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Hydrocarbon Generation by the Rocks of the Bremer Formation in Adjacent Areas of the Nonvolcanic Passive Margins of Australia and Antarctica

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Abstract—This paper analyzes differences in the history of hydrocarbon (HC) generation by the rocks of the Bremer 1–6 formations in adjacent areas of the nonvolcanic passive continental margins of Australia and Antarctica. The problem is examined by the example of the numerical reconstruction of the burial and thermal history of two sedimentary sequences of approximately equal thicknesses: the section of well 19-2012 in the Bremer sub-basin of the southwestern margin of Australia and the section of pseudowell 2 in the adjacent area of the passive margin of Antarctica on seismic profile 5909 across the Mawson Sea. The asymmetry of Gondwana rifting in the region of interest resulted in asymmetry in the tectonic structure and development of adjacent areas of passive margins and, as a consequence, significantly different histories of HC generation by the rocks of the Bremer 1–6 formations in these areas. Modeling indicates that the rocks of the Bremer 1 and 2 formations are mainly gas-prone in the Bremer basin and can become oil-prone in the Mawson Sea region of the Antarctic margin. In contrast, according to modeling, the rocks of the Bremer 4 and 5 formations generate a minor amount of HC in the well 19-2012 area of the Bremer sub-basin and considerable amounts of heavy and light oil in the adjacent Antarctic margin area at pseudowell 2 in the Mawson Sea.

Keywords: Antarctica, Australia, Bremer sub-basin, Mawson Sea, passive margin, basin modeling, hydrocarbon generation

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INTRODUCTION

This paper analyzes differences in the history of hydrocarbon (HC) generation by the rocks of the Bremer formations in the adjacent areas of the nonvolcanic passive continental margins of Australia and Antarctica. The asymmetry of rifting in this part of Gondwana (Leichenkov, 2013) resulted in asymmetry in the tectonic structure and development of adjacent passive margins of southeastern Australia and Antarctica in the region of the Bremer sub-basin and the Mawson Sea. Thermal evolution is analyzed by the example of the sedimentary section of pseudowell 19-2012 in the Bremer sub-basin and pseudowell 2 on seismic profile 5909 across the passive margin of Antarctica in the Mawson Sea (Fig. 1). The sections selected for the analysis have approximately equally thick sedimentary covers.

The formation of the sedimentary cover of the Bremer sub-basin and the tectonic and thermal history of its development were discussed in detail by Bradshaw (2005). The subsidence history of the sedimentary basin of the Mawson Sea and the thermal and tectonic history of its lithosphere were analyzed by the example of 15 areas along seismic profiles 5909 and 5903 by Galushkin et al. (2017). Therefore, in this paper, we only briefly consider the main results of modeling of the thermal and tectonic history of the basins (Figs. 2–4), whereas the main focus of our study is the description of HC generation by the rocks of supposed source formations (Bremer 1–6) and comparison of the conditions of organic matter (OM) maturation and HC generation in the sedimentary basins of adjacent continental margins. The regions of the Bremer sub-basin and the Mawson Sea are located in conjugate passive margins of Australia and Antarctica, which have a common spreading center but significantly different tectonic development and sedimentation histories.

The paper begins (section 2) with a short description of the conditions of formation, lithology, and geological–geochemical characteristics of the Bremer 1–6 for-

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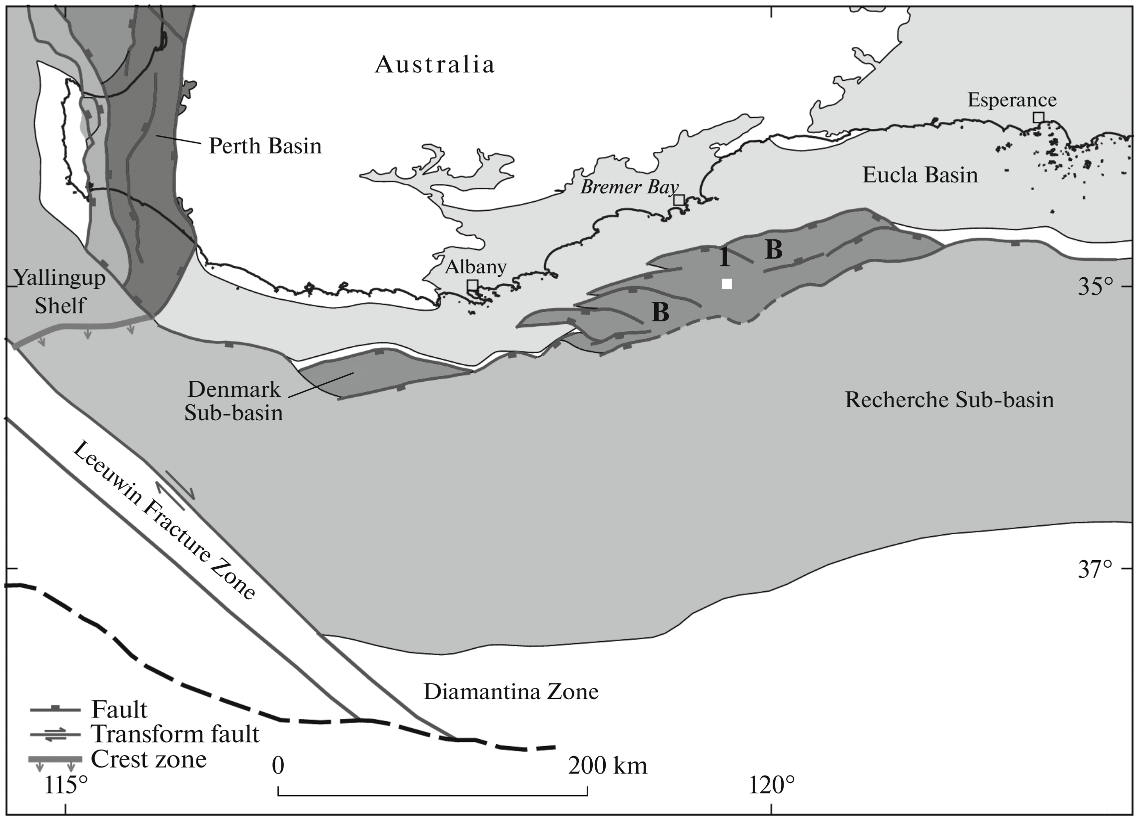

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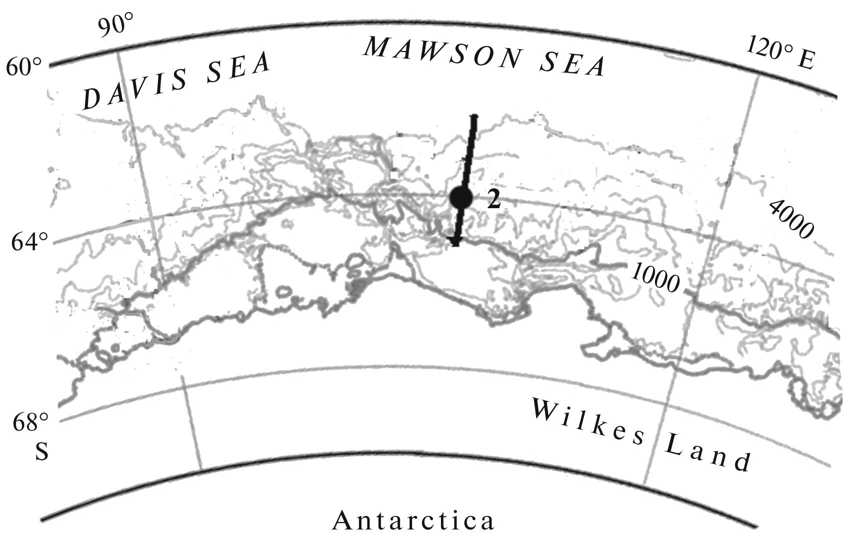

Fig. 1. Location of pseudowell 19-2012 in the Bremer sub-basin at the passive margin of southwestern Australia and pseudowell 2 on seismic profile 5909 across the adjacent area of the Antarctic continental margin in the Mawson Sea. (a) 1, pseudowell 19-2012; B, Bremer sub-basin. (b) 2, pseudowell 2; the bold line show the position of seismic profile 5909; and 1000 and 4000 are isobaths in meters.

mations. Section 3 addresses the differences in the thermal history of Bremer 1–6 sediments in the adjacent areas of the passive continental margins of southwestern Australia and Antarctica. In the same section, we discuss the consequences of these differences for the history of OM maturation in the rock sequences of the adjacent margins of the two continents. It will be shown that the conditions of OM maturation in the Bremer 1–3 formations in the Antarctic margin were in general much milder than those in the Bremer sub-

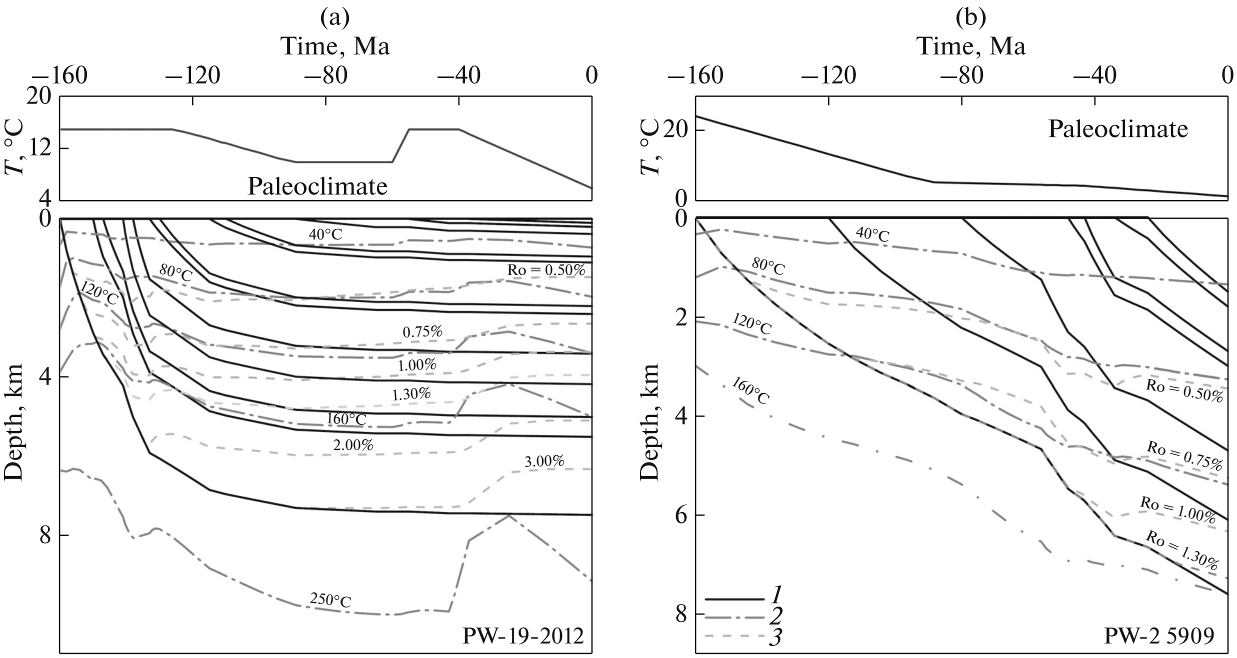

Fig. 2. History of the burial, thermal evolution, and OM maturation in the rocks of the sedimentary sections of (a) the Bremer sub-basin off southwestern Australia in the area of pseudowell PW-19-2012 and (b) the pseudowell PW-2 5909 area in the Mawson Sea. (*1*) Layer bottom; (*2*) isotherm; and (*3*) isoline of vitrinite reflectance, Ro, %. The location of the pseudowells is shown in Fig. 1.

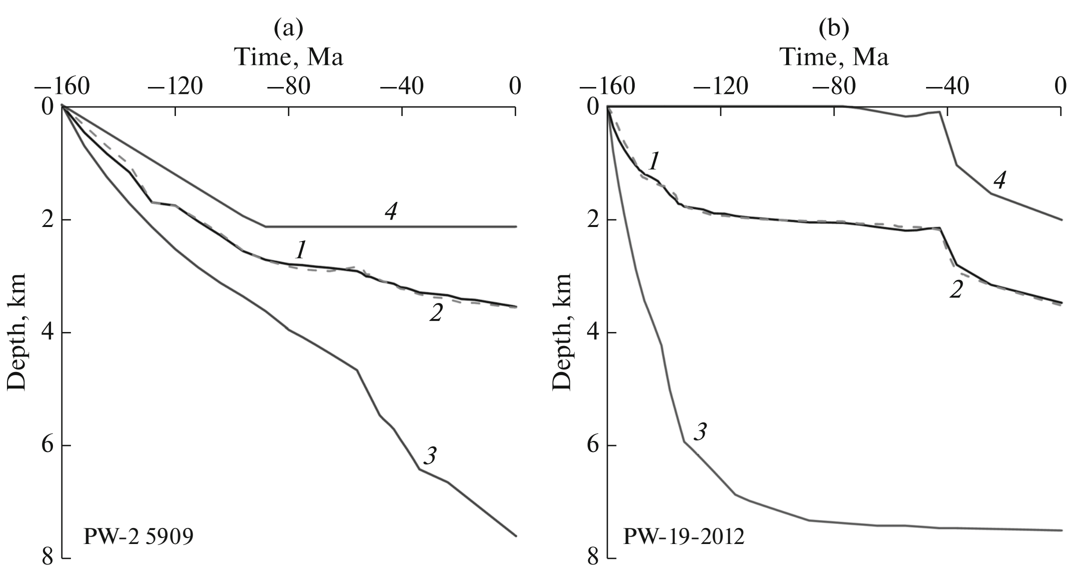

Fig. 3. Variations in the tectonic subsidence of a basin for the sedimentary section of (a) pseudowell PW-2 5909 on seismic profile 5909 in the Mawson Sea and (b) pseudowell PW-19-2012 in the Bremer sub-basin. (*1*) Tectonic subsidence of the basement surface calculated by removing water and sediment loads from the basement surface assuming a local isostatic response of the lithosphere to loading (Galushkin, 2016); (*2*) tectonic subsidence of the basement surface calculated taking into account variations in rock density with depth in the basin basement (Galushkin, 2016); (*3*) depths of the basement surface relative to the ocean floor; and (*4*) sea paleodepth.

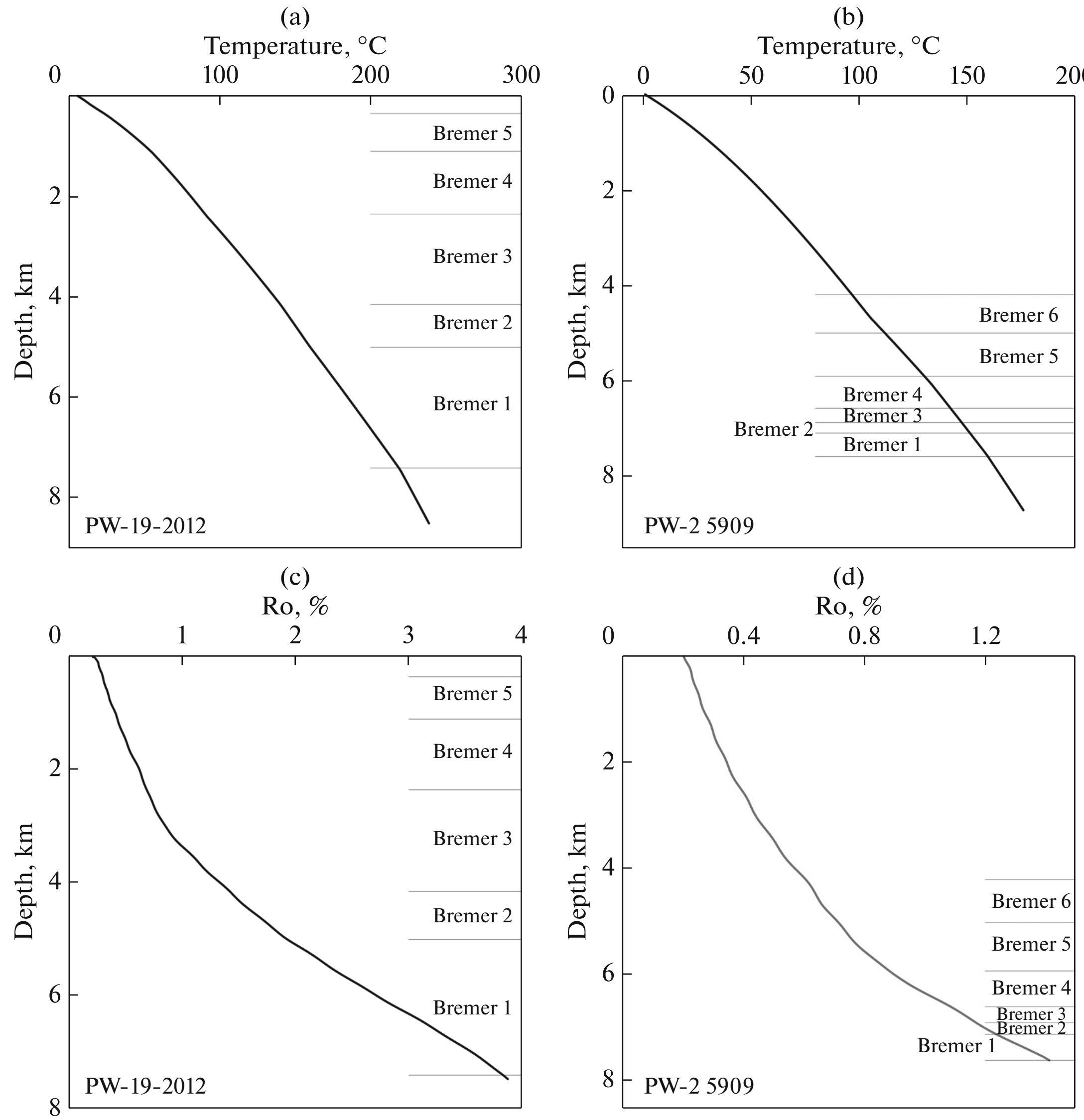

Fig. 4. Calculated distribution of (a, b) temperature and (c, d) vitrinite reflectance, Ro, %, in the present-day sedimentary sections of (a, c) the Bremer sub-basin at pseudowell PW-19-2012 and (b, d) the Mawson Sea basin at pseudowell PW-2 5909. The position of supposed source formations (Bremer 1–6) is shown in the present-day sedimentary sections. Vitrinite reflectance was calculated using the EASY%Ro kinetic model of vitrinite maturation (Sweeney and Burnham, 1990).

basin. Section 4 discusses the consequences of the distinguished differences for the generation of various HC fractions by the rocks of the Bremer 1–6 formations. Finally, main conclusions are formulated on the conditions of HC generation by the rocks of the Bremer 1–6 formations in the adjacent areas of two passive continental margins.

CONDITIONS OF FORMATION AND GEOLOGICAL–GEOCHEMICAL CHARACTERISTICS OF THE BREMER 1–6 FORMATIONS

The geologic history of the region and the development of its sedimentary basins were considered in detail by Leichenkov (2013). Taking into account the main tectonic processes forming the accommodation zone, two structural levels of Late Mesozoic–Cenozoic age were distinguished in the sedimentary cover corresponding to the rift (preceding the breakup of lithospheric plates) and postrift (synoceanic) phases of its development. It is possible that there are older sequences at the base of the sedimentary basins, but they cannot be identified on the available seismic sections.

Six seismostratigraphic units (Bremer 1–6) of Mesozoic age were distinguished in the section of pseudowell 19-2012 in the Bremer sub-basin (Bradshaw, 2005). The Bremer 1 Formation of Middle to

Late Jurassic age is composed mainly of river and lacustrine mudstones and sandstones. The rocks of the Bremer 1 Formation from the Australian passive margin are considered to be both source and potential reservoir sequences (Bradshaw, 2005). The accumulation of river and lacustrine sandstones and mudstones continued during the postrift stage of lithosphere cooling in the Late Jurassic and Early Cretaceous during the deposition of the Bremer 2–4 formations. Lacustrine mudstones at the base of the Bremer 2 Formation are considered potential source and cap rocks, and the overlying channel sandstones of this formation are potential reservoir rocks. In the Bremer 3 Formation of Berriasian–Valanginian age, the OM content varies from 1.5 to 3.4% in mudstones and from 0.7 to 2.0% in carbonate siltstones. The fraction of sandstones in the lower part of the Bremer 3 Formation is significantly lower than that in its upper part; therefore, the former are interpreted as potential source rocks, and the latter, as potential reservoir rocks (Bradshaw, 2005).

The Bremer 4 Formation was deposited during the final stage of lacustrine and, to a lesser degree, marine sedimentation during the Valanginian–Aptian. It is believed that this formation was formed during the second period of moderate lithosphere extension beneath the Bremer sub-basin in the Valanginian and Hauterivian. According to the analysis of the tectonic subsidence of the basin (see below), the lithosphere extension factor (β) of the Bremer sub-basin was 1.08 in the Valanginian and Hauterivian. This value is significantly lower than that of the first extension period and Early Jurassic continental rifting ($\beta = 1.3$) and the last (third) extension period ($\beta = 1.7$), which was accompanied by rapid sea deepening. The OM content of the mudstones of the Bremer 4 Formation varies widely from 0.34 to 22.62% (MacPhail and Monteil, 2005).

The rocks of the Bremer 5 Formation mark the beginning of marine sedimentation during thermal cooling of the sub-basin lithosphere in the late Aptian–Turonian. The formation is dominated by mudstone and siltstone and comprises minor sandstone and limestone. The OM content of the mudstone is 0.36–3.4% (MacPhail and Monteil, 2005). The presence of glauconitic and carbonate rocks in the Bremer 5 Formation indicates a marine transgression. Our modeling suggested that the marine deposits of the Bremer 5 Formation are too shallow to serve as HC source rocks or traps.

The sequences of the Bremer 6 Formation were accumulated during continuing marine sedimentation and are composed mainly of calcareous mudstones and siltstones with low total organic carbon (TOC) contents of 0.41–0.85%.

The period of rifting and breakup of the continental lithosphere had to be followed by a tectonically inactive period of gradual basin subsidence in response to lithosphere cooling. It has continued since the Turonian up to the present day. However, an abrupt increase in spreading rate in the middle and late Eocene resulted in rapid subsidence and sea deepening in the Bremer sub-basin from 100 m at 43 Ma to 1350 m at 35 Ma (Fig. 4.4 in Goncharov et al., 2006). The rapid subsidence of the continental margin in the middle Eocene resulted in the formation of deep submarine canyons, which incise the slope of the Bremer sub-basin to depths of 2 km (Exon et al., 2005).

Note that the main information on the rocks of the Bremer 1–6 sedimentary complexes was obtained from drilling in the Bremer sub-basin and neighboring areas. In particular, the sedimentary section of the pseudowell 19-2012 area was constructed using the data of drilling to depths of 5 km and seismic profiling for greater depths (Bradshaw, 2005). No similar study was conducted for the Antarctic passive margin. Therefore, in was assumed that the lithology of the Bremer 1–6 formations in the Mawson Sea area of the Antarctic continental margin is the same as in the adjacent area of pseudowell 19-2012 in the Bremer sub-basin (Bradshaw, 2005; MacPhail and Monteil, 2005; Goncharov et al., 2006; Leichenkov, 2013; Galushkin et al., 2017). In the following section, numerical reconstructions obtained by the GALO system for basin modeling (Galushkin, 2007, 2016) are used to evaluate the difference in thermal history and conditions of OM maturation between the rocks of the Bremer 1–6 formations in the two adjacent continental margins.

THERMAL HISTORY AND THE DEGREE OF OM MATURATION IN THE ROCKS OF THE BREMER 1–6 FORMATIONS

As was noted in the Introduction, the areas of the Bremer sub-basin and Mawson Sea analyzed in this paper are located in the adjacent passive margins of Australia and Antarctica, which have a common spreading center. However, the tectonic development and the history of sedimentation in these areas were significantly different. The sedimentary section of the Bremer sub-basin in the southeastern margin of Australia began forming approximately 160 Ma ago in the initial phase of Pangea breakup in this segment of the Australia–Antarctica boundary. The Bremer 1 Formation was accumulated during that time period. The sedimentary section of pseudowell 19-2012 includes all formations, from Bremer 1 to Bremer 6, whose ages span from 160 to 65 Ma (Fig. 2a). The sedimentation rate in the sub-basin reached a maximum between 160 and 115 Ma, i.e., during the period of continental rifting (Figs. 2a, 3b). Modeling indicates that the lithosphere of the sub-basin was thinned by a factor of 1.4 between 160 and 133 Ma (during the accumulation of the Bremer 1, Bremer 2, and Bremer 3 formations) (Fig. 3b). In the end Turonian (~90 Ma), the sedimentation rates decreased considerably, and no more than 200 m sediments have been deposited in the sub-basin during the whole Cenozoic (Fig. 2a). However, the sea depth increased considerably during this period, from 100–200 m at 40 Ma to 2000 m nowadays (Fig. 3b). The analysis of variations in the magnitude of tectonic subsidence of the basement suggests that such a sea deepening must be accompanied by a lithosphere extension by a factor of 1.7 between 43 and 35 Ma, while the spreading half-rate increased from 0.3–0.6 cm/yr to 2.7–3.8 cm/yr (Leichenkov, 2013).

The history of sedimentation and sea depth variations at pseudowell 2 in the adjacent area of the Mawson Sea in the passive margin of Antarctica is different (Fig. 2b). Geophysical investigations in this area revealed that the sedimentary section of the pseudowell on profile 5909 across the Mawson Sea is located on a thinned to ultrathinned continental lithosphere. During the extension of the lithosphere of the Antarctic margin, the thickness of the consolidated crust of the Mawson Sea region decreased from an initial value of 36 km at approximately 160 Ma to 7–9 km nowadays (Leichenkov, 2013; Galushkin et al., 2017). The analysis of variations in the tectonic subsidence of the basin suggests that sedimentary rocks were deposited in the adjacent margin of Antarctica on a basement preliminarily extended by a factor of 2.5 during the 5–10 Ma of the initial phase of continental rifting approximately between 170 and 160 Ma, when an arched relief dominated the margin (Gillard et al., 2015; Galushkin et al., 2017).

The sedimentary sections of the Antarctic margin and the adjacent area of the Australian margin in the region of the Bremer sub-basin differ primarily in the thickness of the Cenozoic sequence, which is 2.5–4.0 km in the former and no more than 200 m in the latter (Figs. 2a, 2b). The histories of marine basin formation in the two margins are also different. In our model of the development of the Antarctic margin, the sea depth changed considerably during continental rifting between 160 and 90 Ma and showed probably insignificant variations in the Cenozoic. This is consistent with the absence of evidence for lithosphere extension since 90 Ma and up to the present in the seismic sections of the Mawson Sea (Leichenkov, 2013). In contrast, in the Bremer sub-basin of the adjacent Australian margin, main changes in sea depth occurred since 40 Ma during the acceleration of spreading of the Australian–Antarctic Discordance (Bradshaw, 2005; Fig. 3b). Information on sea depth variations in the history of basin subsidence (curves 4 in Fig. 3) and estimates of the age and thickness of sedimentary formations (Fig. 2) allow us to calculate variations in the tectonic subsidence of the basin since the beginning of formation of its sedimentary cover (curves *1* and *2*, Fig. 3) and determine the duration and amplitude of thermal activation and lithosphere extension events in the basins (Galushkin, 2007, 2016). Curves *3* in Fig. 3 show changes in the thickness of the sedimentary cover during the basin subsidence, and curves *4* in Fig. 3 characterize the history of sea depth variations obtained from the model. The sum of depths corresponding to curves *3* and *4* in Fig. 3 is the total magnitude of subsidence of the basement surface of the basin in the continental margin area.

The analysis of tectonic subsidence at the pseudowell 19-2012 area of the Bremer sub-basin suggests lithosphere cooling from an initial heat flow of 105 mW/m^2, which is typical of the axial zones of continental rifts (Smirnov, 1980), and two lithosphere extension events with magnitudes of $\beta = 1.4$ during the rifting stage of basin development and $\beta = 1.7$ at the stage of increasing spreading rate. The high β values during the last stage of lithosphere extension at its relatively short duration resulted in significant thermal activation of the lithosphere of the Bremer sub-basin, which is clearly seen in Fig. 2a. The analysis of tectonic subsidence for the pseudowell 2 area of the Mawson Sea at the Antarctic passive margin suggests lithosphere thinning by a factor of 2.5 approximately between 170 and 160 Ma during the arch stage of rifting, i.e., before the beginning of formation of the modern sedimentary cover. The same analysis indicates basin lithosphere thinning by a total factor of approximately 1.7 during the rifting stage of basin development between 160 and 90 Ma (Fig. 3a; Galushkin et al., 2017).

Figure 2 shows that the sedimentation rate during the rifting stage of Bremer sub-basin development was significantly higher than that in the pseudowell 2 area of the Antarctic margin. This is why the thickness of the Bremer 1–3 complex is up to 5 km in the sub-basin and only ~1 km in the pseudowell 2 area of the Antarctic margin. Correspondingly, the rocks of this complex in the modern section of the Bremer sub-basin are characterized by OM maturity corresponding to vitrinite reflectance values of $0.70 \le Ro \le 3.90\%$; at such values, only the rocks of the Bremer 3 Formation occur in the oil generation window (Fig. 4c). The same complex in the pseudowell 2 area of the Antarctic passive margin is characterized by significantly lower temperatures and OM maturity (Figs. 2b, 2d). According to modeling, the range of OM maturity in the Bremer 1–3 formations of the modern section of the sub-basin is $1.04 \le Ro \le 1.41\%$, and almost all of these rocks occur in the oil window. Note that the rocks of the Bremer 4–6 formations, which were identified as early mature and immature rocks in the pseudowell 19-2012 section, are also within the oil window (Fig. 2c).

Our estimates of OM maturity in sedimentary rocks are based on the calculation of vitrinite reflectance, Ro, %, using the GALO system and the EASY%Ro kinetic model of vitrinite maturation of Sweeney and Burnham (1990). Short-dashed lines in Fig. 2 show variations in the depth of Ro, % isolines during the subsidence of the Bremer sub-basin (Fig. 2a) and the Mawson Sea (Fig. 2b). The depths of the oil window in this diagram correspond to the interval between the Ro = 0.50% and Ro = 1.30% lines. Figures 4c and 4d show the distribution of Ro, % values with depth in the modern sections of the areas of interest and the depths of the Bremer 1–6 formations in the modern section.

REALIZATION OF THE PETROLEUM GENERATION POTENTIAL OF THE BREMER 1–6 FORMATIONS

The numerical reconstructions of the thermal history of the Bremer sub-basin and the Mawson Sea (Figs. 2, 4) were used to estimate the development of the HC potential of supposed source rocks of the Bremer 1–6 formations in the adjacent passive margin areas. The yield of HC was calculated using standard kinetic spectra of the popular four-fraction model of HC generation (heavy and light oil, gas, and coke). We used standard kinetic spectra of the maturation of type II and III kerogen developed at the French Petroleum Institute (IFP) and implemented in the widely used MATOIL computer code. The computational algorithm for the generation of various HC fractions was discussed by Galushkin (2007, 2016).

The model changes of rock temperature and degree of OM catagenesis during the burial of the supposed source formations of the Bremer sub-basin and the Mawson Sea basin are shown in Figs. 2a and 2b. It can be seen that the temperature of rocks and OM maturity increased significantly in the Eocene in response to the rapid lithosphere extension in the Bremer sub-basin and an increase in sedimentation rate in the Mawson Sea during that time period (Figs. 2, 4). As was noted above, the strong extension of the lithosphere of the Bremer sub-basin in the Eocene was responsible for the simultaneous sharp increase in sea depth (Fig. 3a). Consider in more detail the history of the development of HC potential in each of the supposed source formations (Bremer 1–6).

Bremer 1

In the modern section of the pseudowell 19-2012 area in the Bremer sub-basin, the Bremer 1 Formation lies at depths of 5–7.47 km, and its OM maturity increases, according to our modeling, from Ro = 1.93% at the top to Ro = 3.87% at the bottom (Fig. 4d). Consequently, OM from this formation in the Bremer sub-basin can be considered overmatured, and the rocks are gas prone. Such an estimate is consistent with the analysis of the maturity of Bremer 1 rocks by Bradshaw (2005).

The OM content of the mudstones of the Bremer 1 Formation ranges from 1.1 to 3.4% (Goncharov et al., 2006), which allows their interpretation as possible source rocks. These rocks contain coaly type III kerogen with an initial Hydrogen Index (HI) of approximately 160 mg HC/g C_{org}. The high degree of OM maturity in the Bremer 1 rocks of the sub-basin results in the realization of 80–100% of the initial HC generation potential (Figs. 5b, 5d). Figures 5b and 5d show that the heavy oil that was generated by the Bremer 1 rocks in the Bremer sub-basin was decomposed owing to secondary cracking already in the Neocomian. The generated light oil also degraded to a large degree and was retained only in small amounts in the top levels of the formation (curve *3* in Fig. 5d). Thus, the dominance of gas-prone rocks in the Bremer 1 Formation is supported by the history of generation of various HC fractions in the 19-2012 area of the Bremer sub-basin.

A different situation is characteristic of the adjacent area of the Antarctic passive continental margin, where the degree of OM maturation in the rocks of the Bremer 1 Formation is from 1.2 to 1.4% (Ro), and the realization of the initial HC potential is no higher than 43% (Fig. 5a). In the pseudowell 2 area of the Mawson Sea, even heavy oil generated by the rocks of the Bremer 1 Formation could be preserved in the source rocks, especially at the top of the layer, whereas light oil was not affected by secondary cracking at all (Figs. 5a, 5c). Thus, it is suggested that the Bremer 1 Formation is dominated by oil-prone rocks in the pseudowell 2 area of seismic profile 5909 in the Mawson Sea adjacent to the Bremer sub-basin.

Bremer 2

According to our modeling, the rocks of the modern sedimentary section of the Bremer 2 Formation contain OM with 1.43 ≤ Ro ≤ 1.93% in the Bremer sub-basin and 1.17 ≤ Ro ≤ 1.23% in the pseudowell 2 area on seismic profile 5909 in the Mawson Sea (Figs. 2, 4c, 4d). Hence, the rocks of the Bremer 2 Formation occur within the condensate generation window in the former area and in the oil generation window in the latter area.

The Bremer 2 rocks contain a mixture of 50% standard type II kerogen with an HI value of 377 mg HC/g C_{org} and 50% type III kerogen with an HI value of 160 mg HC/g C_{org}. Thus, the initial HI value of the rocks is 268.5 mg HC/g C_{org}, which is significantly higher than that of the previous formation. At a rather high OM maturity, the realized potential of OM generation in the rocks of the Bremer 2 Formation is also significantly higher than that of the Bremer 1 Formation (Figs. 6a, 6b). Moreover, the kerogen of the Bremer 2 Formation is more labile. Therefore, the yield of various HC fractions (per one gram of C_{org}) by the rocks of this formation is in general higher than that of the Bremer 1 rocks (compare Figs. 5 and 6). Owing to the higher OM maturity, the heavy oil generated by the rocks of the Bremer 2 Formation in the Bremer sub-basin completely degraded, and the rocks generated light oil and a smaller amount of gas (Fig. 6b). In the pseudowell 2 area of the Mawson Sea, heavy oil was only partly affected by secondary cracking, and the rocks generate mainly heavy oil with minor amounts

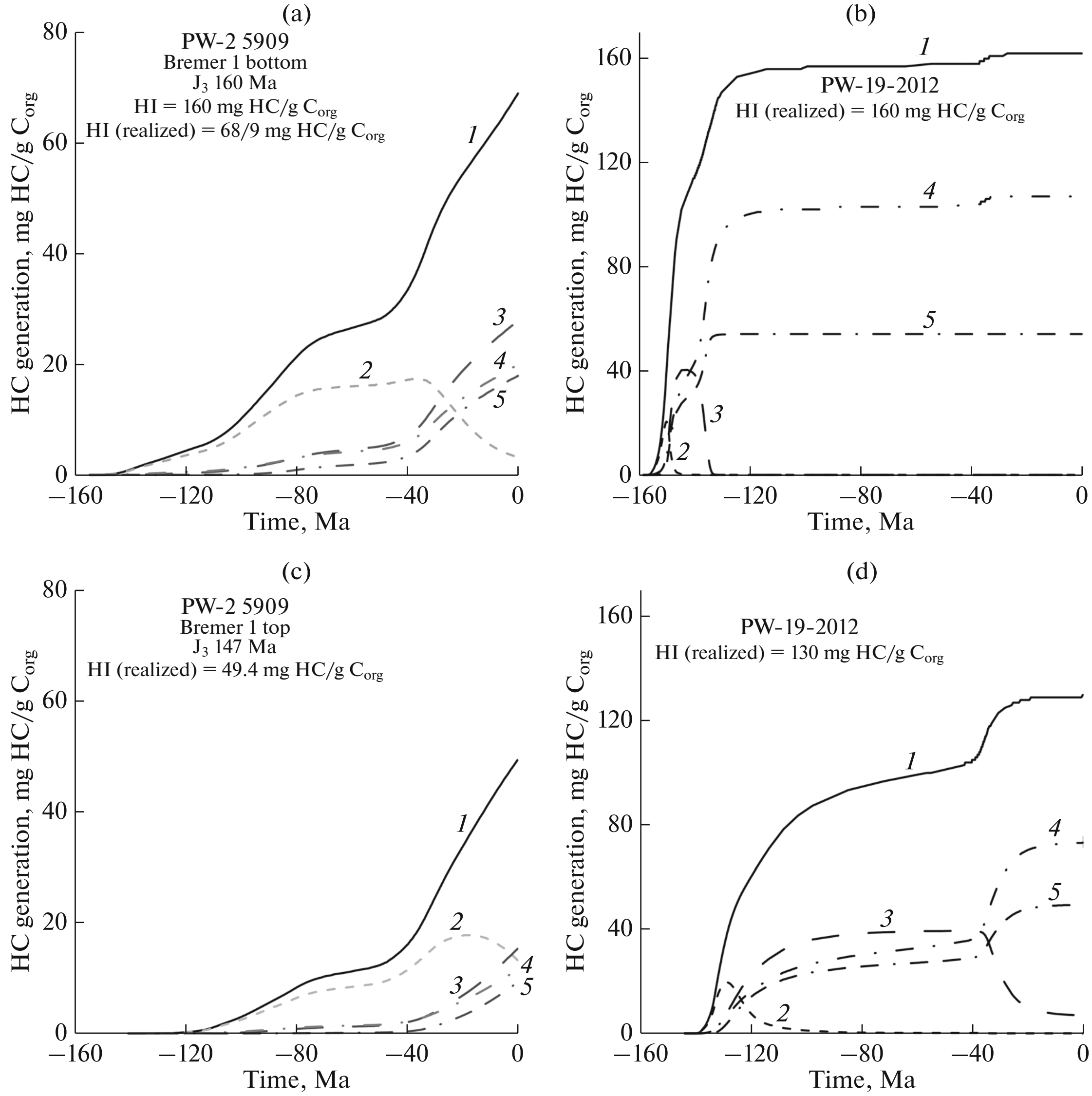

Fig. 5. Realization of the oil- and gas-generation potential of rocks at (a, b) the bottom (160 Ma) and (c, d) top (147 Ma) of the Bremer 1 Formation calculated within the model of four-fraction HC composition for the sedimentary sections of (b, d) pseudowell PW-19-2012 in the Bremer sub-basin and (a, c) pseudowell PW-2 5909 on seismic profile 5909 in the Mawson Sea. It is assumed that the Bremer 1 Formation contains type III kerogen with the initial HC generation potential HI = 160 mg HC/g C_{org}. (*1*) Total HC generation; (*2*) heavy oil generation (C15+); (*3*) light oil generation (C6–15); (*4*) gas generation (C1–5); and (*5*) coke generation.

of light oil and gas (Fig. 6a). Thus, the rocks of the upper levels of the Bremer 2 Formation can be oil-prone in the adjacent areas with dominant generation of light oil in the Bremer basin and heavy oil in the pseudowell 2 area of the Antarctic margin.

Bremer 3

The degree of OM maturation in the modern sedimentary section of the Bremer 3 Formation is estimated as $0.70 \le Ro \le 1.43\%$ in the Bremer sub-basin and $1.08 \le Ro \le 1.17\%$ in the pseudowell 2 area of seismic profile 5909 in the Mawson Sea (Figs. 2, 4c, 4d). Thus, the degree of OM maturation in the Bremer 3 Formation corresponds to the oil generation window in both adjacent areas.

The lower part of the Bremer 3 Formation contains the same mixed-type kerogen that was observed in the Bremer 2 Formation, i.e., a mixture of 50% standard type II kerogen with an initial HI value of 377 mg HC/g C_{org} and 50% type III kerogen with an initial HI value of 160 mg HC/g C_{org}. Similarly, the initial HC generation potential of such a mixture is 268.5 mg HC/g C_{org}. However, the degree of OM maturation decreases with increasing depth, and, consequently, the fraction of heavy oil increases. Therefore, the rocks of the lower half of the Bremer 3 For-

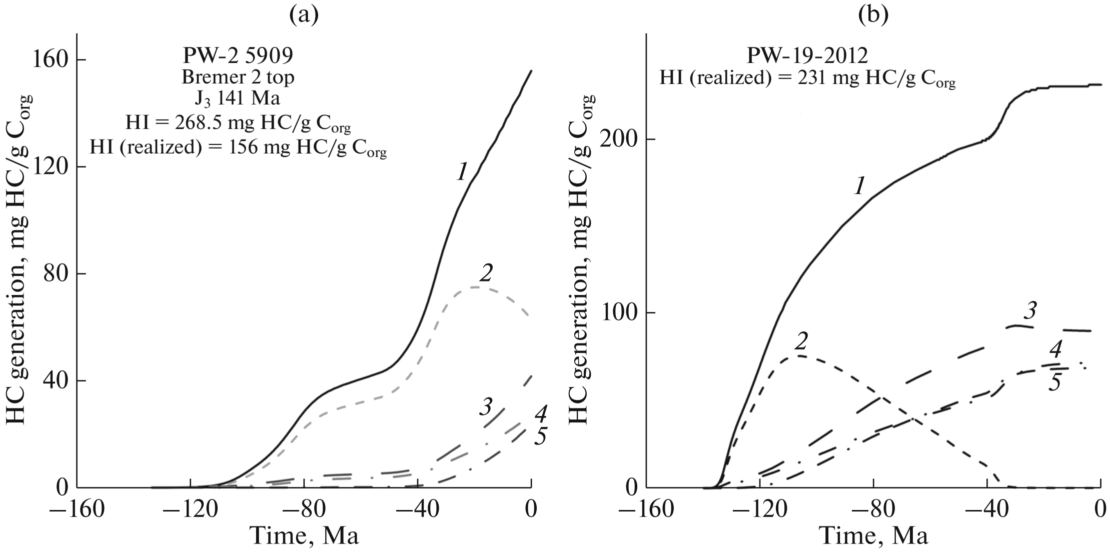

Fig. 6. Realization of the oil- and gas-generation potential of rocks at the top of the Bremer 2 Formation (141 Ma) calculated within the model of four-fraction HC composition. (a) Calculation for the sedimentary section of pseudowell PW-2 5909 on seismic profile 5909 in the Mawson Sea. (b) Calculation for pseudowell PW-19-2012 in the Bremer sub-basin. It is assumed that kerogen from the Bremer 2 Formation is a mixture of 50% standard type II kerogen with the initial HC generation potential HI = 377 mg HC/g C_{org} and 50% type III kerogen with HI = 160 mg HC/g C_{org}; the initial HI value of the mixed kerogen is 268.5 mg HC/g C_{org}. Curves *1–5* are as in Fig. 5.

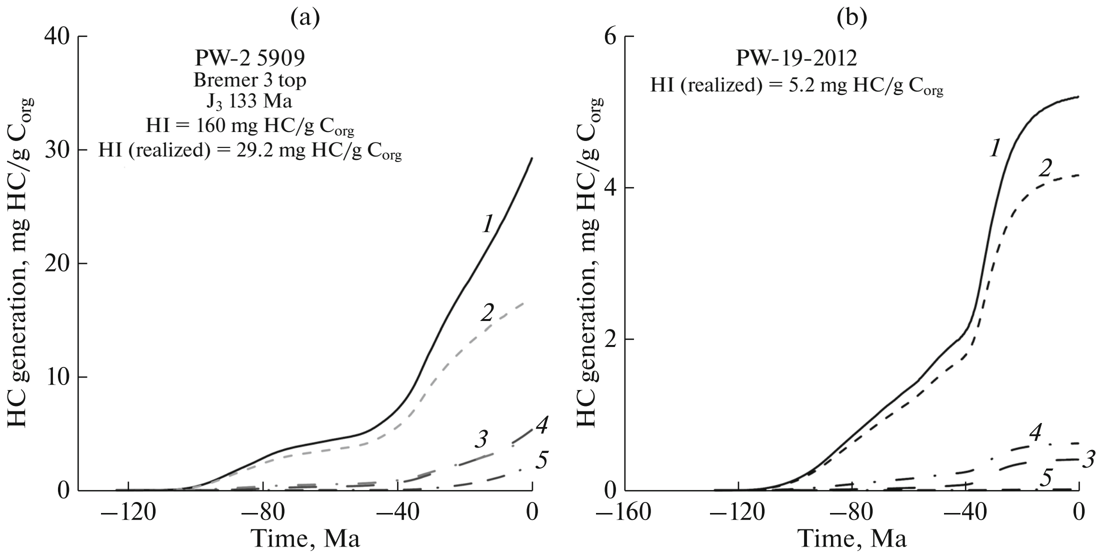

Fig. 7. Realization of the oil- and gas-generation potential of rocks at the top of the Bremer 3 Formation with an age of 133 Ma calculated within the model of four-fraction HC composition. (a) Calculation for the sedimentary section of pseudowell PW-2 5909 on seismic profile 5909 in the Mawson Sea. (b) Calculation for pseudowell PW-19-2012 in the Bremer sub-basin. It is assumed that the Bremer 3 Formation contains standard type III kerogen with the initial potential of HC generation HI = 160 mg HC/g C_{org}. Curves *1–5* are as in Fig. 5.

mation are oil-prone and generate both light and heavy oil in the two adjacent passive margins.

The rocks of the upper Bremer 3 Formation contain type III kerogen with an initial HI value of 160 mg HC/g C_{org}. This coaly kerogen type is poorly matured, and the yield of HC by the rocks of the top of Bremer 3 Formation is very low in the Bremer sub-basin (Fig. 7b) and moderate in the pseudowell 2 area of seismic profile 5909 in the Mawson Sea (Fig. 7a).

Bremer 4

The degree of OM maturation in the modern sedimentary section of the Bremer 4 Formation is estimated as $0.43 \leq Ro \leq 0.70\%$ in the Bremer sub-basin

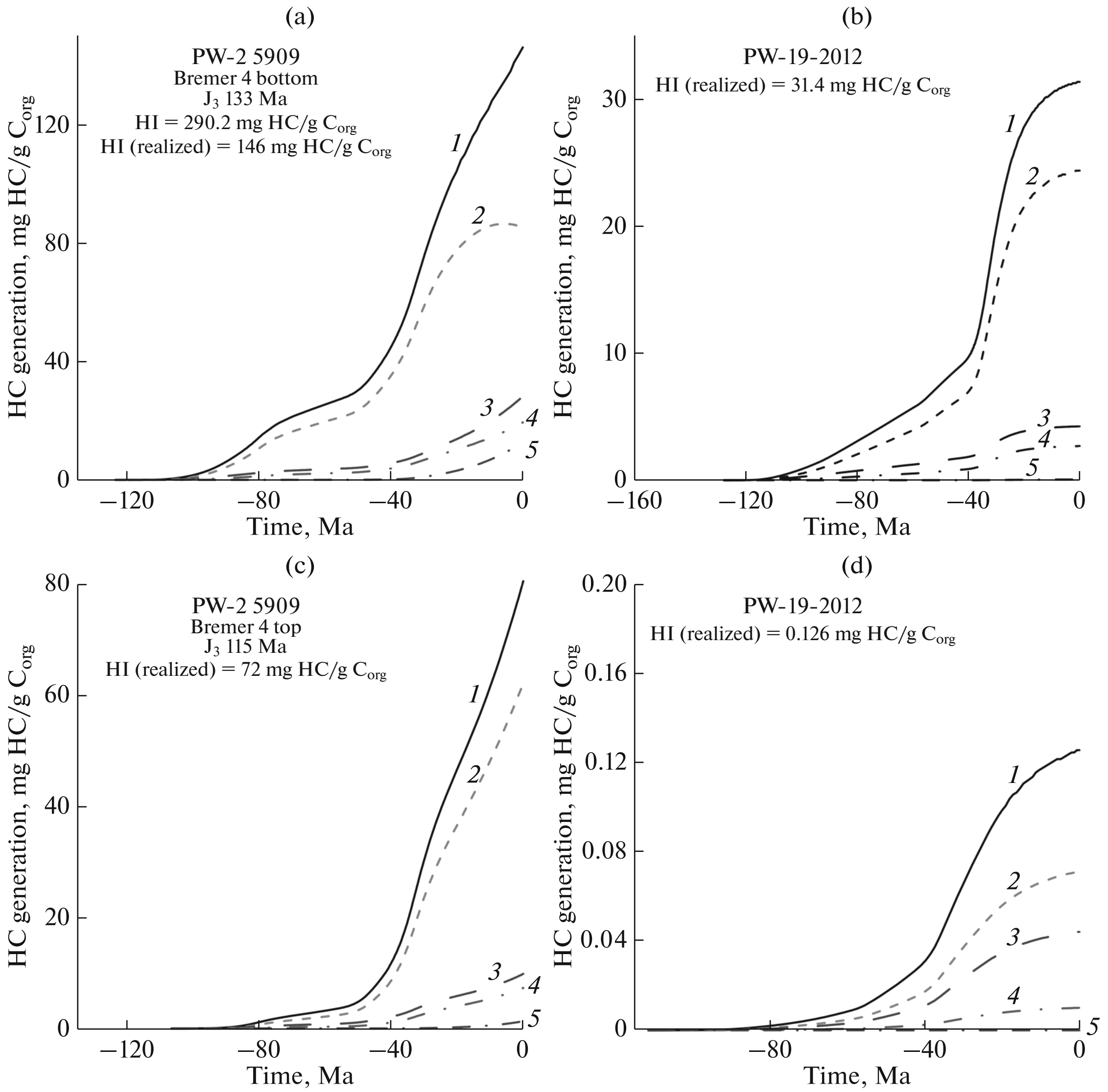

Fig. 8. Realization of the oil- and gas-generation potential of rocks at (a, b) the bottom of the Bremer 4 Formation (133 Ma) and (c, d) the top of the formation (115 Ma) calculated within the model of four-fraction HC composition. (a, c) Calculation for the sedimentary section of pseudowell PW-2 5909 on seismic profile 5909 in the Mawson Sea. (b, d) Calculation for pseudowell PW-19-2012 in the Bremer sub-basin. It is assumed that the rocks contain a mixture of 60% standard type II kerogen with the initial potential of HC generation HI = 377 mg HC/g C_{org} and 40% type III kerogen HI = 160 mg HC/g C_{org}; the HI value of the mixture is 290.2 mg HC/g C_{org}. Curves *1*–*5* are as in Fig. 5.

and $0.88 \leq Ro \leq 1.08\%$ in the pseudowell 2 area of seismic profile 5909 in the Mawson Sea (Figs. 2, 4c, 4d). Thus, in terms of OM maturity, the OM of the Bremer 4 Formation corresponds to the early mature stage in the pseudowell 19-2012 area and to the stage of intense oil generation in the adjacent area of pseudowell 2 in the Mawson Sea.

The OM of the Bremer 4 rocks is composed of 60% standard type II kerogen with an initial HI value of 377 mg HC/g C_{org} and 40% type III kerogen with an initial HI value of 160 mg HC/g C_{org} (Bradshaw, 2005; Goncharov et al., 2006). Thus, the initial potential of HC generation is up to 290 mg HC/g C_{org}, which is higher than that of the Bremer 1–3 formations. Note also that the highest OM contents of approximately 10% were observed in the rocks of the Bremer 4 Formation (Section 2; Bradshaw, 2005). The OM of the Bremer 4 Formation in the Bremer sub-basin is early mature and immature (Figs. 2a, 4d), and these rocks could generate only limited or negligible amounts of HC (Figs. 8b, 8d). In contrast, HC generation in the pseudowell 2 area of the Mawson Sea is significant even at the top of the formation (Figs. 8a, 8c) and is dominated by heavy oil (Figs. 8a, 8c).

Bremer 5 and Bremer 6

In the pseudowell 19-2012 area, the degree of HC maturation in the rocks of Bremer 5 and 6 formations

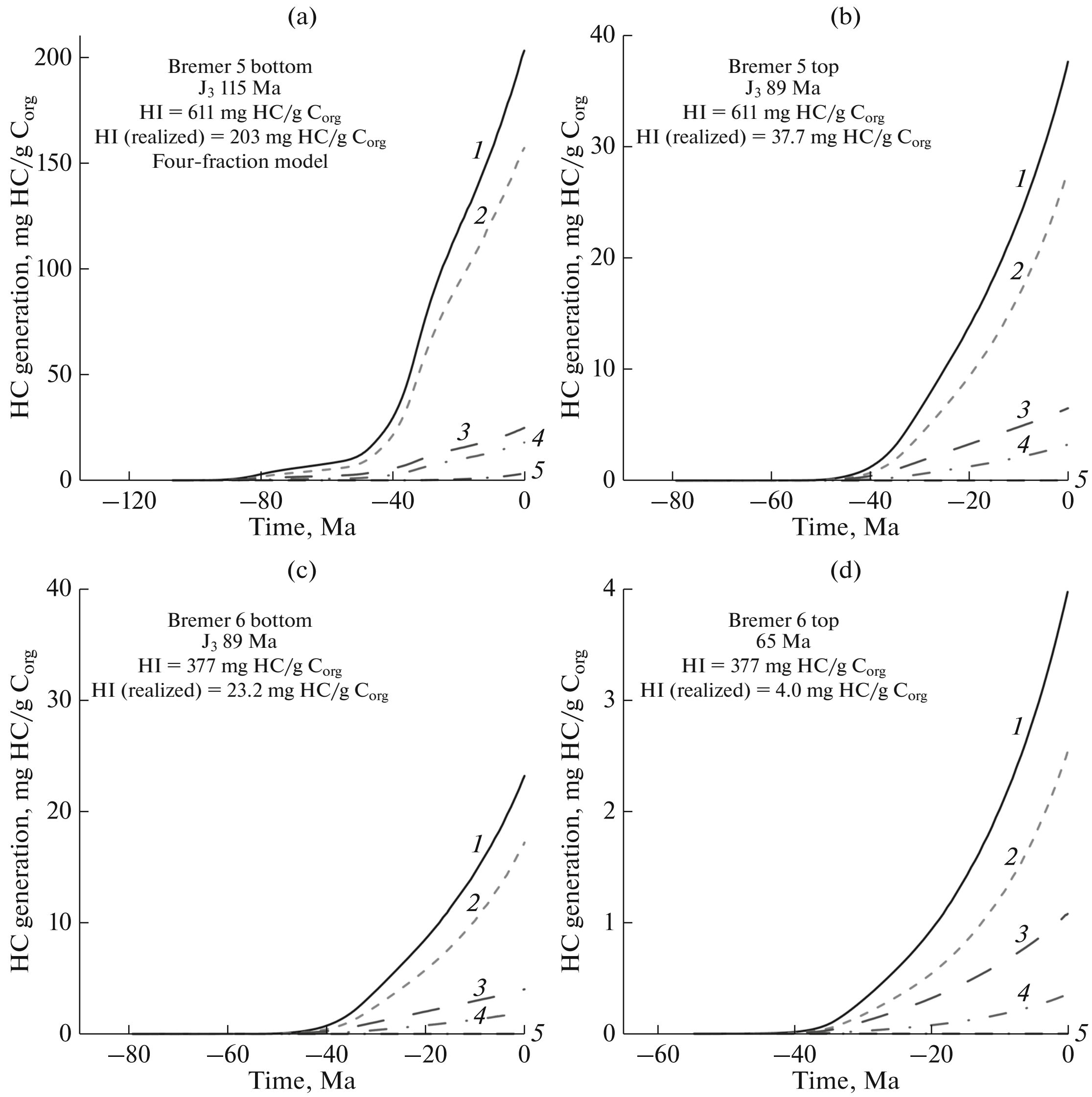

Fig. 9. Realization of the oil- and gas-generation potential of the rocks of the Bremer 5 and Bremer 6 formations calculated within the model of four-fraction HC composition for the sedimentary section of pseudowell PW-2 5909 on seismic profile 5909 in the Mawson Sea. (a) Generation by the rocks of the bottom of the Bremer 5 Formation with an age of 115 Ma. (b) Generation by the rocks of the top of the Bremer 5 Formation with an age of 89 Ma. (c) Generation by the rocks of the bottom of the Bremer 6 Formation with an age of 89 Ma. (d) Generation by the rocks of the top of the Bremer 6 Formation with an age of 65 Ma. It is assumed that the Bremer 5 Formation contains marine type II kerogen with the initial potential of HC generation HI = 611 mg HC/g C_{org}, and the Bremer 6 Formation contains type II kerogen with HI = 377 mg HC/g C_{org}. Curves *1–5* are as in Fig. 5.

is $0.27 \le Ro \le 0.43\%$, and their OM is immature; hence, HC generation can be ignored there (Figs. 2a, 4d). Therefore, we discuss here only HC generation in the pseudowell 2 area of the Mawson Sea (Figs. 9a–9d). Modeling showed that the degree of OM maturation in the rocks of the Bremer 5 Formation is $0.72 \le Ro \le 0.88\%$. The OM is dominated by marine type II kerogen with an initial HI value of 611 mg HC/g C_{org} (Bradshaw, 2005). Figures 9a and 9b illustrate good generation at the base of the formation and moderate generation at the top of the formation. Heavy oil is mainly generated. The rocks of the Bremer 6 Formation contain less mature OM ($0.61 \le Ro \le 0.72\%$; Figs. 4b, 4d) with a lower initial HI value (377 mg HC/g C_{org}). Correspondingly, the HC generation potential of the rocks of the Bremer 6 Formation is significantly lower than that of the Bremer 5 Formation (Fig. 9). Similar to the previous formation, heavy oil is mainly generated (Figs. 9c, 9d).

CONCLUSIONS

The asymmetric character of Gondwana breakup (Leichenkov, 2013) resulted in asymmetry in the tectonic structure and development of the adjacent passive margin areas of the Bremer sub-basin in southwestern Australia and the Mawson Sea in Antarctica. It was shown that the asymmetry caused significant differences in the history of hydrocarbon (HC) generation by the rocks of the Bremer 1–6 formations in the adjacent areas of nonvolcanic passive continental margins of Australia and Antarctica. Modeling suggested that the rocks of the Bremer 1 and Bremer 2 formations are mainly gas-prone in the Bremer basin in the passive margin of southwestern Australia and may become gas-prone in the Mawson Sea of the Antarctic margin. In contrast, the Bremer 4 and Bremer 5 formations can generate only a small amount of HC in the pseudowell 19-2012 area of the Bremer sub-basin and considerable amounts of heavy and light oil in the adjacent area of pseudowell 2 in the Mawson Sea.

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