Prospect evaluation based on integrated petroleum system analysis: Block E case study, south-eastern edge of Precaspian Basin (Kazakhstan)

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Abstract

Generative potential and thermal maturity for Upper Palaeozoic source rocks from the south-eastern edge of Precaspian Basin were determined using Rock–Eval. A high hydrocarbon source rock generative potential and high degree of thermal maturity for the Lower Permian, Mid-Carboniferous strata have been revealed based on 39 rock samples. TOC values of 0.4–5.5% have been obtained for mature source rocks. Integrated geochemical analysis determined from Rock–Eval studies combined with 1D basin modelling was utilized in order to reconstruct thermal evolution for the Upper Palaeozoic source rocks. Calibrated 1D models for three wells had been constructed to understand petroleum system. For two deep exploration wells (Nur-1 and Tassym SE-1), which penetrated pre-salt strata at the depths of 5.7 and 7 km, respectively, the impact of salt diapirism on timing of maturation was modelled. Type II kerogen was used, which is based on previous palaeogeographic studies. The stratigraphic framework and major stages of geodynamic evolution were analysed. Salt-related structural traps in post-salt strata have been described based on 3D seismic data, and additional intra-salt sediment packages have been delineated. Discovered producing oil fields in the Upper Triassic and Jurassic–Cretaceous stratigraphic sections are mainly confined to the four-way dip structural closures above the steep flanks of salt structures. Based on burial and thermal modelling, the maturation and generation behaviour of kerogen Type II below salt-related minibasins and close to thick salt diapirs were inferred. For Lower Permian SR with type II kerogen, the generation peak (maturity over 50%) occurs in Middle to Late Jurassic. For predominantly carbonate and terrigenous-carbonate Mid-Carboniferous marine SR, generation peak occurs earlier below salt withdrawal minibasins. Implications for deeper hydrocarbon prospectivity were made for the study area, and methodology for evaluating hydrocarbon potential adopting 1D basin modelling technique and geochemical data is presented.

Keywords Precaspian Basin · Hydrocarbon prospectivity · Salt · Source rock maturation · Thermal modelling

Introduction

The Precaspian Basin (PCB) is one of the world's largest hydrocarbon provinces; it is a deep (over 20 km) salt-dominated continental margin basin located mostly in Kazakhstan with the western and north-western edges extending to Russia (Fig. 1).

In PCB, there are several proven conventional plays: Jurassic and Cretaceous clastics, Permian–Triassic minibasins in salt-related structural traps, pre-salt Permian and

Carboniferous isolated carbonate platform reefs and shoals. The evaporitic sequences and salt diapirism control the evolution of petroleum system and thermal regime of sedimentary basins (Hudec and Jackson 2007, Jackson and Hudec 2017; Peel et al. 2014; Cedeno et al. 2019). Salt acts as an effective seal for largest Precaspian pre-salt oilfields, and salt evacuation leads to minibasin welding, through which generated hydrocarbons can migrate vertically from pre-salt source rocks (Rowan et al. 2012).

Exploration in PCB started in the early part of the twentieth century; the majority of presently producing oil fields had been discovered within post-salt shallow Jurassic and Cretaceous clastic reservoirs by 1970. Further supergiant and giant pre-salt discoveries were made in the 1970s to early 1980 s and included Tengiz, Karachaganak, Zhanazhol.

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Fig. 1 Location map of the Precaspian basin and the study area in the south-eastern edge of Precaspian Basin (a). The base map of the studied well locations in the Block E (b)

The supergiant Kashagan carbonate field was discovered in 2000 (Ronchi et al. 2010).

Despite the long exploration and production history, the Precaspian petroleum system remains poorly understood; it is generally accepted that Upper Devonian to Lower Permian source rocks charge the pre-salt and post-salt reservoirs. Devonian source rocks are poorly known as only a few wells on the northern and eastern edges have penetrated these sediments (Pairazian 1999; Barde et al. 2002).

The discovery of super giant fields in the pre-salt complex of Precaspian Basin in the 1970s and policy reforms in the early 1990s led to a suspension in exploration activities for the post-salt complex and shifting the hydrocarbon exploration focus to the pre-salt Palaeozoic strata (Akhmetshina 1993; Volozh and Antipov 2003; Akhmetkalieva and Shestoperova 2011). Significant upside hydrocarbon potential is associated with the deep pre-salt Palaeozoic complex of the Precaspian Basin (Belopolsky and Talwani 2007; Abilkhasimov 2016; Zholtayev et al. 2018; Abishev and Kassenov 2016). Most recent exploration shifted back to post-salt Permian–Triassic and Jurassic–Cretaceous reservoirs (Okere and Toothill 2012).

3D seismic surveys acquired in Block E during 2007–2013 have resulted in numerous commercial oil

discoveries within the shallow Upper Triassic and Jurassic–Cretaceous sandstones in the south-eastern edge of PCB indicating that the post-salt complexes have not been adequately studied and that new oil fields may be discovered.

This study aims to better understand generative potential and thermal evolution of Upper Palaeozoic source rocks, timing of hydrocarbon generation based on 1D basin modelling. Seismostratigraphic and geochemical analysis was carried out, and thermal maturity of potential source rocks had been described based on Rock–Eval pyrolysis.

Qualitative evaluation of hydrocarbon potential for the pre-salt, salt and post-salt complexes is of great theoretical and practical importance and is a challenging task at the same time. Sparse exploration data and results of 3D seismic interpretation at Block E were used in order to understand the Precaspian petroleum system and identify exploration opportunities.

The main stages of the geodynamic evolution of the study area were analysed based on the published literature (Zonsenshein et al. 1990; Khain 2000; Brunet et al. 1999; Volozh et al. 2003; Shein et al. 2020), and thermal history was reconstructed. The results of thermal modelling confirm the possibility of vertical migration of hydrocarbons generated in pre-salt source rocks. A revision of the 3D seismic data

interpretation has been carried out, and for the first time, intrasalt sedimentary packets of presumably Upper Permian age have been identified as independent objects, which can be potential hydrocarbon traps in the intra-salt play and that have been previously overlooked.

Geological setting

The geological history of the PCB is well described in numerous works (Zonenshein et al. 1990; Dalyan and Bulekbayev 1993; Khain 2000; Nikishin et al. 1996; Pairazian 1999; Volozh et al. 2003; Zholtayev 2003; Zuza and Yin 2017).

The Block E study area (9300 km²) is tectonically located within the Guryevsky height of the south-eastern part of the Precaspian Basin (Western Kazakhstan). The area also features a complex history of geological development and salt tectonics (Fig. 1).

More than 30 small oilfields have been explored in the Mesozoic post-salt complex at Block E. Oil deposits are four-way dip structural closures, mainly confined to the crestal parts of the salt domes (Fig. 2). No hydrocarbon accumulations have been identified in the inter-dome depressions yet. Cretaceous, Jurassic and Upper Triassic strata have been penetrated, logged and cored by numerous dedicated exploration and production wells and carefully characterized (Dalyan et al. 1993; Kukhtinov and Crasquin-Soleau, 1999; Barde et al. 2002; Zholtayev et al. 2019; Akhmetzh-anov et al. 2020).

Three deep exploration wells were drilled within and close to the boundaries of the study area of the Guryevsky height (Fig. 1). Two of them, Akatkol P-3 (1990) and Tassym Southeast-1 (2010), yielded representative Upper Palaeozoic rock samples which were further analysed by Rock–Eval 6 in the present study (Table 2). All wells drilled in the studied area display similar lithostratigraphy (Fig. 3), most of the wells targeted the hydrocarbon production from the shallow Upper Triassic and Middle Jurassic reservoirs, and only 3 deep exploration wells drilled to the Upper Palaeozoic section (Fig. 1).

The Akatkol P-3 exploration well penetrated the 150-m-thick Asselian–Sakmarian sediments and was drilled to the total depth of 6455 m (Kukhtinov et al. 1999; Pronin 2009). According to well logging data and laboratory core analysis, the Lower Permian sediments are lithologically thin-layered mudstones interbedded with silts, tuffs, limestones with conodonts of Gzhelian–Asselian age. Limestones are dolomitized with radiolarian fossils, sponge spicules and small foraminifers *Hyperamminoides samarensis*, *Glomospira pusilla*, *G. elegans*, *Globivalvulina bulloides*, *Geinitzina spandeli*, *G. minima* of Artinskian age (Kukhtinov et al. 1999). On a drill stem test in the 6455–6372-m

Fig. 2 Structure map of the Top of Kungurian salt (seismic reflector VI) based on geological and seismic surveys, salt domes feature prominently as diapir belts or isolated salt bodies. Exploration wells penetrated pre-salt strata: Nur-1, Akatkol P-3, Tassym Southeast-1; appraisal wells for the post-salt producing petroleum play completed in Upper Triassic to Cretaceous strata: ASK-1, Bor-1, KZIE-1, SAGW-4, BCHW-1, ZMA-12. Dashed line representing areas covered by depth–migrated 3D seismic reflection survey

interval, gas was yielded with 4.6m³/day flow rate under more than 8.5 MPa pressure drawdown.

The Nur-1 deep exploration well (2011) at Block E was drilled in centre of partially welded minibasin (Figs. 2, 4, 5). The targeted Devonian reservoirs were not reached due to the multiple differential drill string struck, and the well was abandoned near the top of the Kungurian salt at a depth of 5721.5 m. Real-time mud gas monitoring detected hydrocarbons shows increasing with depth for Jurassic (at 1300–1520 MD) and Permian–Triassic strata (at 3650, 4200, 4500, 4900 MD).

According to the logging interpretation results of Tassym Southeast-1 drilled in a neighbouring area (Fig. 2), the well penetrated hydrocarbon-bearing Lower Permian and Carboniferous carbonate–terrigenous reservoirs.

In this study, the authors conducted an integrated evaluation of the generative potential of the Upper Palaeozoic source rocks within Block E, constructed 1D basin models using available pyrolysis data and reconstructed the burial and thermal histories based on the major geodynamic stages

Fig. 3 Generalized stratigraphy in the Block E of Guryevsky height, southeastern edge of Precaspian Basin (adopted from Votsalevsky et al. 2000; Barde et al. 2002). Tectonic history is based on palaeogeographic reconstructions (Volozh et al. 2003; Shein et al. 2020)

Fig. 4 Uninterpreted (a) and interpreted (b) South-North seismic cross-section illustrating salt diapirs with the associated thick inter-dome minibasins. Salt complex is severely deformed due to halokinesis, according to Fernandes и Duffy (2017) analogue intrasalt sediment packages can be defined. Low amplitude normal faults confined to the crests of salt domes and related to the later salt tectonics. The salt domes have steeply dipping flanks. Pre-salt complex is uncomfortably overlain by Permian–Triassic sequences. The major angular unconformity at the base Jurassic (seismic reflector V) can be

observed, the basin-wide seismic horizon V is well traced across the study area. Asanketken oil field is structural trap in Jurassic section located above the steep slope of the salt Asanketken dome. The piercing salt dome has northwest strike (Fig. 2). The Nur-1 well has penetrated the bottom of Permian–Triassic strata, in the pre-salt complex at the level of seismic reflector P_{2d} (the presumed top of the Lower–Middle Devonian) and P₂¹ (top of Upper Devonian) stratigraphic traps can be delineated

of the PCB evolution (Shein et al. 2020). Palaeozoic source rocks had been evaluated, and implications for improving hydrocarbon prospectivity for intrasalt and pre-salt complexes were provided based on petroleum system elements and processes (Hood et al. 2002; Dembicki 2017).

Taking into account difficult drilling conditions in salt and pre-salt stratigraphic intervals and deep levels (more than 5–6 km) of possible hydrocarbon plays, comprehensive analysis of petroleum system elements with basin modelling techniques will enable reducing exploration risks.

Fig. 5 West–East uninterpreted (a) and interpreted (b) Nur-1 well seismic cross-section, annotated with major seismic horizons and illustrating poorly defined buried salt swells with the encased sediment packages of presumably Upper Permian age. The top of the salt structures can be picked at the depths of about 2250–3000 m. The

outlines of the salt domes are not clearly defined on seismic and have steeply dipping flanks. In the post-salt complex low amplitude normal faults identified. In the pre-salt complex multiple onlapping/downlapping and truncation reflections can be interpreted

Tectonostratigraphic framework

Three main seismic reflectors have been identified in the Palaeozoic sedimentary succession based on regional geological and geophysical surveys of the PCB. The P_1 horizon corresponds to the bottom of Kungurian sediments, the P_2 horizon corresponds to the surface of the Middle Carboniferous unconformity, and the deepest P_3 horizon, which has been penetrated by several wells and is not precisely dated, could represent the Lower to Upper Devonian (Brunet et al. 1999; Volozh et al. 2003).

Acquisition of 3D seismic surveys (2007–2010) at the study area provided new information on the deep structure

up to 8 km depth (Fig. 2). In the Mesozoic stratigraphic interval, principal seismic reflector III (base of Cretaceous sediments), V (unconformity at the base Jurassic), VI (top of salt) were mapped (Fig. 4 through 7). Seismic reflector IV in the Jurassic section cannot be defined; internal unconformities within the Permian–Triassic sequences can be locally traced (Barde et al. 2002; Kukhtinov and Crasquin-Soleau 1999).

The thick Kungurian diapiric salt section contains internal anhydrites, shales, carbonates, initial thickness of salts estimated as 1000–2000 m within the study area (Akhmetzhanov et al. 2020). Salt tectonics has led to the

formation of numerous salt diapir belts of varying lengths and associated post-salt minibasins (Figs. 2, 4 through 7).

The seismic reflector V (Fig. 2) shows that salt diapirs predominate in the north-eastern part of Block E, with the buried deep-seated salt domes predominating in the south. The extension of diapir belts is predominantly submeridional. The discovered shallow hydrocarbon accumulation in

the Block E (Asanketken and Kyzylzhar-I East oil fields) is structural fault-bounded oil traps that overly the crest of the salt diapirs (Figs. 4, 6).

In general, the salt interface dips gradually or through ledges towards their peripheral areas. In some cases, the steeply dipping flanks of the isolated salt domes or diapir belts have secondary minor salt swells, overlaid by

Fig. 6 Uninterpreted (a) and interpreted (b) KZIE-1 well seismic cross-section (Kyzylzhar I East field area), bowl-shaped minibasin encased in the salt can be delineated. In the post-salt strata low amplitude normal faults confined to the crest of the buried salt domes. In the pre-salt complex multiple onlapping/downlapping and truncation reflections can be interpreted. The outlines of the buried domes are not clearly defined and have gentle slopes. Structural trap of Kyzylzhar I East oil field in Lower Cretaceous and Middle Jurassic reservoirs abutting the crestal part the buried salt dome

Fig. 7 Uninterpreted (a) and interpreted (b) seismic cross-section (Akatkol area). Orange colour indicates the top of Kungurian salt (P_{1k}), the apical parts of the salt diapirs are at the depths of 200–670 m. Intracrust sediment packages deeply rooted in the salt domes.

petroleum traps (Fig. 4). Thus, the halokinesis during the Permian–Triassic has led to the formation of inter-dome minibasins with different sedimentary fill and geometry.

Based on interpretation large 3D seismic data sets intrasalt bodies can be delineated, they are similar to «intrasalt sediment packages» and «encased minibasins» (Fernandez and Duffy 2017; Jackson et al. 2020) in Zharkamys West 1 block (eastern edge of PCB). The mechanism of encasement

In the pre-salt complex major reflective horizons can be interpreted: P_1 (bottom of the salt layer), P_{2C} (top of Middle Carboniferous strata), reflectors P_{2I}^1 (top of Upper Devonian) and P_{2d} (presumably top of the Lower–Middle Devonian)

of minibasins is considered to be density driven; most likely the encased minibasins formed above salt and later were encased (Duffy et al. 2017).

Intrasalt sedimentary bodies are widespread in salt basins around the world and have different mechanisms of their formation. They can form both symsedimentary with salts and after salt deposition. Understanding the origin and evolution of intrasalt inclusions may indicate important stages

in the geodynamic evolution of a particular tectonic region. In addition, prediction the lithology and facies composition for these formations is necessary when planning exploration drilling.

The 3D seismic data interpretation results from Block E were reviewed, and intrasalt sedimentary packages were identified; they are of two major sets, encased minibasins and tabular packages of presumably Upper Permian age, which occur locally and do not have a wide area distribution (Figs. 4, 5, 6, 7). These formations in Block E have not been penetrated by boreholes. The hydrocarbon prospectivity of these formations has been proved by exploration drilling in Zharkamys West-1 analogue area (Fernandes et al. 2017; Jackson 2020).

Discovered and proved Kyzylzhar I East (Fig. 6) oil field abutting the crestal part of the salt dome with encased minibasin may also indicate the high probability of vertical HC migration from the palaeozoic source rocks and possible sedimentary minibasin trap filled with migrated hydrocarbons (Fig. 6).

In the Akatkol area, the quality of seismic data does not allow identifying the intrasalt inclusions; however, at the bottom of salt domes some turtle structures can be delineated interfacing with the P₁ seismic reflector (Fig. 7).

Data and methods

Source rock evaluation

The Late Devonian and Lower Carboniferous source rocks with Type II kerogen are considered major hydrocarbon kitchen for pre-salt reservoirs (Ulmishek 2001; Barde et al. 2002). Early Carboniferous organic deep water organic-rich shales interface with carbonates (Barde et al. 2002). Average TOC values 2–3.5% are documented for the sediments over Tengiz carbonate platform (Pairazian 1999). Lower Permian pre-salt sedimentary successions contain Type II organic matter with TOC up to 2.5% (Yensepbayev et al. 2009; Pairazian 1999). Most authors agree that post-salt reservoirs are charged by pre-salt Upper palaeozoic source rocks.

Recent biomarker studies and geochemical correlations between oils, reservoirs and source rocks in the eastern and southern edges of the PCB have linked Palaeozoic source rocks with the post-salt Precaspian petroleum system (Guryey Warner et al. 2007; Yensepbayev et al. 2009, 2002; Peters et al. 2005), indicating an important role for primary vertical migration from pre-salt to post-salt strata via welded regions. Despite the long-term study into the structure and formation of PCB salt structures, questions related to the mechanisms and pathways of hydrocarbon migration and accumulation in the post-salt complex remain debatable.

In Yensepbayev et al. (2009), earlier study based on Rock–Eval pyrolysis and molecular analysis of a large number of source rock samples from the Eastern Precaspian and Pre-Uralian Basins (Republic of Kazakhstan) determined the following, Early and Mid-Carboniferous source rocks are dominated by algal kerogen Type II, while the mixed kerogen Type II/III is established for predominantly marine siliciclastic Early Permian source rocks. The identified feature is presumably linked to the increasing of collisional processes during the Early Permian and contribution of terrestrial plants.

To evaluate the generative potential and degree of thermal of Upper Palaeozoic strata, Rock–Eval pyrolysis study for 39 rock samples from deep exploration wells of the Guryevsky height was analysed (Figs. 1, 2, 3, Table 2). The rock samples from Tassym SE-1 were analysed using Rock–Eval 6 instrument in the Laboratory of Tomsk Polytechnic University (Tomsk, Russia). For other rock samples, the Rock–Eval results are borrowed from unpublished sources. Thermal maturity of the organic matter inferred from TOC, S₂, HI, PI, T_{max} values.

Model building

Petromod 2018 was used to reconstruct burial and thermal history of the study area; for the deep wells NUR-1 and Tassym South East-1 with TD in Upper Palaeozoic intervals, 1D models were implemented; for the shallow Asanketken-1 well with TD in Permian–Triassic 1D thermal modelling was done in order to estimate scenario for a possible Jurassic source rocks.

Basin modelling techniques integrate conceptual and a priori geological and geophysical information to numerically reproduce subsidence history and thermal evolution of sedimentary sequences. The stratigraphy and lithology model of the Nur-1 well is based on seismic, logging data and cuttings lithological description (Fig. 3, Table 1). Stratigraphic subdivision for modelled wells is based on detailed correlation with reference wells. The Palaeozoic section of the Nur-1 well is modelled by analogy with the penetrated Palaeozoic stratigraphic interval of the Akatkol P-3 and Tassym South-east-1 wells (Fig. 4). The established thermal gradient in the Nur-1 well is 12 °C/km. The 100 °C isotherm is observed at a depth of 4 km in NUR-1 well and at a depth of 5 km in Tassym South-East-1 well (Fig. 8). That is associated with salt structures which control spatial thermal regime (Chekhonin et al. 2020).

The major stages of tectonic evolution used in basin modelling were updated following the latest regional palaeogeographic reconstructions of the East European palaeocontinent for a more reliable prediction of the kerogen thermal evolution (Volozh et al. 2003; Shein et al. 2020).

Table 1 Summary of Input data used for 1D modelling studies by Petromod software (version 2018)

Formation	Age (Ma)		Lithology	Petroleum system element	TOC (wt%)	HI (mg HC/g TOC)	Kinetics
	From	To					
Q-Tertiary	10	0	Sandstone (clay rich)	Reservoir Rock			
Upper Cretaceous	85	65	Sandstone (clay rich)	Reservoir Rock			
Lower Cretaceous	95	85	Sandstone (typical)	Reservoir Rock			
Upper Jurassic	170	135	Limestone (shaly)	Seal			
Middle Jurassic	200	170	Sandstone (arkose, clay rich)	Reservoir Rock			
Lower Juassic	210	200	Sandstone (arkose, clay rich)	Reservoir Rock			
Upper Permian–Triassic	245	240	Sandstone (wacke)	Reservoir Rock			
SALT (Kungurian P1k)	270	260	Salt	Seal			
Lower Permian (P1a–P1ar)	300	277	Limestone, Shale	Source Rock	2	150	Tegelaar(1994)_TII(NorthDakota)
Upper-Middle Carboniferous	310	290	Limestone, Shale	Reservoir Rock			
Lower Carboniferous	345	315	Limestone, Shale	Source Rock	2	250	Tegelaar(1994)_TII(NorthDakota)
Upper Devonian (D3)	380	355	Limestone, Shale	Reservoir Rock			
Lower-Middle Devonian (D1–D2)	400	390	Limestone, Shale	Source Rock	5	250	Tegelaar(1994)_TII(NorthDakota)

Fig. 8 Calibration of the modelled thermal profile against RCI™ tool bottom-hole temperature

The sediment–water interface temperatures were automatically calculated from palaeo-water depths established by Brunet et al. 1999. The calibration of heat flow was done against the measured borehole temperatures by the RCI™ tool from Baker Hughes (Reservoir Characterization Instrument™). The good calibration was obtained by setting the heat flow to 50–55 mwatts/m² from Early Palaeozoic to Late Carboniferous; additionally salt tectonics and piercing Petromod functionality was adopted in order to simulate salt

withdrawal as it severely effects spatial and temporal thermal regime (Fig. 9).

Vitrinite reflectance was simulated using Petromod kinetics (Sweeny and Burnham, 1990). The simulated EASY5Ro for the Upper Palaeozoic source rocks is correlated with the measured vitrinite reflectance values (Ro = 0.8–1.2%) at the

Fig. 9 Diagram of burial and thermal history modelling for Nur-1, Tassym SE-1 and Asan-ketken-1 wells based on tectonic setting analysis. Major phases of tectonic evolution: 1–Progressive subsidence for Eastern European Craton (EEC), marine transgression; 2–Central Precaspian rift opening; 3–Uplifting following collision of EEC, Kazakhstan block and Turan microcontinent; 4–Closure of the Uralian Ocean, deposition of the pervasive thick salt layer, formation of Precaspian Basin orogenic belt; 5–Salt tectonics due to high sedimentation rates; 6–Regional isostatic equilibrium processes between tectonic elements, shallow marine depositional environment; 7–Extension of marine transgression due to collision processes in Caucasus, reactivating of salt tectonics

depths of 7 km for the Lower Permian and Carboniferous source rocks (Shestoperova and Pronin 2011).

The detailed information on the stratigraphy, lithological composition and geochemical characteristics is given in Table 2. The lithostratigraphy is based on exploration

drilling results and 3D seismostratigraphy of the study area (Figs. 3, 4, 5).

Table 2 Determined by Rock–Eval pyrolysis geochemical parameters for the Lower Permian and Middle Carboniferous source rocks from deep exploration wells, Block E

Formation	Well	Depth (tvdss)	Lithology	TOC (%)	Tmax	HI	S1	S2	S3	ROC/TOC	PI	OI
Middle Jurassic J ₂	Botakhan (Karsak West field)	1150	Siltstone	4.86	430	113	0.36	5.5	2.83		0.06	58
P ₁ a	Akatkol-P3	6188–6192	Calcareous shale	0.92	435	275	2.48	2.53	0.29		0.50	31
C ₂ m	Akatkol-P3	6345–6356	Limestone	1.8	442	56	1.69	1.02	0.19		0.62	10
Middle Jurassic J ₂	Tassym-14	3095–3102	Calcareous shale	1	439	102	0.05	1.02	0.09		0.05	9
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6295	Calcareous shale	0.86	426	116	0.15	1	4.75	0.67	0.13	552
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6301	Limestone	1.95	427	89	0.31	1.74	4.25	0.82	0.15	218
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6321	Dolomite	9.98	427	96	1.42	9.59	48.68	0.76	0.13	488
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6323	Calcareous shale	13.54	426	86	1.11	11.63	56.08	0.79	0.09	414
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6331	Calcareous shale	8.9	427	70	0.32	6.27	11.59	0.88	0.05	130
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6363	Calcareous shale	0.65	369	128	0.23	0.83	3.08	0.69	0.22	474
P ₁ -C ₂	Tassym SE-1	6711	Calcareous shale	0.94	353	103	0.27	0.97	5.05	0.69	0.22	537
P ₁ -C ₂	Tassym SE-1	6733	Calcareous shale	1.32	357	87	0.3	1.15	5.69	0.75	0.21	431
P ₁ -C ₂	Tassym SE-1	6791	Calcareous shale	1.46	386	57	0.24	0.83	4.83	0.79	0.22	331
P ₁ -C ₂	Tassym SE-1	6803	Dolomite	1.76	409	308	1.12	5.42	8.85	0.45	0.17	503
P ₁ -C ₂	Tassym SE-1	6805	Dolomite, limestone	1.08	350	136	0.41	1.47	8.94	0.50	0.22	828
P ₁ -C ₂	Tassym SE-1	6851	Limestone	1.76	350	48	0.46	0.84	2.5	0.88	0.35	142
P ₁ -C ₂	Tassym SE-1	6853	Limestone	1.3	369	74	0.5	0.96	1.99	0.83	0.34	153
P ₁ -C ₂	Tassym SE-1	6873	Limestone	2.24	323	38	0.38	0.85	4.42	0.89	0.31	197
P ₁ -C ₂	Tassym SE-1	6938	Calcareous shale	1.34	344	57	0.42	0.77	4.14	0.81	0.35	309
P ₁ -C ₂	Tassym SE-1	6939	Dolomite	2.17	390	35	0.36	0.76	10.29	0.80	0.32	474
P ₁ -C ₂	Tassym SE-1	6952	Calcareous shale	5.11	421	81	0.89	4.15	6.46	0.86	0.18	126
P ₁ -C ₂	Tassym SE-1	6977	Limestone	1.52	325	66	0.43	1.01	1.13	0.88	0.30	74
P ₁ -C ₂	Tassym SE-1	7039	Limestone	5.3	459	11	0.53	0.58	4.29	0.96	0.48	81
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6379	Calcareous shale	0.45	521	44	0.11	0.2	10.6	0.93	0.36	38
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6381	Calcareous shale	0.59	608	22	0.06	0.13	20.2	0.97	0.30	24
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6386	Calcareous shale	0.69	605	30	0.13	0.21	20.6	0.94	0.38	23
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6394	Calcareous shale	0.56	531	32	0.09	0.18	15.9	0.95	0.35	20
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6404	Calcareous shale	0.4	418	28	0.11	0.11	5.1	0.93	0.49	38
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6411	Calcareous shale	0.8	591	20	0.12	0.16	5.6	0.96	0.43	24
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6419	Calcareous shale	0.4	409	28	0.09	0.11	3.4	0.93	0.46	32
P ₁ a-P ₁ ar (Asselian–Artinskian)	Tassym SE-1	6423	Calcareous shale	0.15	417	47	0.03	0.07	2.4	0.93	0.32	47
P ₁ -C ₂	Tassym SE-1	6802	Calcareous shale	5.49	470	23	0.53	1.27	13	0.97	0.29	11
P ₁ -C ₂	Tassym SE-1	6805	Calcareous shale	1.79	471	22	0.18	0.4	7	0.96	0.31	19
P ₁ -C ₂	Tassym SE-1	6814	Calcareous shale	2.36	478	32	0.56	0.75	9	0.94	0.43	19
P ₁ -C ₂	Tassym SE-1	6818	Calcareous shale	0.85	473	38	0.2	0.32	7.9	0.94	0.38	24
P ₁ -C ₂	Tassym SE-1	6826	Calcareous shale	0.89	473	37	0.18	0.33	5.8	0.93	0.36	19

Table 2 (continued)

Formation	Well	Depth (tvdss)	Lithology	TOC (%)	Tmax	HI	S1	S2	S3	ROC/TOC	PI	OI
P ₁ –C ₂	Tassym SE-1	6829	Calcareous shale	1.53	477	27	0.33	0.42	10.6	0.95	0.44	22
P ₁ –C ₂	Tassym SE-1	7043	Limestone	2.17	465	26	0.46	0.56	3.1	0.95	0.45	9
P ₁ –C ₂	Tassym SE-1	7044	Limestone	2.83	510	32	0.53	0.9	3.6	0.95	0.37	9

TOC: total organic carbon (%), S1 peak: free hydrocarbons, at 300 °C (mg HC/g rock), S2 peak: heavy HC compounds, at 300–650 °C (mg HC/g rock), HI: hydrogen index, (100*S2)/TOC (mg HC/g TOC), OI: oxygen index, (100*S3)/TOC (mg HC/g TOC), S3: the amount of CO₂ (mg CO₂/g rock), Tmax: temperature at which the maximum release of HC from cracking of kerogen occurs, top of S2 peak (°C), PI: Production index, S1/(S1+S2), ROC, residual organic carbon content. Rock samples from Tassym SE-1 well were analysed using Rock-Eval 6 instrument

Results and interpretation

Burial history

Effective re-exploration of the petroleum province requires considering the processes of hydrocarbon generation, expulsion and migration within a sedimentary basin from the geodynamic evolution perspective.

Palaeotectonic reconstructions indicate that the PCB origin and evolution are related to the spreading between the East European and Kazakhstan tectonic plates followed by formation of the Atlantic-type continental margin Uralian palaeocean by the end of Ordovician (Zonenshain et al. 1990; Khain 2000).

The thick carbonate–terrigenous succession of passive continental margin of the Precambrian East European plate was deposited during Late Devonian–Carboniferous. The subsequent collision of the Eastern European and Kazakh continents in the Late Palaeozoic led to the formation of the Ural-Tien-Shan orogenic belt. Numerous concepts of geodynamic evolution were developed by various researchers worldwide during many years of study into the tectonic evolution of the East European craton (Zonenshain et al. 1990; Nikishin et al. 1996; Khain 2000; Brunet et al. 1999, 2007; Volozh et al. 2003; Zuza and Yin 2017; Shein et al. 2020).

The authors of this study adhere to the concept of East European continental margin revitalizing in Precaspian depression in the Middle Devonian (Fig. 9).

The tectonic evolution and depositional setting within Block E area were established based on the comparison with the regional palaeogeodynamic and palaeogeographic reconstructions of the East European Platform during the Riphean-Cenozoic period (Shein et al. 2020; Volozh et al. 2003; Brunet et al. 1999; Atlas of the Lithology-Palaeogeographical, Structural, Palinspastic and Geoenvironmental Maps of Central Eurasia 2002).

The Middle Devonian was marked by a major gradual transgression due to the subsidence of the East European continent, lasting until the end of the Tournaisian. The opening of the Central Precaspian rift in the Late Devonian–Early Carboniferous led to the formation of the Uralic palaeocean gulf, along the continental passive margin the sedimentation of thick carbonate–terrigenous successions occurred, favourable for petroleum generation and petroleum accumulation. Thus, potential source rocks of the Devonian–Lower Permian, partially penetrated by the wells at Block E, have a high generation potential.

The collision of Kazakh continent and the margin of the East European palaeocontinent progressed throughout the Visean age. The rising of the Ural Mountains served as a source of clastic sediments. The Early Permian collision of the East European plate with the Kazakh continent and

the Turan microcontinent accelerated the uplift of the Precaspian depression and led to the beginning of strong salt accumulation compared to the northern regions of the East European palaeocontinent, where a shallow palaeobasin of increased salinity continued to exist and deposition of dolomite silt, gypsum and salt took place (Shein et al. 2020). By the beginning of the Kungurian age, the formation of the PCB margins with folded belts had been completed. By the end of the Kungurian age, the Uralic palaeocean had completely closed, contributing to the formation of the regional salt sequence. There was a significant shift in sedimentation towards lagoon-continental conditions after a hiatus in sedimentation during the Late Permian age. In the Late Permian–Early Triassic period, the territory of the Precaspian depression was an area of erosion, periodically flooded by the sea. The Late Triassic to Cenozoic was dominated by isostasy and partitioning of previously formed structures into blocks with the formation of vertical faults that may have served as migration pathways for hydrocarbons from previously formed deposits in the Palaeozoic sediments (Zhenyuan et al. 2015). During the Jurassic times, the Precaspian palaeobasin was dominated by a marine depositional environment (Atlas of the Lithology-Palaeogeographical, Structural, Palinspastic and Geoenvironmental Maps of Central Eurasia 2002); the expansion of marine transgression during the Late Cretaceous is related to plates collision in the Caucasus region (Shein et al. 2020). The described above geodynamic stages had been incorporated during burial and thermal modelling (Fig. 9).

Thermal maturity

Interpretation of pyrolysis studies of potential Middle Carboniferous–Lower Permian source rocks of Block E revealed the following geochemical characteristics (Fig. 10). The Rock–Eval Tmax values and corresponding sample depths, lithology and ROC parameters are listed in Table 2. As shown in Fig. 10, thermal maturity of Lower Permian and Mid-Carboniferous rock samples is varying from immature to overmature.

The Lower Permian Asselian–Artinskian carbonate–terigenous sediments have fair to good generative potential in terms of S1 + S2 ratios and TOC content (Fig. 10). Some source rock samples from Tassym SE-1 well can be interpreted to contain type II kerogen, high values of ROC/TOC ratio indicating that source rocks might have generated hydrocarbons.

The degree of maturation of Lower Permian source rock samples is represented by Tmax values ranging from 410⁰ to 450⁰C, corresponding to the oil zone (Fig. 10, Table 2). For the Akatkol area, the Tmax values correspond to the onset of the oil window. The thermal evolution modelling results for the Block E wells complement the conclusions on kerogen maturity from pyrolysis study; there is a trend of gradual increasing of thermal maturity with depth (Fig. 12).

Thick intervals of Kungurian salt has significantly influenced the spatial thermal regime in the study area and lowered the oil window near salt structures. Maturity modelling results are shown in Figs. 11, 12.

Fig. 10 Plot of TOC versus S1 + S2 for generative potential justification: I—poor, II—fair, III—good, IV—very good, V—excellent (a). The kerogen maturity diagram (b) (Hunt 1996). TOC: Total organic carbon (%). S1 peak: Free hydrocarbons, at 300°C (mg HC/g rock). S2 peak:

heavy HC compounds, at 300–650 °C (mg HC/g rock). HI: hydrogen index, (100*S2)/TOC (mg HC/g TOC). Tmax: Temperature at which the maximum release of HC from cracking of kerogen occurs, top of S2 peak (OC.) PI: Production index, S1/ (S1 + S2)

Fig. 11 Simulated burial and thermal history for Nur-1 (a) and Tassym SE-1 (b) exploration wells for potential Upper Palaeozoic source rocks, showing hydrocarbon zones based on Sweeney and Burnham (1990) EasyRo%

Fig. 12 Modelled generation behaviour of the source rocks through time using Type II kerogen kinetic model for Nur-1 (a) and Tassym SE-1 (b) deep exploration wells. Maturation gradually increases with depth (b)

Thermal modelling

The integrated geological, geophysical and geochemical data on Block E are used for constructing 1D basin models of thermal evolution for the wells that reached Jurassic and Upper Triassic productive horizons at Block E; 1D basin modelling of multiple scenarios confirmed that the possible Jurassic and Upper Triassic source rocks did not enter the oil window zone. According to borehole temperature data, the average isotherm at the level of the Jurassic and Upper Triassic oil reservoirs is 44–55 °C at Nur-1 well. The model is calibrated to borehole temperature data from Nur-1 well; the discrepancy is less than 5% (Fig. 8).

1D thermal history modelling and calculated vitrinite reflectance (*EasyRo*%) using Sweeney and Burnham (1990) algorithm for Nur-1 and Tassym SE-1 wells potential Upper Devonian, Mid-Carboniferous and Lower Permian Asselian–Artinskian source rocks indicate that the source rocks were entering the main oil zone (0.7–1%*R*_o) progressively from Triassic to Early Jurassic. Lower Permian SR are predominantly in the late oil generation zone (Fig. 11).

The Middle Carboniferous source rocks with predominant type II kerogen (Yensepbayev et al. 2009; Gurgey 2002; Ulmishek 2001) entered the main oil zone during the Late Triassic and Jurassic and may have been a source of HC for Mesozoic structural traps formed due to salt tectonics. The deepest Devonian source rocks are predominantly in the zone of wet gas generation (1.3–2%*R*_o).

Based on burial and thermal regime modelling, the maturation and generation behaviour of kerogen types II occurred differently below salt-related minibasins (Figs. 3, 11). For Lower Permian SR with type II kerogen, the generation peak (maturity over 50%) occurs in Middle to Late Jurassic. For predominantly carbonate and terrigenous-carbonate Mid-Carboniferous marine SR, generation peak occurs earlier below salt withdrawal minibasins (Fig. 12). Thus, Palaeozoic SR generated hydrocarbons progressively through time depending on salt-related thermal regime. The amount and type of expelled hydrocarbons will depend on the quality and areal extent of potential source rocks in the pre-salt hydrocarbon kitchen (Dembicki, 2017).

Additionally, analysis of oil physical properties of oils at the discovered multilayer accumulations in the Upper Triassic and Jurassic–Cretaceous stratigraphic sections demonstrates a decrease in oil density from 45° to 33°API upwards through the section, which also indirectly confirms the hypothesis of vertical HC migration from the pre-salt complex.

Conclusions

- Geochemical analysis of potential Upper Palaeozoic source rocks within the study area was implemented. The results demonstrate fair to good generative potential. The degree of thermal maturity ranges from immature to overmature. For mature and overmature Upper Permian and Mid-Carboniferous SR with Tmax between 430 and 480°C, there are high TOC values 0.4–5.5% and high ROC/TOC ratio, which indicated that source rocks had generated hydrocarbons. Kerogen Type II is predicted based on previous studies and regional palaeogeographic reconstructions.
- Calibrated 1D models for 3 wells were constructed based on integrated geodynamic history analysis. The thermal regime is controlled by salt withdrawal and contributes to timing of maturation.
- Revision of 3D seismic interpretation was done, and for the first time intrasalt sediment packages and encased minibasins of presumably Upper Permian age had been delineated as separate features, which may be potential HC traps near welded regions. Additionally, potential structural and stratigraphic traps in pre-salt strata can be delineated based on 3D seismic.
- The integrated modelling results on southeastern Precaspian petroleum system suggest deeper hydrocarbon prospectivity of Guryevsky height within the study area. Similarly, to other salt-dominated sedimentary basins halokinesis in southeastern Precaspian basin controls thermal evolution, source rocks maturation and migration pathways.
- The methodology described in the present paper was used for evaluation and justification of deeper hydrocarbon prospectivity at Block E; the method is based on tectonic evolution analysis, seismostratigraphy, geochemical analysis and thermal modelling. The integrated approach can be applied not only in other acreages in Precaspian Basin with the lack of exploration data but also in other salt-dominated basins to modify exploration strategies and models.

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Declarations

Conflict of interest On behalf of all the co-authors, the corresponding author states that there is no conflict of interest.

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