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Geology and Hydrocarbon Systems in the Western Black Sea

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Abstract: This paper presents the author's integrated regional studies during the last decade. The main purpose is to present an overall understanding of the geological structure, sedimentary basins and hydrocarbon systems of the whole Western Black Sea Zone (WBSZ). This study is based on original data from boreholes, seismic and gravity-magnetic surveys and hydrocarbon accumulations.

Many geophysical borehole data obtained for WBSZ during the last 3–4 decades were interpreted mostly at a national level using different approaches, terminology and nomenclature for the same or similar lithostratigraphic and tectonic units. Therefore, a unified approach to interpretation of borehole-seismic data and correlation of stratigraphic, sedimentological and tectonic units has a key importance for overall clarification of the deep geological structure and the hydrocarbon challenges.

A set of regional geological cross-sections along good quality basic seismic lines and basic boreholes was constructed. A detailed tectonic map of the WBSZ has been compiled by integrated interpretation of seismic borehole and gravity-magnetic data. The definition of hydrocarbon systems and promising exploration trends is made by source rock assessment, Oil-Oil and Oil-Source rock correlations, analyses of the reservoir/seal pairs and the hydrocarbon migration and accumulation. Genetic correlations are based on many Rock-Eval, Gas Chromatography/Mass Spectrometry (GC-MS) and carbon isotope analyses.

The complex geological structure of the WBSZ is defined by four groups of tectonic units: (1) Western Black Sea basin (WBSB) – its western zone with the Kamchia and the Histria westward wedging branches (sub-basins); (2) portions of the Moesian, Scythian and East European platforms; (3) fragments of the North Dobrogea, Eastern Balkan, Eastern Srednogorie and Strandzha orogens; (4) Burgas and Babadag basins.

Four different oil genetic types have been identified. Three main hydrocarbon systems with economic potential are defined, they relate to: WBSB and its Histria and Kamchia branches, the East-Varna trough and the Bourgas basin. Conceptual models for hydrocarbon systems and their prospect exploration trends are constructed.

Key Words: Western Black Sea Zone, tectonic structure, hydrocarbon systems

Batı Karadeniz'in Jeolojisi ve Hidrokarbon Sistemleri

Özet: Bu makale yazarın son on senede yürüttüğü bölgesel çalışmaların sonuçlarını içerir. Makalenin amacı tüm Batı Karadeniz Zonu'nun (BKZ) jeolojik yapısını, sedimenter havzalarını ve hidrokarbon sistemlerini anlamaya çalışmaktır. Sonuçlar kuyulardan elde edilen verilere, sismik ve gravite-manyetik ölçümlerine ve hidrokarbon oluşumları hakkındaki bilgilere dayanır. Son 30–40 senede BKZ'da çok sayıda jeofizik kuyu verisi elde edilmiştir. Buna karşın bu veriler ülke bazında farklı yaklaşımlar, farklı terminolojiler kullanılarak, ve aynı litostratigrafik veya tektonik birimler için farklı isimlendirilmeler yapılarak değerlendirilmiştir. Bu değerlendirmelerde ve stratigrafik, sedimentolojik ve tektonik birimlerin korrelasyonunda ortak bir yaklaşım benimsenmesi, bölgenin derin jeoloji yapısının ve hidrokarbon özelliklerinin anlaşılmasında büyük önem taşır. Bu çalışma kapsamında kuyular ile denetlenmiş kaliteli sismik hatlar boyunca bölgesel jeoloji kesitleri yapılmıştır. BKZ'nun ayrıntılı bir tektonik haritası gravite, manyetik, sismik ve kuyu verileri baz alınarak hazırlanmıştır. Kaynak kaya analizi, petrol-kaynak kaya, rezervuar-kapan ilişkileri ve hidrokarbon göçü ve depolanmasına dayanılarak hidrokarbon sistemleri tanımlanmış ve ümit vadeden aramacılık yaklaşımları belirlenmiştir.

BKZ'nun jeolojik yapısı dört tektonik unsur tarafından belirlenir: (1) Batı Karadeniz Havzası (BKH) ve onun batıya doğru dallanan Kamçiya ve Histriya alt havzaları; (2) Moesya, İskit ve Doğu Avrupa platformlarının bazı parçaları; (3) Kuzey Dobruca, Doğu Balkan, Doğu Srednogoriye ve Istranca orojenlerine ait parçalar; (4) Burgaz ve Babadağ havzaları. Dört farklı jenetik kökenli petrol tipi tanımlanmıştır. Ekonomik potansiyel taşıyan üç hidrokarbon sistemi belirlenmiştir, bunlar BKZ ve onun Histriya ve Kamçiya kolları, Doğu Varna çukuru ve Burgaz havzasıdır. Bu hidrokarbon sistemlerinin aranması ile ilgili modeler sunulmuştur.

Anahtar Sözcükler: Batı Karadeniz Zonu, tektonik yapı, hidrokarbon sistemleri

Introduction

The Western Black Sea Zone (WBSZ) comprises the entire Bulgarian and Romanian offshore sectors, the western part of the Odessa Gulf from Ukrainian offshore, the westernmost part of the Turkish offshore sector, as well as adjacent onshore zones (Figure 1).

Hydrocarbon exploration in the WBSZ started during the 1970s and was mostly undertaken on the shelf area. As a result 15 oil and gas accumulations have so far been discovered (Figure 2).

Many geophysical (gravity, magnetic and mainly seismic) and borehole data have been obtained during the last 3–4 decades. However, these data were interpreted and generalized mostly at a national level. Moreover, the four countries in the region have used different interpretation approaches, terminology and nomenclature for same or similar litho-stratigraphic or tectonic units and faults, crossing international borders. Therefore, a unified correlation of stratigraphic, sedimentological and tectonic units and a uniform approach to the interpretation of borehole seismic data is of key importance for the clarification of the deep geological structure and the evolution of the entire region.

This paper presents the results of author's integrated regional study, carried out during the last decade. The main purpose is to gain a better understanding of the geological structure and evolution of the whole WBSZ, as well as its sedimentary basins and hydrocarbon systems. The main tasks are: (i) integration of regional research and exploration data (mainly borehole, seismic and gravity-magnetic) by unified precise correlation and interpretation; (ii) clarification of tectonic structure and interrelations between tectonic units; (iii) characterization of promising hydrocarbon sedimentary basins and their evolution; and (iv) identification and estimation of main petroleum systems and exploration trends.

This study is based on a very large database that integrates almost all original basic data from: drilled exploratory wells, seismic and gravity-magnetic surveys and discovered hydrocarbon accumulations, as well many analytical and research results (Figure 2).

The detailed study of the deep geological structure and relationships between different tectonic units is based on unified precise correlation of basic well sections and their integration in the geological interpretation of seismic and gravity-magnetic results. For this purpose a map of the main gravity and magnetic anomalies has been compiled (Figure 2), based on data from Sava (1985), Dachev (1986), Sava *et al.* (1996, 2000), Morosanu & Sava (1998), Stavrev & Gerovska (2000) and Starostenko *et al.* (2004), and a set of regional sections crossing the whole WBSZ (Figure 2), which follow good quality basic seismic lines and pass through the basic borehole sections have been constructed (Figures 3 & 4). The location and orientation of these lines were also defined in accordance with the distribution of the main gravity – magnetic anomalies. These regional cross-sections have a key importance for the identification of deep geological structure and the construction of a detailed tectonic map for the whole WBSZ (Figure 5).

The reconstruction of some important episodes from the Mesozoic–Tertiary geological evolution of the WBSZ, in the frame of a greater Scythian-Black Sea – Caucasus-Pontides domain, is based on integration of our data (Emery & Georgiev 1993; Dachev & Georgiev 1995; Georgiev & Dabovski 1997, 2001; Tari *et al.* 1997) and published regional data (Okay *et al.* 1994; Robinson 1997; Finetti *et al.* 1988; Nikishin *et al.* 2001; Stampfli *et al.* 2001; Ziegler *et al.* 2001). The general concept is an alternation of phases of Mesozoic and Tertiary back-arc rifting and back-arc compression that controlled the evolution of this region.

The hydrocarbon source complexes have been evaluated by all available well, log and seismic data, using modern investigative methods and techniques, such as Gas Chromatography-Mass Spectrometry analyses (GC and GC-MS), Rock Eval Pyrolysis, Carbon isotope analyses (C^{12}, C^{13}) and vitrinite reflectance analyses (Ro) of cuttings and core samples from many wells. Some lithological and seismic facies data have also been used for to recognize facies changes, thicknesses and burial depths towards the Western Black Sea deepwater zone.

The genetic hydrocarbon links (Oil to Oil and Oil to Source) were investigated by correlation of their biomarker profiles (n-alkanes, triterpanes – m/z 191, steranes – m/z 217, triaromatics – m/z 231 and monoaromatics – m/z 253), which form the main pattern characteristics of the source material.

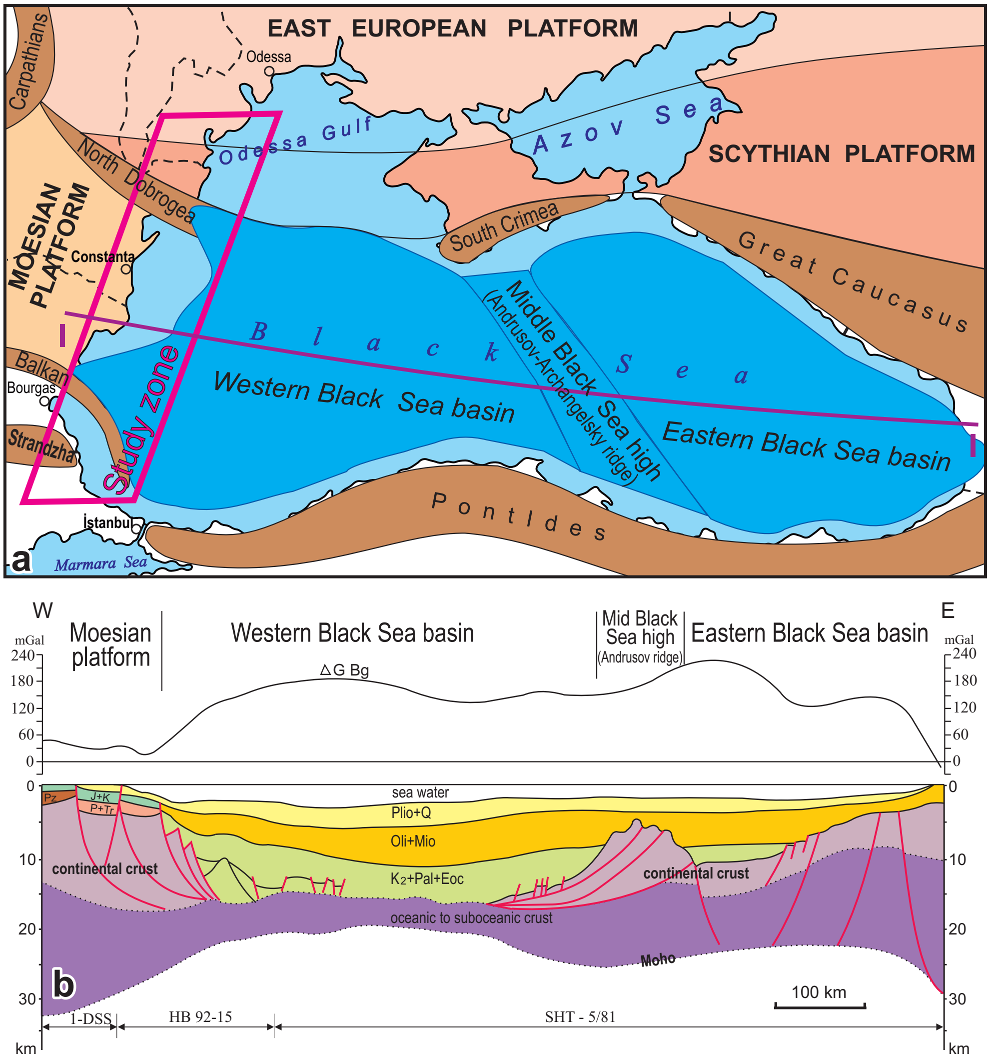

Figure 1. **(a)** Tectonic units in the Black Sea domain with location of study zone (after Rempel & Georgiev 2005); **(b)** Geological-seismic cross-section along line I-I (after Dachev & Georgiev 1995).

Definition of hydrocarbon systems and promising exploration trends was made by: evaluation of source rocks and their spreading, Oil to Oil and Oil to Source correlations, analyses of reservoir/seal pairs and hydrocarbon migration directions, also taking into account the latest exploration and investigative results (Robinson *et al.* 1996; Bega & Ionescu 2009; Khriachtchevskaia *et al.* 2009; Sachsenhofer *et al.* 2009; Tari *et al.* 2009).

Tectonics of Western Black Sea Zone

The Black Sea is considered by many authors to be a Late Cretaceous to Palaeogene back-arc extensional basin that developed north of the Pontide magmatic arc, itself formed by northward subduction of the Neo-Tethys ocean that was initiated in the Albian (Tugolesov *et al.* 1985; Finetti *et al.* 1988; Görür 1988; Okay *et al.* 1994; Dachev & Georgiev 1995; Robinson *et al.* 1995; Banks & Robinson 1997; Nikishin *et al.* 2001, 2003). The Black Sea basin, in terms of crustal structure, consists of Western and Eastern rift-type sedimentary basins, separated by the Andrusov (or Mid-Black Sea) ridge (Figure 1). Both basins are different with respect to time of opening, structure, stratigraphy and thickness of their sedimentary fill (Figure 1b).

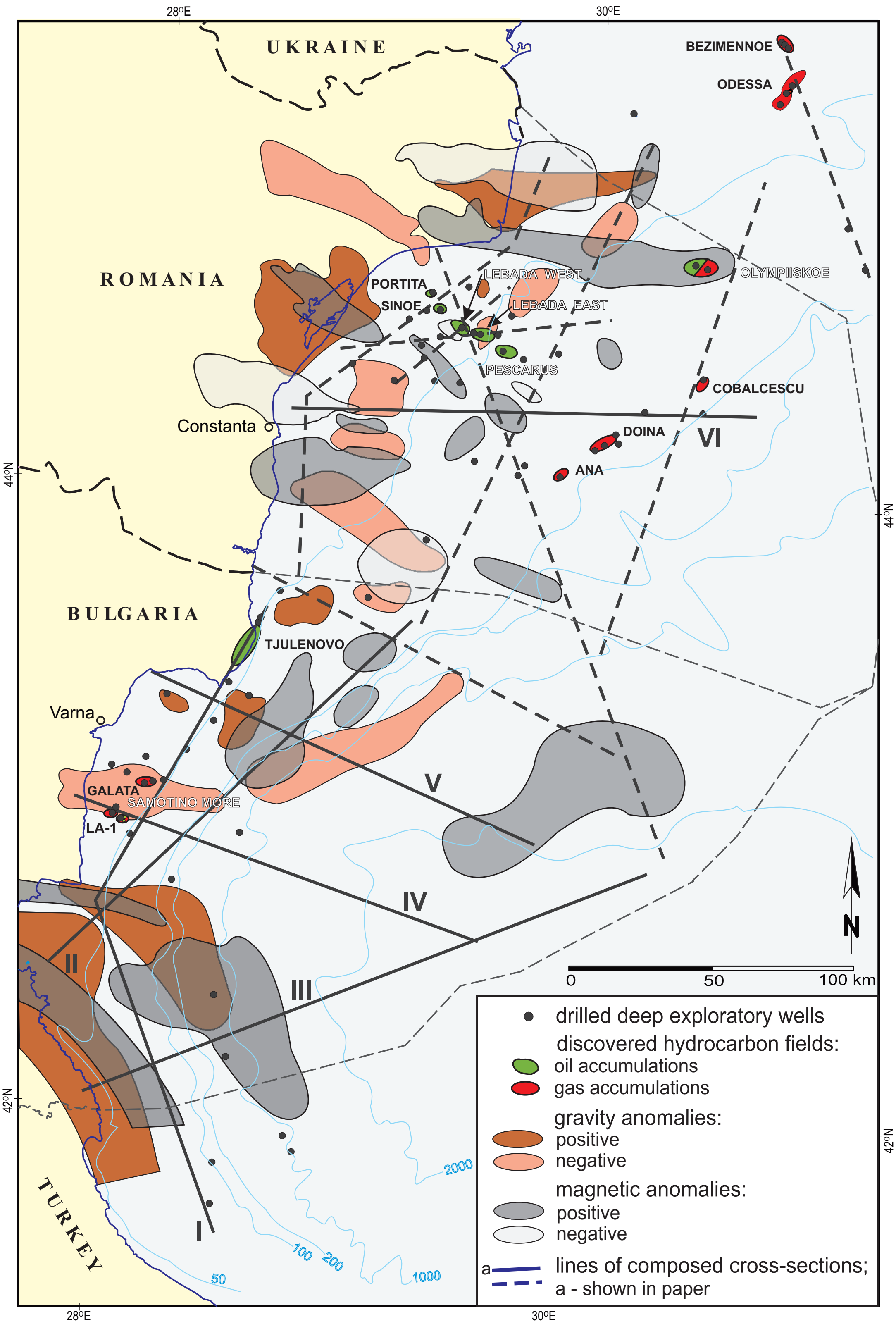

Figure 2. Database map showing drilled exploratory wells, discovered hydrocarbon fields, gravity and magnetic anomalies and composed regional cross-sections.

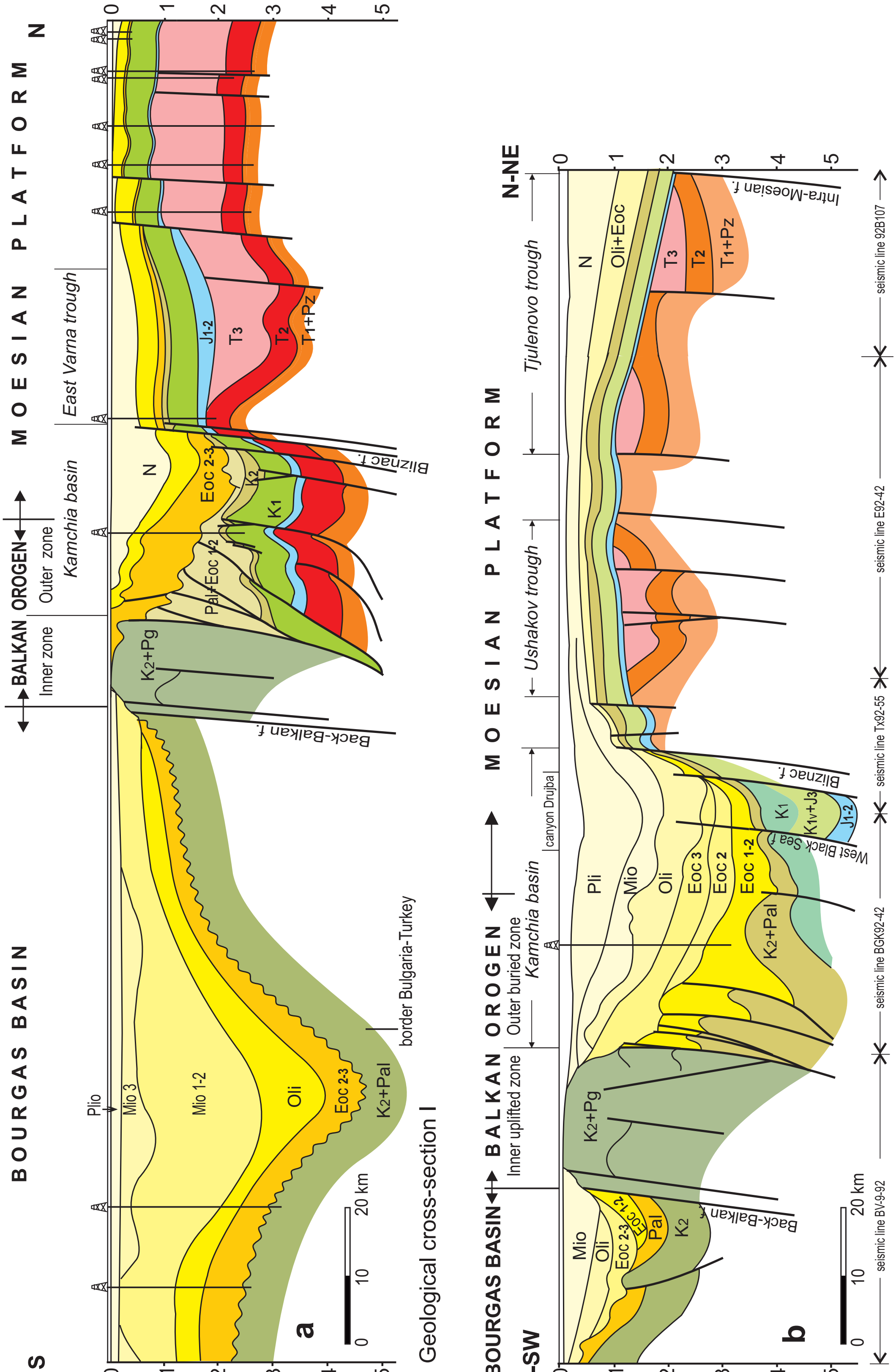

Figure 3. Geological cross-sections I and II across WBSZ (for location see Figures 2 & 5).

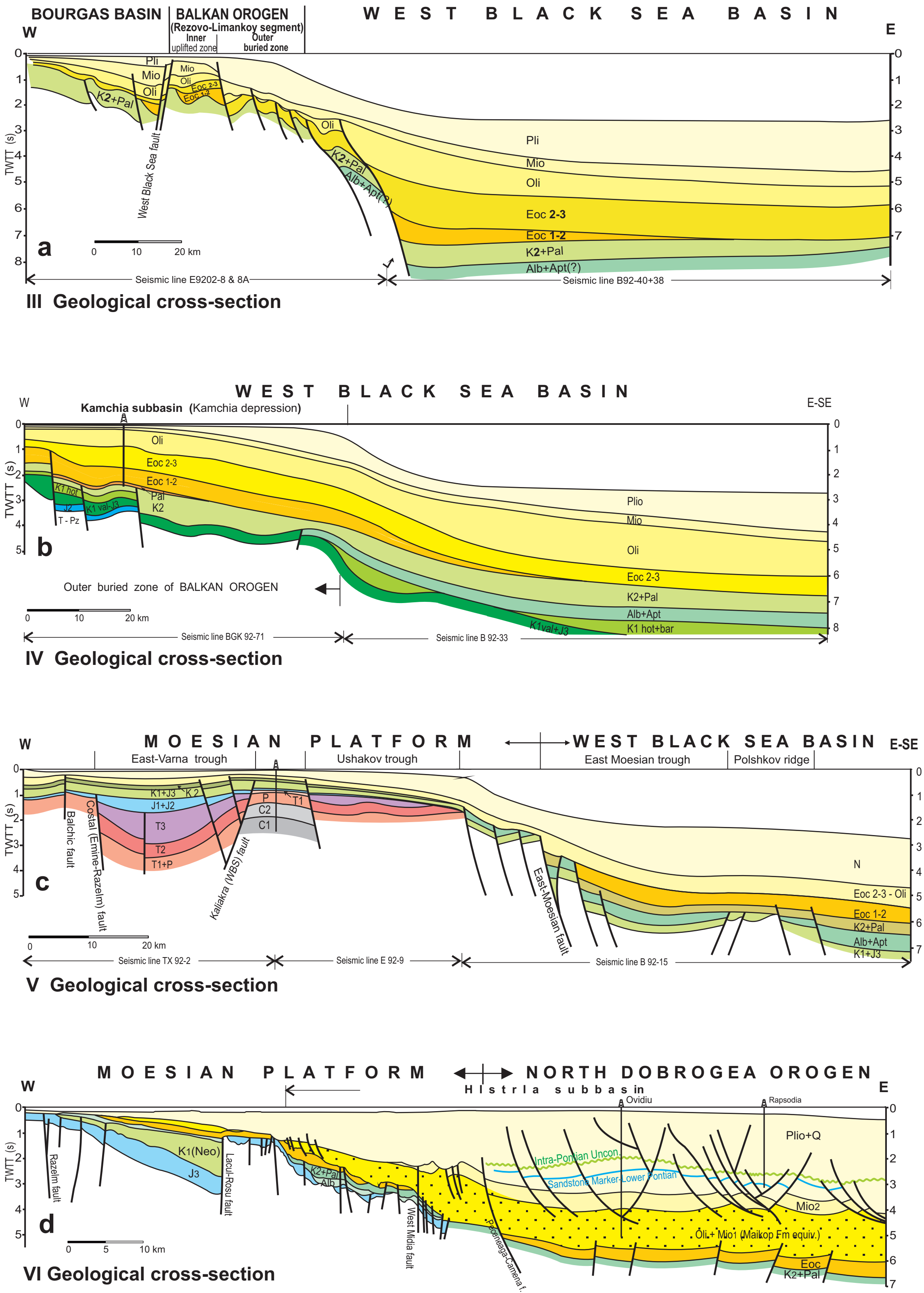

Figure 4. Geological cross-sections III, IV, V and VI across WBSZ (for location see Figures 2 & 5).

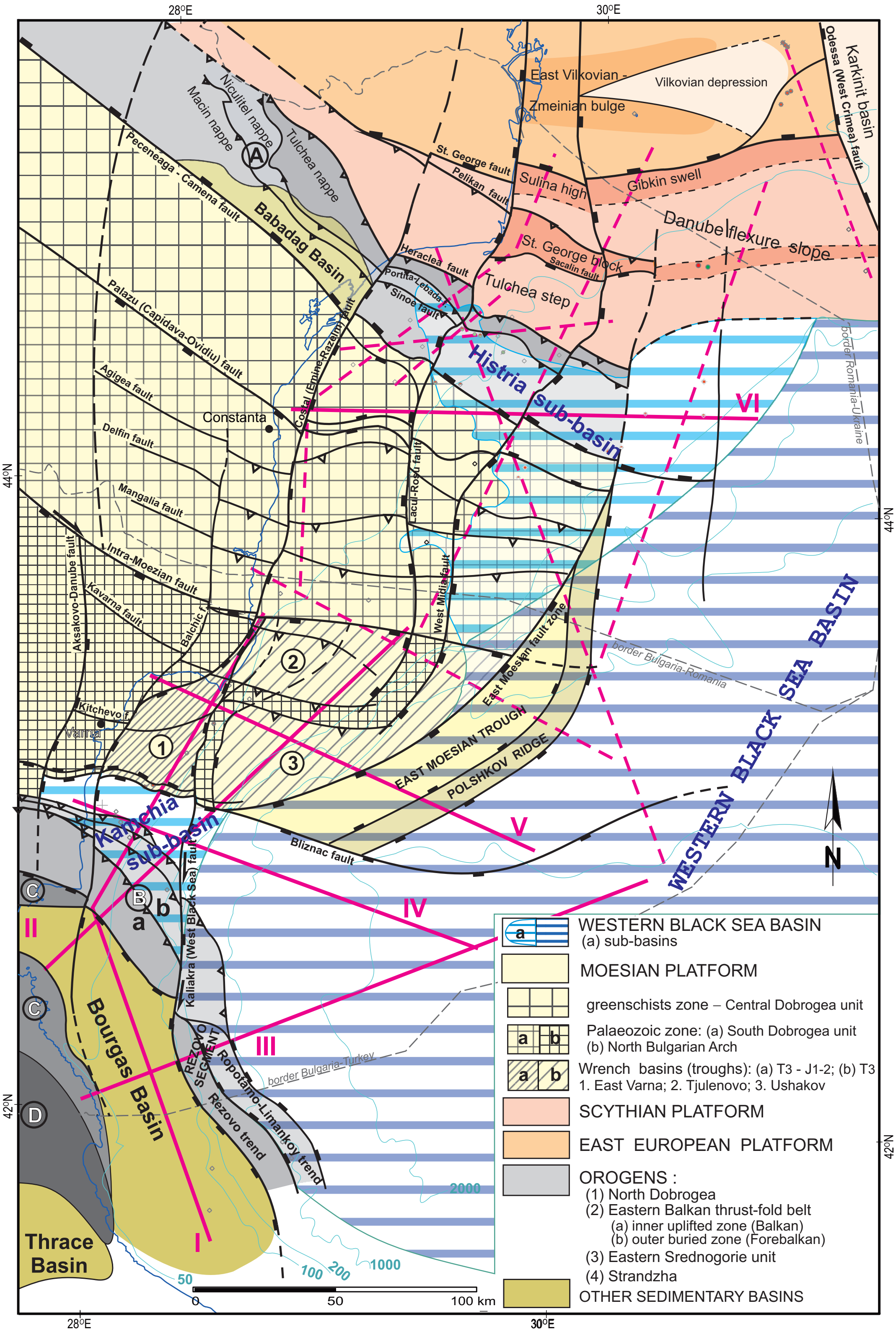

Figure 5. Tectonic map of the Western Black Sea zone.

The Western Black Sea Basin (WBSB), underlain by oceanic to sub-oceanic crust, started to open in the Cenomanian and the sedimentary cover is about 14–16 km thick (Görür 1988; Okay *et al.* 1994; Robinson *et al.* 1995; Banks & Robinson 1997; Nikishin *et al.* 2001, 2003). The Eastern Black Sea Basin (EBSB), underlain by a thinned continental crust, started to open during the Coniacian or at the beginning of the Palaeogene and the thickness of the sedimentary fill is about 12 km (Robinson 1997; Nikishin *et al.* 2001, 2003). The Andrusov ridge is formed by a continental crust, overlain by 5–6 km of sediments (Nikishin *et al.* 2001, 2003).

The Western Black Sea region (WBSR) is located on the European continental margin, and covers parts of the northern periphery of the Alpine orogen and its foreland. The Mesozoic–Tertiary evolution of the region was governed by geodynamic processes in the northern Peri-Tethyan shelf system (Nikishin *et al.* 2001, 2003; Stampfli *et al.* 2001). The southern margins of the Scythian and Moesian blocks were repeatedly affected by Mesozoic rifting cycles, interrupted and followed by compressional events, causing strong shortening of these two margins and ultimately their overprinting by the Alpine orogen (Georgiev *et al.* 2001; Nikishin *et al.* 2001).

The main problem in reconstructing the evolution of the Western Black Sea Region (WBSR) in the frame of the greater Scythian-Black Sea – Caucasus-Pontides domain lies in the superposition of the sequences of Mesozoic and Cainozoic extensional and compressional deformation phases, during which the interaction of different tectonic units has repeatedly changed (Nikishin *et al.* 2001; Stampfli *et al.* 2001).

Geologically the WBSZ has a rather complicated geological structure, consisting of the western portion of the WBSB and some parts of ancient platforms (Moesian, Scythian and East European) and of Alpine orogenic units (Strandzha, Eastern Srednogorie, Eastern Balkan, Fore-Balkan and North-Dobrogea).

The tectonic map of the WBSZ compiled in this study is given on Figure 5. The main tectonic units in the WBSZ are: **(1)** Western Black Sea Basin – western zone, with two westward wedging deep branches: Kamchia sub-basin and Histria sub-basin; **(2)** Platforms: (i) Moesian platform–the easternmost zone, comprising several units: (a) Green Schist zone (Central Dobrogea unit), (b) Palaeozoic zone (South Dobrogea unit and North Bulgarian arch), (c) Late Triassic and Early–Middle Jurassic wrench/pull-apart basins, (d) Southern and Eastern platform edges and margins, (ii) Scythian platform– the westernmost fragment, (iii) East European platform– a small part of the southernmost zone; **(3)** Orogens: (i) North Dobrogea thrust-fold belt (inverted North Dobrogea rift zone), (ii) Eastern Balkan thrust-fold belt and its easternmost Rezovo segment: (a) Inner uplifted zone (Balkan), (b) Outer buried zone (Forebalkan), (iii) Eastern Srednogorie, (iv) Strandzha, **(4)** Smaller sedimentary basins: (i) Bourgas basin and (ii) Babadag basin.

Western Black Sea Basin (WBSB) – Western Zone

The deep structure of this zone was revealed by seismic data and resulting geological interpretation only.

The WBSB is a typical rift basin with steep western slopes and a deep flat floor. The rifting started during the Aptian (Okay *et al.* 1994; Robinson *et al.* 1995; Banks & Robinson 1997; Nikishin *et al.* 2001, 2003) and lasted until the beginning of the Middle Eocene, as can be seen from cross-sections III & V (Figure 4). The Middle Eocene to Quaternary sedimentary succession is relatively undeformed and has a thickness exceeding 3–3.5 km (Figures 4a–c & 9a). In some areas the syn-rift Middle to Upper Cretaceous deposits also belong to this undeformed sequence, as it is in the middle of this zone, characterized by the eastern part of cross-section IV. East of the Moesian platform edge the Mesozoic sediments occur at great depth – below 4–5 km (Figure 4c).

The western zone of the WBSB has a complex and variable structure. Its southern and northern parts have different characteristics. In both parts western slope of the basin is marked by a sheaf of listric extensional faults with a dominant N–S trend, through which a fast stairs-type subsidence was realized (Figure 4a, c). The presence of extensional faults and blocks, rollover anticlines and tilted graben-troughs in this slope indicates rifting processes. These structural elements are unevenly distributed, linear in form and parallel to the basin palaeo-slopes.

In the south, east of the basin western slope, a relatively flat floor is developed (Figure 4a), while in the north the basin floor structure is complicated by a narrow SW–N-trending intra-basin linear high, named the *Polshkov ridge*, which is seen in the Cretaceous–Lower Palaeogene succession (Figure 4c). To the north the ridge gets closer to the East Moesian platform edge and merges with it. Between the SE Moesian platform edge and the Polshkov ridge is a narrow syncline, called the *East Moesian trough* (Figures 4a & 5). It contains Lower Palaeogene and Aptian–Albian(?) sequences onlapping to the west and east. East of the Polshkov ridge a gentle monocline marked the transition to the WBSB floor.

The WBSB comprises two deep westward wedging branches: *the Kamchia and the Histria sub-basins*, which limit the easternmost offshore portion of the Moesian Platform to the south and north, respectively. They are superimposed over ancient rift zones, developed during the Late Permian–Early Triassic and Late Triassic (Figure 6).

Kamchia Sub-basin

The westernmost periphery of this unit, called by many authors the 'Kamchia depression', extends onshore (Figure 5) where it has been explored by seismic survey and deep drilling for more than 60 years. Many seismic and borehole results for the offshore zone have been obtained during the last 3 decades. All this information has allowed detailed deciphering of the sedimentary succession and structural characteristics of this basin (Figures 3, 4b, 5 & 9b).

Many authors considered the Kamchia depression as a post-Early Eocene foredeep, based mainly on the position and geometry of its westernmost periphery exposed onshore (Figure 5). However, results from offshore seismic surveys show that the basin gradually deepens and expands eastwards and merges with the WBSB floor (Georgiev 2004) (Figure 4b). Hence, this geometry defines the Kamchia elongated basin as *westward wedging branch of the WBSB.*

Basin sedimentary fill comprises Middle Eocene to Quaternary deposits. The Eocene–Oligocene sequence represents the major sedimentary fill in the western shallower periphery of the basin, while the Neogene thickness increases notably towards the WBSB floor (Figures 3, 4b & 9b).

The Kamchia basin trends to the west just in front of the Balkan thrust-fold belt. Its westernmost periphery covers a small area onshore, where its width is about 10–15 km and the sedimentary thickness is up to 1300–1400 m. But eastwards offshore the basin gradually widens to 60–70 km and deepens to 7000

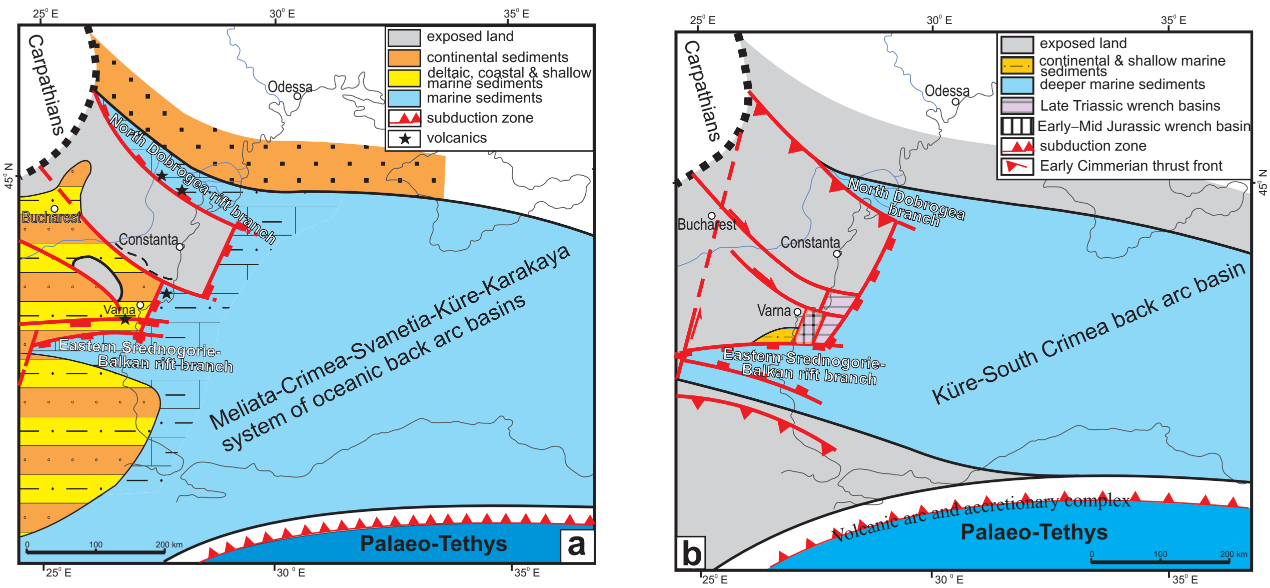

Figure 6. **(a)** Late Permian–Early Triassic palaeogeography and depositional environment; **(b)** Late Triassic–Early–Middle Jurassic palaeogeography and depositional environment.

m (Figures 4b & 5). The basin basement is marked by intra-Middle Eocene *Illyrian unconformity* (Figure 3) and its structure is characterized by the geometry of the Upper Cretaceous carbonate sequence.

Tectonically this basin is superimposed on both the southern margin of the Moesian platform and the frontal zone of the Balkan thrust-fold belt (Dachev *et al.* 1988) (Figure 3). The northern basin slope dips steeply through listric faults in the southern Moesian Platform margin. The southern basin slope is thrust-folded (this is actually the buried Forebalkan unit of the Balkan thrust-fold belt). A chain of local thrust-folds, trending W–SE, is observed within the southern basement slope. So, the basement structural geometry is extensional in the northern basin slope and compressional in its southern slope.

Initial formation of the Kamchia basin was coeval with the stacking of the Eastern Balkan thrust-belt during the Illyrian northward compression in the early Middle Eocene (Georgiev & Dabovski 2001). Further basin development was controlled by: (i) the uplift and N–NE propagation of the Balkan thrust-fold belt and (ii) the opening and expansion of the WBSB. Throughout this evolution the basin depocentre migrated north due to the SW one-sided sourcing of sedimentary filling, controlled by the erosion of the uplifted Balkan thrust-fold belt.

Histria Sub-basin

This northern branch of the WBSB, called by many authors the 'Histria depression', is located offshore from Romania (Morosanu 1996, 2007; Morosanu & Sava 1998; Seghedy 2001; Dinu *et al.* 2002, 2005).

The basin sedimentary fill comprises Oligocene to Quaternary deposits (Figures 4d & 9c), hence it is *younger than the Southern Kamchia branch*. Oligocene and Pontian sequences dominate the sedimentary succession.

The NW-trending Histria basin was developed on the southern and middle nappes of the North Dobrogea orogen and covers also the northeasternmost part of the Moesian Platform (Morosanu 1996, 2007; Dinu *et al.* 2002, 2005). According to Morosanu (1996, 2007) the offshore seismic data allow some over-thrusts to be traced, separating three subunits (Figure 5), which can be correlated with the three onshore North Dobrogea nappes (Sandulescu 1984; Seghedy 2001).

The basin gradually widens and deepens towards the SE and merges with the WBSB floor (Figures 4d & 5).

Platforms

Moesian Platform-The Easternmost Zone – The Moesian Platform forms the foreland of the Alpine thrust belt and is separated from the Scythian platform by the North Dobrogea orogenic belt on its north-eastern margin (Figure 5).

Baikalian consolidated basement and Phanerozoic sedimentary cover form the structural architecture of the Moesian Platform. The basement, exposing the so-called 'Green Schist formation', outcrops onshore locally in the Central Dobrogea. None of the boreholes in Northern Bulgaria reached it.

The Phanerozoic sedimentary cover comprises three main structural sequences: Palaeozoic, Triassic and Jurassic–Tertiary, which reflect the main tectonic stages of platform evolution. Numerous Late Triassic (Norian?–Rhaetian) folds in the Moesian Platform are interpreted as fault-bend folds involving various Palaeozoic decollement levels (Tari *et al.* 1997). In a wider palaeotectonic scenario, this thrust-fold belt represents the frontal part of the Mediterranean Cimmerides propagating into the European foreland (Tari *et al.* 1997). The main structural configurations from Jurassic to Tertiary are clearly oblique to each other.

The results from offshore exploration during the last 30 years proved the platform extension in Black Sea and deciphered its structure. The easternmost part of the Moesian platform extends up to 120 km offshore and occupies a large central part of the WBSZ. The platform is delimited by the Peceneaga-Camena fault and the North Dobrogea orogen to the north, by the Bliznak fault and the Kamchia sub-basin to the south, and by the WBSB to the east (Figures 3–5).

In the south-eastern Moesian platform zone the faults trend in two main directions (Figures 3–5): normal and reverse east-trending faults, and strike-slip north-trending faults, related to the WBSB opening, These two major fault systems create a complex structure of vertically displaced blocks and of small wrench/pull-apart basins. Four different tectonic units occur within the eastern Moesian Platform zone:

Green Schist Zone (Central Dobrogea Unit) – This unit, well-known as Central Dobrogea (Figure 5), comprises uplifted basement blocks, in which the Upper Proterozoic 'Green Schist formation' cropping out on the surface or thinly overlain by thin Jurassic–Tertiary sequences. This unit extends into the Central Dobrogea horst onshore, bounded by the Peceneaga-Camena and the Palazu crustal reverse faults, and it extends offshore bounded by the Emine-Razelm, Lacul-Rosu and West Midia faults (Morosanu 1996, 2007).

Palaeozoic Zone (the South Dobrogea Unit and the North Bulgarian Arch) – This zone (Figure 5) represents a mosaic of relatively small, vertically displaced blocks. Its Upper Proterozoic crystalline basement is overlain by thick Palaeozoic sequences, which crop out onshore in some zones of the South Dobrogea. In the North Bulgarian arch and offshore the dislocated and vertically displaced Palaeozoic blocks are overlain by Jurassic to Tertiary sedimentary sequences. Lower Triassic, mainly continental clastics are preserved in some blocks, located onshore on the eastern slope of the North Bulgarian arch (Kalinko 1976) and in the Romanian offshore sector (Morosanu 1996).

Late Triassic and Early–Middle Jurassic Wrench/Pull-apart Basins – This unit comprises three relatively small troughs, namely the East Varna, Tyulenovo and Ushakov troughs (Figure 5). Identified in the south-eastern platform offshore zone by seismic data (Drannikov *et al.* 1979; Dachev *et al.* 1988), these troughs are filled mainly by Upper Triassic clastics up to and exceeding 1500 m thick, as shown by the drilled sections (Figure 3a).

Results from offshore exploration (seismic and drilling) during the last 20 years proved the local presence of thick Triassic and thickened Lower–Middle Jurassic successions. This, together with basin size and geometry, inferred their wrench/pull-apart nature.

This offshore wrench stage occurs in the Late Triassic as a system of wrench/pull-apart basins (troughs), formed mainly by strike-slip movements along the bounding Balchik, Kaliakra and East Moesian faults (Figures 3, 4c & 5). The basin development terminated towards the end of the Early Cimmerian orogeny (Tari *et al.* 1997), which partly complicated their structure. Only the East-Varna trough was reactivated in the Early–Middle Jurassic and a clastic-shale succession up to 300–500 m thick was deposited (Figures 3 & 4c). Some seismic indications of slight thickening of the Lower–Middle Jurassic sequence can also be observed in the southern part of the Ushakov trough (Figure 4c). This Early–Mid Jurassic offshore wrench stage is synchronous with the rift stage onshore in the East Srednogorie-Balkan zone (Georgiev *et al.* 2001; Figure 6b). Hence, the presence of the same thick Lower–Mid Jurassic sequences in the Kamchia zone (southwards of Bliznac fault) is quite possible (Figures 3b, 4b & 5).

Southern and Eastern Platform Edges and Margins

Well-defined platform edges and margins can be recognised in the northern Bulgarian offshore sector. The southern and eastern platform edges are well shaped by narrow uplifted strips with horst-like structure in some fragments, in which the Lower–Middle Triassic levels are exposed on the pre-Jurassic subcrop (Figures 3, 4c & 5). Part of the southern platform margin is buried below the Tertiary sedimentary fill of the Kamchia basin. The eastern platform margin is affected by the East-Moesian north-trending fault system, through which a stair-like subsidence manifests the transition to the WBSB.

Scythian Platform

The Scythian platform in the WBSZ is covered offshore by the Histria branch of the WBSB (Figure 5). According to Nikishin *et al.* (1998a, b, 2001) this westernmost fragment of the Scythian Platform is a southern marginal step of the East European Platform. The southern margin of the East European craton is flanked by the Scythian orogen, which was consolidated during the Late Carboniferous–Early

Permian. The border between them is marked by a narrow faulted zone, whose location and designation are controversial (Morosanu 1996, 2007; Maystrenko *et al.* 2000; Dinu *et al.* 2005; Stovba *et al.* 2006; Khriachtchevskaia *et al.* 2009).

The Late Palaeozoic folded basement of the Scythian Platform is covered by a Mesozoic–Tertiary sedimentary succession, rapidly increasing in thickness and deepening to the Histria basin to the south. Thus a southward deepening flexural slope about 50–55 km wide can be differentiated (Figure 5), complicated by northward thrusting provoked by the North Dobrogea orogeny. The Pelikan thrust fault in the pre-Palaeogene sedimentary sequences is the main evidence of compressional tectonics (Morosanu 1996). Two parallel E–W-elongated highs (uplifted blocks/swells) occur on this slope – the northern one comprises the Sulina high and Gubkin swell; the southern one is located on the middle part of the slope and includes the St. George block (Figure 5).

East European Platform

The studied WBSZ includes a small part of the East European Platform (Figure 5), mainly the East Vilkovian-Zmeinian bulge (Maystrenko *et al.* 2000; Stovba *et al.* 2006), consisting of the Zmeinien and East Vilkovian rises. They are separated by the Vilkovian depression offshore. The platform basement consists of Carboniferous and older rocks and was affected by strong deformation and intensive erosion. The thickness of the overlying Mesozoic–Neogene sedimentary succession increases rapidly eastwards in the Vilkovian depression and southwards on the Danube flexure slope. The Zmeinian rise is extensively faulted. The structure of the Vilkovian depression is complicated by many reverse faults.

Recently some authors included this part of East European Platform as a westernmost fragment of the Scythian Platform (Dinu *et al.* 2005; Khriachtchevskaia *et al.* 2009).

Orogens

The orogen system in the WBSZ includes the following units: *North Dobrogea thrust-fold belt* (*inverted North Dobrogea rift zone); Eastern Balkan thrust-fold belt with its endmost Rezovo segment; Eastern Srednogorie and Strandzha*.

North Dobrogea Thrust-fold Belt (Inverted North Dobrogea Rift Zone) – This NW–SE-trending orogen is generally considered to be a Mesozoic north verging fold- and thrust-belt (Seghedi 2001). It is delimitated to the NE and SW by the crustal-scale Heraclea and Peceneaga-Camena faults (Figure 5; Sandulescu 1984; Morosanu 1996). Geologically the North Dobrogea orogen has been variably interpreted as an intracratonic fold belt, a short-lived failed rift, a Middle Cretaceous transpressional strike-slip belt, a fragment of a former back-arc basin related to a north-dipping Triassic subduction zone (Seghedi 2001). The thrust-folded structural model, constructed first for the exposed onshore orogen portion, shows a system of NE-verging high-angle imbricate thrust sheets, involving Mesozoic sediments and Hercynian basement. They can be grouped into three nappes – the Macin, Niculitel and Tulcea ones, which are thrust northeastwards (Sandulescu 1984; Morosanu 1996, 2007).

Recent geological investigations, synthesized by Seghedi (2001), indicate that the North Dobrogea orogenic belt is a Late Permian–Early Triassic rifted basin with maximum magmatic activity during Middle Triassic, and was inverted during the Late Triassic and the Early Cretaceous orogenic phases. These caused compressional reactivation of the syn-rift extensional faults, accompanied by the propagation of the dominantly NE-verging thrusts (Seghedi 2001). The NE-directed compressional tectonics and movements ceased during the Albian, when the entire North Dobrogea structural assemblage was completed (Sandulescu 1984; Seghedi 2001; Nikishin *et al.* 2001).

The orogen is well exposed in the central onshore zone of the North Dobrogea, but towards the ESE in the coastal zone and offshore it is buried progressively to greater depths beneath the Cretaceous Babadag basin and the post-Eocene Histria basin.

Eastern Balkan Thrust-fold Belt and its Endmost Rezovo Segment – The Balkan orogen in Bulgaria is a E–W-trending thrust fold belt traversing the whole country and it represents a segment of the Alpine orogen in Eastern Europe (Boncev 1986).

The Balkan orogen consists of a stack of dominantly north-verging thrust sheets that developed during multiphase collisional events along a long-lived convergent continental margin. The compression culminated toward the end of the Early Cretaceous and in the early Middle Eocene (Emery & Georgiev 1993). These thrust sheets contain a range of rock sequences of different provenance and age. Accordingly, they can be subdivided into four groups, namely basement, basement-cover, cover and exotic nappes (Georgiev & Dabovski 1997). The first three groups comprise some sequences derived from the European continental margin, including Proterozoic and Palaeozoic basement rocks and their dominantly Mesozoic cover that consists of platform, marginal basin and island arc sequences. The exotic nappes are composed of Palaeozoic and Triassic low-grade metasediments of probable slope to slope-base origin.

The Balkan orogen is made up by an inner (southern) uplifted overthrust zone (called the Balkan or Stara Planina) and an outer (northern) subsided thrust and folded zone (called Forebalkan).

The Eastern Balkan unit is rather different from the Western one (Byrne *et al.* 1995). They are separated by the NE-trending Tvarditsa transverse strike-slip fault system (Boncev 1958). The Tvarditsa fault system is believed to separate two domains with different Cenozoic evolutions (Boncev 1986; Byrne *et al.* 1995; Georgiev *et al.* 2001). The Western Balkan orogen is dominated by Palaeozoic and Lower Mesozoic exposures, whereas in the Eastern Balkan segment the Palaeogene and Upper Cretaceous sediments are widely exposed. This K_2-Pg series is underlain by Lower Cretaceous, Jurassic and Triassic sediments exposed in the narrow Kotel strip associated with the frontal East Balkan thrust unit (Georgiev *et al.* 2001). The Lower–Middle Jurassic black shales are typical of the Kotel strip. In some localities, these black shales are closely associated with thick Upper Triassic flysch-like deposits.

Recently the Eastern Srednogorie-Balkan rift zone (ESBRZ) has been defined by Georgiev *et al.* (2001). This zone limits the Moesian Platform to the south. The ESBRZ is characterized by several spatially superimposed rifted basins, which are strongly deformed by multiphase north-verging thrusting during the Early Cimmerian (Late Norian–Hettangian), the Mid-Cimmerian (Middle Jurassic), the Late Cimmerian (Tithonian), the Austrian (Middle Cretaceous), the Laramian (Late Senonian) and the Illyrian (early Middle Eocene) compressions. The Lower–Middle Jurassic black shales and the Upper Triassic flysch-like deposits in the Kotel strip were accepted as a sedimentary fill of the ESBRZ (Georgiev *et al.* 2001).

The Eastern Balkan thrust-fold belt has a different strike and morphology in the coastal and offshore zones. The outer Forebalkan zone disappears as a surface exposure and subsides beneath the Tertiary sedimentary fill of the Kamchia basin. Offshore, the East Balkan orogen first turns towards the SE, then, through strike-slip movement along the Western Black Sea fault (or the Kaliakra wrench fault), shifts considerably to the south at about 15 km distance (Figure 5). In this way the endmost Rezovo segment of the East Balkan orogen was detached after the early Middle Eocene.

The Rezovo Segment is a complex positive structure, representing the endmost SE extension of the offshore Balkan orogen. It consists of two positive fault bounded trends: *Rezovo* and *Ropotamo-Limankoy* (Figure 4a). Both trends correlate well with the inner elevated and outer subsided zones of the EBTFB (Figures 3). The inner *Rezovo trend* is relatively raised. The outer *Ropotamo-Limankoy trend* is relatively subsided and manifests the structural transition towards the WBSB.

Easten Srednogorie – This onshore exposed unit is covered by Pg-N sediments of the Bourgas basin (Figure 5). The Eastern Srednogorie mostly contains products of Late Cretaceous island arc magmatic activity (volcanics, volcaniclastics and intrusive bodies), locally intercalated by thin deep marine sediments (Dabovski *et al.* 2009). Back-arc rift sequences are preserved in the northern parts of the unit. The pre-Upper Cretaceous Mesozoic rocks are neither exposed nor have they been drilled in depth. However, the presence of thick Triassic and Jurassic rift-related sequences is indicated by some seismic data (Byrne *et al.* 1995; Georgiev *et al.* 2001).

Strandzha – This orogen represents the eastern part of the Rhodope-Strandzha crystalline region, extending across Southern Bulgaria, Turkish Thrace and Northern Greece.

The stratigraphy of the Strandzha Orogen is strikingly different from that in other Bulgarian zones and in the Turkish İstanbul Zone (Savov *et al.* 1995). Its basement is composed of Precambrian high-grade and Palaeozoic low-grade metamorphic rocks. The sedimentary succession comprises Triassic clastics and platform carbonates and Lower–Middle Jurassic sandy-calcareous and shaly-silty series (autochthonous), which are topped by slices of exotic nappes (allochthonous), consisting of Palaeozoic(?) low-grade metamorphic rocks and Triassic (Spathian-Norian) deep marine carbonates.

The Triassic to Middle Jurassic sequences, as well as the crystalline basement, were folded and thrust-faulted during the Early and Mid Cimmerian orogeny (Georgiev *et al.* 2001; Nikishin *et al.* 2001). Other authors have considered the earliest Mesozoic compressional deformations of the Strandzha Orogen to be Mid Jurassic (Okay & Tüysüz 1999) or post-Mid Jurassic (Banks 1997).

Smaller Sedimentary Basins

Bourgas Basin – This NW-oriented Tertiary basin is located mainly offshore in the SW part of the WBSZ; only a small part of its NW periphery is exposed onshore (Figure 5). The basin is explored mainly by seismic data in the Bulgarian offshore. There is drilling in the Bulgarian onshore part (the Bourgas area) and in the Turkish offshore part: the Igneada and Karadeniz wells.

This basin has half-graben geometry, bounded to the east by the Back-Balkan fault. The basin is bounded by the Eastern Srednogorie unit to the west and north, and by the endmost Balkan unit and its Rezovo segment to the northeast and east (Figures 3, 4a & 5). Its extension in the Turkish offshore sector remains obscure: most probably it has no connection with the one located south of the Strandzha Thrace Basin (Turgut *et al.* 1991; Okay *et al.* 2010).

The basin sedimentary fill contains Mid–Late Eocene, Oligocene and Neogene clastics and clay (Figure 10b). Seismic data indicate that the basin depocentre is situated in the Turkish offshore sector near the Bulgarian border, where over 4 km of sediments have been deposited (Figure 3a).

The basin opened during the Middle Eocene on the limb of the rollover anticline in the hanging wall of the Back-Balkan fault line (Doglioni *et al.* 1996). The North-western termination of the basin is controlled by the E-trending right-lateral transfer zone of the Back-Balkan fault line along which the rollover ends. The Late Eocene extension is also supported by occurrence of coal and black shale and marls of this age filling the basin. The basin development took place mainly during the Neogene and Quaternary (Figures 3a & 10b).

Babadag Basin – This small sedimentary basin in the Romanian coastal area covers the southern Macin nappe of the North Dobrogea orogen (Figure 5; Seghedy 2001, figure 2a). It opened during the Late Albian–Cenomanian as a half-graben to the north of the genetically linked Peceneaga-Camena fault (Sandulescu 1984) and developed in a back-thrust front position (Morosanu 1996). The basin sedimentary fill consists of Upper Albian to Lower Campanian sediments over 1600 m thick.

Hydrocarbon Systems

Hydrocarbon Discoveries and Oil Genetic Types

In total 15 hydrocarbon discoveries have been made in the WBSZ (Figure 7), including 6 gas, 2 gas-condensate and 7 oil or gas-oil fields. 9 fields are in the Romanian offshore sector, 4 in the Bulgarian offshore sector and 2 in the Ukrainian offshore sector. The Olimpiyskoe discovery was made by Ukraine, but now belongs to Romania. The basic characteristics of the discovered fields are shown in Table 1.

Most of the fields have not been appraised yet due to different reasons, such as limited hydrocarbon reserve and lack of investments.

All the discovered hydrocarbon accumulations are in shallow-water shelves in less than 100 m water depth (Figure 7). They are related to different sedimentary basins – 8 are in the Histria sub-basin; 2 in the Vilkovian depression, interpreted as a western branch of the Karkinit basin; 3 in the Kamchia sub-

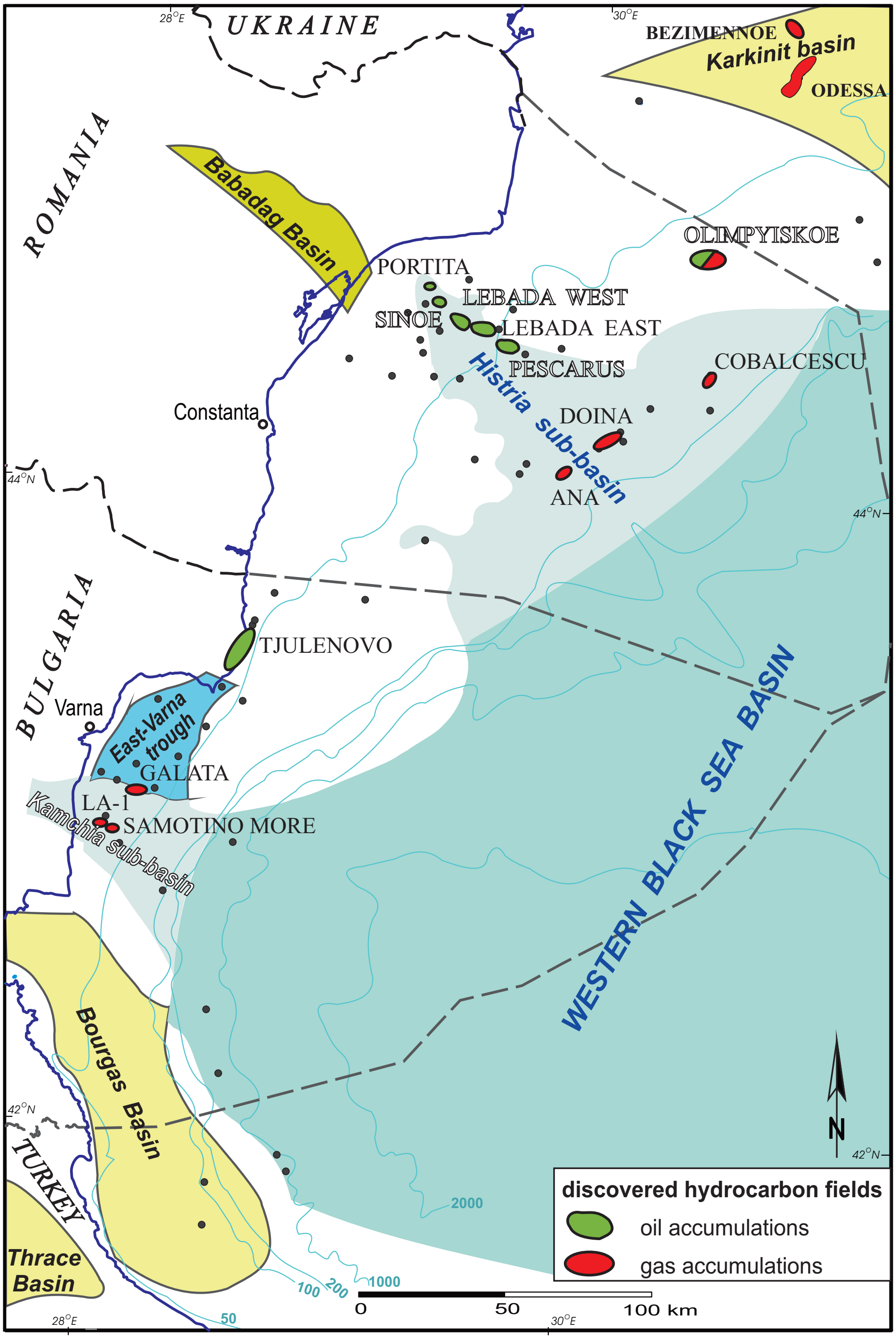

Figure 7. Map of sedimentary basins in WBSZ and discovered hydrocarbon fields.

basin and the adjacent southern edge of the Moesian Platform. The Tyulenovo field is very close to the East Varna trough, while the Olimpiyskoe field is close to the Histria basin.

Hydrocarbon accumulations in the WBSZ were discovered within reservoirs of rather different age. In this respect, their genetic correlations are of great importance.

Table 1. Basic characteristics of the discovered Hydrocarbon fields in WBSZ.

№	Field name	Field Type	API	Reserves	Discovery Year	Reservoir Age	Reservoir Lithology	Status
1	Bezimennoe	Gas		140 Bcf	1997	Palaeocene	siltstone	apprising
2	Odessa	Gas		427 Bcf	1987	Palaeocene	siltstone	apprising
3	Olimpyiskoe	Oil Gas	28.8	70 Mbs >350 Bcf	2001	Eocene & Palaeocene	sandstone & siltstone	apprising
4	Lebada East	Oil Condensate Gas	37.5	42 Mbs 2 Mbs 242 Bcf	1979	Albian	sandstone	producing
5	Lebada West	Oil Gas	36.3	40 Mbs 200 Bcf	1984	Eocene	sandstone	producing
6	Sinoe	Oil Gas	24.0	25 Mbs 30 Bcf	1987	Eocene	sandstone	apprising
7	Portita	Oil	35.4			Oligocene	sandstone	shut-in
8	Pescarus	Oil-Gas		70 MbOE	1999	Cretaceous	sandstone	apprising
9	Cobalescu	Gas			1997	Pliocene	sandstone	apprising
10	Doina	Gas		200 Bcf	1995	Mio–Pliocene	sandstone	apprising
11	Ana	Gas			2007	Mio–Pliocene	sandstone	apprising
12	Tjulenovo	Oil Gas	19.4	30 Mbs 30 Bcf	1951	Valanginian	carbonates	producing
13	Galata	Gas		55 Bcf	1993	Eocene & Upper Cretaceous	sandstone & carbonates	production-end
14	Samotino More	Gas- Condensate	53.5		1986	Middle Eocene	sandstone & siltstone	apprising
15	LA-1	Gas- Condensate			1994	Valanginian	carbonates	shut-in

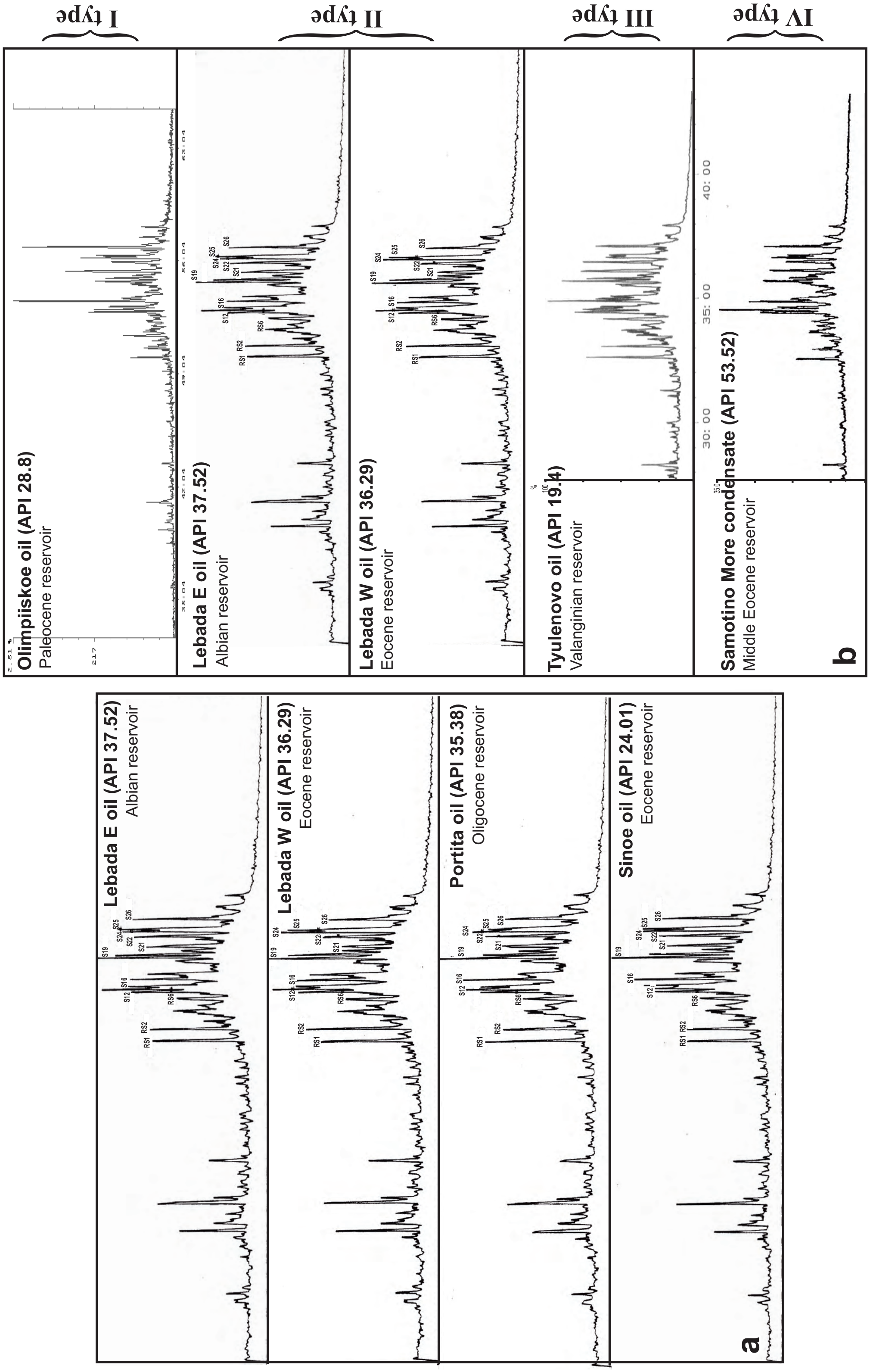

Figure 8. Oil to Oil Biomarker correlation (Sterane m/z 217): **(a)** all oils in Histria sub-basin (Romania); **(b)** main crude oils in Western Black Sea zone.

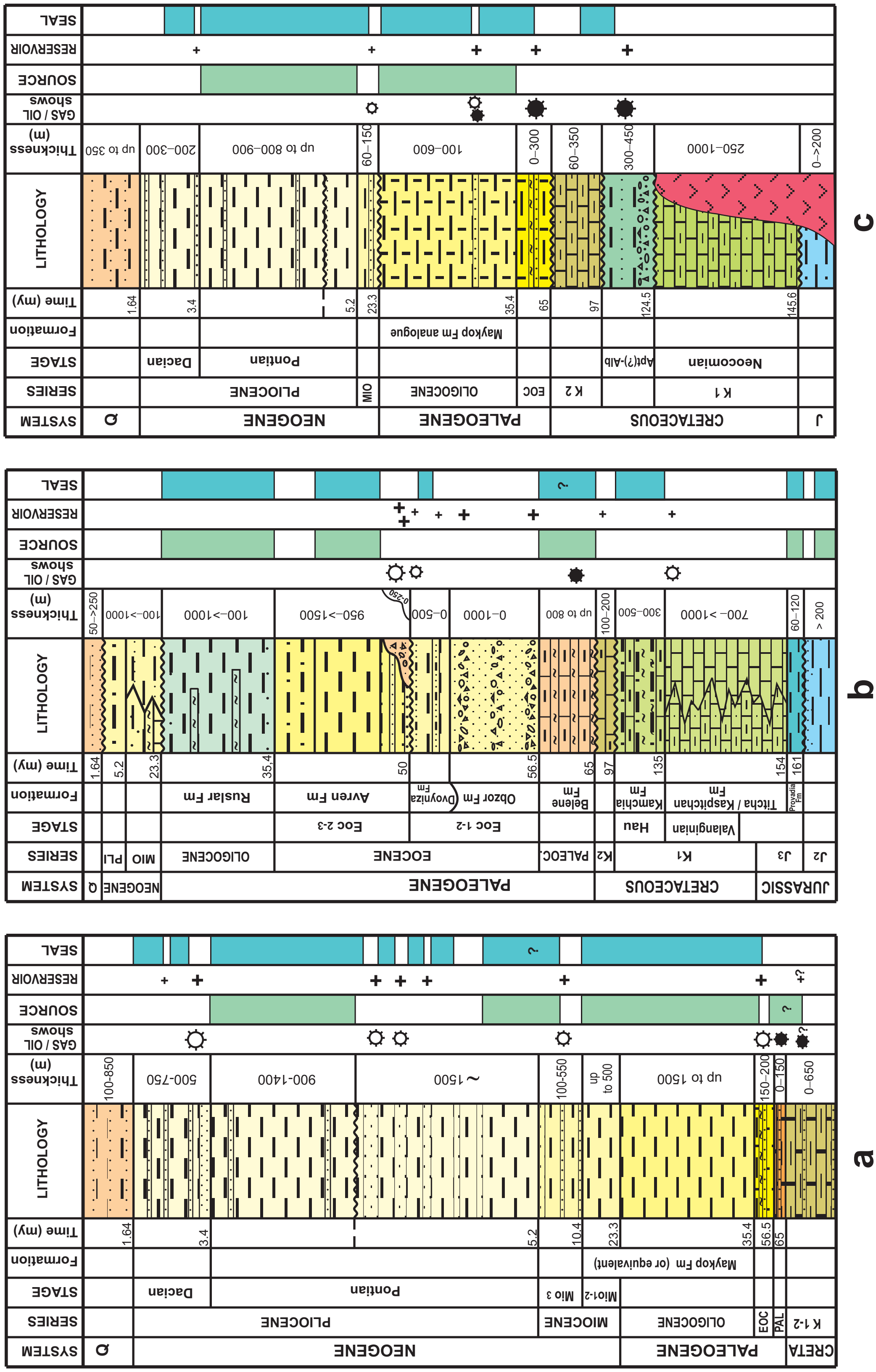

Figure 9. Lithostratigraphic columns with Hydrocarbon features: **(a)** WBSB (deepwater zone); **(b)** Kamchia sub-basin; **(c)** Histria sub-basin. Lithology legend is shown on Figure 10.

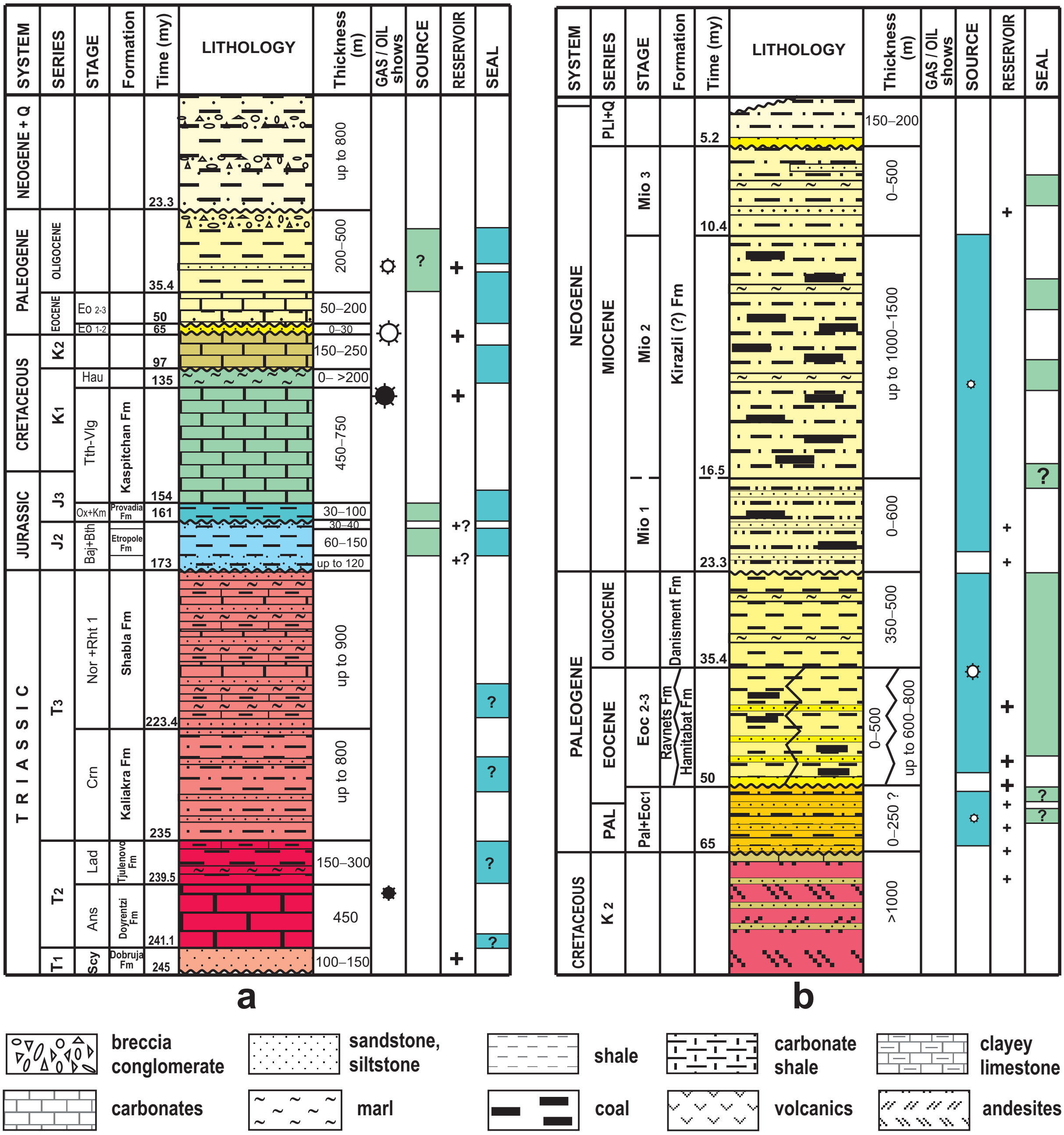

Figure 10. Lithostratigraphic columns with Hydrocarbon features: **(a)** East-Varna trough basin; **(b)** Bourgas basin.

The genetic Oil to Oil correlation comprises crude oils from the following fields: Lebada East (Albian reservoir), Lebada West (Eocene reservoir), Sinoe (Eocene reservoir), Portita (Oligocene reservoir) and Olimpiyskoe (Palaeocene reservoir) in the Romanian offshore sector; Tyulenovo (Valanginian reservoir) and Samotino More (Middle Eocene reservoir) in the Bulgarian offshore sector. The correlation has been made by obtained alkane, triterpane (m/z 191), sterane (m/z 217), triaromatic steroids (m/z 231) and monoaromatic steroids (m/z 253) profiles, which are of good quality (Figure 8).

Although the four oil fields in the Histria sub-basin (Labada East, Lebada West, Sinoe and Portita) are in reservoirs of different age and lithology, and the Sinoe oil is strongly biodegraded, all have very similar biomarker patterns by triterpanes (m/z 191) and steranes (m/z 217) (Figure 8a). The *correlation between them is very good,* indicating the same source, i.e. the *same genetic type.* All four oils contain traces of Oleanane (Georgiev 2000), usually interpreted as an indicator for a Tertiary source.

The triterpane (m/z 191) and sterane (m/z 217) correlations between all crude oils in the WBSZ clearly identified *four different genetic types of oils* with distinctive differences between them (Figure 8b). They are as follows: I– Olimpiyski type, II– Lebada type, III– Tyulenovo type and IV– Samotino More type.

The difference between the first two types (Olimpiyski and Lebada) is not so evident; they may be related with facies and maturity changes of the same source. The Triterpanes (m/z 191) correlation shows very slight similarities between the fourth Samotino More condensate type and the third Tyulenovo type: only in the Tyulenovo oil there are traces of Oleanan.

Hydrocarbon Source Estimation

Estimation of the hydrocarbon generation potential is made for each of the main sedimentary basins in the WBSZ (Figures 7, 9 & 10).

Western Black Sea Basin – The Tertiary sediments within the WBSB were considered to be the principal potential source complex a long time ago (Geodekjan *et al.* 1982, 1984). The results from some recently drilled wells in the Romanian and Turkish offshore sectors (Limankoy, Cobalcescu, Ovidiu, Rapsodia, Delfin & Olimpiyski – Figure 2), however, allowed a more precise source rock assessment to be made.

The Lower Miocene and Oligocene sedimentary sequences (Maykop Fm or equivalent) were drilled from only a few wells. Therefore the estimation of source complexes is mainly based on seismic data and extrapolation wells in the Kamchia and the Histria sub-basins, and in the Danube flexure slope to the north (Figures 5 & 7).

The deepwater part of the WBSB contains the thickest Tertiary sequences, some of which are potential source units across the whole WBSZ. There are several sequences with source features (Figure 9a):

The Oligocene–Lower Miocene Sequence (Maikop Formation Equivalent) is considered to be a primary hydrocarbon source within the Tertiary succession. This sequence is defined in the Ukrainian and the Romanian offshore as a major gas/oil prone source rock (kerogen type II and II–III) of regional extent. The nature of the kerogen in the deepwater zone is unknown and may be oil or oil/gas prone. Such discoveries as Olimpiyski, Lebada and Pescarus (Figure 7) proved the oil potential of the Oligocene–Lower Miocene shales.

The Palaeocene–Eocene shale intervals are considered as a secondary hydrocarbon source. They can contain deepwater and lacustrine shales, each of which has potential as source rocks.

The Middle Miocene–Pliocene sequence, which is rich in diatomaceous shales, is also considered as a secondary hydrocarbon source. The diatomaceous shales demonstrate high micro-porosity, with over 50% gas saturation in the Limankoy wells, but they have a very low permeability (Sefunç *et al.* 2000). They are immature up to depth of 3500 m. Hence, their high gas saturation indicates the presence 'in situ' of biogenic gas. Some Pliocene gas discoveries in the Romanian offshore sector (Cobalescu, Doyna, Ana) are also biogenic.

Several gas-hydrate accumulations are recognised by seismic data within the Tertiary succession of the WBSB. The gas in these fields is also considered as biogenic in origin.

According to the maturity results from the Rapsodia and Doina wells in the Romanian offshore sector and the Limankoy wells in the Turkish offshore sector the burial depth for marginal organic maturation (Ro– 0.55%) and the onset of oil generation should be more than 3500 m. However there are some 'warmer zones' in the WBSB (Duchkov & Kazantsev 1985; Kutas *et al.* 1998), in which modelling results show that the 'oil window' begins at depths of about 2500 m.

Kamchia Sub-basin – The sedimentary fill of the Kamchia sub-basin (Figure 9b) comprises the succession above the Illyrian unconformity in the

Middle Eocene. It contains two main sequences: Mid-Upper Eocene–Oligocene and Neogene, of 1000–1500 m total thickness nearshore and up to about 6000 m in the transition to the deepwater zone of the WBSB. The basin basement comprises thick Lower–Middle Eocene, Palaeocene and Upper Cretaceous sequences, which are intensively thrust and folded on the southern basin slope and listric-faulted on the northern slope.

The Oligocene sequence (Ruslar Formation) is considered to be a primary hydrocarbon source. This sequence mainly comprises shale and claystone, occasionally grading to siltstone, with a total thickness increasing northwards from 100–400 m on the southern basin slope to more than 1000–1500 m in the basin axial zone and eastwards to the WBSB. It is an equivalent of the Maykop Formation, which is the basic source unit in the larger Black Sea-Caspian domain.

The organic matter content is good to very good (>1%). The amorphous kerogen type II dominates. The Pyrolysis Hydrogen index (HI) ranges from 30–50 to over 300, which indicates mainly degraded humic organic composition. The dull-orange to brown fluorescence is due to the low level of maturity, so the kerogen is interpreted as primarily gas-prone, although some oil generative opportunities are also possible. The Pyrolysis Potential yields (S2) are fair to good; the values are often over 2000 ppm, ranging up to 6000–8000 ppm. At the drilled depth intervals the formation is immature (0.27–0.35% Ro) and can generate only biogenic gas.

Overall, the Ruslar Formation has fair to good gas source potential, although considerably greater burial depth would be required for it to be realized.

The Mid-Upper Eocene sequence (Avren Formation) is considered to be a secondary hydrocarbon source. It comprises alternating shale, mudstones, siltstones and sandstones, with thin limestone beds and conglomerates at the base. Northwards and eastwards the facies becomes more shaly and deepwater. The total formation thickness increases from 950 m near shore to more than 1500 m towards the WBSB.

TOC in shale is moderate to good (0.6–1.85%). The highest TOC values are measured at the top and base of the formation intervals. This organic enrichment indicates marginal to good source potential. The organic matter is dominated by degraded humic kerogen type II–III (gas-oil-prone) with probably oxidised vitrinite composition. The Pyrolysis Potential yield (S2) reaches values from over 1000 ppm up to 10000 ppm, indicating a fair to good source potential. The organic matter is immature, as the values of Ro (0.31–0.39%), Tmax (422–438°C) and spore coloration (2.5–4) indicate.

Overall, the Avren Formation is able to generate only biogenic gas. But towards the WBSB the shale content, TOC, burial depth and maturity become higher and the oil/gas source potential increases, respectively.

The Upper Cretaceous–Lower Eocene sequence is also considered to be a secondary hydrocarbon source. It contains some intervals with dark marl and shale present (Byala and Dvoynitza formations); their total thickness is about 100–200 m. They are enriched with organic matter type II and II–III up to 2–2.5%. The Gas Chromatography/Mass Spectrometry (GC-MS) data indicate early mature humic kerogen. The predominance of normal alkanes between n-C_{27} and n-C_{34} appears to be consistent with this interpretation. The analyzed samples have high values of S2 (300–5000 ppm) and moderate values of HI (40–200). It is quite possible that these mature stage intervals may be a source of liquid hydrocarbons, as the biomarker correlation between them and the Samotino More condensate showed.

The Neogene sequence is thin near shore (< 400 m), but towards the WBSB it thickens to 2000 m. In its succession there is a considerable amount of mudstones, enriched with organic matter type II (TOC 1.3–2%). The HI values are high (340–400 ppm) and Pyrolysis Potential yields (S2) are fair to good (4810–7140 ppm). All these characteristics suggest a good source potential at the burial depth appropriate for maturation.

Histria Sub-basin – The source rock assessment in the Histria sub-basin is accomplished by many well, seismic and analytical data as well in conformity with the complicated facies architecture of the sedimentary fill (Ionescu 2002; Ionescu *et al.* 2002).

Oligocene calcareous shales (equivalent of the Maykop Formation) with TOC values near and above 0.90% and up to 1500 m thick, appear to be the primary hydrocarbon source in the basin (Figure 9c). The Hydrogen index (HI) values indicate mixed gas/oil prone kerogen, in which a dominant component is the vitrinite, but the proportion of sapropel is also good. A marine depositional environment is indicated by the relatively high abundance of diverse dinoflagellate cysts. The S2 values indicate a transitional poor/moderate potential for hydrocarbon generation. The organic matter is immature (<0.5% Ro) and only biogenic gas can be generated. But at a greater depth (> 3500 m) and maturity these sediments can generate a considerable volume of oil and gas.

The Pliocene (Pontian) mudstones are considered to be a secondary hydrocarbon source. The TOC content is moderate – 0.66–0.67%. The HI values indicate that gas-prone kerogen appears to be dominant. The S2 values show poor to moderate potential for hydrocarbon generation. The main kerogen components are vitrinite and, to a smaller extent, sapropel. The presence of C_{30} sterane biomarkers and the predominance of $C_{27}\alpha\alpha\alpha$ steranes indicates marine depositional conditions. The n-alkane distributions and palynomorph assemblage are consistent with this interpretation. At this immature stage (<0.5% Ro) only biogenic gas can be generated, but at a greater depth (> 3500 m) and higher maturity oil generation is also possible.

The Neocomian sequence in the Egreta and Lebada sedimentary successions is 500–700 m thick, but the thickness of possible source intervals is much smaller (Ionescu 2002; Ionescu *et al.* 2002). The measured TOC values are 1.16–1.89%. The HI values indicate a mixed gas and oil prone kerogen. But the visual kerogen analysis shows that all three components – sapropel, vitrinite and inertinite are significant. Several degraded palynomorphs and palynodebris and the pristane/phytane ratio indicate that oxidation has occurred. Hence the kerogen type is II–III and III (mainly gas prone). The organic matter appears to be at peak maturity (0.75% Ro) for hydrocarbon generation. But S2 values show a transitional poor/moderate to moderate potential for hydrocarbon generation, which together with the low values of PI (<0.1) and the reduced thicknesses, indicate very negligible hydrocarbon (gas) potential.

East-Varna Trough Basin – Very valuable new information for the basin source potential was obtained from the Galata 1 well, drilled in 1993, which first provided information about the presence of thicker Lower–Middle Jurassic sequences in the Bulgarian offshore sector (Figure 10a). They are comparable with the same lithostratigraphic intervals onshore, known as Etropole Formation and Provadia Formation. Note that the thick shales of the Etropole Formation, across the Southern Moesian Platform margin, are the main source for most of the oil and gas fields discovered in Northern Bulgaria (Georgiev & Dabovski 1997; Georgiev 1998, 2000; Georgiev *et al.* 2001). Hence, the presence of the same shale unit in the East-Varna trough basin is a very positive result, especially considering their increasing thickness north of Galata well, as indicated by the seismic data.

The primary hydrocarbon sources are the Etropole and Provadia formations, according to the parameters from the Rock-Eval analyses, log records and biomarker correlations.

The Etropole Formation (Bajocian–Bathonian in age) is about 70 m thick in the Galata section, but to the central basin zone its thickness reaches 100–120 m and more, as indicated by the seismic data. Shales in the lower and the upper parts of the formation have different source characteristics.

The upper interval has a better source potential. The TOC content is up to 1.5%. The organic matter is transitional mature to early mature according to the vitrinite reflectance, Tmax and biomarker compositions. Gas/oil prone kerogen type II–III dominates. The Pyrolysis Potential yield (S2) is higher than those of the lower interval.

The lower interval is poorer in TOC content – up to 0.5–0.8%. The vitrinite reflectance (Ro) and the Tmax value show a transitional mature to early mature stage. The organic matter has different biomarker compositions, which indicates mainly gas prone kerogen type III.

Overall the source potential of the Etropole Formation is fair to good. The proven genetic link between Tyulenovo oil and Etropole Formation

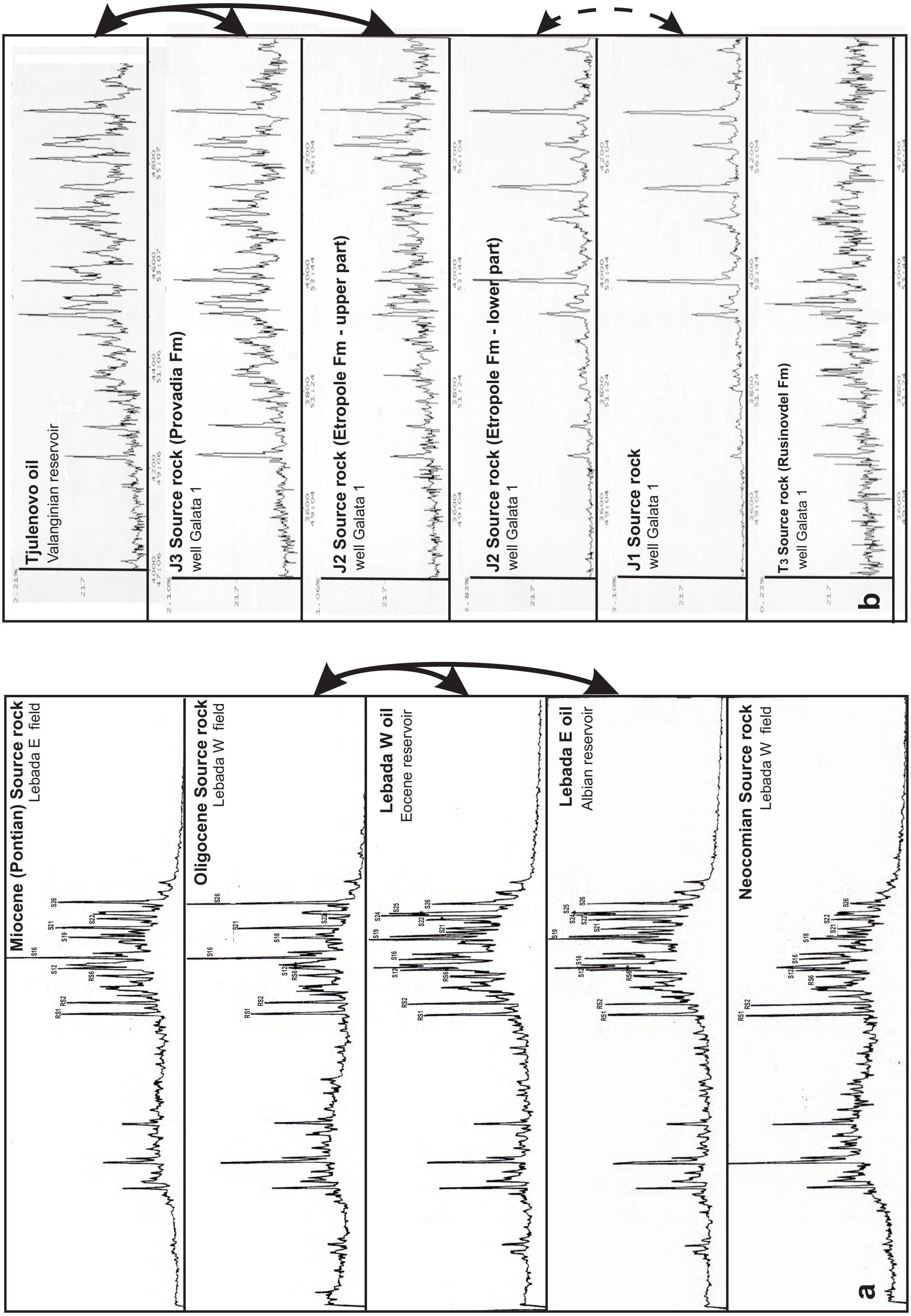

Figure 11. Oil to Source Biomarker correlation (Sterane m/z 217): **(a)** for Lebada oil type; **(b)** for Tyulenovo oil type.

(Figure 11b) is a very important fact, which cannot be disregarded (Georgiev 2007).

The Provadia Formation (Oxfordian–Kimmeridgian) only occurs in the southeasternmost zone of the Moesian Platform. Its thickness is not more than 100–110 m. Rich oil saturation in carbonate breccia, overlying the Provadia Formation, has been established by some onshore boreholes near Varna. The organic enrichment of shale is fair to good – the TOC ranges from 0.5% to 1.5%. Kerogen is oil/gas prone - type II or II–III, the maturity is transitional to early mature. The genetic correlation between Tyulenovo oil and the Provadia Fm is very good (Figure 11b) (Georgiev 2007), so the oil generative potential of the Provadia Fm is beyond doubt.

Bourgas Basin – In the Bulgarian offshore part of this basin there are no drilled wells, but in its Turkish part two wells were drilled in 1971 – Igneada and Kara Deniz. The presented hydrocarbon source analysis for this basin is based on the following: (i) lower basin sequences cropping out onshore in the Bourgas area (Radev *et al.* 1994; Velev *et al.* 1994); (ii) some available information from Igneada and Kara Deniz wells and (iii) good quality seismic data, acquired in 1992/1993.

At least two probable source intervals can be identified in the sedimentary succession (Figure 10b):

The Upper Eocene–Oligocene shale sequence has a total thickness of 300–500 m. The burial depths are 800–1200 m. The TOC is up to 1.5–2%, the Pyrolysis yield (PY or S2) – 7 kg/t and the Hydrogen Index (HI) is about 300. The lacustrine lignite coals and shallow to marginal marine shale (Danişment Formation), drilled in the Turkish zone, showed good source parameters: PY up to 41.6 kg/t and HI up to 387. In outcrop the coals and shale (Ravnets Formation) are immature (0.35% Ro), but their burial depth offshore increases up to 2200–3000 m in the basin depocentre, located around the Bulgarian/Turkish border. Hence, an increasing organic maturity up to early oil generation can be expected, proven by basin modelling. Overall, this source unit is mainly gas-prone and can generate mainly biogenic gas.

The Lower–Middle Miocene predominantly clastic sequence (Kirazlı Formation), about 1700 m thick in the Igneada well, contains numerous lignite coal beds with 3 m maximum individual thickness. The number of drilled coal beds in the Kara Deniz well is 28. So, this rich coal content could produce a considerable amount of gas.

Oils to Sources Correlations

There is no unified perception among the authors who studied the genesis of the main crude oils in the WBSZ before 1990. Most of them used traditional bulk methods, such as physical characteristics, compositional fractionation, element concentrations and ratios. However, the recent investigations have shown that non-genetic processes (as biodegradation, thermal maturation, water washing and migration) affect such characteristics dramatically (Curiale 1994; Peters & Cassa 1994).

The presented results focus on the genetic correlation between the discovered types of crude oils in the Bulgarian and Romanian offshore sectors and their possible sources, based on molecular characteristics (biomarkers profiles) and stable carbon isotope ratios (C^{12}/C^{13}). All correlation results have been interpreted in the context of the regional geology.

The genesis of the Lebada oil type II has been studied by biomarker correlations with all possible source intervals in the Histria basin, which are Miocene–Pontian, Oligocene and Neocomian. The correlation of the Lebada oils with the Oligocene source rocks by triterpanes (m/z 191) and steranes (m/z 217) patterns is the best one (Figure 11a). Its correlation with Miocene (Pontian) source rocks is also good, even though some differences in the triterpane patterns (m/z 191) can be observed. The presence of Oleanane traces in the Miocene pattern cannot be accepted as strong evidence for genetic relations with the two oils. The differences between the Lebada oils and the Neocomian source rocks do not suggest any genetic relationship. *Hence the genetic links of the Lebada oil type with Oligocene source rocks look most likely.*

The genesis of the Tyulenovo oil of type III has remained obscure more than 45 years since its discovery in 1951. But the Galata 1 offshore well,

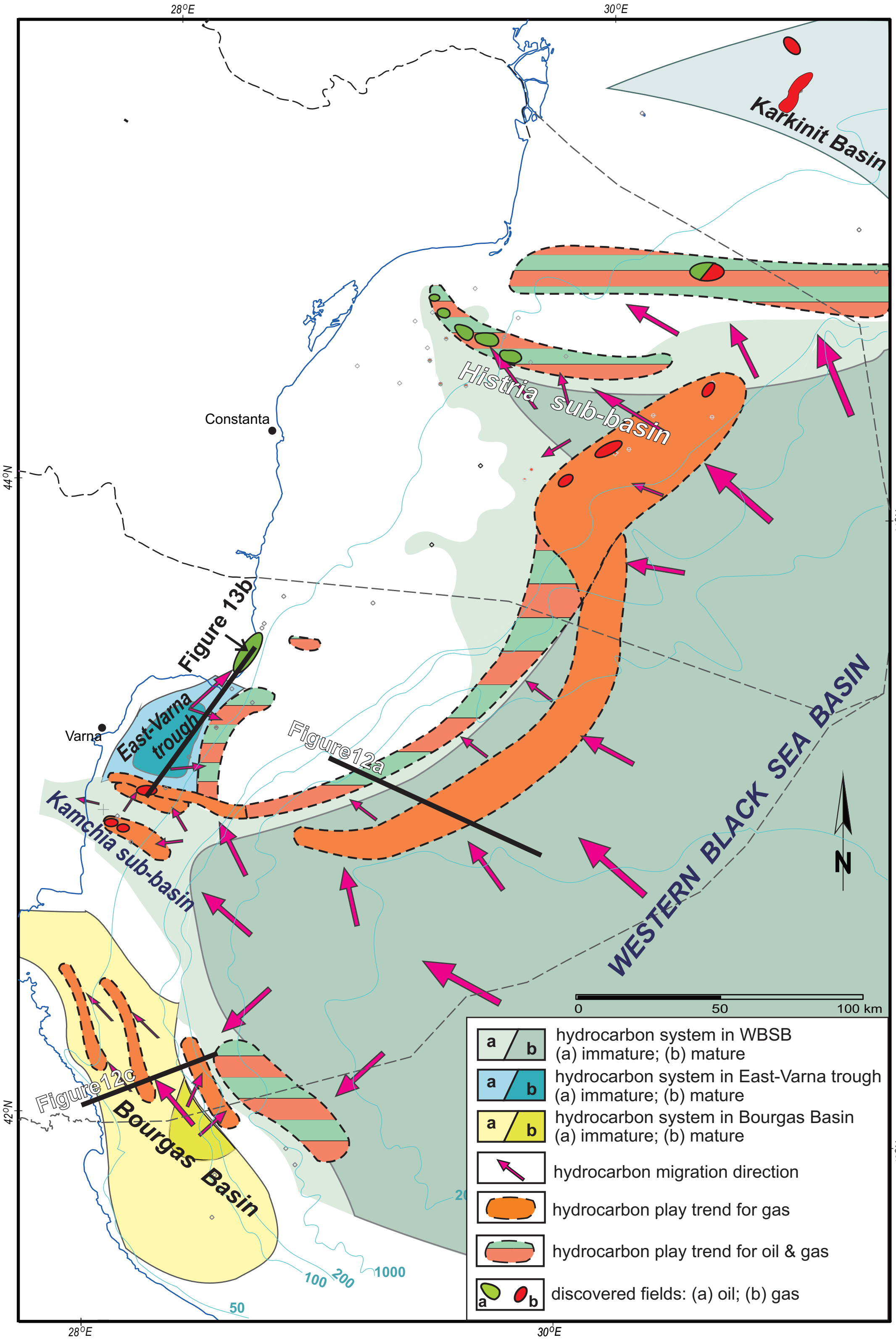

Figure 12. Map of Hydrocarbon systems and Exploration trends in Western Black Sea zone.

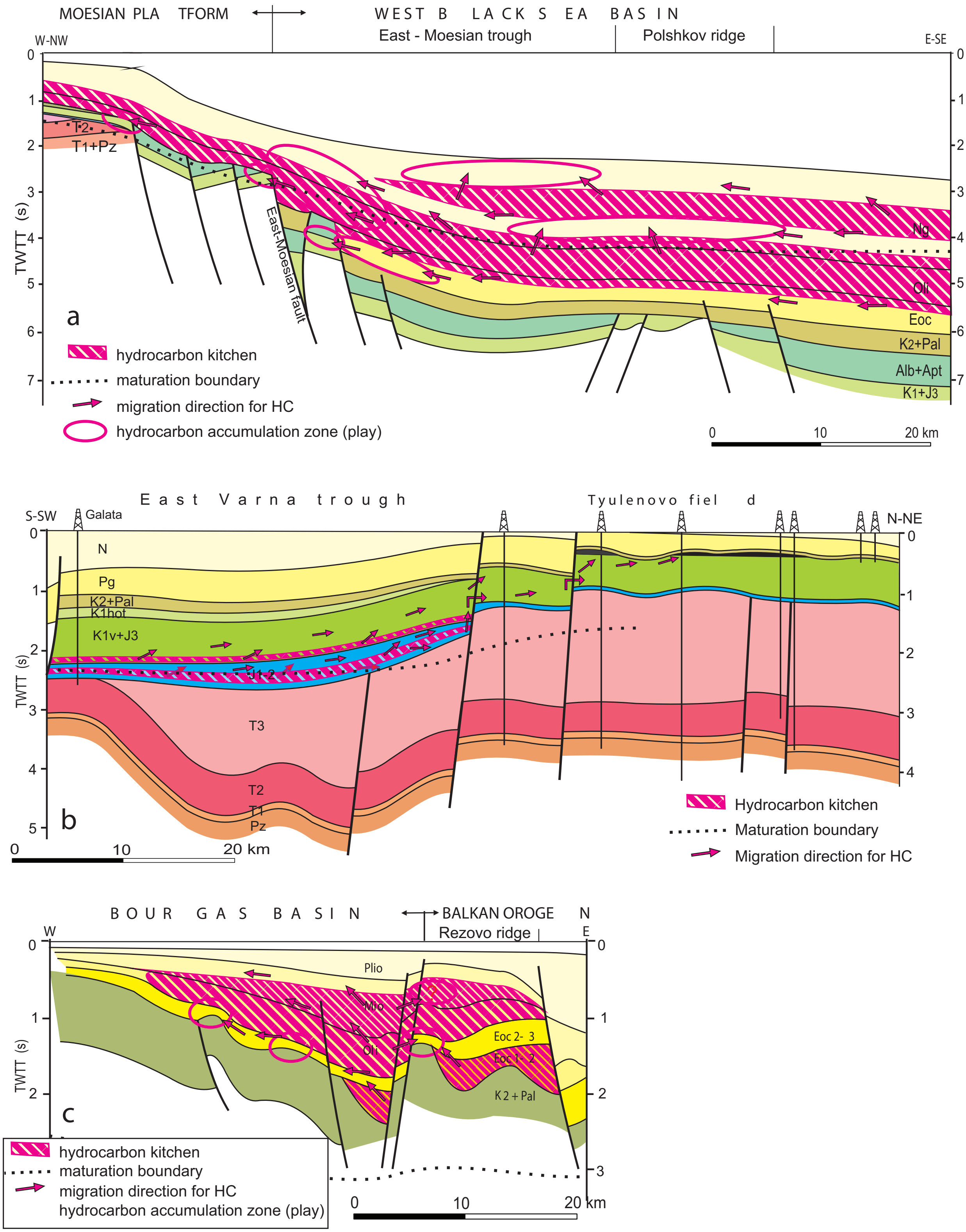

Figure 13. Conceptual models for hydrocarbon systems and exploration trends in: **(a)** Western Black Sea basin, **(b)** East-Varna trough, **(c)** Bourgas basin (location of profiles is shown on Figure 12).

drilled in 1993, has suggested an excellent opportunity to solve this problem. All possible source intervals in the Galata section, related to the Upper Jurassic, Middle Jurassic, Lower Jurassic and Upper Triassic succession have been analyzed with GC-MS, Rock Eval and stable carbon isotope (C^{12}/C^{13}) analyses.

A very good biomarker correlation of the Tyulenovo oil with the Upper Jurassic (Provadia Formation) and the Middle Jurassic (the Etropole Formation – the upper part) source intervals was established (Georgiev 2007), although the genetic links between the Tyulenovo oil and the Provadia Formation looks slightly better (Figure 11b). The stable carbon isotope (C^{12}/C^{13}) correlation between the Tyulenovo oil (27.5‰) and the Middle Jurassic interval (27.73‰) looks very good. Hence *the most probable source for the Valanginian oil accumulation in the Tyulenovo field is the Provadia Formation (J_3) and the upper part of the Etropole Formation (J_2).* We consider that the hydrocarbon output from the Etropole and Provadia formations obviously combines during the migration, especially considering that the two formations are separated in the sedimentary succession by very thin and permeable clastic-carbonate sediments (Figure 10a).

The Samotino More condensate (type IV), accumulated in a Middle Eocene reservoir, contains a distinctive distribution of molecular biomarkers, which is of considerable assistance for correlation with the oil stain occurrences and the possible source rocks.

The good genetic correlation of the Samotino More condensate and the Lower Eocene oil stains with the Lower Eocene (the Dvoynitsa Formation) and the Palaeocene–Upper Cretaceous (the Byala Formation) source intervals in the sedimentary succession of the Kamchia sub-basin (Figure 9b) deserves special consideration. Mainly the C_{27}–C_{29} distributions indicate good genetic links between them.

Hydrocarbon Systems and Exploration Trends

Three main hydrocarbon systems with economic potential were recognised in the Western Black Sea offshore zone (Figure 12). They are related respectively to the following: (1) the Western Black Sea basin and its two western branches – the Kamchia and the Histria basins; (2) the East-Varna trough basin and (3) the Bourgas basin. The first two hydrocarbon systems are proven by the discovered hydrocarbon fields in the Histria and the Kamchia sub-basins, the third one is prognostic.

The conceptual models for the hydrocarbon systems and their basic characteristics are shown on Figures 12 & 13. The estimation of the prospect exploration trends for gas and oil-gas is based on kerogen type and maturity.

The West Black Sea basin hydrocarbon system (Figures 12 & 13a) is related mainly to presence and large distribution of the primary Oligocene–Lower Miocene source complex (the Maykop Formation or equivalent). Its huge generation potential was proved by many economic gas-oil discoveries in the North Caucasus-South Caspian region as well as the discoveries in the Histria and the Kamchia sub-basins. Additional hydrocarbon sources in some zones may be provided by the Middle Miocene–Pliocene shale, Pliocene (Pontian) mudstones in the Histria sub-basin and the Palaeocene–Eocene shale in the southern zone of the Kamchia sub-basin.

The mature zone of this system comprises burial depth of under 3000 m for the primary Oligocene–Lower Miocene source complex. Hence, the active hydrocarbon generation pod (kitchen) is located in the deep-water zone of the WBSB.

The basic hydrocarbon migration is vertically and laterally westwards to higher elevated tectonic units and structures, or the reservoir targets and the entrapping zones related to the channel systems (fans, deltaic bottom-set beds of the Danube and Kamchia pro-delta).

The major hydrocarbon accumulation zones or play trends are as follows: the southern flexural slope of the Scythian Platform; the northern slope of the Histria sub-basin; the East Moesian marginal fault zone and the Polshkov ridge; the northern and the southern slopes of the Kamchia sub-basin and the tilted blocks in the Ropotamo-Limankoy trend of the Rezovo segment.

The East-Varna trough hydrocarbon system (Figures 12 & 13b) is considered mainly due to the presence of the Middle and Upper Jurassic source rocks (the Provadia and Etropole formations) with a modest generative potential in the restricted wrench basin. However the economic significance of this source is proved by the discovered Tyulenovo oil field (Georgiev 2007).

The source assemblage is transitional to early mature, hence the active hydrocarbon generation is launched. The hydrocarbon migration is directed laterally eastwards and laterally-vertically to the N–NE.

The main accumulation zone is related to narrow horst blocks, separating the three wrench basins, where the Upper Jurassic–Valanginian carbonates and the Lower Triassic clastics can be the main exploration targets (Georgiev 2007).

The Bourgas basin hydrocarbon system (Figures 12 & 13c) is immature and not yet explored by drilling. The main reason for its definition is the presence of numerous coal-bearing beds and organically enriched shale in the Upper Eocene–Oligocene and the Lower–Middle Miocene sequences, which can be sources for a coal-generated biogenic gas. The mature hydrocarbon generation is likely to be launched in the deepest and very restricted basin depocentre, located on the Bulgarian/Turkish border, as the basin modelling shows.

Some positive swell-like structures in the western basin slope, mapped by seismic data beneath and above the basin bottom unconformity, as well as the uplifted Rezovo trend (horst), are promising zones for hydrocarbon entrapment, especially if we consider the shallow depths.

Conclusions

The WBSZ has a complex geological structure and evolution, engendered by complex interrelations between different tectonic units and events. A detailed tectonic map for the whole Western Black Seas zone was compiled using an integrated unified approach, interpretation and synthesis of seismic and borehole data along many regional cross-lines, also considering the distribution of gravity-magnetic anomalies (Figure 5).

The complex geological structure of the WBSZ is defined by four groups of tectonic units: (1) Western Black Sea basin (WBSB) – its western zone with the Kamchia and the Histria westward wedging branches (sub-basins); (2) portions of the Moesian, Scythian and East-European platforms; (3) fragments from the North Dobrogea, Eastern Balkan, Eastern Srednogorie and Strandzha orogens; (4) smaller Burgas and Babadag basins.

The Kamchia southern branch of the WBSB, called the 'Kamchia depression', is superimposed on both the southern margin of the Moesian Platform and the frontal zone of the Balkan thrust-fold belt. Its sedimentary fill comprises Middle–Upper Eocene, Oligocene and Neogene clastic and clay successions. The basin origin and development is controlled by the following: (i) the uplifting and N–NE propagation of the Balkan thrust-fold belt and (ii) the opening and expansion of the WBSB. The basin gradually deepens and expands eastwards and merges with the WBSB floor.

The Histria northern branch of the WBSB, called the 'Histria depression', is superimposed on the southern and middle nappes of the North Dobrogea orogen and covers also the northeasternmost part of the Moesian Platform. Oligocene and Pontian sequences dominate the sedimentary succession. The basin gradually expands and deepens towards the SE and merges with the WBSB floor.

The Kamchia and North Dobrogea branches of the WBSB have been already settled during the Late Permian–Early Triassic and the Late Triassic–Early-Mid Jurassic rifting (Figure 6).

Two tectonic units are defined in the deep-water part of the WBSZ: the Polshkov ridge and the East Moesian trough.

Four different types of tectonic units occur within the eastern Moesian Platform zone, they are: the Green Schist zone (the Central Dobrogea unit); the Palaeozoic zone (the South Dobrogea unit and the North Bulgarian arch); the System of Late Triassic and the Early–Middle Jurassic wrench/pull-apart basins and the Southern and Eastern platform edges and margins. The following three relatively small troughs are defined: the East Varna, Tyulenovo and Ushakov ones. They are formed mainly by strike-slip movements along the bounding Balchik, Kaliakra and East Moesian faults in the Late Triassic. Only the East-Varna trough was reactivated during the Early–Middle Jurassic, coeval with the rift stage in the East Srednogorie-Balkan zone. Hence, presence of the same thick Lower–Mid Jurassic sequences in the Kamchia zone is quite possible.

The Eastern Balkan thrust and fold belt changes the strike and the morphology in the coastal and offshore zones – first it turns towards SE, then it shifts through strike-slip movement along the Western Black Sea fault (or the Kaliakra wrench fault) considerably to the south at about 15 km distance. Thus the endmost Rezovo segment was detached after the early Middle Eocene. The Rezovo segment comprises two positive fault-bounded trends: the Rezovo (relatively elevated) and Ropotamo-Limankoy (relatively subsided) ones. They correlate well with the inner elevated and the outer subsided zones of the Balkan orogen.

The oil-gas potential of the WBSZ is proved by the 15 hydrocarbon fields discovered: 7 are mainly oil: 2 are gas-condensate and 6 are gas ones.

Four different oil genetic types were indentified by biomarkers correlations. They are: the Olimpiyski, Lebada, Tyulenovo and Samotino More types (Figure 8).

The opportunities for hydrocarbon generation are estimated for all main sedimentary basins in the WBSZ (Figures 7, 9 & 10).

The oil accumulations in the Histria basin are related to the Oligocene source (Figure 11a). The likeliest sources of the Valanginian oil accumulation in the Tyulenovo field are the Provadia Fm (J_3) and the upper part of Etropole Formation (J_2), in the East-Varna trough (Figures 11b & 13b). The good genetic correlation of the Samotino More condensate in the Kamchia basin with source intervals in the basin basement (Dvoynitsa Formation, Lower Eocene and Byala Formation, Paleocene–Upper Cretaceous) deserves special consideration. The origin of the Olimpiyski oil type remains obscure.

Three main hydrocarbon systems with economic potential are recognised. They relate to: the WBSB with its two western branches, the East-Varna trough and the Burgas basin. Conceptual models for the hydrocarbon systems and their exploration trends are constructed (Figures 12 & 13).

Major hydrocarbon accumulation zones in the WBSB hydrocarbon system are: the southern flexural slope of the Scythian Platform; the northern slope of the Histria sub-basin; the East Moesian marginal fault zone and the Polshkov ridge; the northern and the southern slopes of the Kamchia sub-basin and the tilted blocks in the Ropotamo-Limankoy trend of the Rezovo segment.

The main accumulation zone in the East Varna trough hydrocarbon system is related to narrow horst blocks, separating the three wrench basins, where the Upper Jurassic–Valanginian carbonates and the Lower Triassic clastics can be the main exploration targets.

In the Bourgas basin hydrocarbon system some positive swell-like structures in the western basin slope as well as the elevated Rezovo trend (horst) are promising hydrocarbon entrapment zones.

Among all defined exploration trends, those related to the transition zone between the Moesian Platform and the WBSB as well a those related to the southern edge of the Scythian Platform are of the highest potential. The main risk factor is the presence of good reservoirs and more volumetric traps.

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