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Angola-Brazil Geotraverse: Ocean-bottom seismoacoustic observations

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RESUMEN

Se describen las observaciones sísmicas sobre el perfil Angola-Brasil durante 1980-1986 empleando estaciones submarinas (OBS). Se describe la sismicidad en la Dorsal del Atlántico Sur, el registro de fases T de un sismo localizado en las South Shetlands, y los residuos de dos telesismos para la Cuenca de Angola.

PALABRAS CLAVE: OBS, Cuenca de Angola, Dorsal del Atlántico Sur, fases T.

ABSTRACT

OBS observations were carried out during the period 1980-1986 at more than 100 sites along the Angola-Brazil Geotraverse (12°S between 12°E and 30°W). Microearthquake activity was registered in the region of the Mid-Atlantic Ridge (MAR) within the area where strong earthquakes exist. Standard features are similar to other MAR segments: (1) the occurrence of earthquakes at contrasting relief forms; (2) shallow hypocenter depth (2 to 7 km); (3) rapid attenuation of seismic waves under the seafloor; (4) velocity ratio Vp/Vs=1.74. Frequency-temporal variations in the seismic background and in the microseismicity of the Gabon Fault were detected, presumably connected with volcanic processes. T-phase variations at distances exceeding 5000 km suggest the formation of a hydroacoustic signal near the epicenter on the continental slopes (maximum), and on smooth slopes of the continental margin. The intensity of the hydro-acoustic waves in the frequency range 3 to 20 Hz decreases with depth of recording. Residuals of PKP-waves, recorded in the Angola Basin and in Europe, suggest that the properties of the medium under these structures are similar. No lateral variations of velocity were found under a 600 x 600 km area in the Angola Basin.

KEY WORDS: OBS, Angola Basin, South Atlantic Rise, T-phases.

INTRODUCTION

Geological and geophysical studies were made along the Angola- Brazil Geotraverse (ABG) by researchers from the Russian Academy of Sciences (RAS) and other organizations within the GEOPOL Project (study of geophysical heterogeneities of the seafloor) in 1980-1986 [13]. The project is intended to acquire and interpret data on natural geophysical fields and seismic parameters of typical seafloor features. The ABG runs across very different seafloor structures showing different degrees of activity, including seismic source regions of the Mid-Atlantic Ridge (MAR). The interpretation of ABG observations relies on data from the lithospheric seismic sounding profile [20] carried out by the Laboratory of Deep Seismic Studies, Institute of Physics of the Earth, RAS. Thirteen ocean-bottom seismograph (OBS) arrays have been deployed during the four expeditions in 1980, 1982, 1984, and 1988 (Figure 1). Each array of 6 to 10 OBS was in continuous operation for 150-200 hours. Valuable information has been obtained at over 100 sites on the transect in very different geotectonic settings, the total duration of recording being over 15 000 hours.

The results of deep seismic sounding constrain the basis of the velocity structure model of the lithosphere and underlying mantle [20]. This paper addresses results obtained from the analysis of natural signals, i.e. microseisms and waves from near and distant earthquakes. The data of the local earthquake sources and the propagation conditions of body, surface and hydroacoustic oscillations generated by seaquakes, and spectral and spatio-temporal relations and characteristics of the natural seismic field allow us to investigate deep-seated features of the medium and present-day tectonic processes. Until recently, the seismological data for the South Atlantic have been rather general and based on land-station records only. Earthquake sources were located in the MAR crest zone exclusively. In the North Atlantic, expeditions with OBS were conducted in well-known seismoactive segments of the MAR only. Detailed observations [5, 10, 14, 17, 18, etc.] specified the dominant depth of microearthquake sources (and possible strong events). They have shown the self-similarity of seismic regime and focal mechanisms in a broad energy range, and allowed estimates of the medium kinematic parameters. The earlier results of the detailed studies of the northern MAR seismicity appear to be valid for the South Atlantic, too, and experiences of observations with OBS were applied in a special experiment in the Gabon Fault region (deployment IV). On the ABG, seismic observations were in general conducted with profile OBS-arrays; individual sites were spaced on the average 50 to 80 km.

The OBS used were developed and built at the Institute of Physics of the Earth [19]. A steel cylindrical case with the instrument inside was lowered by rope to depths of 6 km. The bottom assembly included a magnetograph with continuous 8-channel analog recording on 12-mm magnetic tape. The OBS operation time was 200-250 hours with tape speed of 0.4 mm/s. Vertical NS-3 seismographs were used with a free frequency of 4.5 Hz, a sensitivity of 25 V m/s (and a damping of 0.6 of critical). The electronic noise was below 10 nm/s in the frequency band of 4-20 Hz. The precision of absolute timing was within 0.05s. OBS coor–

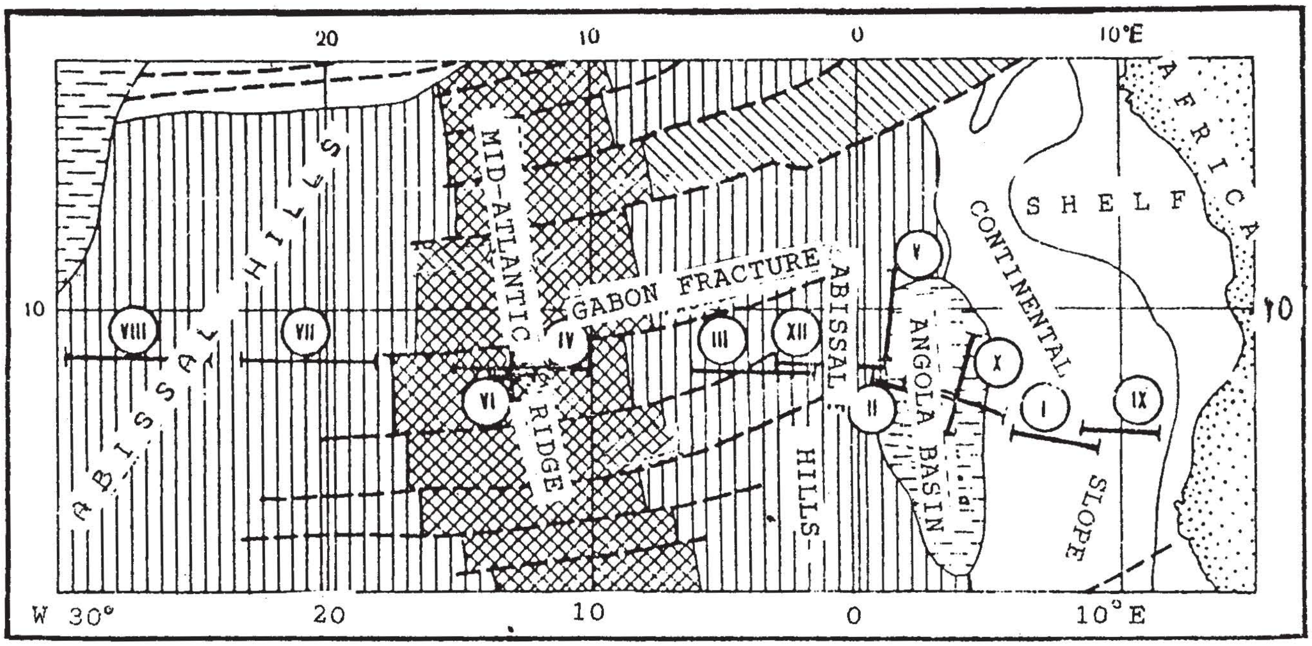

Fig. 1. Structural map of the Angola-Brazil Geotraverse and OBS arrays during the 1980-1986 expeditions of the Institute of Physics of the Earth, RAS.

dinates were determined by different methods, including acoustic tracking, to an accuracy of 0.7 km.

1. FEATURES OF SEISMIC BACKGROUND

A bottom seismograph operates at the interface of a solid and a fluid. These conditions involve a great variety of wave sources, and peculiarities of propagation and recording. Geophysical signals are recorded on a background of natural and man-made noise. Because the hydroacoustic waves in the frequency range of interest attenuate slowly, sound propagating in sea water may cause a high background noise due to the rugged bottom topography and multiple reflections. The sample records shown in Figures 2 and 3 show the high complexity of recorded events. With slow playback speeds (Figure 2), the waves from local earthquakes are distinctly seen as spikes in the noise, slowly varying at periods of a few hours or even days.

Summary seismograms such as shown in Figures 2, 3 (with records in a logarithmic amplitude scale) allowed analysis of OBS records in different frequency selection modes. A two-day segment of OBS42 recorded in the Gabon Fracture Zone (array VI) is shown in Figure 2. Six 1/3-octave frequency bands over the range of 1.5 to 20.0 Hz show several background disturbances lasting about 8 hours each with intensity of 20 to 25 dB above the minimum level. The pattern of variation is similar: low frequencies (below 10 Hz with rapid falloff toward higher frequencies) at the start, and higher frequencies (above 7 Hz with rapid falloff toward lower frequencies) toward the end. The noise is accompanied by an increase in the number of spikes similar to microearthquake waves (5 to 10 spikes per hour). The larger of these spikes precede or accompany the background disturbances and are associated with sharp changes of noise spectral content. For the larger shocks it has been possible to determine source locations clustering around the Gabon Fault.

The frequency-temporal structure of the noise resembles that of volcanic regions, where volcanic tremors, hydrothermal and explosive processes are observed. The OBS may well have recorded some tectonovolcanic events from the crest of the ridge.

Figure 3 shows several segments of the seismogram of Figure 2 played back at different speeds. These episodes illustrate the changes in wave intensity in the band of 12-16.5 Hz, just prior to the long background disturbances (marked A to C in Figure 2). The amplitude of these high-frequency components varies by 25-30 dB at the start and end of a pulse, for 5-10 s. The pulses appear on the background of a steady increase in the low-frequency components (see the 1.8-4.5 Hz traces in Figure 2). A possible source reconstruction is increased discharge of water and gas jets and accompanying low-frequency tremors with occasional explosions. The reconstruction seems justified for neovolcanic structures in mid-oceanic rises (such as the TAG hydrothermal field in the North Atlantic [1, 14]). These long background disturbances have amplitudes similar to the short pulses due to microearthquakes (Figure 2). The frequency ranges are identical, but the disturbances are a few orders of magnitud larger than the microearthquakes. If both the microseismicity and the background disturbances are due to volcanic processes, the role of volcanism in the MAR geotectonic balance may have been underestimated. Self-contained OBS stations can be used to study submarine volcanoes and hydrotherms, to locate volcanic edifices, and to evaluate the dynamics and energy balance of the process.

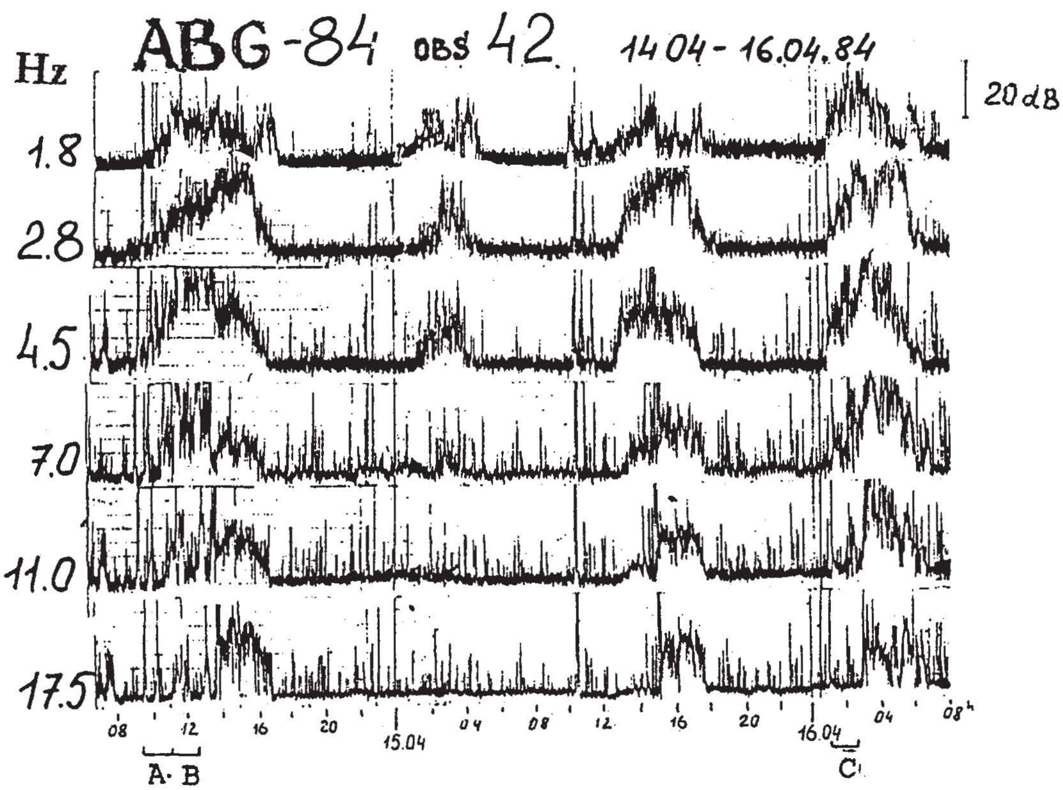

Fig. 2. Time-frequency picture of a segment of an OBS42 record.

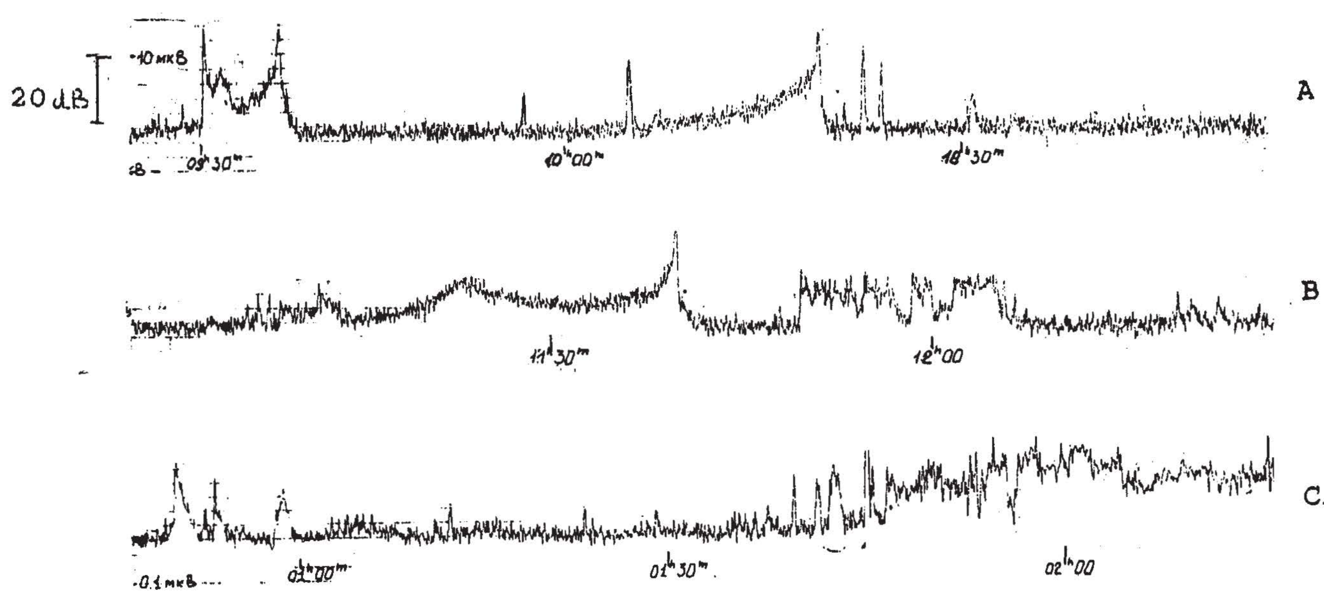

Fig. 3. Details of the OBS42 record for 12-16 Hz. The segments are labeled as in Figure 2.

Extended (up to 6-10 h) disturbances of the background were also recorded away from the neovolcanic zone; for instance, in the Angola Basin (by array I) and on the MAR slope (array III). Different OBS in a given array recorded these disturbances with different intensities (5 to 30 dB), and often at different times. Unlike the stations deployed on the MAR crest, the spectra of these disturbances are similar in the 3 to 20 Hz band and do not vary in time. As described in [18], their genesis may be attributed to atmospheric and hydrospheric eddies. Thus, nearly 1/3 OBS recording times are occupied by various background disturbances. The disturbances also include short pulses due to explosions, earthquakes, air guns and ship engines which are to some degree present in every OBS record. The remaining time may be considered "undisturbed", the level being controlled by microseisms, noise produced by passing ships and living organisms. However, some OBS recorded long-period (longer than 20 hours) changes in noise level, which do not correlate with records at neighboring stations. Such changes are most noticeable (up to 5-7 dB) at lower frequencies (2-5 Hz). The "undisturbed "background level was estimated by averaging over the entire period of observation. The measurements were made on seismograms in 1/3-octave frequency bands covering the range 1-30 Hz, and the noise spectral density was calculated using calibration signals.

More than 200 episodes that did not involve any obvious noise in the band of 5-30 Hz were used to plot Figure 4. The episodes were usually segments of records that preceded some events. The reliability of spectral densities is probably around 50-70 percent, considering the errors in all phases of dynamic measurements. The mean spectral density and the 70 percent confidence interval are shown against mean world background [12]. The spectrum of noise for the ABG is similar to that in [12] but still nearly one order of magnitude higher than the mean generalized level. The highest background values for the geotraverse are obtained on the MAR crest (arrays IV and VI) and on the continental slope of the Angola Basin (array I). The noise intensity from array III at 4.5 km depth on the hilly eastern slope of the MAR in February 1982 was about 5 to 7 dB less than for the MAR crest zone.

Figure 4 illustrates the records obtained for probable noise rather than definite objective estimates of the background noise, because short recordings at different OBS arrays are not representative in terms of factors such as geotectonic structure, OBS operation depth etc. This is the cause of four-order scatter in averaged spectral density in reference [12]. The high background noise level in the transect is explained by the measurement and computational procedure used: thus in December, 1983 the noise level in the Brazil Basin, according to the OBS data of the RAS Institute of Oceanology [4], was 15 dB lower than at array VIII (operating in May 1984), which was situated nearly 200 km to the north.

2. PROPAGATION OF HYDROACOUSTIC OSCILLATIONS FROM A DISTANT EARTHQUAKE

On March 10, 1982, at 22:55 (GMT), 8 stations of array IV recorded a strong signal lasting up to 15 minutes. The amplitude (10 mcm/s) was 10 to 30 dB higher than background noise. The most probable source of the signal was a strong earthquake in the South Sandwich Islands (55.97°S; 26.85°W), with magnitude mb=6.0 and focal depth 110 km (Figure 5). The maximum pulse was recorded by the OBS almost simultaneously. The epicentral distance (greater than 5000 km) took a travel time of 56 minutes at a velocity of 1600m/s. No P- and S-waves were seen.

The shape of the T-phase pulses and spectral-temporal characteristics are virtually the same at all OBS. The only difference was the signal level and elevation above the background. The leading front of the pulse consists of several units with different rates of increase of the record level (Figure 6). Considering the submarine topography in the epicentral zone, we may assume two areas of the T-phase origin which are denoted on Figure 5 by heavy lines. The continental slope region in the trench facing the ABG corresponds to the sharply increasing signal level in its maximum phase. A smooth increase of amplitude in the earlier part of the record may be related to the sound generated by the northern slope of the continental margin which is approximately 400 km to the north of zone 1. The time differences calculated for P-wave arrivals of the T-phase in these areas, and the travel times for the T-phase to the OBS group, match the observations. The shapes and intensities of hydroacoustic oscillation radiation in these structures are estimated on the assumption that the coefficient of compression wave transmission from a solid to a liquid is similar in both areas [9]. The variations of T-phase levels computed in this manner are shown on Figure 6, along with the data observed. Observe that the assumed generation zones match the kinematic and dynamic criteria.

The rear front of the T-phase pulse (Figure 6) appears to be as exponential and the intensity of hydroacoustic oscillations for $t > T$ can be approximated by $A(t)/A(T)= \exp[k(t-T)]$, where $A(t)/A(T)$ is the ratio of current to maximum amplitudes in a record, and T is the recorded time of the signal maximum. For practically all stations the factor k is equal to -0.014 and does not depend on frequency in the range of 2 to 25 Hz. The time (t-T) is measured in seconds. If the compression wave transformation from solid to fluid is supposed to be similar in the whole region of the T- phase generation and if the hydroacoustic oscillation damping is negligible, the k parameter may reflect the quality factor Q in the epicentral area.

The east-west alignment of OBS array IV (Figure 1) practically coincides with the T-wave front and therefore the epicentral distances to various OBS vary little. The T-phase signal formation took place in a zone whose dimensions are much smaller than the epicentral distance. Thus, the intensity of the T-phase is governed by propagation and recording conditions, the variations being up to 20 dB. According to [11], some rises within OBS array IV are composed of crystalline rocks and some depressions of sediments with thickness of up to 300 m. In general, the differences of deployment conditions for different OBS do not affect the level of recording between 1 to 20 Hz.

The MAR crest zone where the OBS were situated includes two ridges trending north-south on an intensely fractured topography (Figure 7,c and 7,d). The western ridge contains present-day rift valley, between OBS sites 34 and 32. The local seafloor elevation is about 100 to 1500 m above the adjacent sea floor. The second ridge runs close to OBS 30, where elevation variations are less than 500 m. The intensity of variation of the T-phase maxima (light circles) and of the background (dark circles) correlate with the floor topography: amplitudes of hydroacoustic oscillations and microseismic noise increase with relief. Hence the noise in this frequency band may be due to hydroacoustic oscillations of different origin, and its intensity may depends on the distance of the receiver to the submarine

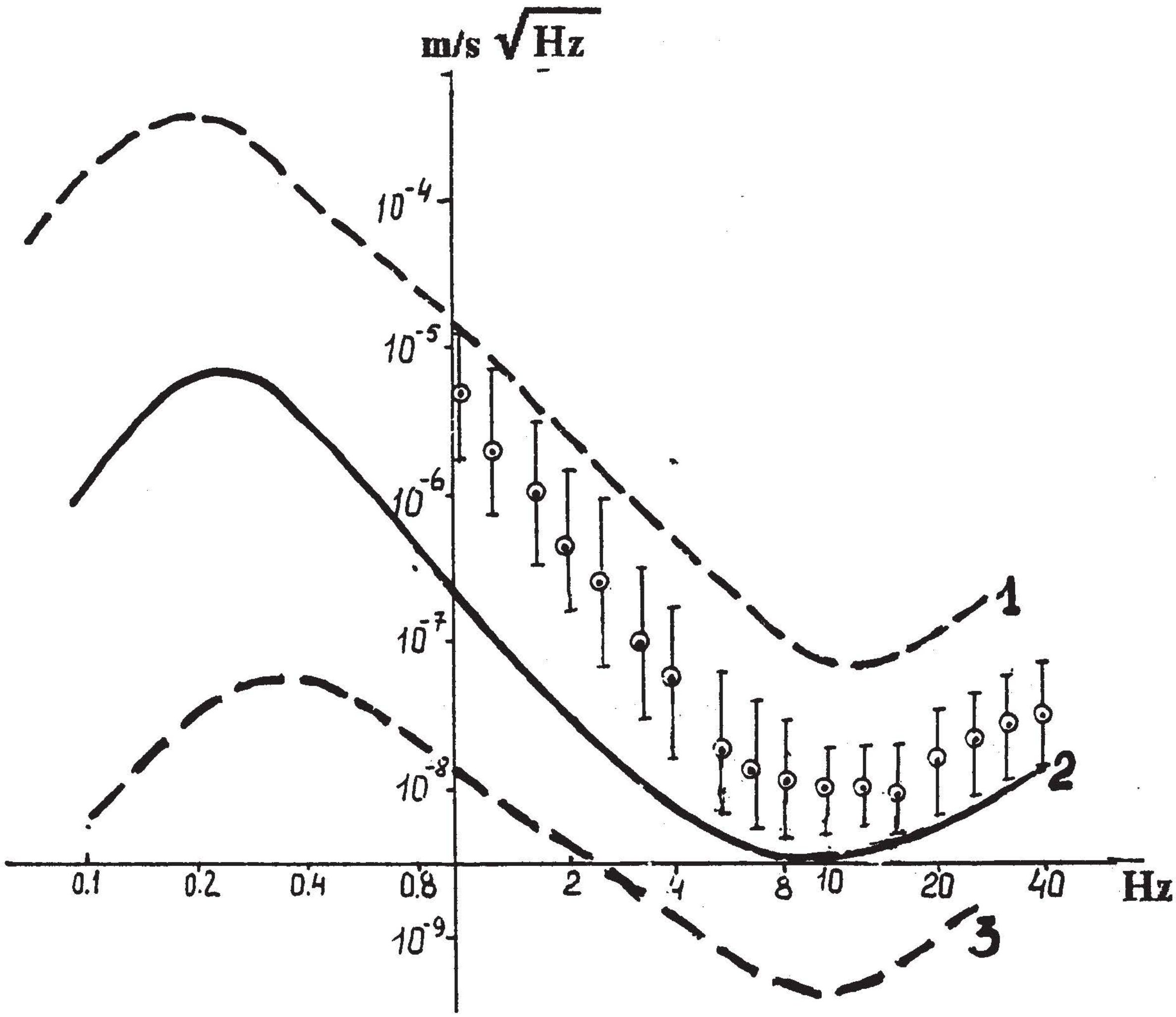

Fig. 4. Average seafloor noise spectrum for the Angola -Brazil Geotraverse and average world-ocean spectrum (1--maximum, 2--mean, 3--minimum level [12]).

sound channel. In the Central Atlantic, this channel axis runs at a depth of about 1000m.

The spectral amplitude of the maximum T-phase (light circles) and the averaged values of the sound background (dark circles) are plotted in Figure 8. The data are shown for OBS 34 to 36, for rays to those OBS west of the MAR and not crossing the rift zone (Figure 8,a), and for OBS 32 to 28 (eastern group) situated beyond the crest (Figure 8,b). In the second case, the T-phase levels vary considerably relative to background, unlike the rays crossing the MAR where the T-phase intensities are about the same. The crest areas in the MAR feature a kind of scattering sound that may depend on the complex topography of the sea floor and on temperature inhomogeneities of sea water in the MAR rift zone and associated neovolcanic features.

3. MICROEARTHQUAKES OF THE GABON TRANSFORM FAULT

During the ABG experiment, reliable records of local earthquakes, were obtained from the MAR crest zone only, at arrays IV and VI (Figure 1). The highest frequency of events, over 40 per day, was observed at OBS sites located near zone of rapid changes in seabed topography, and the maximum frequency was observed on the crest. The crest also showed the greatest number of long background disturbances.

Array IV (on the crest) was recording over 500 shocks for 8 days. Most of these records have emergent onsets and seem to be hydroacoustic waves (T-phases) of local earthquakes on the Gabon Fault, along which the OBS had been deployed. The sources of these oscilations were weak and few events were recorded by at least two stations within a distance of 50 km.

Compressional and shear waves of local earthquakes, particularly direct waves, are poorly recorded by vertical instruments. This is due to a variety of factors, the main one being that small (mb=0-1) earthquakes release low stresses and the radiation intensity varies over time. Many re–

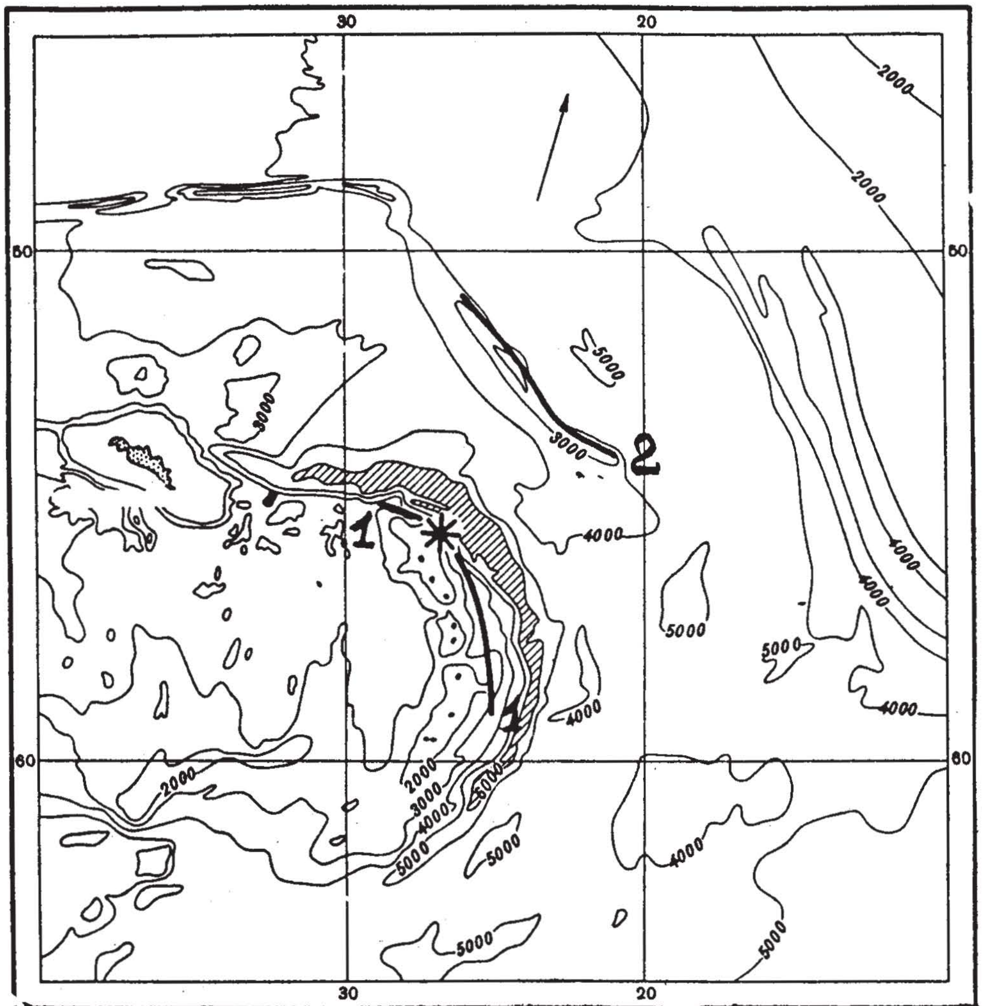

Fig. 5. Presumed origin of the T-phase from the 82.03.10 earthquake. The asterisk denotes the epicenter. Solid contours denote the areas assumed from hydroacoustic radiation (numbers as in Figure 6). The region of the deep-ocean trench with depth greater than 6000 m is hatched. The arrow indicates the direction of propagation.

searchers have also pointed out a rapid attenuation of body waves with distance. Low-velocity sediments (less than 1.5 km/s) are absent in the neovolcanic MAR zone; hence seismic rays from local earthquakes frequently arrive at low angles of incidence. Thus the signal/noise ratio at vertical seismometers on the seabed is smaller by factors of 2 or 3 than that of hydrophones [16].

The specialized seismological experiment with OBS in 1984 (array VI), was intended to conduct a comparative study of Gabon Fault microseismicity and of the rift in the MAR, and to estimate the distribution of velocities beneath the OBS sites. We used the GEBCO map [6] to select a flat and tectonically uniform area south of the Gabon Fracture at about equal distances from the rift and from the faulted MAR zones. Five OBS were deployed for 9 days (11 to 20 April, 1984) in the shape of a rhombic array with one diagonal parallel to the geotraverse. The distance between stations was chosen so that timing (±0.05 s) and OBS location (±0.5 km) did not affect travel times by more than 3 percent. With a mean compressional velocity of 8 km/s at 5-30 km depth the optimal interstation distance would not be less than 25 km [3].

However, the 1978 General Bathymetric Chart of the Ocean (GEBCO) [6] did not provide sufficient detail on the complex seafloor structure in the array area. Thus the junction of the Gabon Fracture with the southern extension of the ridge turned out to be 30 km eastward [11], and the two east-west troughs, a major structural feature of the Gabon Fracture which had not been detected, fell in the middle of the array. As a result, OBS42 was deployed in the northern trough, OBS 43, 44, and 46 in the southern trough, and only OBS45 operated as planned (Figure 9). This configuration caused high background noise, particularly at OBS42 (see Figures 2 and 3). The background disturbances in the area reached 15-20 dB in the frequency band 5-15 Hz 80 percent of the total operation time. Under such conditions, the interstation distances of 25-40 km were too large, and most events were recorded by one or two OBS only.

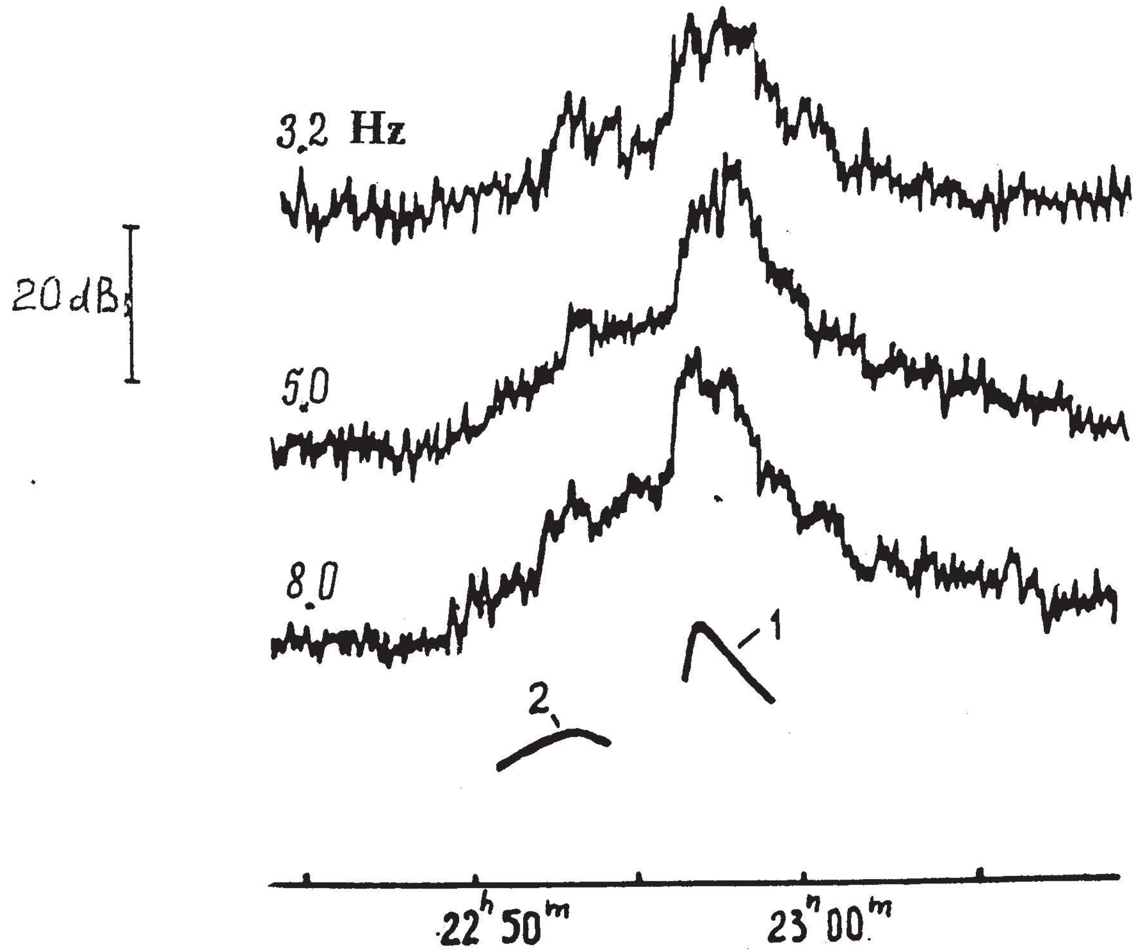

Fig. 6. Temporal variations of T-phase levels for frequencies of 3.2, 5.0 and 8.0 Hz (the curves are positioned arbitrarily in the vertical). 1 and 2, partial variation curves of T-phase levels for different zones of radiation (see Fig. 5).

The five-station array recorded simultaneously for 150 hours. P and S waves were recorded for 205 events and the total number of seismograms was over 300. Only 6 earthquakes were recorded by all five stations, 8 events by four, 12 by three, and 28 by two OBS. All events were local: nearly no records are available with (S-P) times above 6 s; that is, the distances to the sources were 50-60 km at most. Most records have weak, emergent onsets and doubtful later phases. OBS45,the farthest from the transform fault (Figure 9), recorded as few as 35 shocks, only one third of them having readable P and S onsets, while OBS42 in the central portion of the fault zone recorded more than 90 shocks, with identifiable body wave phases for 60 of them.

We estimated the velocity ratio Vp/Vs for paths in the array area, as a ratio of the difference of S-wave arrivals from an earthquake recorded by two OBS and the difference of P-wave arrivals from the same source recorded by the same stations. The mean value is 1.74 (±0.12) for events within 60 km of the array. The confidence interval is 90 percent. Within this scatter, the ratio tends to increase with increasing hypocentral distance (that is, Poisson' ratio increases with depth). A similar value (1.76) was obtained from Wadati plots in most cases.

Hypocenters have been located for 39 events (Figure 9). They include all earthquakes recorded by at least three OBS, plus 16 events with good P and S onsets recorded by two OBS which were aftershocks of the larger earthquakes recorded immediately after these, with similar S-P times. The locations are determined from station values of (Tp-To), Ts-p and from the hodograph used in similar studies in the North Atlantic [2]. This graph was based on a 6-layer model referred to 3 km below sea level (Table 1). Deep seismic sounding along the transect at the MAR crest gave about the same P-waves velocity distribution [20]. The To values were used in calculations together with (S-P) of the nearest stations and the mean value Vp/Vs=1.75. The uncertainty in To is around ±0.3 s.

Table 1

Velocity structure used for location of near earthquakes

Layer	I	II	III	IV	V	VI
h km	0.6	1.0	0.5	0.8	4.7	
Vp km/s	2.8	5.2	5.8	6.2	7.2	7.6
Vs-p km/s	3.8	7.1	8.1	8.5	9.8	10.4

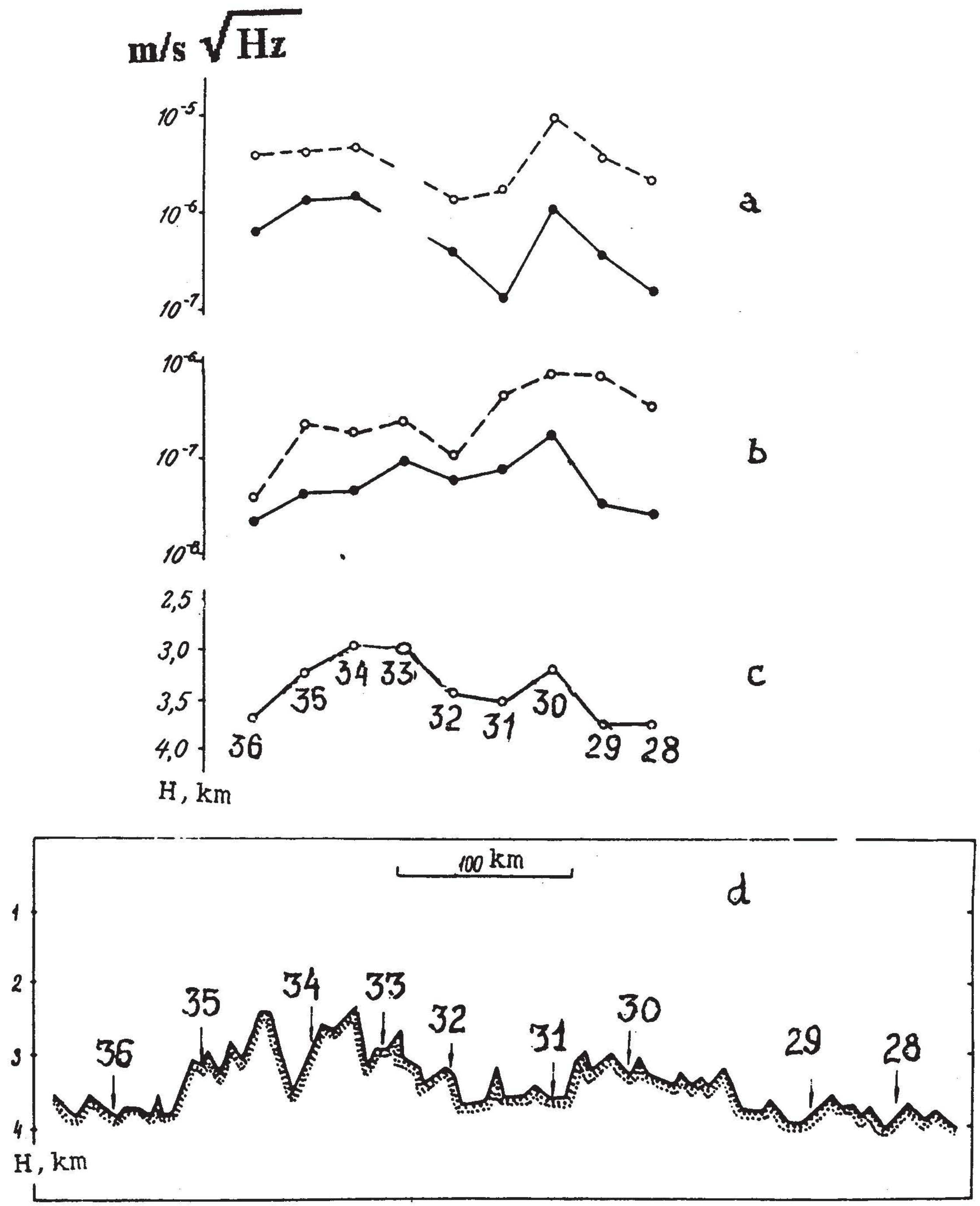

Fig. 7. MAR topography in the OBS deployment region (c) and (d), compared with maximum amplitudes of T-phase (open dots) and background (solid dots) at frequencies of (a) 3.2 Hz and (b) 8.0 Hz.

The location uncertainty, or the discrepancy between observed and theoretical travel times was 2 km for the epicenter and up to 5 km for the depth (with a mean of H=5 km). The uncertainty is caused by errors in arrival times and OBS coordinates, and by assuming a one-dimensional velocity distribution. The magnitudes were found from a P-wave calibration curve for Iceland earthquakes [2]. For a maximum magnitude of 2.1, the magnitude-frequency relation had a slope of b=1.35, which is typical for transform faults [5]. A similar b-value was obtained for the entire set of recorded earthquakes (130 events).

The epicenter distribution (Figure 9) is for April 1984. Two thirds of all sources, including the largest, are near OBS 42, within the ridge between the two troughs in the Gabon Fracture area. This includes events that initiated or accompanied the background disturbances at OBS42 (Figure 2) and other stations of the array. The most likely depth H=5 km is in the Vp=7.2 km/s layer. Earthquakes of lower magnitude occur in the southern trench where the relief is more rugged [11]. Overall, the microearthquake epicenters in the array area and the epicenters of larger events recorded by the worldwide seismic network coincide to

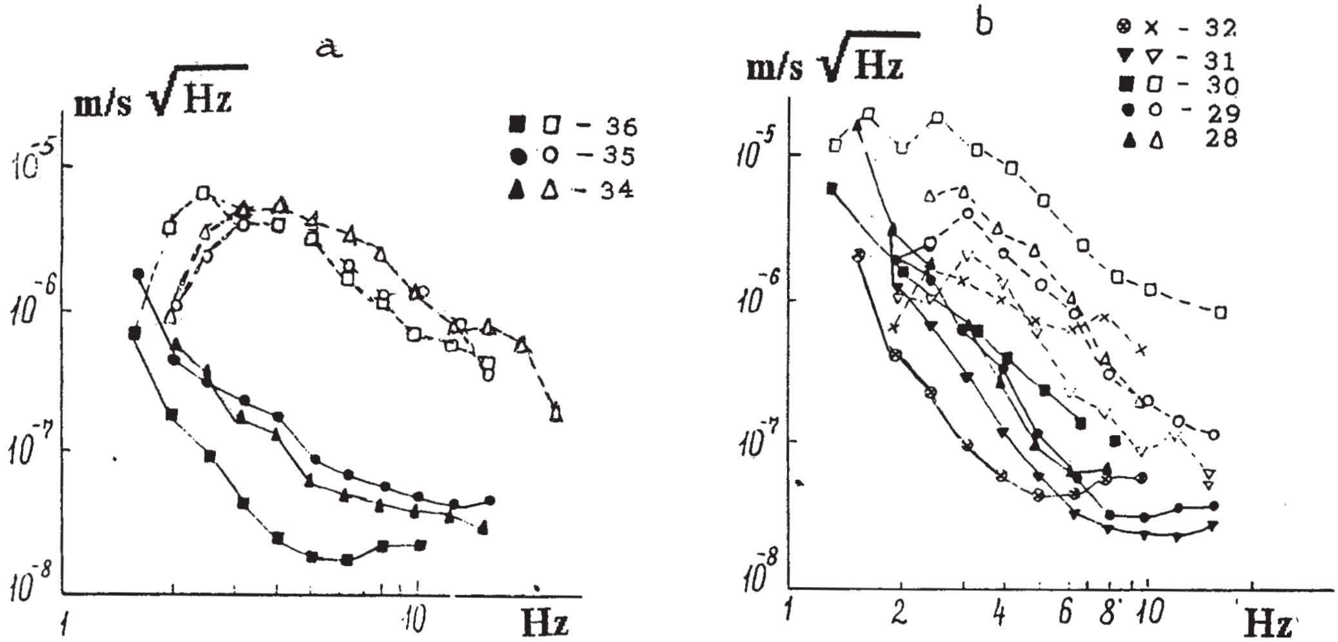

Fig. 8. T-phase spectra of the 82.03.10 earthquake (dashed) and of background noise (solid lines), recorded by OBS for paths (a) not crossing, and (b) crossing the MAR.

within the location uncertainty and are confined to the structures of the MAR crest.

4. MEDIUM PROPERTIES IN THE ANGOLA BASIN FROM RECORDS OF DISTANT EARTHQUAKES

Shots of 400-600 kg explosive used for seismic sounding along the transect are approximately equivalent to energies of earthquakes with mb=2.0-2.5. The energies of many earthquakes are higher than these by several orders of magnitude. In the four expeditions of the Angola-Brazil Geotraverse, there have been only three cases in which the OBS reliably recorded waves from teleseismic events reported in catalogs. One is the Sandwich Islands earthquake for which the OBS of array IV recorded T waves (see section 2). A shallow mb=4.8 earthquake occurred in the equatorial Atlantic on May 14, 1984. This earthquake was recorded on top of the shots fired. Nine OBS deployed in the Angola Basin (array X in Figure 1) recorded to two deep-focus earthquakes with magnitudes above 6.0 from the Fiji Islands on May 26, 1986. These events were located by the International Seismological Centre using records of over 300 stations.

The earliest waves of both earthquakes show impulsive onsets 15-25 dB above noise on all nine OBS. The records were above the noise for 5 minutes and consisted of numerous wave groups 0.75 to 2.0 s long. The dominant frequency of the first event (mb=6.4, depth H=583 km) during the first 5 s of the record was 3 Hz on average for all OBS, and about 5 Hz for the second (mb=6.4, H=538 km). The amplitude of the second event was 15 percent higher than the first. Since the instrument response curve decays by 30 dB per octave at frequencies below 5 Hz, and the signal is hidden in noise above 7 Hz, it follows that most of the energy is in the lower frequencies, below 2 Hz.

P travel time residuals relative to the Jeffreys-Bullen tables [8] were computed for known hypocentral and OBS coordinates, in addition to epicentral distance and source-station azimuth (Az). The parameters (Table 2) take into account earth ellipticity and OBS deployment depth (6 km below sea level).

Table 2

Earthquake Data

OBS number	earthquake I h, min, s	Δ°	Az	Δt, s	earthquake II h, min, s	Δ°	Az	Δt, s
89	18 59 18.0	143.83	189	1.9	19 24 57.7	146.07	192	3.6
90	19.7	145.53	185	2.5	59.9	146.92	189	4.9
91	20.5	145.71	184	3.0	25 00.6	147.13	188	5.3
92	21.4	146.01	182	3.4	01.3	147.51	186	5.4
93	21.3	146.11	181	3.2	01.9	147.64	187	5.8
94	25.4	147.68	186	5.1	05.2	149.02	190	7.0
96	21.9	146.13	185	3.8	01.5	147.50	189	5.6
97	17.4	144.64	184	1.6	24 57.7	146.05	188	3.6
98	13.3	143.39	184	-0.6	54.1	144.81	187	2.0

The first phase at 143-149 was the core phase PKP. The wave went by way of the South Pole (Az=181-192°). For such paths the residual varies from -0.6 s at the nearest station to +7.0s (that is, the P wave is late compared with the tables at the most distant station). The hypocenters are at different depths and distances to the array, but the residuals as a function of distance are practically identical within the range of epicentral distance (Figure 10,b). The linear

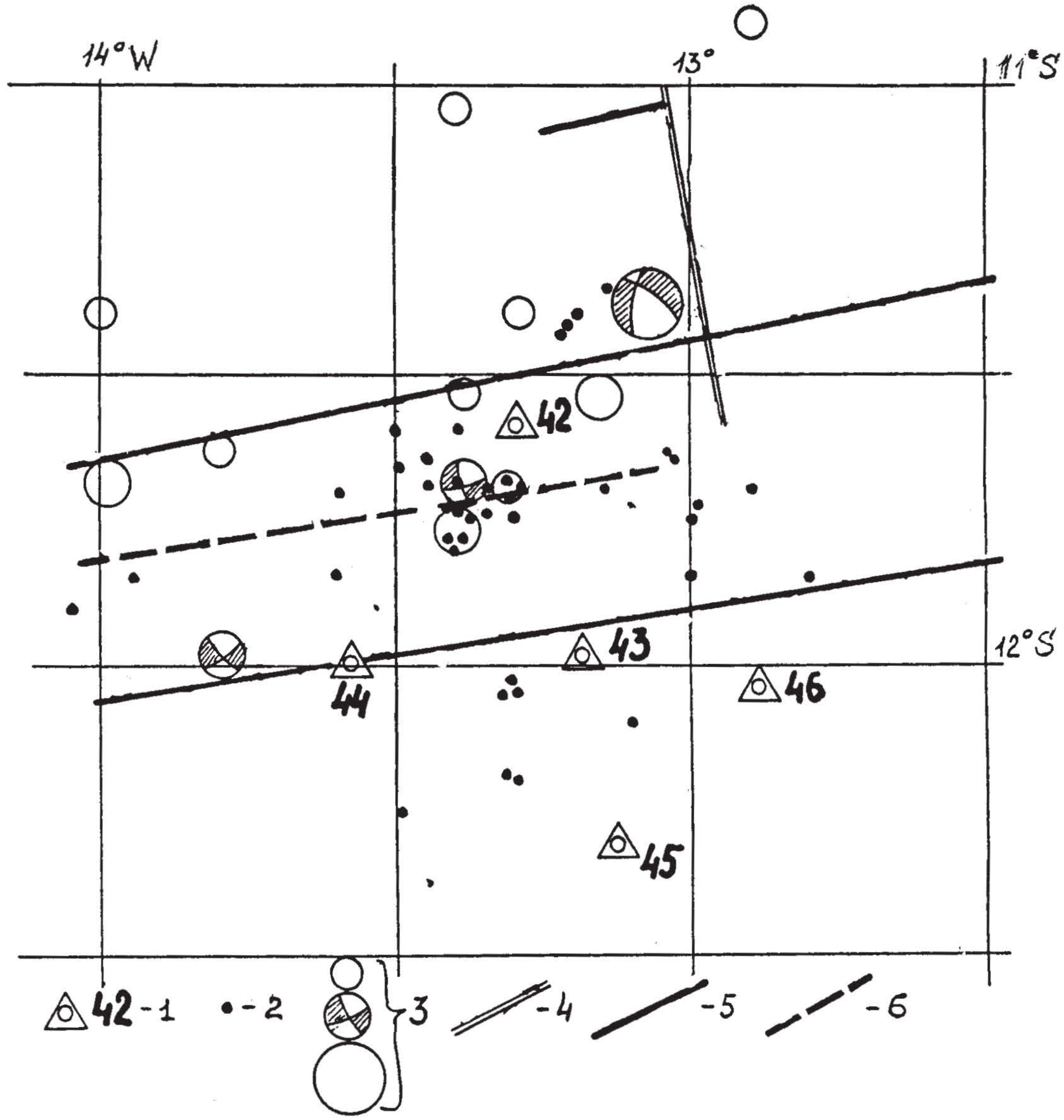

Fig. 9. Seismotectonic map of array VI. 1--OBS; 2--microearthquake epicenters; 3--epicenters of large events from the ISC; 4--MAR rift zone; 5--axes of the troughs in the Gabon Fracture Zone; 6--ridge between the two troughs.

approximation for the joint plot fits the expression $\Delta tp = 1.36 (\Delta° - 143.7°)$. The deviations are within 0.35 s and are even smaller for a smooth curve (0.25 s). The scatter is random, since the average residual for both earthquakes at any of the nine OBS is within ±0.15 s. The absence of significant (above 0.2 s) systematic departures of station residuals from the fit seems to indicate a uniform structure beneath the Angola Basin area. Similarly, the amplitude of the earliest waves smoothly decreases with distance (about 3 dB/deg) without any azimuthal or station-dependent features, even though the scatter involved is about 15 dB. The residuals and their variations seem to be controlled by global causes, including errors in the Jeffreys-Bullen tables [8].

Thus the plotted residuals (Figure 10) reflect P travel times as recorded by the OBS in the Jeffreys-Bullen reduction; branch DF (the solid lines in Figure 10,b) show PKP travel times (for GH, AB, and DF phases). No branch fits the observed times either in level or pattern of variation. For comparison, Figure 10,b shows ISC residuals for 20 deep-focus southwest Pacific earthquakes, 1000 values in all. Most of these were recorded by European stations. The dashed lines and the vertical hatching mark a 2.5s wide band containing over 90 percent of station values. The OBS times follow a slightly steeper line, but they are wholly within the band based on continental data and both are appreciably different from the tables. The deviations from the Herrin tables [7] are of the same order. In other words, the recording conditions are practically identical in the ocean basin and in Europe.

The apparent wave velocities exceed 40 km/s. With a mean velocity of 8.5 km/s in the lithosphere of the Angola Basin [20], seismic rays should be incident at 80-82 deg., that is, the lateral shift does not exceed 30 km within 200

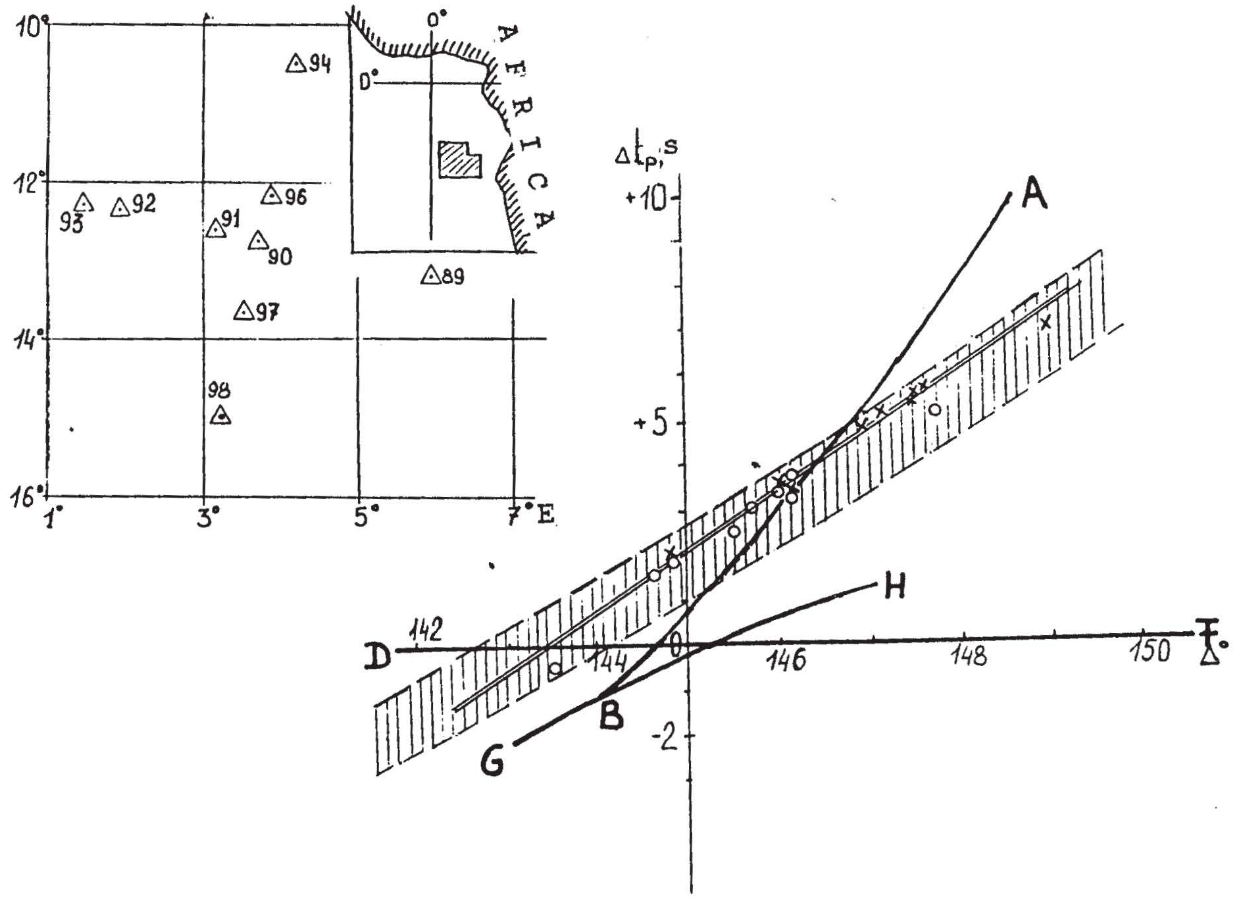

Fig. 10. (a) OBS array in the Angola Basin. (b) P-wave residuals versus epicentral distance. Crosses and circles denote residuals for two Fiji earthquakes recorded by the OBS. The residual area according to European stations is hatched. The solid lines AB, DF, GH indicate branches of the travel-time tables [8].

km depth. Within the uncertainties the overall velocity characteristics of the lithosphere are thus identical over the array area, that is, the lithosphere of the Angola Basin area does not involve significant local velocity anomalies. The slightly steeper OBS curve relative to the European residuals (0.8 s for 600 km distance) is probably caused by lower mean mantle velocities north of the array area compared with the south. However, the difference is more likely to be due to global and deep-seated features.

CONCLUSION

The large-scale study of the Angola-Brazil Geotraverse marks an important step forward in the geological and geophysical investigations of the world ocean. The Soviet research ships carried out multidisciplinary studies in a band of 1000 km within less than a decade. The scale and detail of research from this geotraverse are unprecedented anywhere. Seismic studies with OBS provided the first homogeneous data set on the seismicity of different seafloor structures, on the natural seismic background and its spatio-temporal variation, and on the deep velocity structure in some areas.The present paper deals with some general issues arising in the OBS observations, and is not intended to be exhaustive.

A comparative analysis of the natural seismic background by OBS arrays revealed considerable fluctuations of the noise and the number of shocks over time and from area to area. Microseismic activity was recorded in the areas of strong earthquake activity only. Other structures, including the heat-generation zone beneath the Cameroon Rise, were aseismic throughout the period of our observation at the level m>0. Most activity is exhibited by the area adjacent to the MAR crest. The area generates large earthquakes, microearthquakes, and noise. The complicated time-frequency character of background disturbances and their association with seismoacoustic pulses are likely to be due to underwater volcanism. The seismoacoustic energy of the disturbances considerably exceeds the energy of seismic waves excited by local earthquakes. OBS recordings detect and locate the background sources, determine their probable nature, and estimate their intensity and temporal evolution.

The T-phase variations registered by the OBS group at distances exceeding 5000 km suggest the formation of hydroacoustic signals near the epicenter on the continental slope of a deep-ocean trench (maximum), and on the smooth slope of the ocean floor. The intensity of hydroacoustic waves in the range of 3 to 20 Hz decreases with depth of recording. The similarity between the T-phase and the noise background in the South Atlantic suggests that the noise may be due to a combination of effects from navigation, storm microseismic waves, seismoacoustic phenomena, etc., that propagate in the water. Any factor may become dominant in specific regions of the World ocean during a given time.

Seismological observations near neotectonic areas of the MAR reveal (1) spatial coincidence of epicentral zones of large and small earthquakes; (2) earthquakes at contrasting relief forms; (3) small hypocentral depth (2 to 7 km); (4) rapid attenuation of seismic waves under the seafloor; (5) velocity ratio of Vp/Vs=1.74, as in other MAR segments. The epicentral areas of microearthquakes coincide with the sources of long-term background noise. Moreover, most recorded earthquakes occurred during rapid changes in the background disturbances. The total energy of earthquake waves is a small fraction of that released in hour-long background disturbances associated with submarine activity. Volcanism at the MAR may control the geothermal and geomorphic features of the area as well as its seismotectonics and seismoacoustics, at least at the microseismicity level.

We were fortunate in recording two teleseismic events on an OBS array, thus enabling us to show that the kinematics of the lithosphere and upper mantle in the Angola Basin are largely identical with those in the European continent. However, the upper mantle velocity is slightly higher in the basin. The compressional velocity at a depth of 50-70 km is 8.9 km/s according to deep seismic sounding [20]). There is no noticeable lateral variation of velocity under a large (600x600 km) area in the Angola Basin.

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