Petroleum geology of the Black Sea: introduction

M. D. SIMMONS[1]*, G. C. TARI[2] & A. I. OKAY[3]

[1]*Halliburton, 97 Jubilee Avenue, Milton Park, Abingdon OX14 4RW, UK*

[2]*OMV Exploration & Production GmbH, Trabrennstrasse 6–8, A-1020 Vienna, Austria*

[3]*Eurasia Institute of Earth Sciences, İstanbul Technical University, 34469 Maslak, İstanbul, Turkey*

**Correspondence:* mike.simmons@halliburton.com

Abstract: The exploration for petroleum in the Black Sea is still in its infancy. Notwithstanding the technical challenges in drilling in its deep-water regions, several geological risks require better understanding. These challenges include reservoir presence and quality (partly related to sediment provenance), and the timing and migration of hydrocarbons from source rocks relative to trap formation. In turn, these risks can only be better understood by an appreciation of the geological history of the Black Sea basins and the surrounding orogens. This history is not without ongoing controversy. The timing of basin formation, uplift of the margins and facies distribution remain issues for robust debate. This Special Publication presents the results of 15 studies that relate to the tectonostratigraphy and petroleum geology of the Black Sea. The methodologies of these studies encompass crustal structure, geodynamic evolution, stratigraphy and its regional correlation, petroleum systems, source to sink, hydrocarbon habitat and play concepts, and reviews of past exploration. They provide insight into the many ongoing controversies regarding the geological history of the Black Sea region and provide a better understanding of the geological risks that must be considered for future hydrocarbon exploration. The Black Sea remains one of the largest underexplored rift basins in the world. Although significant biogenic gas discoveries have been made within the last decade, thermogenic petroleum systems must be proven through the systematic exploration of a wide variety of play concepts.

The Black Sea, located between Russia, Georgia, Turkey, Bulgaria, Romania and Ukraine, covers an area of approximately 423 000 km^2 with a maximum water depth of 2245 m. Sedimentary thickness can exceed 14 km. The Black Sea holds an abiding fascination for petroleum geologists and is a true frontier basin with very few wells drilled in its deep-water sector. Abundant seepage, outcrops of potential source rocks around its margins, large potential traps imaged on seismic data, and a variety of potential reservoir and play concepts point towards considerable potential to reward the successful explorer. This volume brings together several geoscience studies (Fig. 1) that provide additional information about the origins of the Western and Eastern Black Sea basins, their tectonostratigraphic history, sedimentary fill and petroleum potential.

The Black Sea and its surrounding regions have a long history of geological research: for example, it has long been regarded as the type example of an euxinic basin in which bottom water anoxia and free hydrogen sulphide (H_2S) result in an absence of benthonic life and the preservation of organic matter (Wignall 1994). Somewhat ironically, the term 'euxinic' is derived from an ancient Greek name for the sea, *Pontus Euxinus*, meaning the welcoming or hospitable sea. Another ancient Greek name (probably derived from an Iranian name), *Pontos Axeinos* (the dark or somber sea: King 2004), may better reflect the widespread anoxia in its deep waters. Nonetheless, it is indeed a welcoming region for the geologist wishing to unravel its geological history and petroleum potential, although its secrets are not given up lightly.

The Black Sea comprises two distinct depositional basins: the Western Black Sea and the Eastern Black Sea separated by the Mid Black Sea High (the Andrusov Ridge and the Tetyaev and Archangelsky highs) (Fig. 2) (Finetti *et al.* 1988). The Eastern Black Sea contains the Tuapse Trough, the foreland basin to the Caucasus fold and thrust belt. The Tuapse Trough is separated from the main part of the Eastern Black Sea by the Shatsky Ridge.

From the Oligocene onwards, the Black Sea and its constituent basins formed part of Paratethys, a remnant of the closure of Tethys. It lies at the southern margin of Laurasia, which formed the northern margin of Tethys. The basins of the Black Sea are

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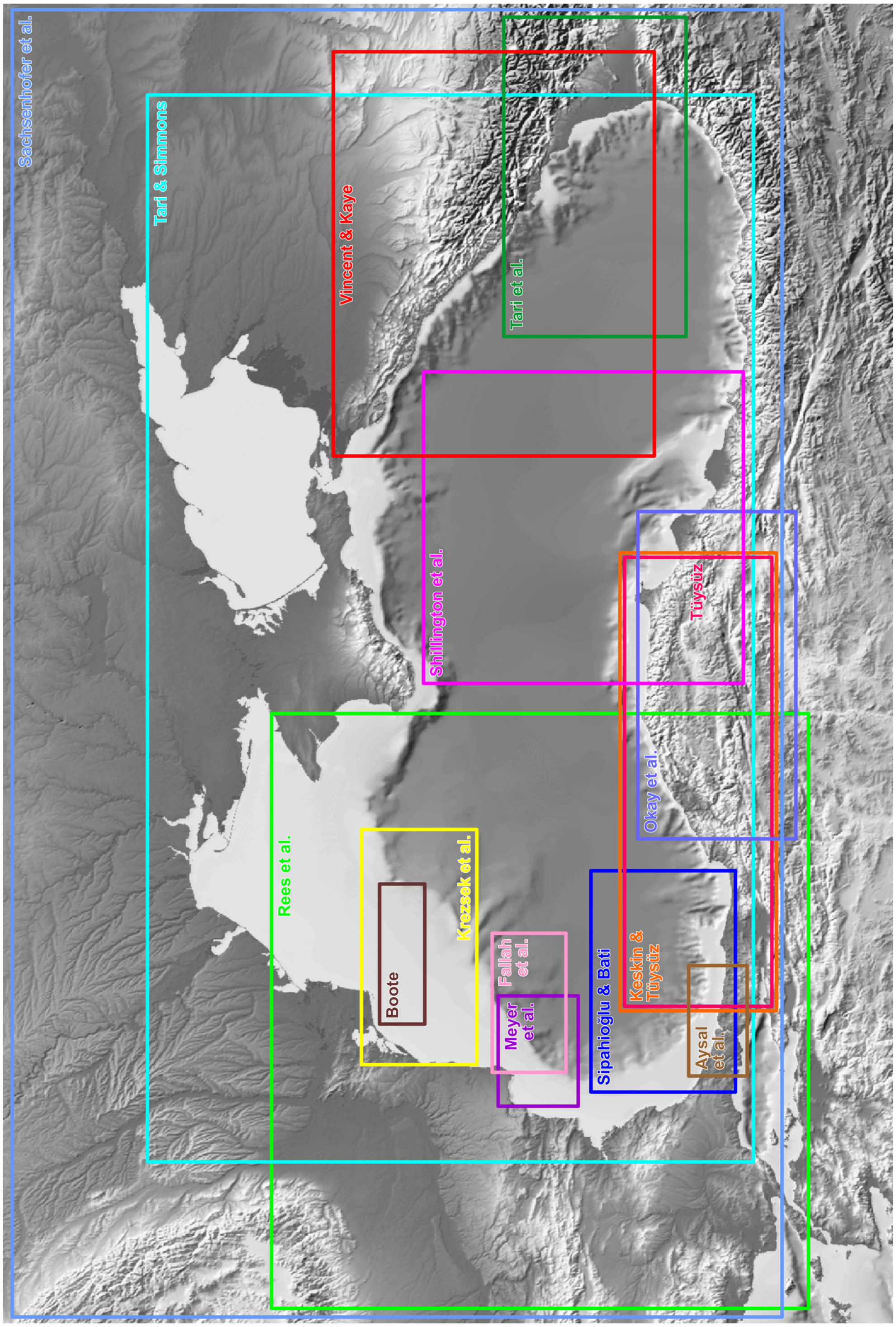

Fig. 1. Location of the studies that comprise this volume.

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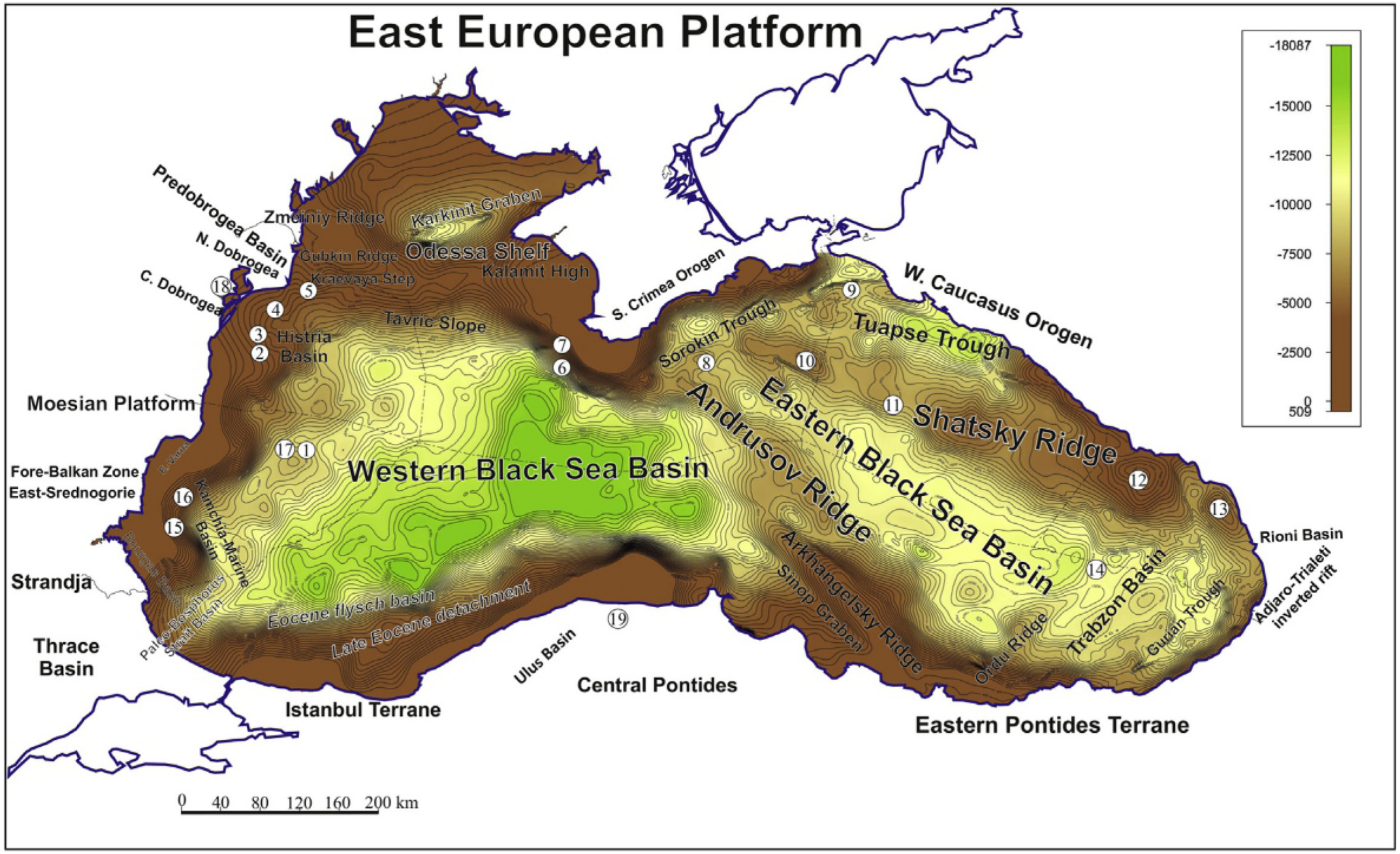

Fig. 2. Basement topography of the Black Sea basins (after Nikishin *et al.* 2015*a*, *b*) with key tectonic and depositional elements as mentioned in the text. 1, Polshkov Ridge; 2, Tindala-Midia Ridge; 3, Tomis Ridge; 4, Lebada Ridge; 5, St George Ridge; 6, Sevastopol Swell; 7, Lomonosov Massif; 8, Tetyaev Ridge; 9, Anapa Swell; 10, North Black Sea High; 11, South-Doobskaya High; 12, Gudauta High; 13, Ochamchira High; 14, Ordu-Pitsunda Flexure; 15, Rezovo-Limankoy Folds; 16, Kamchia Basin; 17, East Moesian Trough; 18, Babadag Basin; 19, Küre Basin.

extensional in origin (Zonenshain & Le Pichon 1986; Okay *et al.* 1994), relating at least in part to the northwards subduction of strands of Tethys beneath Laurasia, but are surrounded by compressive belts. Crimea and the Greater Caucasus, formed by the inversion of the Mesozoic Caucasus Basin in the Cenozoic, border the Black Sea to the north and east. A small basin, the Rioni, lies to the east in Georgia. The Balkanides and Pontides orogenic zones, formed from an accretion of terranes and island arcs, lie to the south and SE (Fig. 2).

Many oil and gas fields lie around the margins of the Black Sea (Robinson *et al.* 1996; Benton 1997), both in shallow-marine areas and onshore. More recently, the first efforts to explore in the deep-water offshore have met with mixed success, despite the presence of a variety of play types (Tari *et al.* 2011; **Tari & Simmons 2018**). In 2017, respected analysts Wood Mackenzie reported an estimate of 1.35 BBOE (billion barrels of oil equivalent) of yet-to-find reserves for the Black Sea (Wood Mackenzie 2017). This may be a modest estimate, given the presence of widespread source rocks, seepage and large potential traps. By contrast, in 2000, the USGS World Petroleum Assessment estimated in excess of 7 BBOE (https://pubs.usgs.gov/dds/dds-060/index.html#TOP). However, the current contribution of the Black Sea to global petroleum production is minor, especially when compared to the neighbouring Caspian Sea region. Interestingly, similarities exist between the two regions in terms of key petroleum geology elements. Partial isolation from the world's oceans from the Eocene onwards led to deposition of the Kuma and Maykop suites and their equivalents. These are important source rocks in both the South Caspian Sea and the Black Sea. Both the Black Sea and the South Caspian have been influenced by the Cenozoic influx of sediment from palaeo-river systems that occupy very different drainage pathways than the current equivalent systems. These sediments can form key proven and potential reservoir targets.

To date, the limited exploration in the deep water of the Black Sea has mostly resulted in discoveries of biogenic gas as at Domino in the Romanian offshore (a play first described by Bega & Ionescu 2009). Thermogenic petroleum systems, although proven, are yet to yield major finds, although at the time of writing several play concepts are being tested. On the shelf of the Black Sea, additions to the discoveries listed by Benton (1997) continue to be made. These include, for example, Subbotina, discovered in 2005 offshore Crimea. A thrust anticline with reservoirs in Maykop Suite sands, the field is reported to have recoverable reserves of 100 Mt (million tons) of oil (*c.* 680 MMBO (million barrels of oil)) and 3.5 TCF (trillion cubic ft) of gas (Stovba *et al.* 2009). Similar (and larger) untested anticlinal structures extend southwards into the deep water (Tari *et al.* 2011).

Geological history: ongoing uncertainties

The geological history of the Black Sea region is related to the history of the amalgamation of the tectonic terranes that have accreted around it (Figs 2–4). Anatolia to the south of the Black Sea is a notable collage of different continental and oceanic fragments (Okay & Tüysüz 1999; Okay 2008; Hippolyte *et al.* 2015). Uncertainty exists with regard to the timing of the amalgamation events and their consequences (Sosson *et al.* 2010, 2017). Nonetheless, the subduction of branches of Neotethys to the south of the present-day Black Sea led to phases of arc volcanism and extension (although the two are not always clearly related) on the southern margin of Laurasia within the Mesozoic (Fig. 3) (Nikishin *et al.* 2003; Dinu *et al.* 2005; Okay & Nikishin 2015). This was followed by uplift and compressional deformation as strands of Neotethys progressively closed (Allen & Armstrong 2008; Vincent *et al.* 2016).

The relative timing of the opening of the two basins remains controversial. Evidence of rifting exists in the Western Black Sea during the Early Cretaceous (Barremian–Aptian) (Görür 1988, 1997; Nikishin *et al.* 2003; Hippolyte *et al.* 2010). Deep seismic studies indicate that oceanic crust is present in the Western Black Sea (Belousov *et al.* 1988; Görür 1988; Okay *et al.* 1994; Graham *et al.* 2013; Tari *et al.* 2015*b*; Schleder *et al.* 2015; Nikishin *et al.* 2015*a*, *b*). Interpolation between the onshore stratigraphy and seismic data suggests that the ocean crust in the Western Black Sea is Santonian in age (Okay *et al.* 2013; Nikishin *et al.* 2015*a*, *b*). In much of the Central Pontides, a large hiatus of *c.* 20 myr exists between the deposition of the Barremian–Aptian sequence and the start of arc volcanism in the Santonian (Fig. 3). In the southern margin of the Pontides near the Tethyan subduction zone, this stratigraphic gap is represented by accretion of oceanic edifices involving deformation and metamorphism of the Barremian–Aptian depositional sequence (Okay *et al.* 2013). An uncertainty in the geology of the Black Sea is whether the Barremian–Aptian rift succession is related to the opening of the Western Black Sea, or represents an unrelated earlier event.

The main phase of the opening of the Eastern Black Sea has been variously interpreted as coeval with the Western Black Sea (Okay *et al.* 1994; Nikishin *et al.* 2003, 2015*a*, *b*; Stephenson & Schellart 2010); as late Campanian–Danian (Vincent *et al.* 2016), as Paleocene–Early Eocene (Robinson *et al.* 1995, 1996; Spadini *et al.* 1996; Shillington *et al.* 2008) or as Eocene (Kazmin

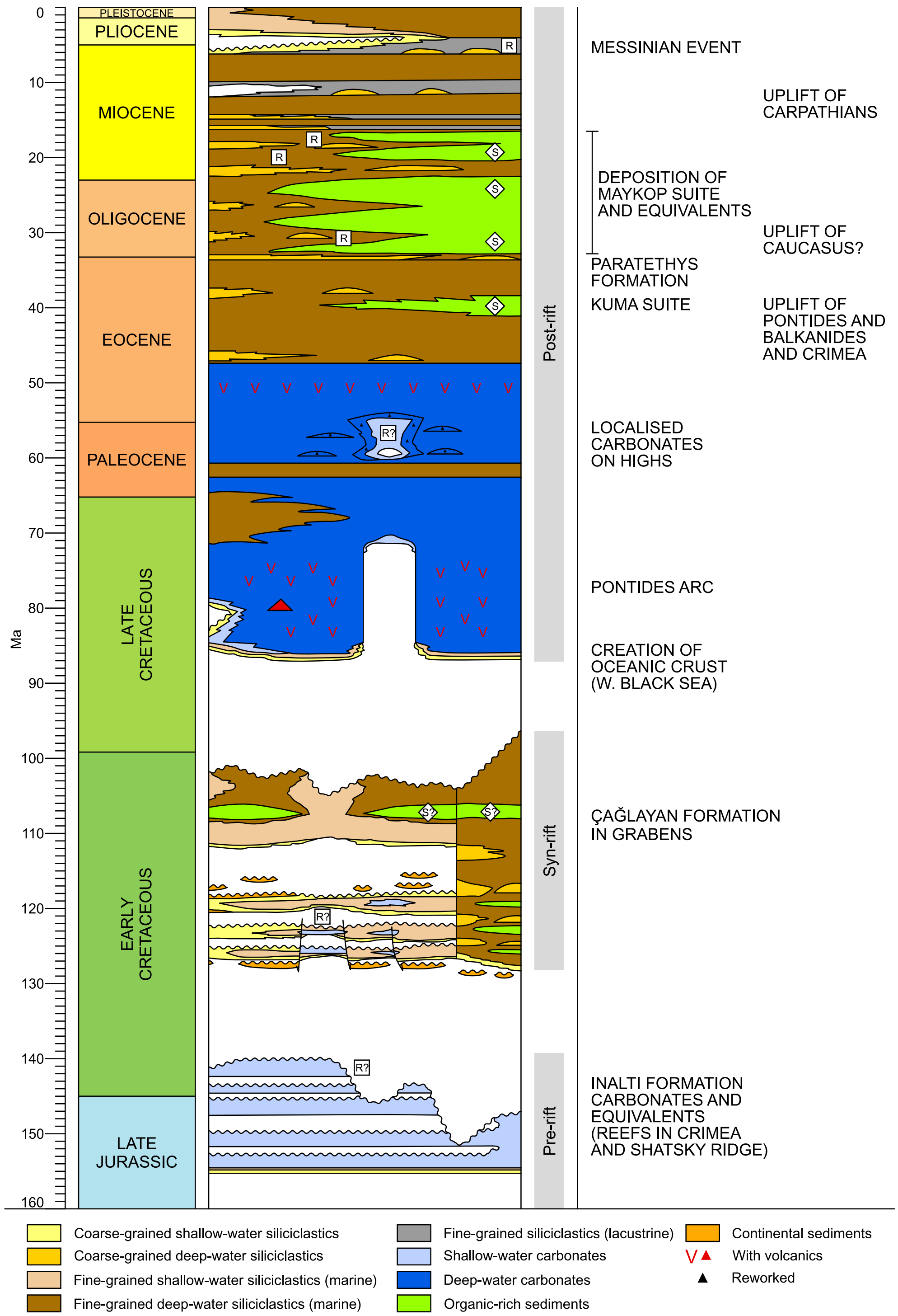

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Fig. 3. Simplified chronostratigraphic chart of the stratigraphy present in the Black Sea. Based largely on the Western/Central Pontides and an interpretation of the Western Black Sea but may be largely applicable to the Eastern Black Sea depending on the timing of the opening of that basin.

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Fig. 4. Major tectonic terranes in the Black Sea/Anatolia region (after Okay & Tüysüz 1999).

et al. 2000). It is notable that the rift-related successions of the Western and Central Pontides (e.g. Çağlayan Formation) have no equivalents in the Eastern Pontides (Okay & Şahintürk 1997; Hippolyte *et al.* 2015).

Given that the Western Greater Caucasus Basin to the north of the Shatsky Ridge opened in the Early Jurassic as a result of Neotethyan subduction, there may have also been a proto-Eastern Black Sea south of the Shatsky Ridge during the Jurassic, or at least an initial phase of rifting (Vincent *et al.* 2016).

A commonly cited model for the Cretaceous opening of the Western Black Sea was described by Okay *et al.* (1994) that involved the Istanbul Terrane (modern-day Western Pontides) splitting away from Moesia along two major faults – the West Black Sea Fault and the West Crimea Fault – as a consequence of subduction of the Neo-Tethyan Ocean to the south. Notwithstanding evidence for Albian-aged volcanism south of the Karkinit Trough (offshore Ukraine), in Crimea and on the Shatsky Ridge (Kazmin *et al.* 2000; Nikishin *et al.* 2013, 2015*a*, 2017), it is now argued that initial rifting may not be back-arc related (Tari 2015; **Okay *et al.* 2017**) and, moreover, that the nature of the key faults cited by Okay *et al.* (1994), especially the West Crimea Fault, can be reappraised (Tari *et al.* 2015*b*) in the light of excellent regional 2D seismic data that have been gathered across the Black Sea for both petroleum exploration and academic purposes (Graham *et al.* 2013; Nikishin *et al.* 2015*a*, *b*). For example, the West Crimea Fault can be shown to be a major transform fault running NW–SE on the margin of the Andrusov High (Fig. 2). This enables the Western Black Sea to open by means of a 15–20° counterclockwise rotation of the Istanbul Zone around a Euler pole located to the SW of the Black Sea (Stephenson & Schellart 2010; Schleder *et al.* 2015; Tari *et al.* 2015*b*). This discussion highlights the ongoing uncertainties associated with the Black Sea tectonics and geodynamic history, and the role that petroleum industry data can play in resolving these issues.

The formation of the semi-isolated Paratethys at the end of the Eocene through a combination of eustatic sea-level fall (Miller *et al.* 2005) and orogenesis (Schulz *et al.* 2005) is an important element in the petroleum geology of the Black Sea region. Isolation led to deposition of the Oligocene–Early Miocene Maykop Suite and equivalents, which includes important source rocks deposited in a restricted basin and potential reservoir sands derived from the surrounding orogens (e.g. from the Balkanides, Pontides and Caucasus).

The timing of the uplift of one of these orogens, the Greater Caucasus, is a matter of dispute. Vincent *et al.* (2007, 2016) favour a base Oligocene age, based on the onset of massive microfossil reworking and palynological data, indicating palaeoaltitudes of the Greater Caucasus of *c.* 2 km at this time. Palaeocurrent vectors and heavy mineral compositions also support this notion (Vincent *et al.* 2007), as does some fission-track data (Vincent *et al.* 2013*a*, *b*). Several other authors (e.g. Lozar & Polino 1997; Adamia *et al.* 2011) draw similar conclusions, and abundant evidence exists that Crimea experienced Eocene, then Oligocene, uplift (Panek *et al.* 2009; Nikishin *et al.* 2017). Conversely, Avdeev & Niemi (2011), Forte *et al.* (2014) and Cowgill *et al.* (2016) have suggested that the major phase of uplift occurred no earlier than *c.* 5 myr ago, whereas Rolland (2017) prefers a Miocene (*c.* 15 Ma) age for the onset of Caucasus uplift, based on geodynamic context and fission-track constraints on 'hard' Arabia–Eurasia collision (e.g. Okay *et al.* 2010). The resolution of this controversy has important consequences for the petroleum prospectivity of the Eastern Black Sea plays within the Maykop Suite or younger, because the timing of inversion would also affect the timing of structural uplift within the Black Sea (e.g. of the Shatsky Ridge). A young age for uplift would limit the amount of clastic (potential reservoir) sediment entering the basin from its margins during the deposition of the Maykop Suite, for example. Seismic data (Afanasenkov *et al.* 2007; Nikishin *et al.* 2010; Mityukov *et al.* 2011) demonstrate thickening of the Maykop Suite into the Tuapse and Indolo-Kuban foreland basins to the south and north of the Greater Caucasus, respectively, supporting the notion of Vincent *et al.* (2016) that the Caucasus were forming during the Oligocene.

Contents of this Special Publication

In addition to this introduction, 15 studies (Fig. 1) are included that relate to the tectonostratigraphy and petroleum geology of the Black Sea region. The methodologies used include examination of crustal structure from seismic data, geodynamic evolution, stratigraphy and its regional correlation, petroleum systems, source to sink, hydrocarbon habitat and play concepts, and reviews of past exploration. Their intent is to provide insight into the many ongoing controversies regarding the geological history of the Black Sea region and to provide a better understanding of the geological risks that must be considered during future hydrocarbon exploration.

The papers are grouped thematically. The first section corresponds to crustal structure and tectonostratigraphy, including geodynamic aspects of the evolution of the Black Sea region; it includes papers about the evolution of the Pontides that, as well as sedimentary geology, encompass Late Cretaceous volcanism and magmatic intrusions. The second section includes papers that examine hydrocarbon plays in the Western Black Sea, including sediment routing systems. The third section features a set of papers that focuses on regional petroleum systems and source rocks. The Messinian and Holocene stratigraphy of the Black Sea is addressed in two papers, whereas the petroleum potential of the Eastern Black Sea is discussed in a review of the Rioni Basin, with a closing paper reviewing the exploration history of the deep-water Black Sea to date.

Crustal structure and tectonostratigraphy

Shillington *et al.* (2017) review the crustal structure of the Mid Black Sea High, formed of two en echelon basement ridges: the Archangelsky and Andrusov ridges (Fig. 2). This high separates the Western Black Sea Basin from the Eastern Black Sea Basin. Using a densely sampled wide-angle seismic profile, Shillington *et al.* demonstrate that the basement ridges are covered by approximately 1–2 km of pre-rift sedimentary rocks and 20 km of thinned continental crust that are suspected of being related to the Pontides geology. Thinning factors of 1.5–2.0 are implied by thickness variations between the Mid Black Sea High and the adjacent crust in the Turkish Pontides. The velocity structure suggests little magmatic addition during rifting. That the Western and Eastern Black Sea basins are separated by continental crust lends support to the notion that the two basins have different times and mechanisms of opening (Okay *et al.* 1994).

Okay *et al.* (2017) evaluate the broad geological evolution of the Central Pontides, whereas **Tüysüz (2017)** focuses on the Cretaceous evolution of this region. An understanding of the geology of the Pontides is important for understanding the evolution of the Black Sea because it represents the active northern margin of Tethys; consequently, its stratigraphy records many events that reflect the geodynamic evolution of the region. Using new field observations, sedimentology, detrital zircon geochronology and biostratigraphy, the framework of tectonostratigraphic evolution is established in these two papers, although there are contrasts in interpretation.

The Central Pontides represents two terranes (the Istanbul Zone in the west and the Sakarya Zone in the east) that, in the view of **Okay *et al.* (2017)**, were amalgamated before the Late Jurassic, given the uniformity of deposition on both terranes after this time. Shallow-marine carbonate deposition (İnalti Formation) was widespread and is confined to Kimmeridgian–Berriasian time from new biostratigraphic analyses (Fig. 3). Shallow-marine carbonate deposition was widespread around the Black Sea at this time (including the formation of reefs in Crimea and the Caucasus, but not in the Pontides) (Muratov 1969; Krajewski & Olszewska 2007; Guo *et al.* 2011), and it is likely that the Black Sea region was the site of a widespread carbonate platform on the northern margin of Tethys with only relatively minor bathymetric differences.

Uplift and erosion occurred in the Valanginian and Hauterivian, and was followed in the Barremian–Aptian by synrift deposition of a more than 2 km-thick succession of turbidites (the Çağlayan Formation) in basinal depocentres (Okay *et al.* 2013); whereas on the present-day Black Sea coast, shallow-marine and continental deposition occurred (Yılmaz & Altiner 2007; Masse *et al.* 2009) (Fig. 3). Sediment provenance of the turbidites from the East European Platform (Akdoğan *et al.* 2017) demonstrates that while rifting was occurring, the Black Sea was yet to open. Albian-aged accretion of Tethyan oceanic crust is demonstrated by deformation and metamorphism in the present-day southern Central Pontides (Okay *et al.* 2013; Hippolyte *et al.* 2015).

In contrast, **Tüysüz (2017)** favours a later amalgamation of the Sakarya and Istanbul terranes. In his view, an Intra-Pontide Ocean (Şengör & Yılmaz 1981; Yılmaz *et al.* 1997) between the two terranes existed until Cenomanian times, arguing that open-marine deposition of Berriasian age in the southern part of the Zonguldak-Ulus Basin on the Istanbul Terrane suggests an older formation of this basin than interpreted by **Okay *et al.* (2017)** (and others, e.g. Hippolyte *et al.* 2015, 2016) and that it faced into the Intra-Pontide Ocean. Mid-ocean ridge basalts and volcanic-arc-related magmatic rocks interbedded with radiolarian cherts (Kervansaray Formation) of late Tithonian–Berriasian age offer evidence for oceanic separation of the Istanbul and Sakarya terranes at this time. Both **Okay *et al.* (2017)** and **Tüysüz (2017)** agree that the Çağlayan Basin on the Sakarya Terrane formed later in the Early Cretaceous; the contrast being that **Okay *et al.* (2017)** regard the Çağlayan and Zonguldak-Ulus basins as being one post-terrane amalgamation rift-related basin, whilst **Tüysüz (2017)** suggests that they have separate geological histories. The presence and age of closure of the Intra-Pontide Ocean remains a contentious topic in Turkish geology.

Keskin & Tüysüz (2017) suggest another possibility that the Istanbul and Sakarya Terranes did not collide until the very latest Cretaceous; this occurred with the southwards translation of the Istanbul Terrane, driven by rollback of the subducting slab of the Tethys Ocean beneath Laurasia.

A new depositional cycle occurred in the Late Cretaceous, as demonstrated by the deposition of Turonian–Santonian pelagic limestones and arc-related volcanic rocks that are no younger than mid-Campanian (Fig. 3). This magmatic arc can be traced for approximately 2000 km from the Georgian Lesser Caucasus to the Balkans (Okay & Şahintürk 1997; Okay 2008; Okay & Nikishin 2015) and is the result of the northwards subduction of the Tethys Ocean beneath Laurasia (e.g. Şengör & Yılmaz 1981). Submarine volcanoes related to this arc have been identified on seismic data by Nikishin *et al.* (2015*a*). The Western Black Sea Basin opened behind and to the north of this arc (e.g. Görür 1988, 1997) from the Santonian onwards.

Okay *et al.* (2017) argue that Barremian–Aptian extension and Late Cretaceous Black Sea opening are unrelated because contractional deformation and metamorphism occurred in the Albian. The driving mechanism for rifting in the Early Cretaceous remains enigmatic (Tari 2015), but a wide-style of rifting is increasingly envisaged for the Early Cretaceous. This is, perhaps, related to a flat subduction of the Intra-Pontide Ocean (**Tüysüz 2017**), whereas the Late Cretaceous extension is clearly narrow and back-arc related (**Keskin & Tüysüz 2017**). Nonetheless, an unconformity typically occurs between the Lower and Upper Cretaceous sequences in the Central Pontides, notwithstanding a few local exceptions. Cenomanian and Turonian age sediments are often missing (Hippolyte *et al.* 2015), which is in contrast to, for example, successions in Bulgaria and Crimea where relatively continuous and thick deposition occurred. **Tüysüz (2017)** suggests that the amalgamation of the Istanbul and Sakarya terranes at this time may have caused uplift and erosion; although in the view of **Okay *et al.* (2017)**, these terranes had already amalgamated before the Late Jurassic.

Keskin & Tüysüz (2017) consider in detail the evolution of magmatic activity relating to the development of the Late Cretaceous volcanic arc based on outcrop studies and geochemical data. They recognize a first phase of magmatism during the middle Turonian–early Santonian (Dereköy Formation), relating to subduction of the Tethys Ocean beneath the southern margin of Laurasia. During the Late Santonian, volcanism briefly ceased and pelagic limestones were widely deposited. Interpreted as reflecting increased subsidence and intensified extension, this may in turn be related to the beginning of oceanic spreading in the Western Black Sea Basin as a consequence of a southwards rollback of the subducting slab. Further magmatism occurred in the Campanian (Cambu Formation). This includes magmas derived from an enriched asthenospheric mantle source similar to ocean island basalts. Upwelling of the asthenospheric mantle may occur during the mature stages of rifting. Support for this model of magmatism is provided by the detailed geochemical and isotopic analysis of Late Cretaceous and Early Cenozoic intrusions (dyke complexes) reported by **Aysal *et al.* (2017)**. Older calc-alkaline dykes were probably derived from a shallow mantle source, such as a metasomatized lithospheric mantle wedge, that contained a subduction signal during the initial stages of rifting. Younger alkaline and lamprophyre dykes were derived from a possibly deeper and, consequently, presumably asthenospheric mantle source. This may, in turn, reflect an initial thinning of the lithosphere during back-arc rifting and subsequent upwelling of the asthenospheric mantle that created ocean island basalt type magmas.

Subsequent Late Cretaceous and Early Cenozoic deposition is dominated by siliciclastic and calcareous turbidite deposition, although shallow-marine carbonates are present on depositional highs (Fig. 3). Arc-related volcanism may have ended during the Campanian because of a subduction jump from the north to the south of the Anatolide–Tauride–South Armenian microplate (Rolland *et al.* 2012; Hippolyte *et al.* 2015). Uplift related to the accretion of the Kirşehir Massif ended the majority of marine deposition in the Central Pontides in the Middle Eocene (**Okay *et al.* 2017**). In the Eastern Pontides, thick successions of Eocene arc-related volcanics were deposited as a result of the impinging Anatolide–Tauride block (Hippolyte *et al.* 2015). Extension related to this event provides further evidence of a young age for the Eastern Black Sea as compared to the Western Black Sea.

Hydrocarbon plays of the Western Black Sea

Only a limited number of significant hydrocarbon discoveries have been made in the Eastern Black Sea Basin. In contrast, the Western Black Sea Basin has had more successful discoveries that are both historical and recent (Ionescu *et al.* 2002; Georgiev 2012). Many of these discoveries have been in the Romanian offshore (Moroşanu 2012); **Boote (2017)** and **Krezsek *et al.* (2017)** provide insights into the geological factors that have led to some of this success.

The Histria/Istria 'Depression' or basin contains a Late Mesozoic–Cenozoic succession that represents a polyphase history of sedimentation and subsidence, divisible into second-/third-order sequences bounded by major erosional unconformities, visible on regional 2D seismic data and calibrated from wells (**Boote 2017**). Notable events include those related to Aptian–Albian rifting, major incisions caused by relative sea-level fall at or around the Eocene–Oligocene boundary, and subsequent similar events in the Middle and Late Miocene (Dinu *et al.* 2005; **Boote 2017**).

Rifting in the Early Cretaceous led to uplift and erosion of the Late Jurassic carbonate platform in a similar manner to that observed in the Pontides. Early Cretaceous shallow-marine carbonates and siliciclastics were deposited on the rift shoulders, which in turn were cut by a major west–east-trending incised valley cut in the Late Aptian. A spectacular Eocene–Oligocene boundary age incision follows a similar trend and represents a base-level fall of the order of 2000 m or more. The presence of incised valley systems provides insights into the sediment conduits (a theme explored by **Rees *et al.* 2017**) and the potential distribution of reservoir sediments, and provides locations for subcrop plays beneath the valley bases and onlap plays within the subsequent sedimentary fill.

Insights into the Cretaceous rift history of the Western Black Sea can be gained from an analysis of the successions in onshore and offshore Romania (Munteanu *et al.* 2011; **Krezsek *et al.* 2017**). Initial rifting occurred during the Aptian with the deposition of fluvial and lacustrine clastic successions and local marine carbonates. A second rifting phase occurred during the Cenomanian, marked by shallow-marine transgression. Continental break-up occurred during the mid-Turonian associated with regional uplift and erosion; this was followed by a Late Cretaceous succession of deep-water chalks and marls. Rifting thus was approximately 30 myr in duration, which is long for a single synrift episode in a basin (Tari 2015). Instead, several episodes of rifting may have occurred, even separated by a shortening event. This would reflect a transition from wide to narrow style rifting (*sensu* Buck 1991; Hopper & Buck 1996) and in turn a change from relatively flat subduction with no volcanic arc, to higher-angle subduction and the creation of a volcanic arc.

Maykop Suite is the name given to distinctive, often organic carbon-rich sediments, deposited during the Oligocene–Lower Miocene within a region that spans the Black Sea and its margins, the Greater Caucasus and the South Caspian Sea (Bazhenova *et al.* 2003; Sachsenhofer *et al.* 2017*a*). Deposition relates to the initial isolation of Paratethys at the end of the Eocene and beginning of the Oligocene. The Oligocene–Miocene time period encompasses several eustatic and regional changes in sea level (Popov *et al.* 2010), which are recorded within the Maykop Suite by the cyclic deposition of fine-grained organic-rich sediments and sandstone packages (Nikishin *et al.* 2015*a*) (Fig. 3). These sandstones have long been considered to be an exploration target in the deep-water Western Black Sea, confirmed by recent success within the Han Asparuh Block, offshore Bulgaria (**Tari & Simmons 2018**).

To assess the prospectivity of plays within Maykop Suite sandstones, **Rees *et al.* (2017)** assess sediment provenance and sediment conduits into the Western Black Sea during the time of Maykop Suite deposition. By taking into account the geodynamic history, the palaeotopography of the hinterland surrounding the Western Black Sea can be constrained and sediment provenance areas identified. Subsurface and outcrop data can then be used to further recognize sediment pathways within the basin. The drainage pattern present today on the western margin of the Black Sea (dominated by the Danube) bears little relationship to the drainage planform that would have been present during Maykop Suite deposition, with the Danube only reaching the Black Sea in the relatively recent geological past (de Leeuw *et al.* 2017). Instead, during the time of Maykop Suite deposition, a major river (the palaeo-Kamchia) can be envisaged running axially through the foredeep to the north of the Balkanides and transporting sediment derived from granitic, gneissic and older sandstone source areas. Known shelf-edge canyons (**Mayer *et al.* 2017**) in offshore Bulgaria facilitated this sediment reaching the deep-water offshore (Tari *et al.* 2009) where a sedimentary fan with a length in excess of 150 km is likely to have developed.

Farther to the south, the presence of widespread Late Cretaceous volcaniclastics related to arc magmatism would provide poor-quality sediment in limited volumes. Nonetheless, areas such as the NE Moesian Platform, the Strandja Massif and parts of the Balkanides contain crystalline basement (gneiss) and Variscan and Late Cretaceous granitic plutons that would yield high-quality quartz-rich sediment when eroded.

Regional petroleum systems and source rocks

A key aspect of the petroleum geology of the Black Sea is the assumed widespread presence of potential source rocks. The Oligocene–Early Miocene Maykop Suite (Fig. 3) is important among these but the importance of older source rocks is increasingly being stressed, including the Eocene Kuma Suite (Fig. 3) and a variety of potential Mesozoic stratigraphic units (Mayer *et al.* in press). The source-rock potential of the Maykop Suite and its equivalents are reviewed at a regional scale by **Sachsenhofer *et al.* (2017*b*)**, and on more local scales by **Mayer *et al.* (2017)** and **Vincent & Kaye (2017)**. **Vincent & Kaye (2017)** also consider the potential of the Kuma Suite.

Sachsenhofer *et al.* (2017*b*) note significant regional differences in source-rock potential across Central and Eastern Paratethys. The initial isolation of Paratethys at the beginning of the Oligocene created excellent source rocks in Central Paratethys, whereas coeval sediments in Eastern Paratethys are less organically rich (see also **Sachsenhofer *et al.* 2017*a***). Upper Oligocene and Lower Miocene sediments are generally less rich, although localized upwelling created important diatomaceous source rocks in the Western Black Sea. The potentially poor yields of hydrocarbons from the Maykop Suite (often less than 2 t HC m^{-2}) in Eastern Paratethys suggests that other source rocks may be contributing to charge at some locations. By contrast, potential yields from Maykop Suite equivalent source rocks in the Carpathian Basin (e.g. Menilite Formation) are up to 10 t HC m^{-2}.

Both **Mayer *et al.* (2017)** and **Sachsenhofer *et al.* (2017*b*)** emphasize the importance of local depositional conditions in the creation of good-quality potential source rocks. For example, an erosional unconformity at the base of the Oligocene in offshore Bulgaria creates a spectacular shelf-edge canyon (the Kaliakra Canyon). Source-rock quality appears to be better within the canyon, especially during the Early Miocene when diatomaceous shales with a total organic carbon (TOC) content of 2.5% and hydrogen index (HI) values of up to 530 mg HC g^{-1} TOC were deposited. This may relate to localized upwelling. Conversely, in the Early Oligocene, oxygen-depleted, brackish environments were best developed outside of the canyon and are associated with blooms of calcareous nannoplankton. These source-rock horizons are immature on the shelf, but are within the oil and gas window in the deeper parts of the basin. Long-distance migration within Maykopian sandstones from this highly productive kitchen is proven by published biomarker data with large quantities of hydrocarbons expelled from the Miocene onwards (Robinson *et al.* 1996; Olaru-Florea *et al.* 2014).

Vincent & Kaye (2017) examined potential Eocene–Early Miocene source rocks from outcrops in the western Greater Caucasus in Russia and the margins of the Rioni Basin in west Georgia. These outcrops are important because they are more directly relevant to the Eastern Black Sea than the classic outcrops south of the town of Maykop on the northern side of the Caucasus (e.g. along the Belaya River) (Sachsenhofer *et al.* 2017*a*) that were probably deposited in a separate sub-basin. A significant number of their samples have good to excellent organic richness and source potential with potential yields of 0.7–2.5 t HC m^{-2}, especially the base of the Maykop Suite and from within the Kuma Suite. In western Georgia, the basal Maykop Suite that is organically rich is between 60 and 200 m thick. The thickness of the better source-rock quality of the Kuma Suite is unconstrained, but its regional potential has been highlighted in previous studies (e.g. Beniamovski *et al.* 2003; Distanova 2007; Peshkov *et al.* 2016), and with TOC values of up to 10.3%, and S_1 and S_2 values of up to 30 kg t^{-1}, it merits strong consideration in modelling potential charge, especially in the Eastern Black Sea (Mayer *et al.* in press). It is worth noting that equivalent sediments in the Pontides can have good source-rock potential (Aydemir *et al.* 2009; Menlikli *et al.* 2009), suggesting that anoxia was widespread during Kuma Suite deposition. However, the effects of bathymetric highs, such as the Shatsky Ridge, on the formation of sub-basins that may have each provided a distinctive depositional character must be considered.

Messinian: recent stratigraphy

The major relative sea-level fall within the Messinian that was first described from the Mediterranean (Hsu *et al.* 1973) also has a significant expression across Paratethys (van Baak *et al.* 2017) and notably in the Black Sea (Tari *et al.* 2015*a*, 2016). However, the sea-level fall did not lead to desiccation of the Black Sea and was not of the magnitude once envisaged (cf. 1600 m (Hsu & Giovanoli 1979; Robinson *et al.* 1995) with 500–600 m (Krezsek *et al.* 2016)). This has petroleum significance in that a relatively modest fall in sea level translates to a lower risk of trap failure because of hydraulic seal fracture (Tari *et al.* 2016). Sediments cored in DSDP Leg 380 and previously interpreted as indications of shallow-water deposition can be interpreted as deep-water mass-transport deposits. Using 3D and 2D seismic data, **Sipahioğlu & Batı (2017)** describe the effect of this event in the Turkish sector of the Western Black Sea. They recognize a series of canyons, including the prominent SW–NE-trending Karaburun Canyon, which incises the shelf and acts as a major conduit of sediment to the abyssal floor of the basin. Blind canyons infilled with mass-transport complexes are also recognized and are typically confined to the continental rise where the steep shelf-slope morphology is governed by the presence of the underlying Late Cretaceous volcanic arc.

The modern Black Sea is often considered as an important analogue for source-rock deposition because of a high level of nutrients, high organic productivity, and widespread water stratification and anoxia (Wignall 1994; Arthur & Sageman 2004). Accordingly, it is interesting to investigate controls that enhance or reduce the quality of this analogue. **Fallah *et al.* (2017)** investigated 40 Holocene drop-core samples from offshore Bulgaria with regard to their composition and geochemical parameters, and integrated these data with high-resolution bathymetric surveys. Source-rock quality is relatively poor and is attributed to fine-grained sedimentary input from the Danube River. The sediment input from the Danube has served to limit organic productivity by reducing the thickness of the photic zone and by diluting organic-rich sediment with low TOC sediments. This highlights that anoxia alone is not sufficient to generate potential source rocks. Distance from sedimentary input points and basin geometry are also key factors to consider.

Petroleum potential of the Eastern Black Sea and deep-water exploration review

The Rioni Basin is an underexplored foreland basin located at the Georgian margin of the Black Sea and flanked by the fold belts of the Greater Caucasus and the Achara-Trialet Belt. In a review of this basin, **Tari *et al.* (2018)** argue that the proven plays are not fully understood nor systematically explored using modern technology. The northern Rioni Basin has stratigraphic similarities with the offshore Shatsky Ridge (at the time of writing, a major unexplored structure in the Eastern Black Sea), and the southern Rioni Basin is both stratigraphically and structurally akin to the offshore Gurian fold belt in the Eastern Black Sea.

The existing oil fields in the onshore Rioni Basin are generally small (2–4 MMbbl (million barrels) recoverable), but they demonstrate working petroleum systems, as do abundant seeps in the offshore (Dembicki 2014). The discovery of Supsa dates back to the 1880s where stacked Miocene (Sarmatian) clastic horizons occur in an anticlinal trap formed by the north-vergent leading edge of the Achara-Trialet thrust-fold belt. Charge is interpreted as being derived from both the Oligocene Maykop and the Eocene Kuma suites (Mayer *et al.* in press). The Shromisubani Field is a subthrust accumulation with reservoirs in Miocene (Maeotian) clastics. In the northern Rioni Basin, the Chaladidi Field is formed by two accumulations (i.e. two adjacent compressional ramp anticlines) with reservoirs in fractured Late Cretaceous and Paleocene chalky carbonates. The Okumi discovery is unusual in containing a light oil with an unknown, but suspected, Jurassic source, reservoired in Late Jurassic sands sealed beneath Kimmeridgian–Tithonian evaporites. This discovery opens up the possibility of a new petroleum system that may be operating in the offshore Shatsky Ridge. Other, more speculative, plays may include Middle Jurassic sandstones in synrift fault blocks (as encountered in the subcommercial discovery at Ochamchira-1).

Tari & Simmons (2018) review the history of deep-water exploration in the Black Sea, which is still in its infancy, with approximately 20 wells at the time of writing (end of 2017) having targeted a large variety of plays. Success has been mostly associated with biogenic gas in Miocene–Pliocene reservoirs associated with the palaeo-Dnieper/Dniester or in Oligocene deep-water clastics associated with similar-aged thermogenic source rocks. Synrift and early post-rift targets (mostly exploring for shallow-marine carbonate reservoirs) have met with little success because of the lack of predicted reservoir.

The first deep-water wells drilled in the Black Sea were Limanköy-1 and Limanköy-2 drilled in 1999 in Turkish waters. Encouraged by the presence of amplitude variation with offset (AVO) anomalies, Pliocene sandstone reservoirs were targeted in three-way fault-bound closures. These reservoirs were found to be non-permeable diatomites and diatomaceous shales (Menlikli *et al.* 2009). Secondary Early Miocene sandstones contained small amounts of gas from both thermogenic and biogenic sources. Although this was non-commercial, it usefully demonstrated the presence of a thermogenic petroleum system in the deep-water sector of the Black Sea.

The next deep-water well was HPX (Hopa)-1 drilled in Turkish waters near the maritime border with Georgia. Drilled on a four-way closure on the offshore continuation of the Achara-Trialet (Gurian) fold belt of the Lesser Caucasus, the well targeted Upper Miocene deep-water sand units presumed to be charged from the Oligocene Maykop Suite associated with seeps in the vicinity of the well. The well was unsuccessful, with reservoir quality suspected as the major issue with sediments derived from the Lesser Caucasus likely to be lithic-rich. Targeting older sandstones within the Gurian fold belt may prove to be more successful because these may be derived from more quartz-rich provenance areas. The understanding of the sediment-dispersal patterns in relation to favourable sediment provenance areas at key times of potential reservoir sedimentation is a key issue in reducing risk in Black Sea exploration (e.g. see Maynard *et al.* 2012; Vincent *et al.* 2013*a*, *b*; **Rees *et al.* 2017**).

The failure of HPX-1 resulted in a 5 year hiatus in deep-water exploration. In 2010, attention shifted to plays on structural highs on the Andrusov Ridge separating the Western and Eastern Black seas. The potential of structures on this high had been highlighted earlier by TPAO/BP Eastern Black Sea Project Study Group (1997). Sinop-1 targeted Late Cretaceous–Paleocene carbonate reservoirs on such a high, with charge expected to be from the laterally adjacent Maykop Suite. Although such carbonates are present at outcrop in the Pontides, and can be thick and porous (Menlikli *et al.* 2009; Aydemir & Demirer 2013), their presence was found to be unproven in the basin centre. Furthermore, a thick succession of Cretaceous volcanics and volcaniclastics was found to be present, precluding the exploration of deeper objectives. Yassihöyük-1, drilled directly after Sinop-1, encountered similar issues, with Late Cretaceous–Paleocene reservoir quality carbonates present only in very limited thicknesses (Aydemir & Demirer 2013). As noted by Posamentier *et al.* (2014), volcanoes and volcanic-rich successions can easily be mistaken for carbonate build-ups, even with good-quality seismic data.

Sürmene-1, drilled in the Turkish Eastern Black Sea in 2011, tested a new play concept: a four-way closure located above a Cretaceous palaeo-volcano. Reservoirs were Miocene sheet sands thought to be derived from the Greater, rather than Lesser, Caucasus. Despite multiple oil shows, the well was not successful in opening up a new play fairway in the Eastern Black Sea, perhaps, once again, because of reservoir quality issues. Sile-1, drilled in the Turkish Western Black Sea in 2015, tested a similar play concept: a four-way closure above a large Cretaceous palaeo-volcano. The results of this well remain unpublished at the time of writing.

Kastamonu-1 tested one of the many large and elongated shale-cored anticlines present in the central Western Black Sea between the Central Pontides and Crimea. Drilled offshore Turkey in 2011, it tested thermogenic gas from Pliocene and Miocene reservoirs, arguably the first technical success of the deep-water exploration campaign. Low gas saturations may have been the result of late crestal faulting breaching the trap. Given that Kastamonu-1 was drilled on 2D seismic data alone, analysis of similar prospects with 3D seismic data may identify those without the influence of neotectonics.

In 2012, the first deep-water well was drilled in offshore Romania: Domino-1. This well tested a Late Neogene inversion structure above a basement high with reservoirs occurring in the Miocene–Pliocene palaeo-Dnieper/Dniester depositional system and associated with biogenic gas (Bega & Ionescu 2009; Moroşanu 2012). The well proved to be an economic discovery, and satellite discoveries have been made in the Neptun Deep exploration block in which Domino is located. The full extent of the play remains to be defined.

In 2016, exploration drilling began in the deep-water offshore Bulgaria with the Polshkov-1 well drilled on compactional anticline formed over the prominent Polshkov High (Tari *et al.* 2009), a structural high formed during the rifting of the Western Black Sea. The main reservoir target was channelized deep-water sands within the Maykop Suite associated with the palaeo-Kamchia depositional system described by **Rees *et al.* (2017)**. Deeper plays in the syn- and pre-rift also exist (Robinson *et al.* 1996; Tari *et al.* 2009), and the exploration campaign continues in this block at the time of writing following the successful encountering of hydrocarbons in Polshkov-1.

Looking ahead, the first deep-water well in the Russian sector of the Black Sea is being drilled. Maria-1 is targeting a well-known apparent Late Jurassic carbonate build-up on the Shatsky Ridge (e.g. see Afanasenkov *et al.* 2005, 2007) with charge assumed from the juxtaposed Maykop and Kuma suites (seepage is described by Andreev 2005). If successful, this well has the potential to be a spectacular play opener because many other similar carbonate structures have been mapped in the Eastern Black Sea (Afanasenkov *et al.* 2005). Reservoir quality is a significant risk in carbonate plays, but karstification as noted in age-equivalent outcrops on Crimea (Nikishin *et al.* 2017) may offer some encouragement.

Other plays to be explored in the Russian sector include Maykop Suite deep-water clastics in the Tuapse Trough (Glumov & Viginskiy 1999; Afanasenkov *et al.* 2007; Meisner *et al.* 2009), although the timing of the Caucasus uplift is a key component in determining the volume of sediment flux from potentially granitic and gneissic sediment sources (see Vincent *et al.* 2016 for a discussion of this controversy). Maykop sediments entering into the Eastern Black Sea are likely to be locally derived if the Greater Caucasus were emergent during deposition; these mountains also prevented sediment derived from the Russian Shield (e.g. via the palaeo-Don) from reaching large parts of the basin and being ponded, instead, in the Indolo-Kuban Basin. Spectacular Maykop Suite turbidite fans derived from the Greater Caucasus have been imaged on 3D seismic data from within the Tuapse Trough (Mityukov *et al.* 2011). Vincent *et al.* (2013*a*, *b*) and Khlebnikova *et al.* (2014) have demonstrated that Maykop sandstones in the Russian western Caucasus are significantly more quartz-rich than those located farther SE in western Georgia. This finding suggests that the reservoir quality of Maykop plays within the Tuapse Trough (sediment derived in part from Jurassic granitoids) carries lower risk than offshore Georgia (sediment derived in part from Eocene volcanics). Seepage in the Tuapse Trough has been described by Andreev (2005).

Offshore Crimea, the Tetyaev High has compaction closure above it, leading to the potential within Maykop sandstones analogous to the Polshkov play, offshore Bulgaria. Subbotina, discovered on the Crimea shelf (Stovba *et al.* 2009), demonstrates that the Maykop Suite can offer working plays in the region. Structural analogues to Subbotina extend southwards towards the Shatsky Ridge.

Offshore Turkey, potential also exists with Maykop sandstones (Menlikli *et al.* 2009; Sipahioğlu *et al.* 2013). These plays may function as stratigraphic traps in deep-water fan systems or by onlap onto highs, such as the Kozlu Ridge; however, sediment provenance must be considered (Maynard *et al.* 2012; **Rees *et al.* 2017**) as a guide to likely reservoir quality.

More widely, can synrift plays work in the deep-water Black Sea? The Early Cretaceous synrift sequences exposed in the Pontides have both potential source rocks and reservoirs associated with them (Görür & Tüysüz 1997; Şen 2013), and their potential offshore (in the region of the Kozlu Ridge) was discussed by Menlikli *et al.* (2009), who suggested a lateral charge may be possible from the Maykop Suite. Synrift sediments form reservoirs on the Romanian shelf (e.g. Lebada, Midia) where traps are created by Eocene inversion (Munteanu *et al.* 2011) and, consequently, juxtaposition with Maykop Suite equivalent source rocks (Robinson *et al.* 1996; Cranganu & Saramet 2011). Synrift sandstones may be present in faulted culminations on the Shatsky and Andrusov ridges, and provide an alternative objective to the pre-rift carbonates currently targeted at Maria. The Early Cretaceous synrift succession so well exposed on Crimea (Nikishin *et al.* 2017) may have a seismic expression on the Shatsky Ridge. By comparison with Crimea, nummulitic banks may be present on highs within the Shatsky Ridge (e.g. the Gudauta High).

The deep-water Black Sea is at a similar stage of exploration as the Eastern Mediterranean. After the discovery of large biogenic gas accumulations, the thermogenic petroleum systems must be proven by systematic exploration of the deep-water and multiple play concepts that exist.

Summary

Controversy and uncertainty continue to be key features of Black Sea geoscience. Several deep-water exploration wells have failed because of an inability to predict correctly reservoir presence and reservoir quality. This is true for both carbonate plays and siliciclastic plays. The correct prediction of carbonate presence requires an understanding of the uplift and subsidence history of the highs they might be deposited upon. Does the apparent lack of Late Cretaceous carbonate on the Andrusov Ridge (i.e. at Sinop-1) suggest that that both the Western Black Sea and Eastern Black Sea were rapidly subsiding at this time? This possibility appeals to the fundamental question regarding the relative timing of the opening of the Western and Eastern Black seas. Was this synchronous (e.g. Nikishin *et al.* 2003, 2015*a*, *b*; Stephenson & Schellart 2010), or do they relate to completely separate phases of tectonic evolution (Robinson *et al.* 1995, 1996; Spadini *et al.* 1996; Kazmin *et al.* 2000; Shillington *et al.* 2008; Vincent *et al.* 2016)?

Siliciclastic reservoir presence and quality have also proven to be difficult to predict (e.g. at HPX-1 and at Sürmene-1). This prediction requires an understanding of the source to sink relationships in the basins, specifically sediment conduits and the nature of the rocks being eroded to create potential reservoirs. In turn, this requires an understanding of the uplift history of the orogens from which the sediment is suggested as being sourced: for example, compare the timing of uplift of the Caucasus (cf. Cowgill *et al.* 2016 and Vincent *et al.* 2016).

Petroleum charge can be an issue that limits exploration success. **Mayer *et al.* (2017)**, **Sachsenhofer *et al.* (2017*b*)** and **Vincent & Kaye (2017)** all demonstrate that the Maykop Suite and its equivalents may not be the high-quality source rock in the Black Sea basins that is often assumed. How important are older source rocks, such as the Kuma Suite, and, given the likely depth of burial of that unit, is gas a more likely hydrocarbon phase than oil?

Notwithstanding some recent success with the exploration for post-rift Cenozoic plays, can plays within the synrift and pre-rift Mesozoic stratigraphy be successful? These and many other questions will be answered in part by seismic and drilling campaigns in the years to come, by detailed outcrop studies, and by the application of the latest tools to model geodynamic history and the 3D imaging of the subsurface. The Black Sea will remain a focus for geological research as it continues to yield its secrets.

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