analysis of Maecotian (Pliocene) and Sarmatian (Miocene) outcrop samples supports the model which explains why age-equivalent volcanic clast-rich sandstones in both the Shromisubani and Supsa fields are poor reservoirs (Tari et al., 2018).

Two other examples from the offshore Rioni Basin (or Gurian Trough) further underline the importance of volcanioclastic reservoirs in the broader Caucasus region. The HPX-1 (2005) and possibly the Sürmene-1 (2010) wells drilled in the deep-water Turkish sector of the Eastern Black Sea (Fig. 1) both found the prognosed Miocene reservoir sequence. However both wells are likely to have failed due to reservoir quality issues (Tari and Simmons, 2018). Subsequent work on the provenance of these sandstones highlighted the reservoir quality risk due to the presence of Cretaceous to Pliocene volcanics in the region to the SE of the Black Sea (Vincent et al., 2013, 2014).

Three decades after the pioneering studies by Vernik (1990), Grynberg et al. (1993), Patton (1993) and Levin (1995), the present paper aims to revisit the reservoir quality characteristics of the Middle Eocene volcaniclastic sandstones in the Kartli Basin of central-eastern Georgia using surface samples which are age-equivalent and analogous to the subsurface reservoir rocks at Samgori field. We describe the results of modern petrological analyses in a broader-scale petroleum systems context which is outlined by Boote et al. (2018), Blackbourn et al. (2021 this issue), Sachsenhofer et al. (2021 this issue) and Tari et al. (2021 this issue). Whereas the high volcanic content and associated diagenetic processes have degraded the reservoir quality of the sandstones, subsequent phases of fracturing related to multiple periods of tectonic shortening in the basin appear to be the key process responsible for creating an effective reservoir. This study of a proven volcaniclastic reservoir interval could serve as a template for exploration of, and production from, commercial oil and gas reservoirs in other volcanic basins.

Regional geological setting

Eocene volcanism occurred along the uplifted northern margin of the Lesser Caucasus in eastern Georgia and western Azerbaijan (Fig. 1) and resulted in the deposition of a sequence of volcaniclastic sandstones, several km thick, including deep-water turbidites (Blackbourn et al., 2021 this issue). Field observations suggest that these turbidites, which alternate with shale-rich successions, had a longitudinal transport direction to the ESE along the axis of the deep-water
Kartli Basin which extended from the Dziruli Massif in the west (Blackbourn et al., 2021 this issue).

Along strike to the ESE, the predominantly Middle Eocene clastic and volcanic succession has a thickness of up to 10 km in the Talysh Mountains of Azerbaijan (Fig. 1; Vincent et al., 2005) where a lateral transition from basalts to volcanogenic sandstone-dominated turbidity current and debris-flow deposits has been described passing from west to east. These deposits are interpreted to have accumulated in water depths generally greater than 200 m based on sedimentological observations (Vincent et al., 2005).

Ar-Ar ages established the age of volcanism at around 39 Ma, with the upper 1400 m thick volcanic interval being deposited in only 2.2 Ma. Vincent et al. (2005) attributed this rapid deposition and magmatism to a major back-arc extensional or transtensional event in the Talysh region associated with the north-dipping NeoTethyan subduction zone.

The study area in the Kartli Basin of Central Georgia (Fig. 2) is located close to known Cretaceous and Eocene igneous and extrusive volcanic centres. Early Eocene magmatic rocks in the Bolnisi district of Georgia, south of Tbilisi, have recently been studied by Hässig et al. (2020) and Moritz et al. (2020), and this Eocene volcanism is considered to be a critical part of the paleogeographic reconstructions for the region (e.g. Robinson et al., 1997; Adamia et al., 2010, 2011; Blackbourn et al., 2021 this issue).

The Kartli Basin of central Georgia is located between the Greater and Lesser Caucasus fold-and thrust belts and has therefore been described as an intramontane basin (e.g. Adamia et al., 2010, 2011). To the west it is separated from the Rioni Basin by the Dziruli Massif (basement high), and to the east it shows a gradual transition to the Kura Basin of Azerbaijan (Fig. 1). The thickness of the basin fill increases to the east, from about 5 km in the study area in the Kartli Basin to more than 15 km in the Kura Basin at the edge of the Caspian Basin.

The relatively thick (1200-4500 m) Eocene basin fill locally includes intercalated conglomerates, very coarse-grained sandstones and shales (Fig. 3) representing the deposits of a back-arc extensional basin system. The Middle Eocene volcanic and volcanioclastic sequence is 50-800 m thick and includes the most important reservoir unit in the basin. It is dominated by volcanioclastic units intercalated with deep-water sandstones and marls. It is not clear how much of the volcanic material was derived from submarine eruptions from within the Kartli Basin itself, and how much from continental eruption
centres located some 50-100 km to the south on the uplifted northern rim of the Lesser Caucasus in eastern Georgia and western Azerbaijan (i.e. Somkheto-Agdam Uplift of Blackbourn et al., 2021 this issue). Extrusive volcanics, such as lavas, are rare in the study area and only a few andesitic flow units, up to 30 m thick, were found in outcrops. Boulder beds with a polymict, predominantly volcanic composition locally occur and were interpreted as submarine debris flows originating from volcanic highs (Robinson et al., 1997). A deep-water depositional setting for these rocks is inferred from the presence of deep-water foraminifera (e.g. this study: see below) and from the turbiditic sedimentological characteristics observed in outcrops (Robinson et al., 1997).

Volcanic activity ceased in the early part of the Late Eocene. The Upper Eocene succession contains no volcanics or volcaniclastics and is composed of a 500-1400 m thick shale-dominated unit. Organic-rich claysstones within this unit are the most important source rocks in the basin (Robinson et al., 1997; Sachsenhofer et al., 2018a,b; 2021 this issue). Relatively deep-water sedimentation and continuing subsidence occurred throughout the Late Eocene and Oligocene and is attributed to a combination of diminishing post-rift subsidence and the beginning of shortening along the northern edge of the Achara-Trialet thrust-fold belt (Banks et al., 1997; Alania et al., 2017, 2018, 2019). The shales and claysstones of the thick Oligocene to Lower Miocene Maikop sequence (1700-2700 m), as in many other parts of the Paratethys, provide an extensive source rock (e.g. Boote et al., 2018; Sachsenhofer et al., 2018a,b; 2021 this issue). Sandstones within this sequence also occasionally provide reservoirs, for example at the Norio and Satrakhenisi fields (Robinson et al., 1997).

From the Late Miocene onwards, molasse-type, relatively coarse-grained sedimentation occurred along the basin axis due to the development of thrust-fold belts on both flanks of the basin. The shortening driven by N-S compression continues at the present day (Tsereteli et al., 2016) and has resulted in uplift, within marine sedimentation being replaced by fluvial-alluvial sedimentation in the study area by the Pliocene. Due to the regional neo-tectonic uplift, 1000-2000 m of Cenozoic rocks has been eroded (Patton, 1993). The large number of oil and gas seeps reported from across the entire Kartli Basin (Robinson et al., 1997) underlines the importance of this ongoing deformation which has compromised some of the pre-existing and shallow hydrocarbon traps (Tari et al., 2021, this issue).

On the western margin of study area around Tbilisi, the N-S extent of the Kartli Basin is well-defined by the thrust-fold belts of the Lesser and the Greater Caucasus (Banks et al., 1997) forming retro-wedge and pro-wedge leading edges, respectively (Fig. 4,
Alania et al., 2021). The north-vergent frontal part of the Lesser Caucasus retro-wedge consists of two different thrust systems including a shallow triangle zone and a lower structural wedge. The frontal part of the Great Caucasus pro-wedge is represented by south-vergent thrusts composed of Miocene deposits. The width of the relatively undeformed sediment fill of the Kartli Basin decreases rapidly towards the east. Here the basin lies in a transitional zone between the converging Greater and Lesser Caucasus fold-and-thrust belts (Nemčok et al., 2013).

Geologic setting of the Samgori area near Tbilisi, central Georgia
The “flagship” Samgori field is situated in the eastern part of the Kartli Basin in central Georgia (Fig. 2). Six dry holes were drilled here preceding the discovery of oil in Middle Eocene volcaniclastic turbidites in 1974 (Patton, 1993). The field began producing in 1975 and is still the largest field in Georgia with 550 MM brl oil in-place reserves and an ultimate recovery of about 200 MM brl oil (36.4% recovery factor) and non-associated gas of 35.5 BCF (Nibladze and Janiashvili, 2014; Nachtmann et al., 2015). The oil has a 39-41° API gravity and average gas-oil-ratio of about 350 standard cubic feet per stock barrel with production via aquifer drive (Patton, 1993; Robinson et al., 1997).

The hydrocarbons are trapped in an east-west trending, elongated four-way dip-closed sub-thrust anticline. Towards the east, the overall anticlinal trend projects beneath a major, SW-verging thrust fault at the leading edge of the Greater Caucasus foldbelt, with a highly folded Oligocene-Miocene sequence in the hangingwall (Fig. 5) and a décollement within the Maikop sequence. The surface geology does not therefore express the overall subsurface structure of the Samgori field, even though the surface anticline was first mapped in 1965 and triggered subsequent
exploration drilling in 1967. Cross-sections and seismic profiles across the Samgori field located farther to the west do not show the shallow NW-SE striking thrust (Fig. 6), and the doubly-vergent thrust faults responsible for the overall anticlinal structure are therefore better imaged.

At the level of the top Middle Eocene reservoir sequence, the Samgori field is subdivided by two
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Structural saddles into three domal areas: Samgori, Patardzeuli and Ninotsminda, located in the west, centre and east, respectively (Fig. 7). The field is dominated by a single large-scale oil occurrence within the Middle Eocene reservoir, which has a gas cap at Ninotsminda. At the Middle Eocene level, the composite Samgori-Patardzeuli-Ninotsminda structure is 24 km long and 3-4 km wide, defining a productive area of about 44 km² (Patton, 1993). The structure was filled to spill-point within a four-way dip closure with a single initial oil-water contact (OWC) at -2120 m (Levin, 1995). Subsequently, based on many wells (Fig. 7), the OWC was interpreted to be tilted eastward by ~1° due to hydrodynamic processes within the field (Patton, 1993).

In the Ninotsminda culmination, the crest of the structure occurs at 1370 m below sea-level. The initial gas-oil-contact (GOC) was at -1580 m, translating

Fig. 8. Stratigraphic columns of the Samgori 60 and 170 wells (Patton, 1993) and the recent Patardzeuli-E1 well drilled in 2019. Note the uniform thickness of the Middle Eocene volcaniclastic reservoir sequence. For well locations, see Fig. 7.
to a 210 m gas column and a 540 m oil column. The Patardzeuli apex has a crest at -1520 m with an initial 600 m oil column; and Samgori proper has a crest at -1750 m with an initial 370 m oil column (Patton, 1993).

Although the hydrocarbons are trapped within a four-way dip-closure, the overall structure is bounded on its northern, eastern and southern flanks by steeply dipping thrust faults (Fig. 7) and towards the west it is dip-closed (Stasenkov et al., 1979). The structure is therefore asymmetrical with dips of 15-20° and 30-60° on the northern and southern flanks, respectively (Levin, 1995).

The light oil (39-41°API) is contained in altered and fractured Middle Eocene tuffs within a sequence of volcaniclastic turbidite sandstones sealed by thick Upper Eocene mudstones (Fig. 8). Initial production under aquifer drive increased rapidly, peaking at ~60,000 barrel of oil per day (b/d) in 1982, but then declined to less than 3000 b/d from 1986 as the reservoir pressure dropped significantly. There was increasing water production from “super-producer” wells drilled along high-permeability zones creating areas of bypassed oil, some of which were subsequently targeted by infill drilling (Patton, 1993). Production further declined to about 1500 b/d by 2001, although by then the field had already produced ca. 177 MM bbl oil. Besides the Samgori field, smaller follow-up discoveries were made in similar Middle Eocene reservoirs at Teleti (1977), Samgori Southern Dome (1979) and Rustavi (1983).

The main reservoir target in the Kartli Basin (Middle Eocene turbiditic volcaniclastic sandstones) have a high volcanic content which degrades the reservoir quality to various degrees. In the 1990s, a number of studies were devoted to the better understanding of these unusual reservoir units (Vernik, 1990; Grynberg et al., 1993; Patton, 1993; Levin, 1995). These studies indicated that most of the oil in Samgori is trapped in altered, microfractured, laumontite-rich tuffs that possess both fracture and cavernous porosity averaging ~12%, with 15 mD average permeability. The laumontite tuffs comprise up to 20% of the reservoir section and occur in isolated lenses or pods that cause productivity to be highly variable from one well to another. For the rest of the Middle Eocene volcaniclastic sequence, the total porosity ranges from 5 to 12% and effective porosity (which depends on the degree of fracturation) is typically <1%. Although slightly altered tuffs have better permeabilities than highly altered tuffs, the permeabilities are generally <0.1 mD (Fig. 9).

The presence of secondary minerals such as certain zeolites (e.g. analcime) was reported to reduce permeabilities (Vernik, 1990; Grynberg et al., 1993). However the presence of other zeolites, such as laumontite, was reported to lead to the formation of effective reservoir intervals in the otherwise poor reservoir-quality volcaniclastic succession. In particular, Grynberg et al. (1993) reported porosity values of 3.7-7% and permeabilities of 14.8-460 mD in laumontized tuffs (Fig. 9).

**DATA BASE AND METHODS**

A total of 46 plug samples of Middle Eocene volcaniclastic sandstones were collected from outcrops in the study area in central Georgia during fieldwork in 2019. Of these, a sub-set of ten samples were selected because the corresponding outcrops are located within a few tens of kilometers of producing fields including Samgori (see sample locations in Fig. 2). These ten samples came from outcrop successions which, on the basis of the available detailed geological maps, are age-equivalent to the volcaniclastic sandstones which constitute reservoir rocks in the subsurface.
The samples are all epiclastic (sensu Cas et al., 2008) as demonstrated by the presence of bioclasts and reworked sedimentary lithic grains, and are in general classified as tuffaceous sandstones. Sample locations and lithologies are summarised in Table 1.

The plug samples (10 cm long and 2 cm in diameter) were collected using a core drill. In the field, relatively unaltered rock walls were targeted for sampling; plugs were collected by drilling into the rock as far as 30 cm to minimize weathering effects. Since the 500-600 m thick Middle Eocene sequence (Fig. 8) does not have internal stratigraphic markers recognizable in outcrops, the precise stratigraphic position of the spot samples is unconstrained within the gross volcaniclastic sandstone interval.

The samples underwent routine core analysis (RCA) to obtain porosity and permeability data (Table 1). X-ray diffraction (XRD) analysis (see below) complemented by thin-section analyses were used to determine the mineralogy. This analytical work was intended to verify and refine the observations made earlier by Vernik (1990) and Grynberg et al. (1993) on age-equivalent subsurface core samples.

The rock samples were cleaned in a Dean-Stark device using an azeotropic mixture of chloroform and methanol (boiling point 53.5 °C) to remove contaminants from the pore space. They were then conventionally dried at 60 °C under a mild vacuum. Effective porosity, grain and bulk density were obtained using the He-expansion method (Boyle’s Law double cell porosimeter) at atmospheric conditions. The samples were then trimmed to one-inch diameter cylinders and permeability was measured by injecting gaseous nitrogen \( \text{N}_2 \) under steady-state conditions and an overburden pressure of approximately 35 bar. Combining injection pressures of up to 10 bar and flow rates lower than 1 cm³/min, the device can record permeabilities down to the 0.001 mD range.

The plug samples were analyzed by XRD to determine the bulk mineralogical composition (Table 2). We used a Bruker AXS D8 Advance X-ray diffraction spectrometer (copper Kα radiation generated X-ray tube at 40 kV and 40 mA, and X-ray detector Lynxeye XE-T) and the software programme DIFRAC.EVA V3 to identify different mineral phases. Sample preparation included grinding to a fine powder in an agate mortar or a swing mill; samples were then placed in a plastic sample holder, keeping a flat upper surface to achieve a random distribution of lattice orientations. For quantification of the minerals detected by XRD, the software programme TOPAS (Total Pattern Analysis Software) was used. The TOAPS software utilizes the Rietveld method based on analytical profile functions and least-squares algorithms to achieve the best fit between a theoretical and a measured pattern.
Five representative core samples (DZ-1, KH1-1, KU9-3, R2-1 and SH1-1) were chosen for detailed thin-section analysis. Petrographic characteristics of these samples are summarised in Table 3 and described in detail below. Independent of the instrumental porosity and permeability measurements (Table 1), the reservoir properties of these samples were assessed in thin-section to estimate effective porosity and permeability.

The thin-section descriptions below follow the schemes of Manville et al. (2009) and Cas et al. (2008). The term macroporosity as used refers to pore space which is visible in thin-section.

RESULTS

Petrographic and diagenetic characteristics

In general, the common non-volcanic components in the samples analysed such as sedimentary lithic clasts and bioclasts document the epiclastic reworking of grains (sensu Cas et al., 2008). The presence of moderately to well-rounded volcanic grains also points to reworking and transportation. Based on these observations, the analyzed samples can in general be classified as tuffaceous sandstones to conglomerates (Table 1) and do not represent primary pyroclastic deposits.

Volcanic components include microlithic grains (ash) with an andesitic-basaltic composition, and vesicular grains which are commonly altered and devitrified. Other framework grains include abundant detrital plagioclase (mostly altered) and minor mafic minerals including clinopyroxene (diopside) and amphiboles.

Sedimentary lithic grains include clasts of marlstone containing planktonic foraminifera. Bioclastic components are common and consist of planktonic foraminifera of the genus *Morozovella* and *Acarinina*. Shallow-marine bioclasts are represented by larger benthic foraminifera (orthophragminids and rotaliids) and bryozoans.

The overall interpretation of the analyzed samples suggests a relatively deep-marine depositional setting as indicated by the presence of planktonic foraminifera. The foraminiferal assemblage constrains the age to the Late Paleocene to Early-Middle Eocene. The presence of benthic foraminifera indicates syndepositional reworking from shallow- to deep-marine conditions.

Diagenetic characteristics

In general the petrographic observations indicate that the investigated samples had undergone significant diagenetic alteration. The most important diagenetic processes were mechanical compaction, cementation, and dissolution of framework grains. Mechanical compaction mostly affected soft volcanic grains and less commonly sedimentary lithic grains. Moderate compaction was indicated by the abundant long and concavo-convex to sutured grain contacts, especially where cementation was weak or absent.

Cementation was the most important diagenetic process, and XRD analyses recorded the presence of a complex array of zeolites including clinoptilolite, heulandite, tschernichite, analcime, laumontite, aerinite, stellerite and barrerite (Table 2). Zeolites make up a large part of the volume of authigenic material in the samples, in some cases up to almost 50% or more. Clinoptilolite is in general the most abundant zeolite present and commonly forms a first generation pore-lining to pore-filling cement.

Dissolution of framework grains, particularly plagioclase, was observed creating secondary pore spaces which were either open or were cemented by

| Sample ID | Quartz | Calcite | Plagioclase | K-Feldspar | Chlorite | Diopside | Heulandite | Tschernichite | Analcime | Laumontite | Zeolite | Aerinite | Stellerite | Barerite |
|-----------|--------|---------|-------------|------------|----------|----------|------------|--------------|----------|------------|--------|----------|-----------|---------|
| DZ1-1     | 54.33  | 5.31    | 24.02       | 17.33      | 0.27     | 28.07    | 17.33      |              |          |            |        |          |           |         |
| KH1-1     | 14.86  | 22.85   | 2.46        | 59.83      | 0.27     | 19.46    | 17.84      |              |          |            |        |          |           |         |
| KU9-1     | 19.61  | 40.59   | 14.43       | 18.40      | 15.36    | 19.46    | 17.84      | 21.27        | 21.81    |            |        |          |           |         |
| KU9-2     | 6.41   | 2.47    | 37.62       | 14.55      | 6.80     | 23.21    | 18.40      |              |          |            |        |          |           |         |
| KU9-3     | 7.71   | 14.45   | 53.55       | 7.75       | 5.64     | 14.45    | 17.84      | 18.62        |          |            |        |          |           |         |
| KU9-4     | 9.91   | 5.52    | 40.10       | 25.85      | 18.62    | 25.85    | 18.62      |              |          |            |        |          |           |         |
| R2-1      | 14.47  | 17.99   | 8.97        | 5.62       | 5.15     | 9.75     | 7.08       | 27.59        |          |            |        |          |           |         |
| R2-2      | 7.53   | 53.96   | 31.43       | 7.08       | 27.59    | 31.43    | 7.08       |              |          |            |        |          |           |         |

Table 2. Bulk mineralogical compositions of samples analysed based on XRD measurements. Values are expressed in weight percent.
The effective porosity as measured by RCA was 25.7% with a permeability of 0.7 mD (Table 1), representing potentially good reservoir characteristics. The bulk density was 1.86 g/cm³ while the grain density was 2.50 g/cm³.

Deposition is interpreted to have occurred in a relatively deep-water setting as indicated by the presence of planktonic foraminifera. Post-depositional zeolitization occurred as a result of low-temperature hydrothermal alteration.

**Detailed thin-section descriptions**

**Sample DZ1-1**
Based on its thin-section characteristics (Fig. 10), this sample is described as a tuffaceous pebbly conglomerate, with clasts up to 1 cm (Table 3). Components are dominated by volcanic lithic clasts including microlithic grains with an andesitic or basaltic composition (Fig. 10a); vesicular volcanic grains (pumice) (Fig. 10b); grains of vitric tuff; other altered volcanic grains; and detrital plagioclase (commonly sericitized). The high percentage of plagioclase was confirmed by XRD results (see Table 2).

Calcite spar replaces other grains, and calcite and common zeolite cements occlude interparticle pore spaces (Fig. 10c & d). Based on the XRD results (Table 2), zeolites make up a large part of the bulk volume of the sample (almost 50%) and include clinoptilolite (28.07%) and heulandite (0.27%). Tschernichite, first defined by Boggs et al. (1993), was also recorded (17.33%).

Minor interparticle porosity was preserved due to incomplete zeolite cementation, and intraparticle pore space was also present in dissolved feldspar grains. The effective porosity as measured by RCA was 25.7% with a permeability of 0.7 mD (Table 1), representing potentially good reservoir characteristics. The bulk density was 1.86 g/cm³ while the grain density was 2.50 g/cm³.

Deposition is interpreted to have occurred in a relatively deep-water setting as indicated by the presence of planktonic foraminifera. Post-depositional zeolitization occurred as a result of low-temperature hydrothermal alteration.

**Sample KH1-1**
Sample KH1-1 is composed of a tuffaceous medium-grained sandstone (Table 3; Fig. 11) and had a bulk density of 1.77 g/cm³ and a grain density of 2.36 g/cm³ (Table 1). Detrital crystals comprise plagioclase (Fig. 11a) and amphiboles. Bioclasts in particular planktonic foraminifera, orthophragminid foraminifera, and foraminifera fragments are common, together with rare unidentifiable bioclastic fragments.

Matrix material in the sample included abundant volcanic glass (some shards can be recognized) which has been altered and devitrified. Zeolites (including clinoptilolite) cement pore spaces, and unstable minerals have been replaced by calcite. The zeolite clinoptilolite dominates the sample (60% by weight, Table 2) and has characteristic tabular crystals (Fig. 11c & d). High macroporosity was observed in thin section which is consistent with the RCA-measured 25.2% effective porosity and 2.92 mD permeability (Table 1). However, the thin-section analysis shows...
that the dominant dissolution porosity is in general poorly connected.

Deposition is interpreted to have occurred in a relatively deep-water setting as indicated by the presence of planktonic foraminifera. The Acarinina/Morozovella assemblage constrains the age of the sample to the Late Paleocene to Early-Middle Eocene. The high visible porosity is mainly related to the dissolution of volcanic glass and of other unstable minerals. Some of the volcanic glass has weathered to chlorite (22.85%, Table 2). The extensive secondary zeolite cementation has significantly reduced the pore space.

Sample KU9-3
In this tuffaceous coarse-grained sandstone (Table 3; Fig. 12), the main framework components are detrital plagioclase, commonly zoned and altered/sericitized, which makes up about 38% of the rock (Table 2); clinopyroxene (diopside, 8.74%); sedimentary lithic fragments; bioclasts; and rare volcanic lithic grains. The sedimentary lithic fragments include clasts of marlstone containing planktonic foraminifera. Due to compaction, some shale clasts have been squeezed to look like pseudo-matrix. The bioclasts included planktonic foraminifera e.g. Morozovella sp. (Fig. 12a), rotaliid foraminifera (Fig. 12b) and agglutinated foraminifera. The microlithic volcanic grains are of basaltic to andesitic composition (Fig. 12c) and vesicular volcanic grains are also present (Fig. 12d).

Cements include clinoptilolite (6.8%) together with chlorite (23%) and heulandite (14.55%) (Table 2). Calcite spar occasionally replaces other grains.

A deep-water depositional setting is interpreted based on the presence of the planktonic foraminifera Morozovella which indicates a Late Paleocene to Early-Middle Eocene age. Some reworked material is also present, including clasts of deep-water calcareous shale with planktonic foraminifera. More detailed studies focusing on these reworked clasts will help to constrain the degree of reworking in the Middle Eocene succession.

Initial porosity was partly reduced during mechanical compaction of the unstable components. The pore spaces were subsequently filled by a first generation of pore-lining to pore-filling clinoptilolite cement followed by minor late, poikilotopic calcite. The measured porosity and permeability values (8.5% and 0.03 mD, respectively: Table 1) indicate moderate to poor gas reservoir potential.

Sample R2-1
This tuffaceous medium-grained sandstone (Table 3; Fig. 13) consists mainly of volcanic lithic grains...
including microlithic grains of basaltic/andesitic composition (Fig. 13a), and detrital plagioclase (40.1%). Sedimentary lithic clasts are composed of marlstone with planktonic foraminifera. Due to compaction some of the shale clasts have been squeezed and look like pseudomatrix (Fig. 13b). Bioclasts are represented by planktonic foraminifera, orthophragminid foraminifera (Fig. 13c) and bryozoans.

Little matrix material is present but authigenic calcite spar replaces other grains. Chlorite cement (25.85%) is both pore-lining and pore-filling, and the sample contains extensive laumontite (18.62% Table 2).

The sample is interpreted as a deep-water deposit based on the presence of planktonic foraminifera which provides evidence for a Middle Paleocene to Eocene age. Deep-water sedimentary material was reworked into the sample based on the presence of lithic clasts with slightly different foraminifera assemblages. Porosity was partially destroyed due to compaction of unstable components and as a result of calcite and chlorite cementation, but the ratio between these two processes was difficult to quantify. The first generation of pore-lining chlorite cement was followed by pore-filling laumontite cement (Fig. 13d). The measured porosity and permeability values (11.75% and 0.346 mD, respectively, Table 1) indicate moderate gas reservoir potential.

**Sample SH1-1**

This tuffaceous coarse-grained sandstone (Table 3; Fig. 14a) contains abundant (54%) detrital plagioclase (Fig. 14b) together with volcanic lithic clasts including microlithic (Fig. 14c) and altered vesicular grains (Fig. 14d). Authigenic clay minerals are abundant, especially chlorite which cements pore spaces and replaces grains. The only zeolite mineral recorded in this sample is aerenite (7.08%, Table 2), although another sample (SH1-2) from the same location contained ca. 28% laumontite and no aerenite, indicating that conditions for zeolitization were spatially highly variable.

The sample had the lowest permeability (0.08 mD) of all those measured (Table 1) and this is attributed to the very tight matrix in which chlorite (31.42%) occludes most of the pore space. Although the porosity is 9.5%, the sample had little reservoir potential without significant fracturing.

**Reservoir potential**

Based on thin-section observations, the volcanic material in the samples of Middle Eocene volcaniclastic sandstones analysed was mainly derived from andesitic to basaltic volcanism. Due to the presence of volcanic clasts in the samples, their reservoir potential is generally poor as a result of: (a) mechanical compaction of unstable volcanic lithic grains; (b) the presence of
Fig. 12. Thin-section images of sample KU9-3. (a) Tuffaceous sandstone with a planktonic foraminifera (*Morozovella* sp.) in the centre; (b) close-up of a rotaliid foraminifera (reddish stained); (c) microlithic volcanic rock fragment together with detrital plagioclase; (d) authigenic calcite (pink stained) has cemented/replaced a former vesicular volcanic grain.

Fig. 13. Thin-section images of sample R2-1. (a) Tuffaceous sandstone with microlithic volcanic lithic grain and detrital plagioclase; (b) lithic fragment of sandy calcareous shale with planktonic foraminifera; (c) close-up of orthophragminid foraminifera; and (d) first generation of pore-lining chlorite followed by pore-filling laumontite cement.
pore-lining and pore-filling authigenic chlorite cement; (c) the presence of pore-lining and pore-filling zeolites (of either hydrothermal or early diagenetic origin); and (d) occasional calcite cementation. While the observed porosity range would suggest moderate reservoir quality, the permeability values are consistently very low (Fig. 15). Subsurface analogues of the analyzed samples may exhibit significant volumes of micro-porosity. The irreducible water saturation recorded by well-logs could therefore be high.

In the context of mechanical compaction, much better reservoir properties would be expected in rocks with higher contents of stable felsic components (especially quartz) which are more resistant to compactional porosity loss. However, quartz was found only in relatively small percentages (or not at all) in just six of the ten samples analysed (4-14%; Table 2). By contrast the generally ductile nature of the volcanic clasts and their chemical instability made them susceptible to porosity loss during compaction and burial. The quartz content of the samples (average 8%) would predict very low porosities in the Middle Eocene volcaniclastics at an average depth of 2 km (Fig. 7).

Zeolites, in particular laumontite, do not necessarily enhance the porosity and permeability, as previously observed by Vernik (1990) and Grynberg et al. (1993). The results of XRD analysis reported here add clinoptilolite, heulandite, tschernichite, aerinite, stellerite and barrerite to that list (Table 2). In the samples analysed, zeolites did not improve the reservoir quality. Whether the zeolites formed as a result of eo-diagenesis in near-seafloor conditions or by hydrothermal processes is as-yet unresolved. Authigenic calcite cement was identified in four out of ten samples in proportions up to 14% (Table 2) and occluded some of the pore space.

Based on the petrographic observations and the presence of planktonic foraminifera, the Middle Eocene volcaniclastics analysed are interpreted to have been deposited in a deep-water submarine environment. Volcanic activity to the south of the study area in the Kartli Basin is interpreted to have been near-synchronous with the development of mass flow and turbidite deposits (Fig. 16).

Previous studies on Eocene volcaniclastic reservoir rocks in Georgia only mentioned analcime and laumontite as identifiable zeolites (Vernik, 1990; Grynberg et al., 1993). The results of XRD analysis reported here add clinoptilolite, heulandite, tschernichite, aerinite, stellerite and barrerite to that list (Table 2). In the samples analysed, zeolites did not improve the reservoir quality. Whether the zeolites formed as a result of eo-diagenesis in near-seafloor conditions or by hydrothermal processes is as-yet unresolved. Authigenic calcite cement was identified in four out of ten samples in proportions up to 14% (Table 2) and occluded some of the pore space.

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Petrophysical analyses of subaerial basalt lavas and associated volcanic rocks in Tenerife, Canary Islands (Couves et al., 2016) showed that relatively good reservoir properties may occur in the tops of lava flows and in ignimbrites. By contrast, submarine pyroclastic deposits typically show a significant reduction of the original inter- and intragranular porosity and permeability, often due to the precipitation of micrite, coarser-crystalline calcite and dolomite cement, and
occasionally pyrite (Fensom et al., 2020). Dolomite cement and calcite spar infilling pore spaces likely form near the seafloor and during early burial (Fensom et al., 2020).

**DISCUSSION**

The plug samples analysed in this study were collected from surface exposures of Middle Eocene volcaniclastic sandstones in the Kartli Basin, central Georgia (Fig. 2). However these samples are not directly comparable to the subsurface core samples from 2.2-2.5 km depth studied by Vernik (1990) and Grynberg et al. (1993) which had been subjected to different levels of burial-related compaction and diagenesis. In addition, the surface samples analyzed did not include the 5 m thick, laumontite-dominated tuff interval documented by Vernik (1990) as a high-productivity reservoir in the Samgori field. Future studies should therefore focus on the examination of core samples of laumontite tuff beds from producing fields in the study area, as these lithologies behave anomalously in terms of preserving and enhancing primary porosity and permeability. The Middle Eocene outcrop samples collected for this study may previously have been buried to a depth of 1-2 km prior to uplift and large-scale erosion in the Late Miocene to Pliocene. Although apatite fission-track data is available from the Greater Caucasus (Avdeev and Niemi, 2011) and the Lesser Caucasus (Cavazza et al., 2017, 2019; Gusmeo et al., 2021) to constrain the amount of uplift, no relevant data is available to quantify the amount of missing section in the sampling area. Future fission track analytical studies in the Kartli Basin are needed to address this uncertainty, which has a direct impact on the reservoir quality at depth.

The poor reservoir characteristics portrayed by the samples analysed, which were derived from an outcrop interval analogous to the proven subsurface reservoir at Samgori, underlines the importance of fracturing to account for the presence of “super-producer” wells at the latter field. Production from individual wells is highly variable ranging from high producers (4500-9000 b/d oil) to low producers (200-450 b/d). Most high producers were productive for up to two years before they showed a high water-cut, whereas low producers had steady production levels for more than a decade and had low water-cuts (Grynberg et al., 1993). The order of magnitude difference between the initial production rates, and the rapid inception of high water cut in the high producers, is interpreted to
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be a result of their proximity to fracture corridors. For example, the Samgori-60 well alone produced 6.25 MM bbl oil during the years 1978 to 1993 (Patton, 1993; Robinson et al., 1997). Productivity at Samgori field must therefore be predominantly enhanced by the presence of fractures.

The density of subvertical fracturing across the thick reservoir interval must be such that it should account for the hydrodynamic connectivity across the fairly large Samgori field which has a single OWC (Fig. 7). The most common fracture orientations are NW-SE and NE-SW with subordinate N-S, and E-W trends. These fractures were probably formed during the Late Miocene to Early Pliocene, reflecting late shortening episodes in the area (Alania et al., 2018, 2019, 2020a,b; Gusmeo et al., 2021). This underlines the need to better understand the 3D geometry and temporal evolution of fracturing in the prominent surface anticlines around Tbilisi, which could then be used to serve as analogues for the structures at Samgori field.

In a more regional-scale study of the Upper Eocene and Oligocene sandstones of the Kartli Basin (OMV, unpublished data), a change in the provenance of clastic sediment was observed. Felsic components (quartz, alkali feldspar, metamorphic lithic fragments) became progressively more abundant higher in the section, indicating erosion and sediment supply from the Dziruli Massif basement high located to the west of the Kartli Basin (Fig. 1). Oligocene sandstones were found to contain more stable framework grains especially quartz, and can therefore be expected to be mechanically and chemically more stable during burial. Consequently, the preservation potential of depositional intergranular porosity is predicted to be higher in the Upper Eocene to Oligocene arenitic sandstones than in underlying Middle Eocene volcaniclastics.

CONCLUSIONS

The analysis of samples of Middle Eocene volcaniclastic sandstones collected from surface outcrops around Tbilisi (Kartli Basin, central Georgia) documents synchronous volcanic activity and associated epiclastic sediment reworking into a deep-water basin. The samples analyzed contain abundant volcanic lithic grains of intermediate composition which, together with detrital plagioclase and clinopyroxene, contributed to form deep-marine volcaniclastic marls and sandstones.

Petrographic studies of the surface samples of volcaniclastic sandstones broadly support previous investigations based on the analysis of subsurface samples from the Samgori field made some 30 years ago. In addition to the zeolites laumontite, clinoptilolite and analcime which were reported in the previous studies, other zeolites such as heulandite, tschernichite, aerinite and stellerite were also observed. However, contrary to the results of previous studies, these authigenic cement phases did not improve the reservoir quality of the samples but rather reduced it. This apparent discrepancy may be due to the fact that samples analysed in the present study did not include...
the key laumontite-dominated tuff unit which provides the best pay interval in the Samgori field.

The poor reservoir properties measured in the surface plug samples analysed relative to those of the Middle Eocene reservoir interval at the nearby Samgori field emphasise the importance of fracturing to reservoir performance. Fracturing may explain the presence of exceptional producers (up to 9000 b/d) in the Samgori field complex. The fracturing is associated with progressive Miocene to Pliocene shortening of the area between the Greater and Lesser Caucasus.

Structural deformation is an important factor to consider when targeting undrilled subsurface anticlines in the Kartli Basin. There is a clear need to better understand the 3D geometry and temporal evolution of fracturing in analogue surface anticlines around Tbilisi.

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Data availability statement

The reflection seismic and well log data used in this study are confidential and are not available publicly.

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