

*Dedicated to the memory of Gleb Borisovich Udintsev,
an outstanding oceanologist, for his contribution
to the study of the World Ocean*

West Australian Ridge (Indian Ocean): Microcontinent or Large Igneous Province?

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Abstract—A comprehensive analysis of extensive primary (morphological, geological, geophysical, and geochemical—including deep-sea drilling) data provides deep insight into the morphostructure, geology, and evolution of the West Australian Ridge (WAR) (or Broken Ridge), which unambiguously testify to its continental origin. The northeastern slope was distinguished additionally to two previously known main morphostructural elements of the ridge: the northern and southern slopes. It is inclined towards the Naturaliste abyssal plain and structurally forms its northwestern framing. It has been established that the morphology of the slopes is caused by the peculiarities of the tectonic development of the adjacent basins. It is determined that the sedimentary cover of the central part of the northern slope contains a lower (basal) seismoacoustic complex, which has not been exposed by deep-sea drilling and formed no later than the Early Cretaceous. The final subsidence of individual fragments of the ridge and the formation of its present-day morphostructure, as well as the structural-tectonic rearrangement of the adjacent areas, occurred at the youngest phase of tectonic activation in the Late Miocene–Pliocene.

Keywords: block morphostructure, sedimentary cover, depression depocenter, paleotopography, knoll-structure, georiftogenial

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INTRODUCTION

Aseismic block uplifts are developed along margins and in central parts of the Indian Ocean. They differ in structure from riftogenic mid-ocean ridges and have a peculiar bottom morphology, which is not typical of other three oceans. At present, the continental nature of many such structures leaves no doubts. However, the nature of the West Australian Ridge (WAR), or Broken Ridge, according to western terminology, remains controversial. Its origin has been discussed for over 50 years by the proponents of two alternative concepts of ocean origin: oceanization of continental crust and plate tectonics (Udintsev, 1965b, 1986, 1989; Francis and Raitt, 1967; Udintsev and Koreneva, 1980; Kuzmin et al., 1981, 1983, 1984; Agapova et al., 1983; Mutter and Cande, 1983; Lisitsyn et al., 1984; Zhivago, 1985; Pavlenkova and Shablitsky, 1986; Turko, 1986; Illarionov, 1989; Driscoll et al., 1991; Munsch et al., 1992; Mahoney et al., 1995;

Frey et al., 2000, 2003; Tikku, 2000; Duncan, 2002; Udintsev and Il'in, 2006; Whittaker et al., 2013a; Bulychev et al., 2014, 2016; Williams et al., 2019; etc.).

In the last quarter of the 20th century, the WAR and Kerguelen plateau were interpreted according to the plate tectonic concept as fragments of a single oceanic-type uplift, which, owing to spreading, traveled to its flanks (Zhivago, 1985) (Fig. 1b). At present, proponents of plate tectonic theory believe that the formation of the WAR and Kerguelen plateau is related to the development of so-called large igneous provinces (LIPs) (Coffin and Eldholm, 1992, 1993, 1994; Frey et al., 2000). According to this concept, such provinces were generated by pulses of intense magmatic activity at the Mesocenozoic stage of geological evolution (Bryan and Ernst, 2008; etc.).

However, in our opinion, the final deciphering of the origin of the WAR is complicated by the absence of an integrated model compiled on the basis of the mor-

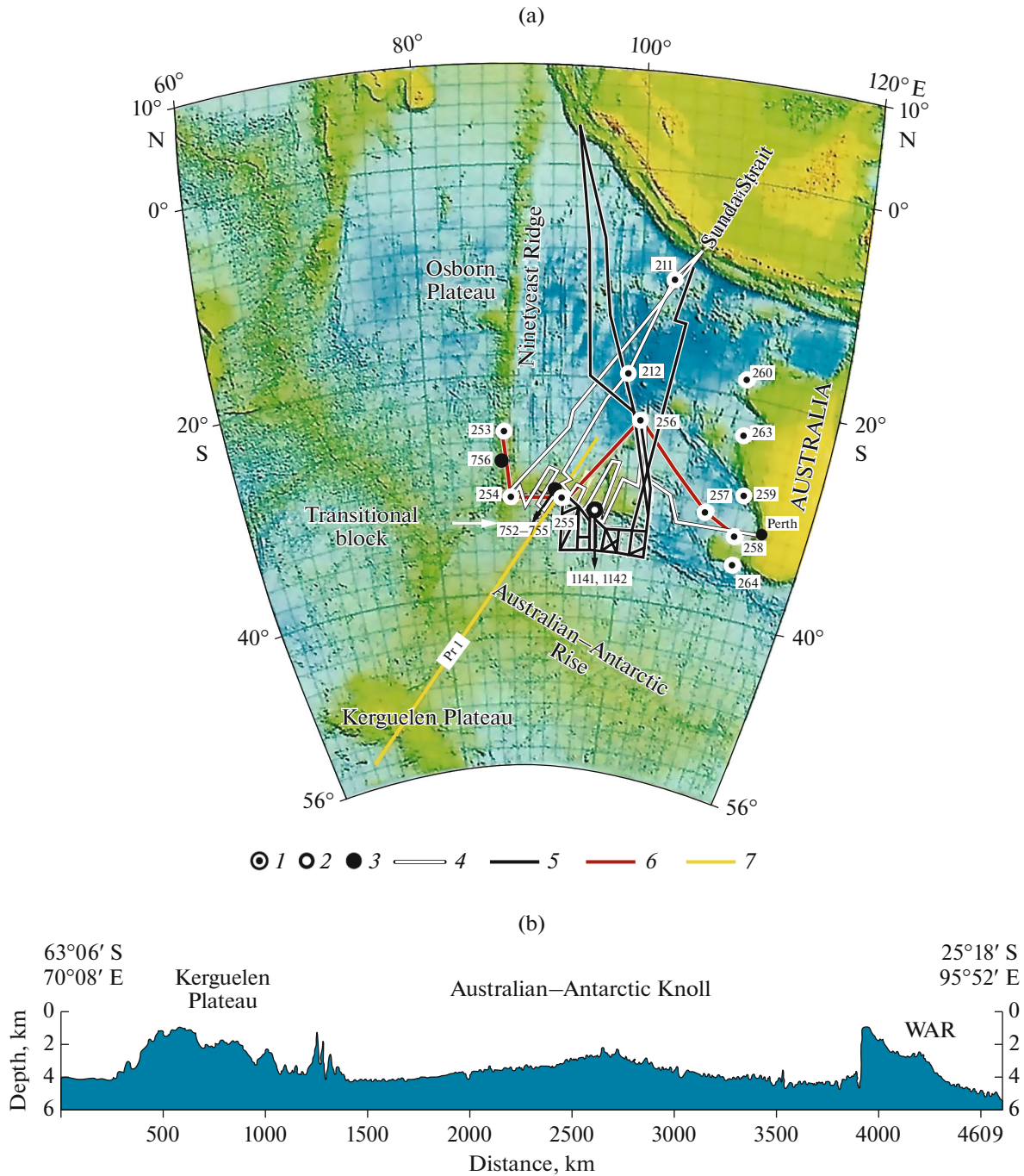


Fig. 1. Bathymetric chart of the eastern Indian Ocean, Lambert projection (a) and bathymetric section along profile 1 (b). (1–3) Deep-sea holes: (1) DSDP, (2) IODP, (3) ODP, (4) leg of R/V *Georgii Maksimov*, (5) cruise of the R/V *Dmitrii Laptev*, (6) cruise 2 of the D/V *Glomar Challenger*, and (7) profile 1.

phological, geophysical, and geochemical data obtained in numerous expeditions.

In their publications, the proponents of plate tectonics apply only to definite primary geological–geophysical information, first and foremost, “resonance data” that are very consistent with the LIP model,

while controversial data are ignored. In particular, among the available geological database spanning a wide spectrum of rocks of different genesis, their attention is mainly focused on basalts as the main component of igneous provinces. At the same time, the fragments of continental rocks over 1 t in weight

dredged from the northeastern slope of the Kerguelen Plateau are interpreted as “ice-rafted debris” transported from Antarctica (Montigny et al., 1993).

Works based on mobilistic ideas give no substantiated explanation for the clearly expressed blocked morphostructure of the WAR principally differing from rifting structures; for deep seismic sounding data, which suggest a subcontinental crust of the WAR; or for the anomalous magnetic field of the WAR, which is not similar to that of oceanic rifting systems. Thus, if the aforementioned and some other data are not taken into account, the plate-tectonic LIP model proposed for the origin of the WAR could be considered only in a simplified form of more complex evolution.

On the other hand, the consideration of the WAR as a fragment of continental crust surrounded by deep basins raises the question of a geodynamic mechanism of formation of the basins and, as a result, the isolation of the ridge from Gondwanan continents. At present, two alternative approaches are proposed to explain the origination of deepwater oceanic basins. According to the plate-tectonic model, they are formed on a continuously spreading oceanic crust during its cooling and subsidence according to the Parsons–Sclater curve (Parsons and Sclater, 1977).

The other point of view is based on the concept that the continental crust is transformed into a transitional (nonspreading) crust under the influence of complex tectonomagmatic and geochemical processes occurring during the intense interaction of the ascending mantle in the form of plumes, diapirs, fluids, and others with Earth’s crust. Such transformations require no significant horizontal extensions of the crust up to its breaking apart, and are well-studied on the continental margins and platform depressions (Belousov, 1982, 1989, 1991; Artyushkov, 1993, 2003, 2005; Pavlenkova, 1996, 2006; Frolova, 2001; *Okeanizatsiya...*, 2004; Artyushkov and Poselov, 2010; Orlenok, 2010; Artyushkov et al., 2013, 2014; etc.).

Results of deep-sea drilling, the study of bottom material, and observations from manned submersibles indicate the high-amplitude and usually rapid subsidence of the ocean floor, including aseismic ridges, which up to the final subsidence evolved under sub-aerial–shallow conditions (Rudich, 1983, 2004; Udintsev, 1989; Rudich and Udintsev, 1987; Blyuman, 1998, 2008, 2011; Gordienko, 1998, 2012; Ioganson, 2002; Lomakin, 2009, 2014; Lomakin et al., 2011; Yano et al., 2011; Illarionov et al., 2016, 2019; Illarionov et al., 2016, 2019; Illarionov and Boiko, 2017, 2018; Illarionov and Boyko, 2018; etc.).

It is obvious that the development of the morphostructure in a shallow setting is determined by not only tectonomagmatic processes, but also by definite paleogeographic environments, which significantly affected the morphogenesis. Therefore, much atten-

tion in this paper is given to the identification of relict landforms formed by exogenic processes.

This paper is based on the primary geological and geophysical data obtained during the expeditions of hydrographic vessels (H/V) *Georgii Maksimov* (1978–1979) and *Dmitrii Laptev* (1980), in which author of this paper, Illarionov, participated. The generalization and analysis of these data and materials of other expeditions, including the results of later foreign studies, supplemented with the available published data, provided a complete insight in the structure and history of the geological evolution of the WAR and its paragenetic relations with adjacent basins (Fig. 1a).

PREVIOUS STUDIES

A spacious rise west of Australia has been long known, being confirmed by the 3rd edition of the General Bathymetric Chart of the Oceans (GEBCO) (*Carte Generale...*, 1938–1942). Unclear outlines of this rise, called the Southeast Indian Ridge, have been preserved for long time on postwar charts (King, 1962). Moreover, the name West Australian Ridge pertained to another (inferred) rise extending oceanward from the northwestern termination of the Australian continent (Fairbridge, 1955). Only studies during Cruise 35 of the R/V *Vityaz* in 1963 established that the area indicated by Fairbridge is not a ridge but two block uplifts, later called Wallaby and Zenith. This cruise also provided the first reliable data on the morphology of the ridge, which is located 300 miles west of Australia and initially called the Latitudinal Indo-oceanic Ridge (Bezrukov, 1963). It was later labeled the West Australian Ridge on Russian charts (Bezrukov and Kanaev, 1963; Kanaev, 1964, 1964, 1965; Udintsev, 1965a and Broken Ridge in foreign publications (Heezen and Tarp, 1965) (Figs. 2, 3).

Studies according to programs of the International Geophysical Year (1957–1958) and International Indo-oceanic Expedition, IIE (1959–1966), made it possible to obtain within a short time comprehensive data on the structure of the entire Indian Ocean floor and the WAR, in particular. These projects, accomplished by 46 R/V vessels from 13 countries, used widely accepted methods such as echo sounding, geomagnetic and gravity survey, continuous seismic profiling (CSP), and deep seismic sounding (DSS). Vessels equipped with trawl winches collected bottom grounds, including dredging bedrocks that compose the crystalline basement.

These studies resulted in the compilation of a geological–geophysical atlas of the Indian Ocean under the edition by Udintsev (1975), which could be regarded as a great scientific achievement. Cartographic generalization of geological and geophysical data for the atlas were prepared by the international scientific team, while its publication was sponsored by UNESCO.

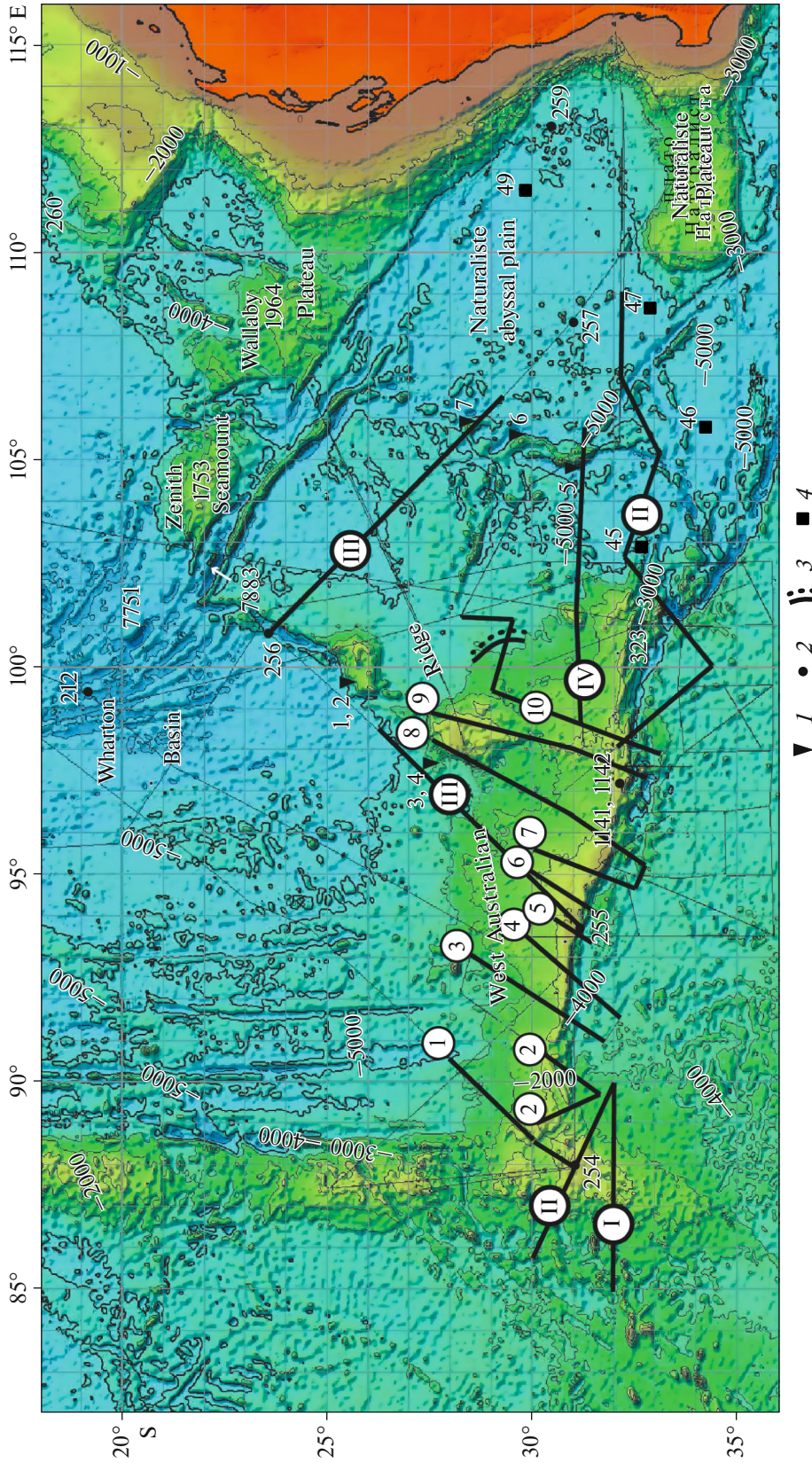


Fig. 2. Position of seismoacoustic and bathymetric profiles in the eastern Indian Ocean used in the paper. (I) Dredging sites (after (Williams, 2011)), (2) position of holes and their numbers, (3) abrasion scarp, and (4) DSS stations after (Francis and Raitt, 1967). Circled numbers: (1–10) leg of the H/V *Georgii Maksimov*; (I) Bathymetric profile of the R/V *Atlantis II* (1965), section along profile see in Fig. 6d; (II) Seismoacoustic profiles of the R/V *Eltanin* (ELT-48, 1971), for sections along profiles see Figs. 4 and 6c; (III) seismoacoustic profiles of the D/R *Glomar Challenger* (Cruise 26, 1972), sections along profiles are shown in Figs. 8a and 10a; (IV) bathymetric profile of the R/V *Knorr* (KN 145 L6, 1995), section along profile is shown in Fig. 10c.

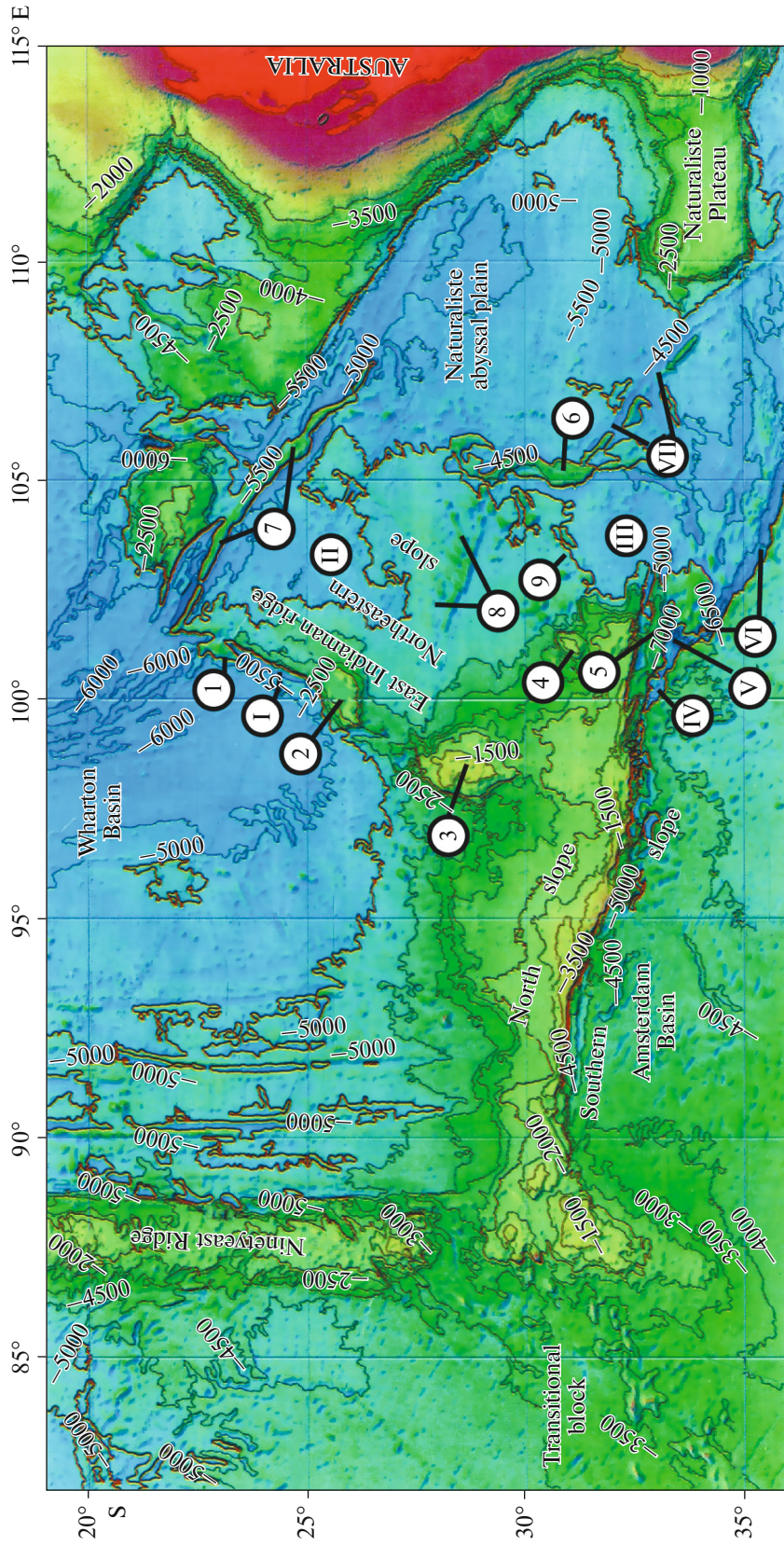


Fig. 3. Main morphostructural features of the WAR and adjacent areas. Circled numbers: (1–9) positive structures: (1) Stone Knoll; (2) Batavia Knoll; (3) Gulden Draak Knoll; (4) Udintsev Knoll; (5) L'espoir horst block; (6) Direk Hartog Ridge; (7) Lost Dutchmen Ridge; (8) Endracht horst block; (9) Tryal Ridge; (I–VII) negative structures: (I) Follau trench; (II) Northern Basin; (III) Broken basin; (IV) Ob trench; (V) Dordrecht Basin; (VI) Diamantina trench; (VII) Naturaliste trench.

Studies of the WAR provided definite concepts on its nature. In particular, characteristic morphostructural features allowed Heezan and Tarp (1965) for the first time to ascribe the WAR to “microcontinents.” DSS studies showed that the WAR crust is 20 km in thickness and can be subdivided into seismic layers with P-wave velocities of 5.81, 6.07, and 6.43 km/s, which are typical of the “granitic” layer of continental crust. The velocity section of the crust allowed authors of the seismic experiment, Fransis and Raitt (1967), to ascribe the WAR to “almost continental structures,” assuming that the WAR and Naturaliste Plateau are affiliated with the West Australian crystalline shield. The existence of a “root” beneath the WAR was later confirmed by seismological data, according to which the thickness of crust accounted for 20–22 km (Souriau, 1981). Similar conclusions were obtained by other researchers on the basis of similarity of sedimentary cover of the WAR and Naturaliste Plateau (Burckle et al., 1967; Laughton et al., 1970; Petkovic, 1975). The similarity of quartz dolerites dredged during Cruise 36 of the R/V *Vityaz* in the eastern WAR (Station 5332, 31°40′ S, 101°30′ E) to the rocks of ancient shields of Australia and Antarctica supported these conclusions (Udintsev, 1965a).

DSDP hole 255 was drilled during Cruise 26 in 1972 in the framework of the DSDP project on the WAR crest (31°08′ S, 93°43′ E). As was mentioned in the report (Initial Reports of DSDP, V. 26), the drilling was stopped in extremely solid cherts dated by the Santonian (Late Cretaceous). Drilling results made it possible to perform the chronostratigraphic correlation of sediments of the upper sedimentary cover with refractory boundaries of seismoacoustic sections and to establish the lithological composition of corresponding horizons. However, the main question—the composition and age of the lower part of the sedimentary sequence and basement—remained unsolved.

The results of these studies allowed Pushcharovsky to draw the following conclusions (Pushcharovsky and Bezrukov, 1973):

- (i) the existence of lithospheric plates diverging from rift zones of the mid-ocean ridge was not confirmed;
- (ii) the ocean floor in the Mesocenozoic evolved from shallow water conditions to the present-day depths;
- (iii) the “newly formed” North Australian, Cuvier, and Perth (Naturaliste) basins were formed at the beginning of Cretaceous under conditions of “extension and subsidence of the corresponding segments of the Earth’s crust”;
- (iv) the WAR, Naturaliste Plateau, and Zenith (Cuvier) and Wallaby horst massifs are distinguished as relict fragments of continental structures.

The evolution of ideas of new global tectonics in 1970–1980s has significantly increased interest in aseismic ridges. This was explained by the following

facts. The continental nature of these ridges is poorly consistent with the existing plate tectonic concepts, while oceanic nature requires the significant complication of kinematics of lithospheric plates. It was assumed that the lithospheric plates are characterized by a wide range of spreading velocities and complex schemes of their rotation relative to theoretically calculated poles. Their motion could be accompanied by the extinction and multiple jumping of spreading axes; conditions were also taken into account when the movement of the plate could be stalled as a result of its “jamming” in the subduction zone. This finally gave rise to new postulates explaining the plate-motion mechanism and generated new hypotheses for the origination of aseismic ridges (Wilson, 1973; Curray and Moor, 1974; Vogt and Johnson, 1974; Luyendyk and Rennick, 1977; etc.).

An initially logical plate tectonic hypothesis later became overloaded with “any horizontal motions in lithosphere” (Belousov, 1982).

Given the importance of deciphering the origin of the WAR in the context of a new geodynamic paradigm, several expeditions have been undertaken since the end of 1970s. In 1978–1979, the structure of the ridge was studied according to program launched by the Schmidt Institute of Physics of the Earth, Academy of Sciences of the Soviet Union. The works were carried out on the H/V *Georgii Maksimov* under the leadership of Udintsev and Pavlenkova (1979). Ten submeridional bathymetric, magnetometric, and seismoacoustic profiles were run across its strike. In addition, deep seismic sounding (DSS) was made in four points and supplemented by seismological observations in the DSDP-254 area.

Of special importance is continuous seismoacoustic profiling (CSP) data. The CSP was carried out using an instrument developed at the Laboratory of Seismoacoustics at the Faculty of Geology of Moscow State University by V.A. Struchkov and L.A. Vanyakin. The instrument consisted of an electric spark source (sparker) of signals up to 30 kJ in power, a seismic cable with 64 PDS-21 piezoelectric hydrophones, and modified *Gorizont* recording station. Refracted signals were received and recorded within a range of 50–120 Hz (*Geologo-geofizicheskie...*, 1986).

In 1980, the expedition of PGO Yuzhmoregeologiya on the H/V *Dmitrii Laptev* studied the Amsterdam Basin in contact with the southern WAR slope in detail and passed four regional profiles, which intersected the poorly studied eastern part of the ridge. Materials of these studies significantly supplemented the database obtained by the H/V *Georgii Maksimov* (Ilyukhin et al., 1987; Golovinskii and Kara, 1990; etc.).

The integrated geological–geophysical studies were carried out at two small test sites in the central part of the southern slope of the ridge during Cruise 25 of the R/V *Dmitrii Mendeleev* organized by the Institute of Oceanology of the Academy of Sciences of the

Soviet Union in 1980. The southern slope of the WAR was also studied by the Institute of Oceanology using Paisis-VII and Paisis-XI manned submersibles with the sampling of a unique collection of geological samples during cruise 7 of R/V *Akademik Mstislav Keldysh* in 1983–1984. Participants of both expeditions arrived at conclusion that the WAR has typical oceanic nature and was formed owing to the active magmatic activity in the rift zone of the mid-ocean ridge (Kuzmin et al., 1981, 1983, 1984; Lisitsyn et al., 1984; Zhivago, 1985; etc.).

In 1986, American scientists from the Lamont–Doherty Earth’s Observatory during Cruise 2708 of the R/V *Robert Conrad* performed a detailed seismoacoustic survey on the test site in the DSDP-255 hole area in order to choose a site for repeated deepwater drilling. The geophysical studies were supplemented by geological works in three sites on the southern slope: dredge 8 (32°24’ S, 98°20’ E), dredge 9 (31°24’ S, 93°20’ E), and dredge 10 (31°14’ S, 93°42’ E) (Mahoney et al., 1995). In 1987–1988, the ODP legs of the D/V *Joides Resolution* performed drilling on the WAR and the Kerguelen Plateau. The WAR was recovered by four holes 752–755, which are located on a 28-km profile oriented orthogonally to the extension of the ridge crest. The profile strikes 20 km west of DSDP hole 255. None of the four holes did reached the basement, while ODP hole 755 was terminated in the Upper Cretaceous (Turonian) sedimentary rocks, which are the oldest deposits recovered by boreholes on the ridge (*Proceedings...*, 2000).

Two holes, IODP-1141 and IODP-1142B, were drilled in the eastern part of the ridge, 350 km away from DSDP-255 hole during IODP Leg 183 of the D/V *Joides Resolution* in 1998–1999. They recovered about 100 m of sediments, the oldest of which are the Middle Eocene sandy limestones, and passed 50–70 m in the basaltic basement dated by K–Ar to be 94–95 Ma (Frey et al., 2000; *Proceedings...*, 2000; Duncan, 2002).

Proponents of plate tectonics consider the results of deep-sea drilling as an argument in support of the existence of the Kerguelen–WAR large igneous province (LIP), which was formed approximately 94–95 Ma owing to the activity of the Kerguelen hot spot (Duncan, 1991; Coffin and Eldholm, 1992, 1993; Frey et al., 2000, 2003; Tikku, 2000; Duncan, 2002; Gibbons et al., 2012; etc.). About 43–47 Ma, this province was broken off along the rift axis of the Australia–Antarctic mid-ocean ridge. After the break off, which lasted for 3.0–7.5 Ma, spreading caused the displacement of the WAR and the Kerguelen Plateau on the flanks of the mid-ocean ridge (Fig. 1b).

Thus, this brief review allowed us to distinguish two stages in the WAR study. At the first stage, conditionally completed in the mid-1970s, well-known Soviet and foreign researchers made conclusions about the continental nature of the WAR. Under the influence

of the increasingly popular plate-tectonic model, the WAR was considered an oceanic structure, while previously obtained conclusions on its continental nature were discarded or interpreted differently.

METHODOLOGICAL FEATURES OF THE OCEAN FLOOR STUDY

Morphostructural and structural geological methods of studying the ocean floor are the most informative, but their opportunities are technically restricted by visual observations over spacious ocean-floor areas. Therefore, the main method for studying submarine topography is echosounding, the opportunity of which increases, which is expressed in the application of side-view locators and multibeam echo sounders. In the United States, these methods are supplemented by satellite altimetry Shuttle radar topography mission (SRTM), which yields high-resolution digital bathymetry data. SRTM data array are available on an open-access basis.

However, confident genetic identification is possible in the present-day bathymetric charts only for some tectonic forms, for instance, for large-amplitude normal-fault scarps or deepwater trenches and tectonic landforms of unambiguous origin (for instance, conical volcanic edifices). It is much more difficult to identify landforms that were produced by exogenic processes under a paleoterrestrial, subaerial, or shallow-water environment and which, at present, represent ocean floor topographies that subsided at a depth of over 5 km. These forms include are the denuded surfaces of some seamounts, marine abrasion–accumulation terraces and plains, riverbed valleys, and others. Recognizing such paleotopographies is a very important morphogenetic problem.

More detailed information from integrated bathymetric and seismoacoustic sections can be obtained using structural geological methods in combination with seismostratigraphic analysis. However, the most comprehensive and reliable information is provided by an integrated analysis of seismoacoustic, geophysical, and geochemical data with allowance for the results of deep-sea drilling and manned submersible observations.

The aforementioned methods are described in numerous scientific–methodological textbooks, in particular, in the *Methodological Guidebook on Geomorphological Studies* (1972), *Seismic Stratigraphy* (1977), *Structural Geology* (1986), *Youngest Tectonics and Geodynamics of Lithosphere* (1988), *Sedimentation Settings and Facies* (1990), *Regional Seismostratigraphy* (1998), *Problems and Methods of Studying the Geological Structure and Mineral Resources of the Shelf* (2004), and *Seamount Terraces and Tectonics of the World Ocean Floor* (2014).

MORPHOSTRUCTURE OF THE WAR

The WAR is the second largest aseismic rise in the eastern Indian Ocean after the Kerguelen Plateau. Its extension in the sublatitudinal direction, including the structurally related southern block of the Ninetyeast Ridge (NER)¹, reaches 1700 km.

The morphology of the WAR is peculiar in its asymmetric structure in submeridional direction. A steep southern slope with dip angles up to 20°–30° and gentle northern slope subsiding at 1°–5° toward the Wharton basin are distinguished on the corresponding profile (Fig. 1b). An analysis of regional bathymetric profiles and seismoacoustic sections, as well as the study of morphostructural features of this region, made it possible to distinguish the third main morphostructural element of the WAR: the northeastern slope. It has a general inclination toward the Naturaliste abyssal plain and forms its northwestern framing (Figs. 2, 3).

Below we consider the features of the southern, northern, and northeastern slopes.

Southern Slope of the WAR

In terms of morphostructural features, the southern slope can be subdivided into eastern, central, and western parts.

The eastern part. This segment has an end conjugation with the Diamantina trench, which in the 101.5° E area joins almost orthogonally the southern slope and ends with a deep graben, which is expressed as the Dordrecht Hole. The graben depth reaches 7.1 km, while the trench near the graben reaches 7.4 km. The trench length is 1300 km (Figs. 3, 4). The Ob trench is extended in the WNW direction up to 99.5° E from the Dordrecht Hole. In topography, it is expressed by two separate graben trenches, the contours of which approximately correspond to 5000 m isobaths; the maximum depth reaches 6.1–6.2 km. The depth of the Ob trench is much less than that of the Diamantina trench, but both the trenches and connecting graben have the maximum depth within the entire southern slope of the WAR. Given that the minimum depth of the L'esoir Ridge adjacent to the Dordrecht Hole is 323 m, the vertical gradient of the eastern part of the southern WAR Slope is 5.5–6.0 km.

Estimating an amplitude of faulting in the eastern part of the southern slope, attention should be focused on the structure of the graben in the crest part of the

ridge, the walls of which are complicated by a series of antithetic normal faults, along which an amplitude of “telescopic subsidence” could be 1.5 km (Fig. 5b). Thus, the vertical shift along the normal fault in the eastern part of the southern slope is 7.2 km.

The central part. The central segment is extended in the western direction up to 93.5° E. The characteristic feature of this segment is that the southern slope is significantly shifted southward (Fig. 5a) and complicated by large normal fault blocks or “bastions” after (Zhivago, 1985). These blocks form a structural salient up to 100 km wide, which provides a characteristic bending of the southern slope to the south and stands out against smoothed topography of the adjacent part of the Amsterdam Basin with depths 4.3–4.5 km. A sharp peak similar to those that crown the crest of the eastern WAR was described on one such block, which was intersected by the transitional leg between 7GM and 8GM profiles in a point with coordinates of 95°20' E and 32°40' S.

The blocks are separated by grabens reaching 5.5 km in depth. The grabens are filled with sedimentary material with an admixture of redeposited Paleogene and Late Cretaceous planktonic remains, which were likely supplied from eroded areas of the ridge crest (Kuzmin et al., 1984).

The calculations showed that the maximum vertical block displacement at the fault surface dip at 60°–70° is approximately 3.6 km. The shift was compensated by horizontal extension no more than 2 km (Illarionov and Yakovlev, 1986). Indeed, an angle of the southern slope is no more than 20°–30°, which is explained by its destruction by tectonic and erosion-denudation processes.

The western part. This segment, in the form of a normal fault, is traced up to approximately 90.5° E. At this segment, the southern slope has practically WE extension along 31° S and is characterized by significant weakening of fault tectonics, which is expressed in the reduction of amplitude of the vertical component of the normal fault up to 1000–1500 m. Diapir structures (dikes), distinguished as the dike and trench province, are distinguished near the slope foot. The trenches have different depths, which likely indicates their relative isolation and differentiated evolution. Thus, they can be considered compensation subsidence basins. They are filled with horizontally lying sediments, the maximum thickness of which reaches 300–400 m. The upper layers of the sedimentary sequence are dated at Neogene–Quarter (Ilyukhin et al., 1987; Kara et al., 1987). The deepest basins are united into a single extended trench, which is outlined by 4.5-km isobaths and extends parallel to the foot of the southern slope (Figs. 6a, 6b).

The transitional block. The southern slope of the WAR in its westernmost point (90.5° E) forms a sharp bending to the southwest and is transformed into the eastern slope of the transitional block, which is char-

¹ In a structural plan, the southern block of the NER serves as a linking chain between orthogonally oriented NER and WAR. Given its “dual” position relative to both ridges, for the sake of convenience, the “southern block of the NER” and the western block of WAR” are termed as the “transitional block” (Fig. 3). The structure and history of the geological evolution of the transitional block were considered in detail (Illarionov and Boyko, 2018). Therefore, in this paper, we report only brief data on this structure.

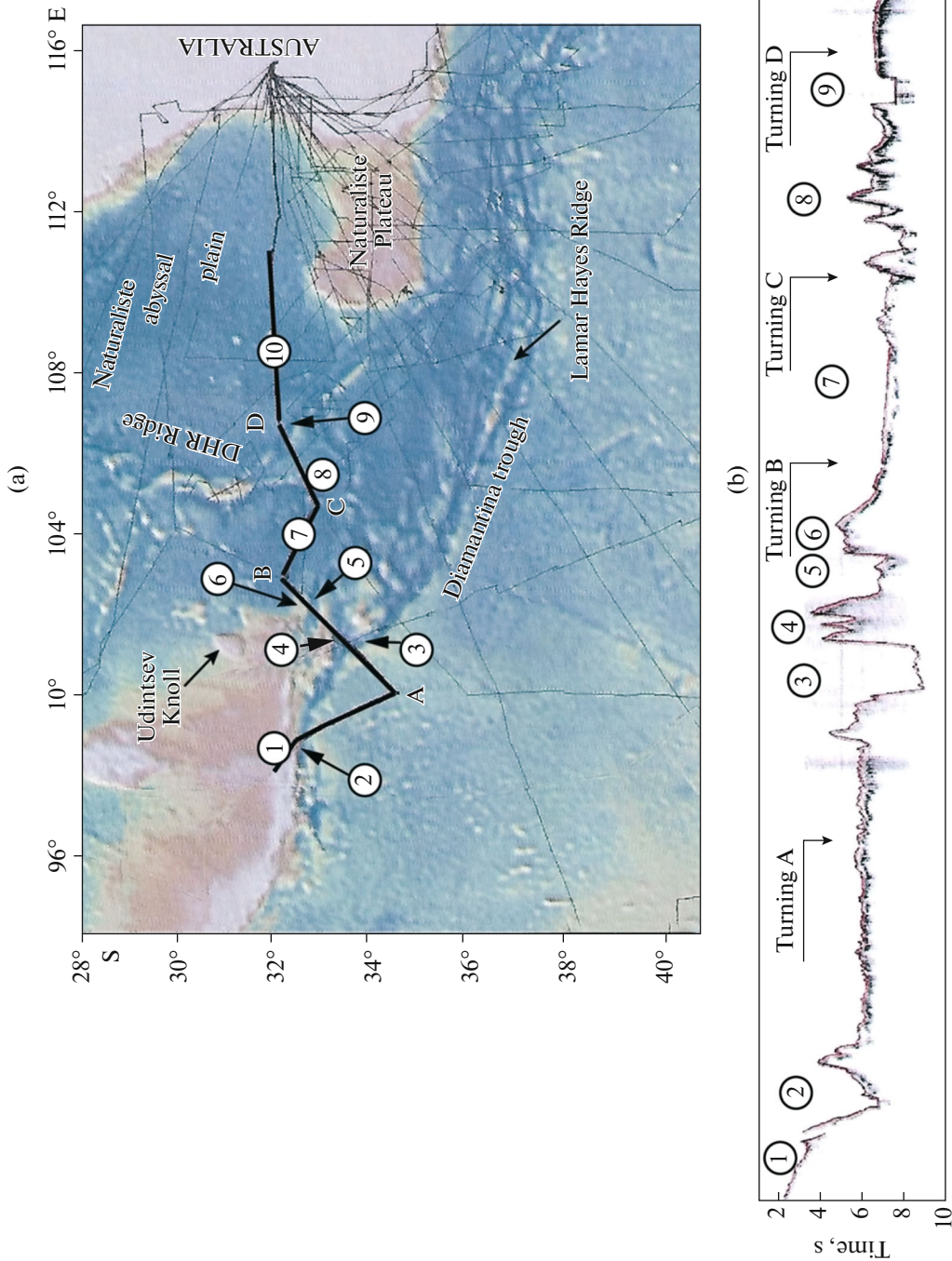


Fig. 4. Position of the profile (a) and seismoacoustic section (b) along the leg of the R/V *Eltanin* (ELT-48, 1971). Circled numbers: (1) southern slope of the WAR; (2) Ob trench; (3) Doredrecht Basin; (4) L'espoir block; (5) linearly extended graben; (6) eastern termination of WAR; (7) Broken Basin; (8) southern spurs of the Dirk Hartog Ridge; (9) Naturaliste trench; (10) Naturaliste abyssal plain.

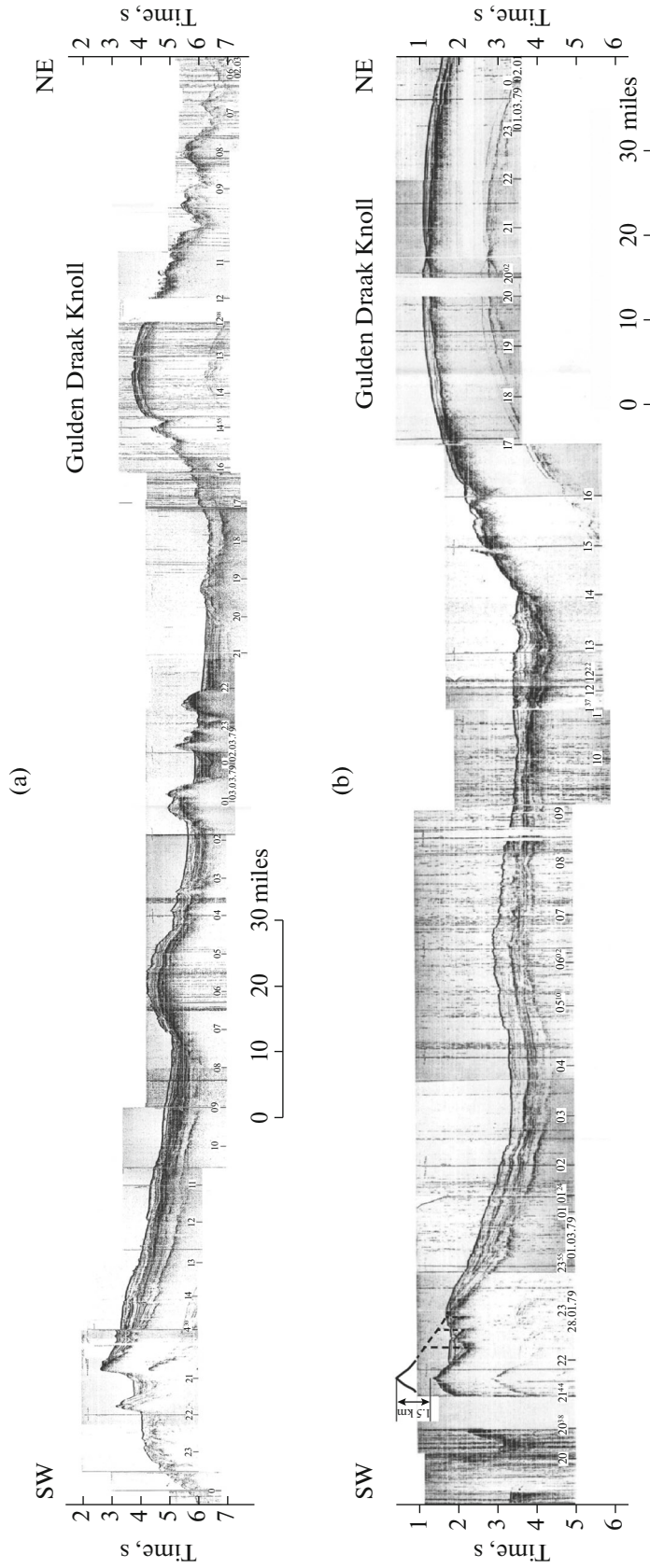


Fig. 5. Seismoacoustic sections along profiles 8GM (a) and 9GM (b), which characterize the eastern part of the WAR. Position of profiles is shown in Fig. 2.

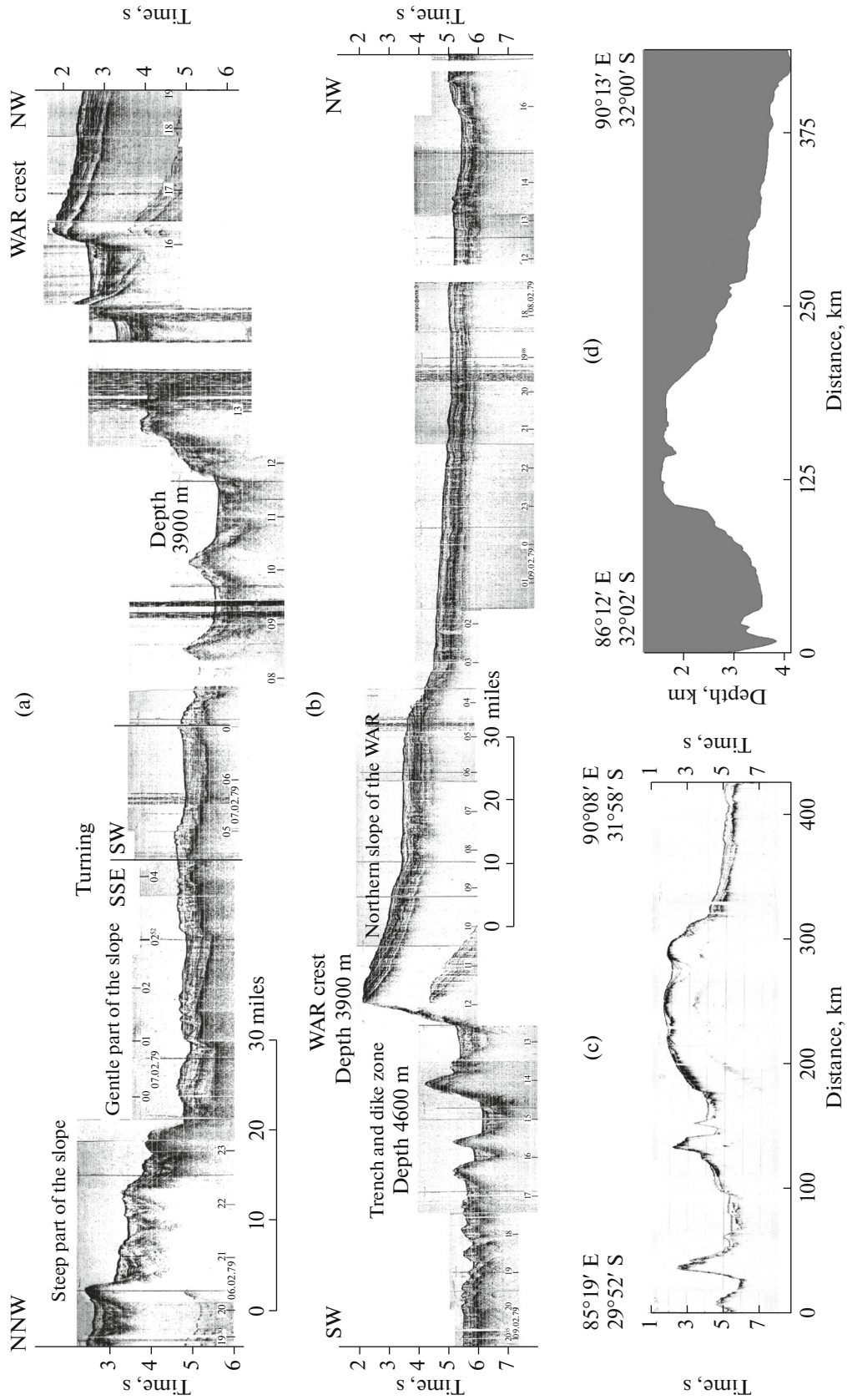


Fig. 6. Seismoacoustic sections along profiles 2GM (a), 3GM (b), ELT-48 (c) and bathymetric profile of the R/V *Atlantis II* (d), which characterize the structure of the western WAR, transitional block and its eastern slope. Position of profiles is shown in Fig. 2. The ELT-48 section and the bathymetric profile clearly show the denuded leveled surface of the transition block.

acterized by a gentle inclination, as is emphasized by the radial arrangement of 3.0, 3.5, and 4.0 km isobaths (Fig. 3). It is seen that the transitional block consists of the upper relatively steep and lower more gentle parts (Figs. 6a, 6c, 6d). The upper step of the slope in the area of transitional block approximately up to a depth of 2.0–2.5 km is complicated by low-amplitude normal faults and magmatic protrusions, which are typical of the adjacent dike and trench province. The lower part of the slope is located within depths from 2.5 to 4.3 km. It represents a smoothed low-angle surface of subsided block with an extremely thick sedimentary cover (Figs. 6a, 6c). It is seen in the seismoacoustic sections that the block surface is the roof of stratified and deformed sequence, whose topography retained traces of erosion activity. Young cover sediments are practically absent. The section of the 400-m sedimentary sequence comprises several angular unconformities which correspond to the chronostratigraphic sedimentation gaps.

In terms of structural morphological and seismostratigraphic features, the structure of the sedimentary sequence on the subsided block is similar to that of the WAR northern slope. It is seen in sections 2GM and 3GM that the sedimentary cover and the basement of the northern slope are truncated by normal fault (Figs. 6a, 6b). The absence of data does not allow us to determine how far the sedimentary cover extends on the subsided block southward, but its structural relationship with the northern wall of the Australian–Antarctica knoll-like rise seems obvious.

The transitional block is neither a riftogenic nor a magmatic structure. During the Cretaceous, it remained a high-stand block and evolved mainly in subaerial conditions, which resulted in the formation of well-expressed denudation smoothed surface (Figs. 6c, 6d). Only in the end of the Miocene was the setting replaced by a general subsidence. Therefore, it is obvious that the youngest tectonic phase significantly affected the morphology of the transitional block and adjacent areas (Illarionov and Boyko, 2018).

According to Udintsev, the transitional block serves as “hinge rock,” which provides a strong structural link between the WAR and NER (Udintsev, 1986, 1989). Its structural–tectonic position is inconsistent with existing plate-tectonic schemes of the “opening” of the Indian Ocean, in which the NER is considered a “tracer” ridge, while the WAR serves as the northern fragment of a magmatic province. Therefore, following the plate tectonics, Zhivago distinguished a wide basin between the WAR and NER (Zhivago, 1985).

The features presented above indicate that all three parts of the southern WAR slope is characterized by specific features. In this way, the southern slope over its entire length shows no signs of listric normal faults and one-sided (overturned) grabens, which are signs of the initial rifting phase of the crustal extension or

divergence of lithospheric plates. In addition, the sub-latitudinal extension of the WAR is 1700 km, while the length of the southern slope is less than 1300 km, which is not consistent with the inferred existence of trans-fault zone, which, according to the plate-tectonic considerations, provided the break-off and subsequent divergence of the WAR and Kerguelen Plateau.

The formation of the southern WAR slope was related to the vertical movements in different directions on the contact of the high-stand stable continental block and subsiding northern flank of the Australian–Antarctic georiftogen². Morphologically, the latter rather resembles the Pacific type arched rise than the typical mid-ocean ridge of the Indian Ocean. At a width of 2600 km, a relative height of 2 km, and the absence of a clearly expressed rift gorge, it is at the incipient stage of its evolution.

According to Udintsev, the southern slope of the WAR marks the limits of the riftogen mid-ocean rift system, thus demonstrating the limited development of the riftogen process and large-scale manifestation of the destruction of continental massifs in the ocean (Udintsev, 1986).

Northern Slope of the WAR

It is seen in the bathymetric chart (Figs. 2, 3) that the foot of the northern slope of the WAR approximately coincides with 5-km isobath, while the slope as “amphitheater” envelopes the Wharton Basin from the southern side. This basin, with a maximum depth of 7751 m, is the deepest area, the depocenter of the Western Australian megabasin. Morphostructurally, the northern slope can be subdivided into the central and western parts, the boundary between which passes at 91°–92° E.

The central part. The structure of profiles 4GM, 5GM, GM, and 7GM (Figs. 7, 8) shows that the central part of the northern slope of WAR is a gently inclined surface. Based on this morphological feature, some authors ascribe the WAR to submarine plateaus (Udintsev, 1987) or carbonate platforms (Driscoll et al., 1991). Regional CSP sections indicate that the sedimentary cover extends for a distance of about 500 km. Therefore, the northern slope, in terms of occupied area, should be considered a transitional shelf area between relict continental margin and marine paleobasin. The surface of the northern slope is practically devoid of loose deposits, which provided a good preservation of accumulation–abrasion landforms. The absence of sedimentary-cover smoothing of the topography indi-

²The term “georiftogen” was introduced by Vinogradov and Udintsev (Vinogradov et al., 1969; Udintsev, 1969) in order to emphasize the morphostructural, petrological, geochemical, geophysical, and geodynamic features of the midocean ridges, which cannot be explained from the plate tectonic concept, according to which midocean ridges are not structural system, but represent parts of the lithospheric plate that were uplifted above the ascending jets of mantle convection.

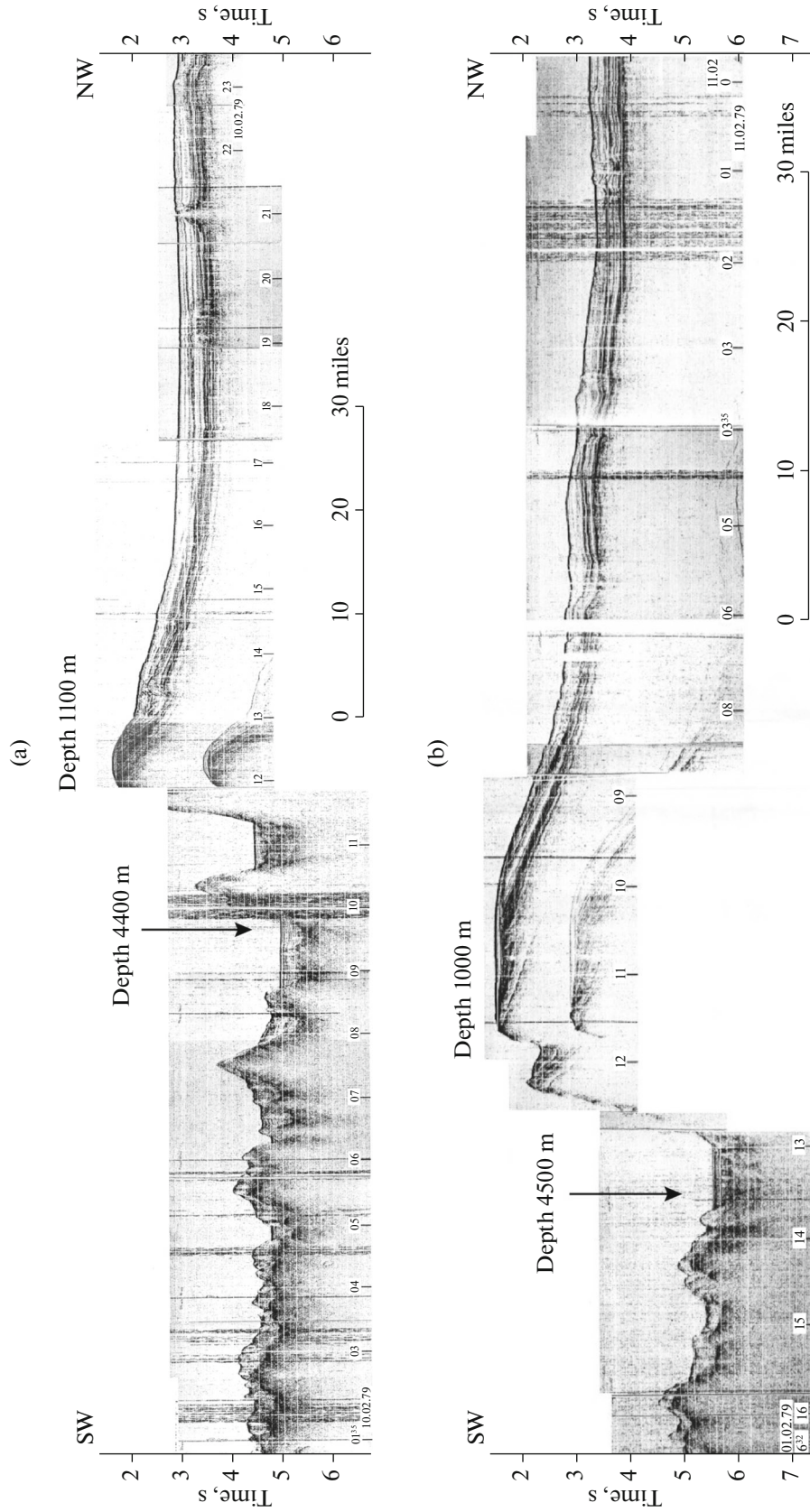


Fig. 7. Seismoacoustic sections along profiles 4GM (a) and 5GM (b), which characterize the central part of the northern slope of the WAR. Position of the profile is shown in Fig. 2.

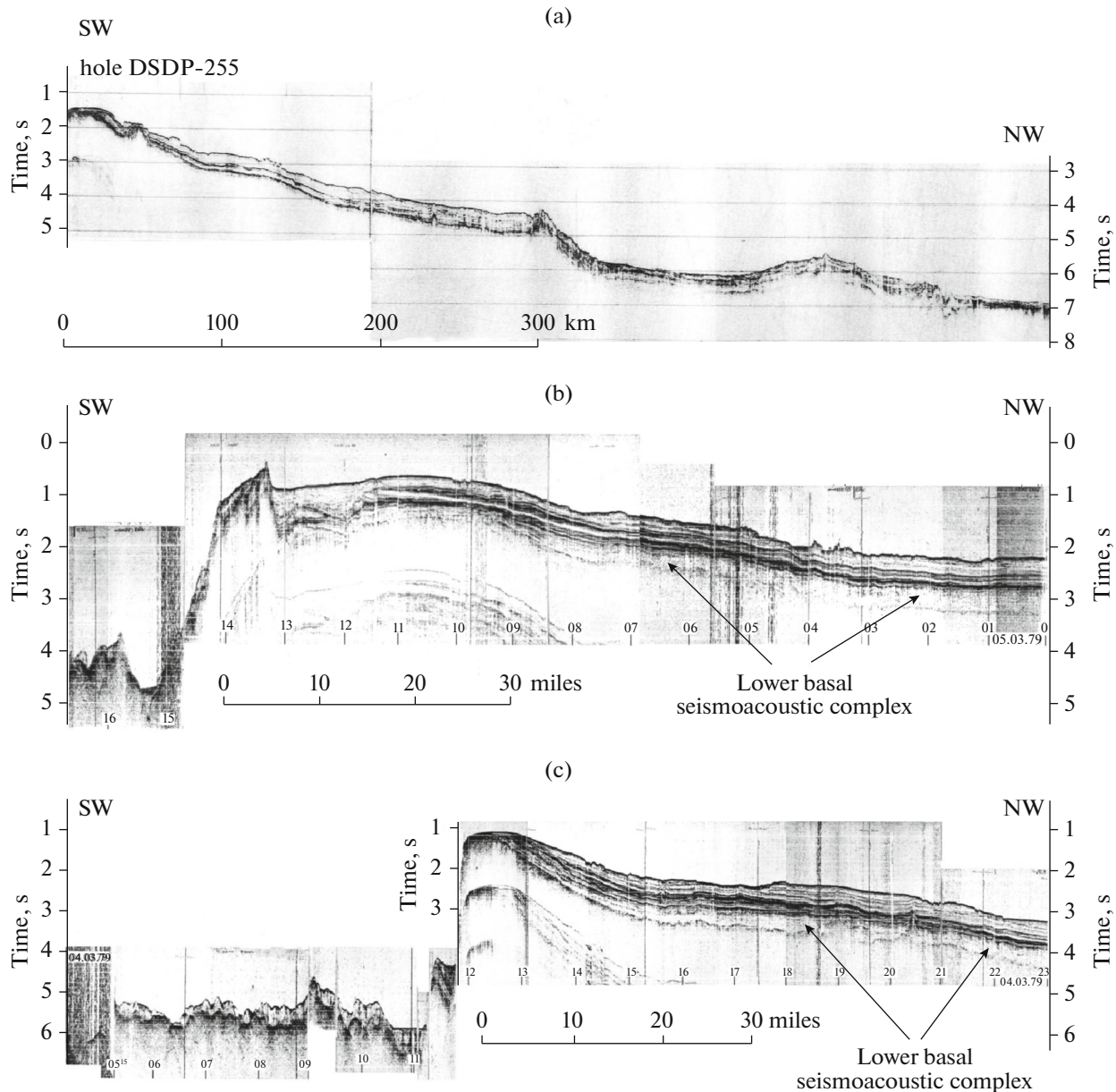


Fig. 8. Seismoacoustic sections along legs of the D/R *Glomar Challenger* (a), 6GM (b), and 7GM (c), which characterize the structure of the central part of the northern slope of the WAR. Position of profiles in Fig. 2. The lower sedimentation profile filling the trough in the crystalline basement of the WAR northern slope is well traced in sections 6GM and 7GM.

cates that the final subsidence of the northern slope was rapid and occurred during neotectonic activation. A terrace 450 km from the edge of the southern slope and at a depth of 3500 m provides insight into spatial limits of sea regressions and amplitude of the final subsidence of the northern slope.

The sedimentary cover of the central part of the northern slope comprises sedimentation complexes separated by regional angular unconformities, which correspond to the sedimentation gaps and partial erosion. The oldest sediments recovered by deep-sea drilling are ascribed to the Turonian. Therefore, the sedimentation sequence of the sedimentary cover

highlights the alternation of transgressive and regressive phases of sea-level fluctuation during Late Cretaceous and Cenozoic.

An analysis of seismoacoustic sections 6GM and 7GM showed that the sedimentary cover is underlain by a basal complex, which was not recovered by deep-sea drilling and, with unconformity, rests on the crystalline basement. In the time scale, it occupies an interval of about 0.3–0.5 s (Figs. 8b, 8c). Given that the lower complex in the velocity section corresponds to a seismic layer with seismic wave velocities of 4.4–4.5 km/s, its thickness may reach 400–600 m. With allowance for the thickness and significant extension

of the lower complex, its formation can be ascribed to the Early Cretaceous.

The western part. The study of the section along the 1 GM profile shows that the topography of the northern slope in this part acquires typical tectonic features. It looks like a multistep normal fault along which the layers of sedimentary cover and acoustic basement are displaced (Fig. 9a). The upper step, which corresponds to the peaked surface of the transitional block, is located at a depth of 1.2–1.5 km. Below, the steps are distinguished at depths of 1.9, 2.4, 3.5–4.0, and 4.7–5.0 km. Thus, the amplitude of the total displacement along normal faults is 3.5–3.7 km. The deepest subsided block, corresponding to the lower step, is overlain by the basaltic cover widespread on the Wharton basin floor.

The fourth step, which inclined gently toward the Wharton Basin, is noteworthy. The high content of sand fraction (up to 10–30%) in the bottom sediments at lowered content of finely dispersed deepwater fractions (*Geologo-geofizicheskii...*, 1975) indicates that this accumulation plain was formed relatively recently under a high hydrodynamic sea activity. Based on analysis of benthic foraminifers from the DSDP-254 hole, the shallow-water paleogeographical environment corresponding to the coastal–marine plain conditions has existed in this region as early as 5–7 Ma, and only in the end of Miocene did the subsidence amplitude reach the upper bathyal depth (Saidova, 1986).

Given these facts, we may conclude that the subsidence amplitudes of the western and central parts of the northern slope relative to the WAR crest were practically identical: 3.5–3.7 km. However, the formation of the morphostructural appearance of the western part of the ridge, including the transitional block, was mainly controlled by fault tectonics, whereas the subsidence of the central part is smooth, without large tectonic ruptures.

Northeastern Slope of the WAR

Only general and usually contradictory concepts are available on the structure of the region between the WAR and the western continental margin of Australia. Of particular controversy is the structural boundary between the WAR and the abyssal plain of the Naturaliste. According to Udintsev, the area between the East Indiaman Ridge and the Tryal Ridge is the lower step of the slope (Udintsev, 1986) (Fig. 3).

According to the paleotectonic schemes constructed in compliance with the plate tectonic concept, this region within 130–36 Ma was spanned by a complex opening of the Indian Ocean. Up to the incipient rifting between India and Australia, the Batavia Knoll was located north of the Naturaliste Plateau, while the Gulden Draak Knoll was south of it, so they were affiliated to the Western Australian shield. At the first stage of rifting, these microcontinents were

broken from the Naturaliste Plateau and, owing to spreading, together with the Indian Plate, were displaced northwestward for 1600 km. At the second stage, the jumping of the spreading center caused repeated accretion to the Australian plate (Gibbons et al., 2012; Williams et al., 2013a; Whittaker et al., 2013a, 2013b, 2016).

The study of morphostructural features of this region confirmed the structural–tectonic scheme proposed by G.B. Udintsev. We distinguish this region located between two abovementioned ridges as the northeastern slope of the WAR, which represents a slope surface faced toward the depocenter of the Naturaliste basin with a depth difference of over 3 km (Fig. 10).

Exposition of the northeastern slope inclined toward the depocenter of the Naturaliste abyssal plain differs principally from the northern slope faced toward the depocenter of the Wharton Basin. A conditional boundary or “watershed” between the northern and northeastern slopes of the WAR lies over the horst basement inliers, which are well-distinguished as characteristic knoll-like peaks against the general topography (Fig. 3). The watershed begins from the Steyn Knoll with a minimal depth of 3437 m and runs through the Batavia Knoll with minimum depths of 1555 m and the Gulden Draak Knoll with the lowest depth of 1001 m. The Gulden Draak Knoll occupies a central position in the WAR structure and is the largest and highest horst inlier of its basement (Fig. 5). The width of the knoll along 3 km isobath is 200 km. All three horst blocks, linked by saddles, form the East Indiaman Ridge, which morphologically more resembles a mountainous range (Fig. 3).

From the Gulden Draak Knoll, the watershed deviates southeast toward the horst block with a depth of 1560 m. In plan, the block has an oval shape with sizes of 75 and 50 km near the base and is peculiar in its knoll-like peaked surface (Figs. 3, 10c). We propose calling this nameless horst block with a separated domal peak the *Udintsev Knoll* in honor of outstanding oceanologist G.B. Udintsev, who contributed significantly to the study of the WAR.

Dredges from the northwestern slope of the Batavia and Gulden Draak knolls showed that the crystalline basement contains typical continental rocks such as granite, gneiss, schist, and others. Solidified sandstones, large rounded pebble, and granitic and gneiss boulders were also dredged from the knolls (Fig. 2). The age of the crystalline basement is 2850 Ma (Williams, 2011; Gardner et al., 2015).

The knoll-like morphologies of horst blocks represent truncated surfaces of Archean crystalline rocks, which are resistant to physical weathering. Such surfaces (peneplains) are formed under continental conditions for long-term calm tectonic evolution spanning from tens to hundreds of million years. This indicates that these structures are the relict fragments of

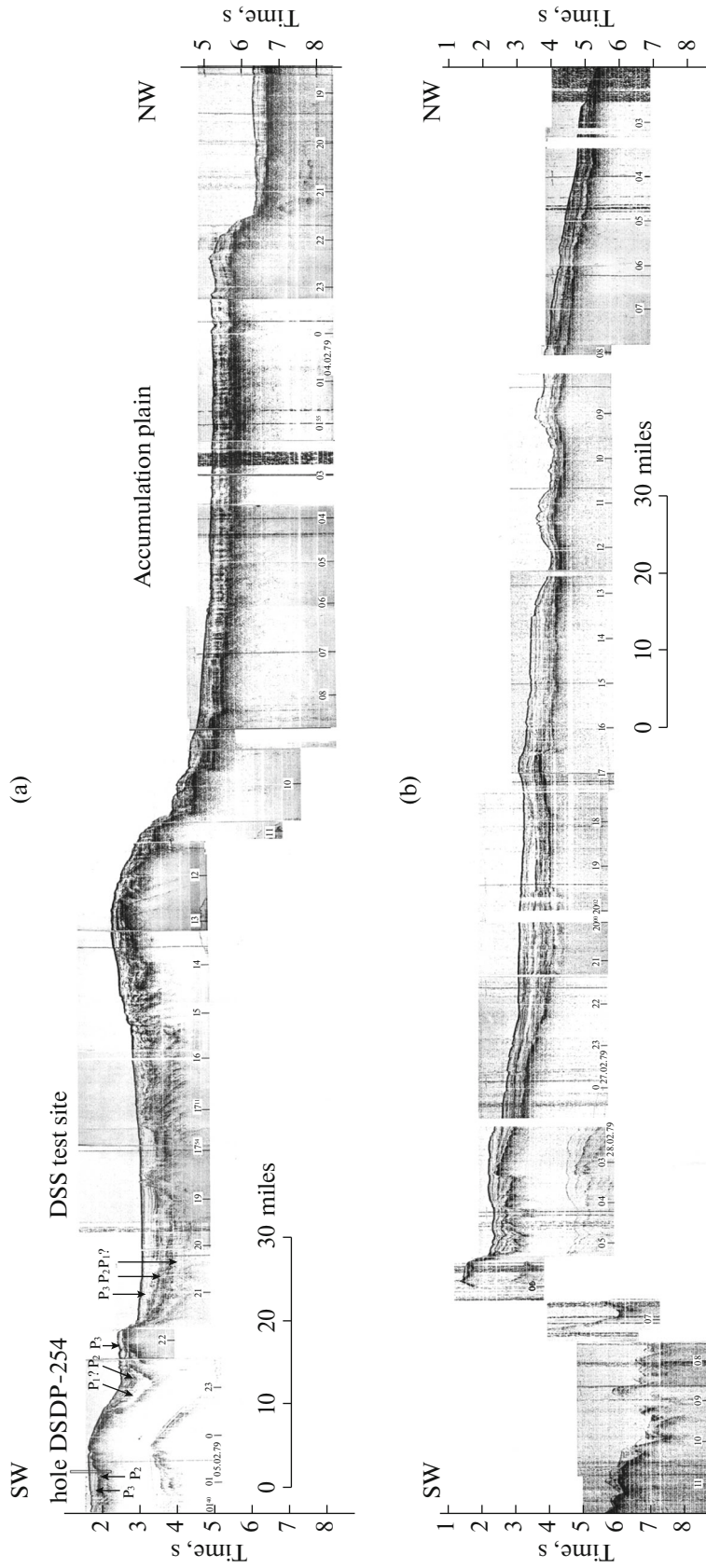


Fig. 9. Seismoacoustic sections along profiles 1GM (a) and 10GM (b), characterizing the structure of the western and eastern WAR. Position of the profiles is shown in Fig. 2. Large erosion incisions and inclination of the crystalline basement toward the Broken Basin are well expressed in topography in the northeastern part of the 10GM section.

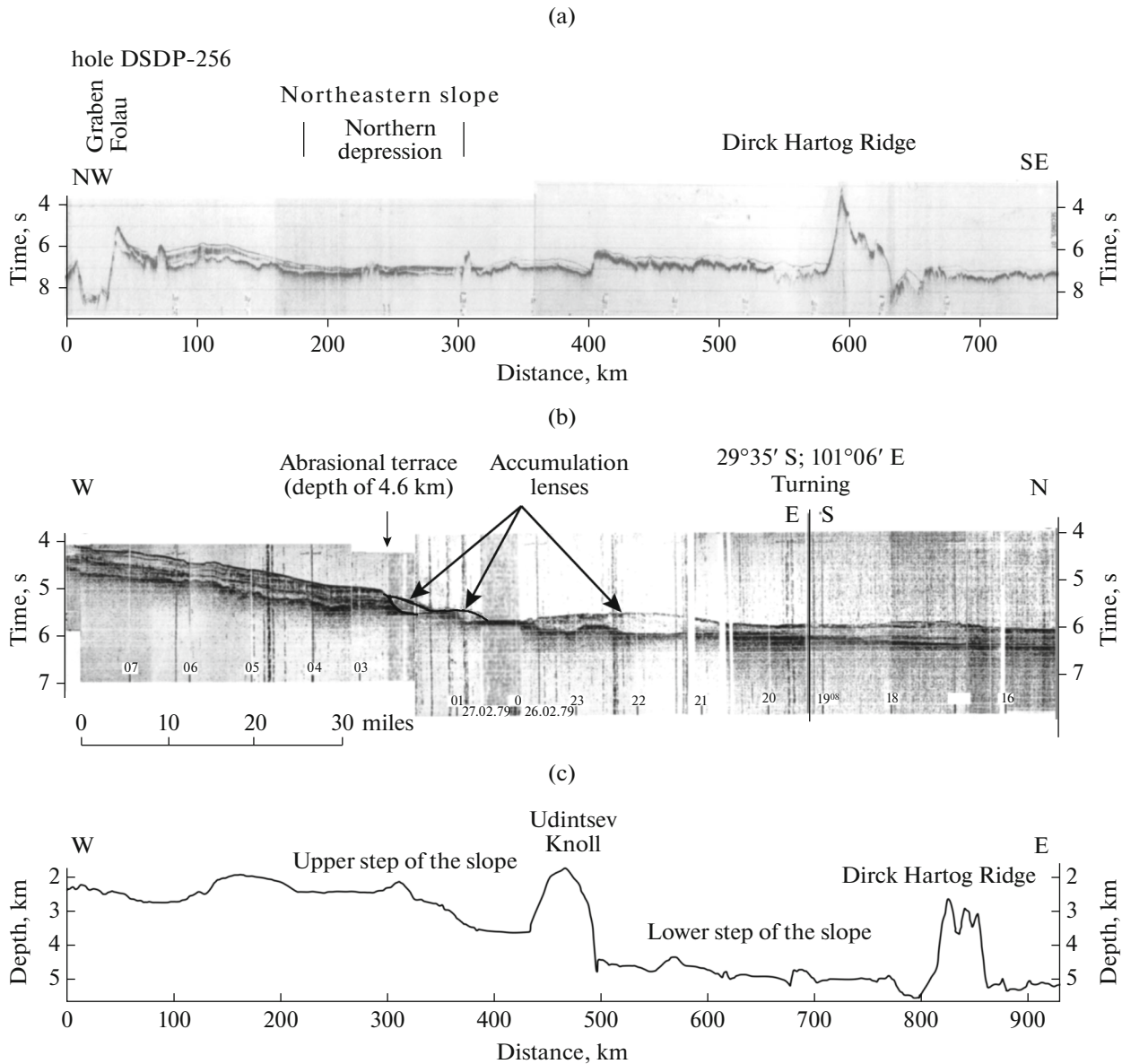


Fig. 10. Seismoacoustic sections along profiles of the D/V *Glomar Challenger* (a), 10GM (b), and bathymetric profile of the R/V *Knorr* (KN 145 L6) (c), which characterize the structure of the northeastern slope of the WAR. Position of the profiles is shown in Fig. 2.

the Western Australian Shield, the peneplaination of which occurred in two stages: Middle Triassic and Late Jurassic–Early Cretaceous (Borisevich, 1980).

Morphologically, the northeastern slope of the WAR can be divided into the upper relatively steep step, the lower boundary of which approximately coincides with the 4.5 km isobath, and the lower gentle step, which subsides in separate cases up to a depth of 5 km. Taking into account the fact that the floor of the Naturaliste abyssal plain is located within the same depths, it is impossible to determine the structural boundary between the plain and the lower step using morphological features (Fig. 10). The solution of this question is also complicated, because the lowest step comprises

two local depressions with a basement located at a depth of 6 km. One of them, the Broken Basin, with a depth of 5.6 km, is an oval depression about 250 km across with maximum basement subsidence up to 6 km. The thickness of the sediments filling the basin increases from its flanks to the center, where it reaches 400 m. This basin is superposed on the crystalline basement of the eastern flank of the WAR (Figs. 3, 4). Other depression with depths of 5.4–5.5 km, conditionally termed as the Northern Depression, is conjugate with the Wallaby–Perth fault zone (Figs. 3, 10a).

Below, we consider the structure of the northeastern slope by the example of seismoacoustic section along profile between the DSDP-256 and DSDP-257

holes, which was obtained during Cruise 26 of the D/V *Glomar Challenger*. The section is of special interest as intersecting the main morphostructural elements of the northeastern slope: the East Indian Ridge, the Northern Basin, the northern block of the Dirck Hartog Ridge, and the Naturaliste abyssal plain adjoining to the east (Fig. 10a). The sedimentary volcanogenic sequence in the northwestern part of the section is subdivided into three sedimentary complexes. The sequence is 250 km long and reaches over 500 m thick. The laminated structure of this accumulation body strongly differs from the chaotic structure of turbidite flows, which are discharged as thick deepwater fans. The formation of this laminated sequence obviously occurred in the shelf zone, at a depth no more than 200–400 m.

The fact that the accumulation body at present is at a depth from 3.5 to 5.5 km suggests that the postsedimentation stage in this region was marked by the large-amplitude subsidence, which spanned not only the northeastern slope, but also the Dirck Hartog Ridge, which follows from samples of red sandstones, fragments of cemented deluvium (talus), and vesicular basalts dredged from its slopes (Williams, 2011). The amplitude of descending movements can be estimated from abrasion scarp at a depth of 4.6 km, which was formed in the wavecut zone (Fig. 10b).

The Dirck Hartog Ridge is the largest horst remnant, which forms a structural boundary between the northeastern slope of the WAR and the Naturaliste basin. It extends longitudinally for over 600 km and is made up of 3–4 horst blocks, which are linked by narrow saddles. The blocks rise up to 2.5 km above seafloor and are subsided at a minimum depth of 2366 m in the northern block. The ridge slopes have complex curved outlines and are conjugate with narrow trenches. The maximum depth (6.4 km) is noted in the trench conjugate with the northern block from the eastern side.

In addition to the Dirck Hartog Ridge, the northeastern slope of the WAR also comprises smaller horst blocks, including the Tryal Ridge and Endracht horst block. The latter is crowned by the eponymous Endracht Seamount with a minimum elevation of 2523 m, likely of volcanic origin (Fig. 3).

These facts allowed us to draw the following conclusions. The perimeter of the northeastern slope is bounded by large fault zones, which causes its angular-blocked structure. In the northwest, the Folau zone separates it from the Wharton Basin. In the northeast, the WAR is separated by the Wallaby–Zenith Fracture Zone (WZfZ) from the Western Australian continental margin. In the southeast, the Dirck Hartog fault and eponymous ridge separate it from the Naturaliste abyssal plain (Figs. 2–4). The northeastern slope includes domal knoll structures, which represent relicts of Archean basement.

The Naturaliste abyssal plain is about 800 km long in latitude at a width of 950 km. The depth of the southern part of the basin is mainly about 5 km; northward, toward the Lost Dutchmen Fracture zone, it increases to 5.6 km and reaches a maximum elevation of 5704 m (Figs. 3, 4). This basin, called the newly formed basin (Pushcharovsky and Bezrukov, 1973), was initiated on the Archean basement. Its evolution defined the structural plan of the region, which adjoins western Australia, in general, and the eastern WAR, in particular.

GEOLOGICAL STRUCTURE AND EVOLUTION OF THE WAR AND THE ADJACENT STRUCTURES

Let us consider the model of geological structure of the WAR and adjacent areas, which is consistent with results of above morphostructural analysis and integrated geological, geophysical, and geochemical data.

Northeastern Part of the WAR and Adjacent Part of the Naturaliste Basin

Australian scientists proved that the basement of the Batavia and Gulden Draak knolls comprises Archean rocks typical of granite gneiss layer of continental crust (Williams, 2011). According to DSS data, the thickness of the granite gneiss layer in the eastern WAR reaches 6.5 km (Francis and Raitt, 1967). In the seismoacoustic sections, the Archean basement has a clear dynamic expression and is distinguished as the reference regional seismic boundary. It is characterized by peculiar roughness, which is expressed by a hummocky pattern of seismic events, the continuity of which is well traced in sections along the profiles 8GM, 9GM, and 10GM (Figs. 5, 9b, 10b).

The wide distribution of the rocks of continental crust in the structure of the crystalline basement of the eastern WAR and southern Dirck Hartog Ridge is confirmed by geological data, as follows from quartz dolerite samples dredged during Cruise 36 of the R/V *Vityaz* from the basement exposure in the eastern WAR (station 5382, 31°40' S, 101°40' E) and on its southern slope (station 5331, 32°24' S, 98°25' E) (Udintsev, 1986) and on the southern Dirck Hartog Ridge (dredge 5, (Williams, 2011)) (Fig. 2). Quartz dolerites and other rocks of continental type were dredged on the slopes of the Naturaliste Plateau (Borissova, 2002).

As is seen in the seismoacoustic sections, the topography of the Archean basements shows both the folded and fault deformations, which serve as channels for magmatic products. In this relation, the sites for drilling the IODP-1141 and IODP-1142 holes were not chosen well, because they are restricted to the zones of EW trending fault and active magmatism. Hole 1141 (water depth of 1242 m) recovered 113-m sedimentary sequence and 71 m of basalts. The basalts are represented by six lava flows ejected in subaerial

conditions, which follows from their brown tint and strongly altered weathered structure. The basalts are alternated with alluvial, mainly sandy material, including fine pebble. The sand fraction contains poorly rounded angular quartz and feldspar grains. Hence, the detrital material was derived from the proximal exposures of granitic rocks.

The lower part of the sedimentary sequence of hole 1141 is mainly represented by a sand fraction with well-rounded fine pebble and coquina fragments; its age is the Middle and Late Eocene. The coastal shelf deposits with a stratigraphic unconformity are overlain by the Early Miocene–Pleistocene deposits, which were formed at deep bathyal. The sections of both holes are devoid of Oligocene sediments, which suggests that active denudation processes were developed within this time interval on the crest of the eastern part of the ridge under subaerial conditions and led to the formation of sharp pointed peaks (Figs. 5, 9).

Holes 1141 and 1142 are spaced less than 1 km apart, but have different sections, which indicates a limited lateral distribution of magmatic processes. At the same time, tectonic and magmatic processes show complex relationships, which are expressed in the fact that basalts in the lower part of the hole-1142 section, in terms of $(\text{Nb}/\text{Ce})_n < 1$, correspond to the contaminated basalts dredged on the southern slope and experienced crustal contamination, whereas other basaltic samples have $(\text{Nb}/\text{Ce})_n > 1$ and show no signs of contamination (Mahoney et al., 1995).

The results of a geochemical analysis of basaltic samples dredged from the southern slope of the WAR showed that the bimodal volcanic series is represented by basalts, dolerites, and rhyolites (Silant'ev, 1986). The rhyolites collected by the bottom corer at station 2089 (32°22' S, 98°04' E) during Cruise 25 of R/V *Dmitrii Mendeleev* have low $\text{Al}_2\text{O}_3 = 13$ wt %, $\text{TiO}_2 < 1$ wt %, and total alkalis of 7 wt % at $\text{SiO}_2 = 70$ wt %. Genetically, the WAR rhyolites resemble Iceland rhyolites, which were formed through the melting of basaltic oceanic crust or the fractionation crystallization of basaltic melt (Kuzmin et al., 1983). However, the WAR rhyolites have higher Pb (22 ppm) and lower Nb (23.1 ppm) contents than Iceland rhyolites (9 ppm Pb and 79 ppm Nb) (Kuzmin et al., 1983). Such characteristics indicate clear negative Nb and positive Pb anomalies in mantle-normalized patterns and are the first signs of crustal assimilation (Borisova et al., 1997, 2001; Frey et al., 2002). Unfortunately, the absence of isotope and REE data makes it impossible to provide comprehensive characteristics of these rocks and to estimate the crustal contribution.

Basalts (dredge 8, 32°24' S, 98°20' E) collected during Cruise 2708 of the R/V *Robert Conrad* from the southern slope of the WAR (Mahoney et al., 1995) have extremely high Th/Nb, La/Nb, La/Ta, $\Delta 7/4$, and $\Delta 8/4$ ratios, which are typical of upper continen-

tal rocks. The hybrid basalts are variably contaminated by the upper continental material (Mahoney et al., 1995; Frey et al., 2002; Neal et al., 2002). Moreover, the isotope composition (high $^{87}\text{Sr}/^{86}\text{Sr}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$) of the basalts indicates an upper crustal contribution (Neal et al., 2002; Frey et al., 2002).

Frey et al. explain the mechanism of involvement of continental material in the WAR protolith by a sharp displacement of the WAR axis at the initial spreading stages between India and Antarctica and dispersal of continental fragments (Frey et al., 2000). Another mechanism also suggests the direct involvement of crustal material in mantle; however, it does not explain the origin of gneiss conglomerates in the ODP-1138 hole drilled in the Elan Bank (Kerguelen plateau) (Ingle et al., 2002; Frey et al., 2000, 2002), which show both age and geochemical similarity with WAR rocks (e.g., Neal et al., 2002). The nature of the gneiss conglomerates is obvious with allowance for the continental origin of the Elan Bank (Borissova et al., 2003).

The geochemical analysis of basaltic samples dredged from the southern block of the Dirck Hartog Ridge shed light on the nature of this enigmatic ridge (Williams, 2011). These samples were studied in detail by Watson et al. (Watson et al., 2016) (dredge 5, 31° S, 105° E). Rock compositions were interpreted in light of the interaction between the oceanic ridge, Kerguelen hot spot, and fragments of continental crust. It was established that the REE contents in these rocks are typical of oceanic basalts (DMORB and NMORB), while the compositions of gabbro and doleritic rocks with high $(\text{Nb}/\text{La})_{\text{pm}}$ and $(\text{Th}/\text{Nb})_{\text{pm}}$ (normalized to the primitive mantle) are different. These geochemical features, as well as the high $(\text{Nb}/\text{Zr})_{\text{pm}}$ ratios, are comparable with the characteristics of crustally contaminated mafic rocks in the Elan Bank area, where basalts are intercalated with continental gneisses (Ingle et al., 2002). These ratios are close to those of basaltic rocks of the Naturaliste Plateau (Mahoney et al., 2002). Watson et al. suggest that the origin of the rocks of the southern block of the Dirck Hartog Ridge was related to the spreading zones in the absence of any plume influence. However, the geochemical features there strongly suggest a crustal contribution.

The low Nb and Ta contents in the oceanic rocks, expressed in the primitive mantle-normalized spidergrams as negative Nb and Ta anomalies, are the first signs of crustal assimilation (Borisova et al., 1997, 2001; Frey et al., 2002). These features of the rocks of the Indian Ocean are thought to be related to the surface contamination in continental fragments or to the contamination by asthenospheric mantle (Mahoney et al., 1995; Borisova et al., 2001; Frey et al., 2002). Subsurface contamination could occur with the Kerguelen plume participation or without it, as is demonstrated by the compositions of samples dredged from the

southern block of the Dirck Hartog Ridge. All data serve as evidence for the presence of continental blocks during the formation of the basalts and rhyolites in this area of the Indian Ocean.

Thus, the Hartog Dirck Ridge is a tectonomagmatic structure. It was formed on the continental crust owing to differentiated tectonic motions accompanied by intense intrusive and extrusive magmatism, which is related to the eponymous deep-seated fault.

From the WAR to the Naturaliste abyssal plain, the structure of the Earth's crust shows a reduction in the thickness of the low-velocity (6.2–6.4 km/s) layer and its replacement by the high-velocity (6.5–6.9 km/s) layer. In particular, the thickness of the low-velocity layer in the eastern WAR is 6.5 km (st. 45) and reduces to 1.2 km easterly, in the tectonically fragmented zone between the WAR and Naturaliste Plateau, while the lower part of the section contains a >5-km-thick layer (st. 46) with a velocity of 6.9 km/s. In the Naturaliste basin, the low-velocity layer is completely replaced by a ~5-km-thick layer (stations 47, 49) with a velocity of 6.5–6.7 km/s (Francis and Raitt, 1967) (Fig. 2). This demonstrates the transformation of the continental crust into a transitional crust with partial or complete reworking of the granite–gneiss layer.

Information on the structure and evolution of the Naturaliste abyssal plain can be obtained from sections of two deepwater DSDP 257 and 259 holes.

Hole 257 was drilled in the central part of the abyssal plain at a depth of 5300 m. It recovered 262 m of sediments and 65 m of basaltic rocks. The basaltic section includes five lava flows of vesicular olivine basalts intercalated with limestone, detritus clay, sand, gravel, and pebble. Basalts were ejected in three stages: Lias (Early Jurassic), Callovian–Oxfordian (late Jurassic), and terminal Albian (end of the Early Cretaceous). They are overlapped by Upper Cretaceous brown detrital clays, which with a large hiatus are overlapped by 57-m sequence of fauna-barren brownish detrital clays practically devoid of organic remains of supposedly Quarter–Pliocene age (Rudich, 1983).

Results of drilling borehole 257 showed the cyclic eruptions of basaltic lavas in the subaerial setting in the area of the Naturaliste basin during the Jurassic and Early Cretaceous. Erosion and denudation occurred between the basaltic eruptions. It should be noted that the basalts recovered when drilling this hole and hole 256 described below have the high silica contents. This results in a high content of normative quartz, which indicates crustal contamination.

The paleogeographical setting by the end of the Cretaceous and Cenozoic can be determined from conditions of formation and precipitation of detrital clays. The initial material for their accumulation was clay gruss formed during the physical weathering of volcanic rocks under arid climatic conditions. Detrital clays are precipitated during rapid burial in close proximity to a source. Otherwise, the long-term transpor-

tation and redeposition led to the rounding of detrital particles, their grinding, and transformation into finely dispersed fractions. On the other hand, under wet climatic conditions, they are swelled and removed as colloids.

The unclear stratigraphic position of the fauna-barren clays makes it impossible to determine the timing of the final subsidence of the floor of the Naturaliste basin. However, with allowance for a long sedimentation gap and the absence of open sea facies in this section, the large-amplitude and rapid subsidence in the Naturaliste basin likely occurred no earlier than the end of the Miocene. Judging from above morphostructural features, the subsidence amplitude reached 4.5–5.0 km.

Hole 259, drilled in the eastern part of the Naturaliste abyssal plain at a depth of 4700 m, recovered 305 m of sedimentary rocks and 40 m of basalts. The upper 16 m of basalts are represented by basaltic breccia filled with dolomite cement. They are overlain by montmorillonite clay with detrital structure and scarce glauconite. These sediments are dated by Aptian and overlain by the Late–Middle Albian clays with dolomite. Upsection, they subsequently grade into the Late Cretaceous gypsum-bearing clay and a Late Paleocene gypsum-bearing clay bed intercalated with oxidized ferruginous rocks. The Paleocene clays are overlain by an Early Eocene member of clay and ooze enriched in dolomite. These rocks, with a stratigraphic unconformity, are overlain by Quarter–Pliocene ooze and clay (Rudich, 1983).

Section of hole 259 indicates that the basalts in the eastern part of the abyssal plain in the Early Cretaceous experienced physical weathering under arid conditions. A rapid transgression at the end of the Aptian resulted in the formation of a shallow basin, where great amounts of weathering products were transferred. A rapid burial of sediments facilitated the preservation of their detrital structure. Significant subsidence up to modern depths coincided with the beginning of overlying of Eocene sediments by the Pliocene–Quarter ooze and clay.

The geological, geophysical, and geochemical data under consideration indicate that the crust of this region contains widespread relicts of Archean basement. It seems that the Stone, Batavia, Gulden Draak, and Udintsev knolls, as well as the southern part of the Dirck Hartog Ridge and Naturaliste Plateau, form the outer contour of the subsided part of the Western Australian shield. The Darling Fracture Zone is a deep-seated suture, along which the western part of the Australian shield was subsided. The fracture extends along the western continental margin of Australia for 1000 km. It is believed that, since the beginning of Paleozoic, the Archean basement was subsided for 15 km (Stagg et al., 1999).

*Northern Slope of the WAR and Adjacent Part
of the Wharton Basin*

The chronostratigraphic correlation of seismoacoustic sections and holes DSDP-255 and ODP-752–ODP-755 makes it possible to distinguish the reference refractory boundaries and to determine the lithological composition of the corresponding layers in the sedimentary cover of the northern slope. The Turonian stage is mainly represented by tuffs and volcanic ashes with intercalations of glauconite and shelly detritus in the lower part; the Coniacian stage was also made up mainly of volcanogenic rocks; the Santonian–Maastrichtian series consists of limestones intercalated with chert. The Paleocene and Lower–Middle Eocene layers are mainly represented by carbonates intercalated with micrites, cherts, and volcanic ash. The aforementioned volcanosedimentary complexes extend for 500 km toward the Wharton Basin, which indicates the existence of an epicontinental basin in this area in the Cretaceous and Paleogene.

Data on the structure and evolution of the basin were obtained from dredges on the northwestern slopes of the Batavia and Gulden Draak knolls, as well as sections of deep-sea holes 212 and 256.

A shallow setting corresponding to the shelf zone has existed along the northwestern slope of the East Indiamin Ridge in the Cretaceous (Barremian). This follows from the fact that sandstones dredged from the slopes of the Batavia and Gulden Draak knolls contain the remains of ostracodes, echinoderms, foraminifers, and spores and pollens of terrestrial plants. Large shingles and boulders were formed in the wave-cut zone during sea regression (Whittaker et al., 2016). The Gulden Draak Knoll was located at the higher hypsometric level and, judging from characteristic seismic record of its apical part between 20–21 h (Figs. 5b), its final subsidence to a depth of 1000 m occurred in the Pliocene–Pleistocene, which follows from a study of hole DSDP-256.

Hole DSDP-256 was drilled at a depth of 5361 m. It is located on a block of the East Indiaman Ridge subsided along the Follau fracture zone (Fig. 10a). The hole bottom recovered basalts ascribed to the end of the Early Cretaceous (92–94 Ma). Judging from silica enrichment, the basalts experienced crustal contamination (Kempe, 1974). Strong alteration of basalt texture and the presence of their breccia suggest that these rocks were subjected to the influence of aggressive aerial or subaerial environment for a long time. The basalts are overlain by a layer of Late Albian clays with glauconite, which were precipitated in shallow conditions. They are overlain by Upper Cretaceous coccolithic clays with glauconite. A 170-m sequence of the Pliocene–Quarter sandy–clayey material rests on the Upper Cretaceous rocks with a large Paleogene–Miocene stratigraphic gap. The characteristic feature of the Pliocene clays is a well-preserved detrital tex-

ture. The section is crowned by a thin ooze layer alternating with brown detrital clays.

The structure of the hole DSDP-256 section indicates that the East Indiamin Ridge in the Cretaceous and Cenozoic evolved in complex tectonomagmatic conditions. Active magmatic activity under subaerial conditions was followed by shallow sedimentation conditions in this area in the Late Cretaceous. Paleogene and Miocene were characterized by geocratic mode, which, judging from the absence of Early Eocene deposits in holes drilled in the eastern Indian Ocean, spanned a spacious territory and provided the formation of a thick weathering crust. The outburst of tectonic activity at the end of Miocene–Pliocene was accompanied by the large-amplitude differentiated movements and completed the formation of the Follau Fracture Zone. Tectonic movements facilitated the “avalanche talus” and burial of detrital material.

Hole DSDP-212 was drilled in the deepwater part of the Wharton Basin at a depth of 6243 m. The hole bottom recovered altered weathered basalts with enclaves of limestone and pillow lavas in the upper part. The basalts are overlain by a layer of undated (fauna-barren) zeolite clays. Upsection, they are replaced by Late Cretaceous biogenic ooze, which are also overlain by zeolite fauna-barren clays. Upsection, they grade into Eocene biogenic schists with glauconite, which in turn are overlapped by a Pliocene–Miocene thick (0–288 m) ooze sequence.

The structure of the hole DSDP-212 section indicates that basaltic eruptions in the Cretaceous occurred in a shallow-water setting. This stage was followed by a geocratic epoch. This follows from samples of altered and weathered basalts dredged from stations located 200–300 km away from a hole during Cruises 33 and 35 of the R/V *Vityaz* (Bezrukov et al., 1966). In the Late Maastrichtian, the area of the Wharton Basin was characterized by the shallow-water conditions, which is supported by the presence of typical shallow-water coccolithophorides (Rudich, 1983). Given the fact that the fauna-barren clays contain 20% feldspar, 20% kaolin, and 20% montmorillonite, i.e., mineralogically correspond to the clay products of weathering crust after magmatic rocks, they were derived from a proximal source.

The unusually thick Pliocene–Miocene sequence also suggests the proximity of the terrestrial source area. Taking into account that the Pliocene–Miocene section demonstrates the “mixing” of the Miocene, Oligocene, and Eocene paleontological remains, which is explained by their erosion and redeposition owing to the active hydrodynamic influence, the final subsidence in the Wharton basin up to its modern depths occurred no earlier than the end of the Miocene.

CONCLUSIONS

The aforementioned facts allowed us to draw the following conclusions:

The area of the WAR or Broken Ridge and adjacent areas in the past was occupied by a large fragment of ancient paleoland, which evolved mainly in the geocratic mode in the Cretaceous and Paleocene.

The formation of the modern morphostructure of the ridge was mainly determined by the evolution of depocenters of the Wharton and Naturaliste basins.

The final phase of the subsidence of the northern slope and formation of the Wharton deepwater basin occurred no earlier than in the end of Miocene.

The northeastern slope of the WAR stands out due to the well-expressed knoll structures made up of Archean (?) rocks, which makes it possible to consider it a subsided part of the Western Australian shield.

The formation of the northeastern slope is tightly related to the development of the Naturaliste basin depocenter. The northeastern slope acquired its modern morphostructure at the end of the Miocene.

Unlike the northern and northeastern slopes, the southern slope of the WAR experienced a long-term geological evolution. Its formation was caused by rifting processes, which led to the breakup of the continental massif from the northern flank of the Australia–Antarctic georiftogen.

Thus, we can conclude that the structural plan of this region was finally formed during the youngest phase of tectonic activation at the end of the Miocene–Pleistocene.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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