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THE MARGINAL SÃO PAULO PLATEAU, COMPARISON WITH THE SOUTHERN ANGOLAN MARGIN *

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ABSTRACT

During the Geobrésil cruise of the R. V. Jean Charcot (1973) several marine geophysical lines, including bathymetry, magnetism, continuous seismic as well as sonobuoy profiles have been run across a deep marginal plateau extending on the southeastern Brazilian margin and known as the São Paulo Plateau. These data indicate the presence of a thick sedimentary cover (more than 4 s DTT) on the upper slope and up to 3 s DTT thick on the lower slope and rise. The entire slope is highly disturbed by salt diapiric structures mostly apparent between the 2 000-3 000 bathymetriclines and comparable to the ones described in the western Mediterranean Sea. The São Paulo scarp, bordering the deep marginal plateau to the South-West, is believed to be a discontinuous and «en échelon» structure probably related to numerous and closely spaced early fracture zones. The overall structures of two areas — the São Paulo Plateau and the Angolan margin — are briefly compared and preliminary results of DSDP holes 356 and 364 suggest a similar sedimentary history, during mesozoic times, for both margins.

INTRODUCTION

Seaward of the São Paulo Embayment (Butler, 1970) and Southeast of the city of Rio de Janeiro, approximately between lat 23º and 28º South, the Brazilian continental margin widens considerably and reaches more than 400 km wide. Inspection of physiographic diagrams of published bathymetric maps (Heezen and Tharp, 1961; Butler, 1970; Leyden **et al.**, 1971; Uchupi, 1971) shows that this widening is mainly due to the presence of a deep and large marginal plateau, known as the São Paulo Plateau (figure 1). On its seaward side, the São Paulo Plateau is bounded by a relatively steep scarp (Leyden **et. al.**, 1971) believed to be a quasi-continuous basement feature (Leyden and Nunes, 1974).

Few studies have been concerned with the geological structure of this particular area of the Brazilian continental margin. Baccar (1970) published a short multichannel refraction-reflection profile recorded across the upper continental slope (fig. 1) and indicated that the sedimentary cover probably exceeds 6.5 km in this area and at least 4.5 km beneath the São Paulo plateau itself. Baccar showed also the presence, at depth, of a relatively disturbed seismic series, characterized by a mean seismic velocity of 4.2 km/s, which he interpreted as a possible evaporitic sequence of Aptian age. Leyden **et al.** (1971) confirm those findings and propose that

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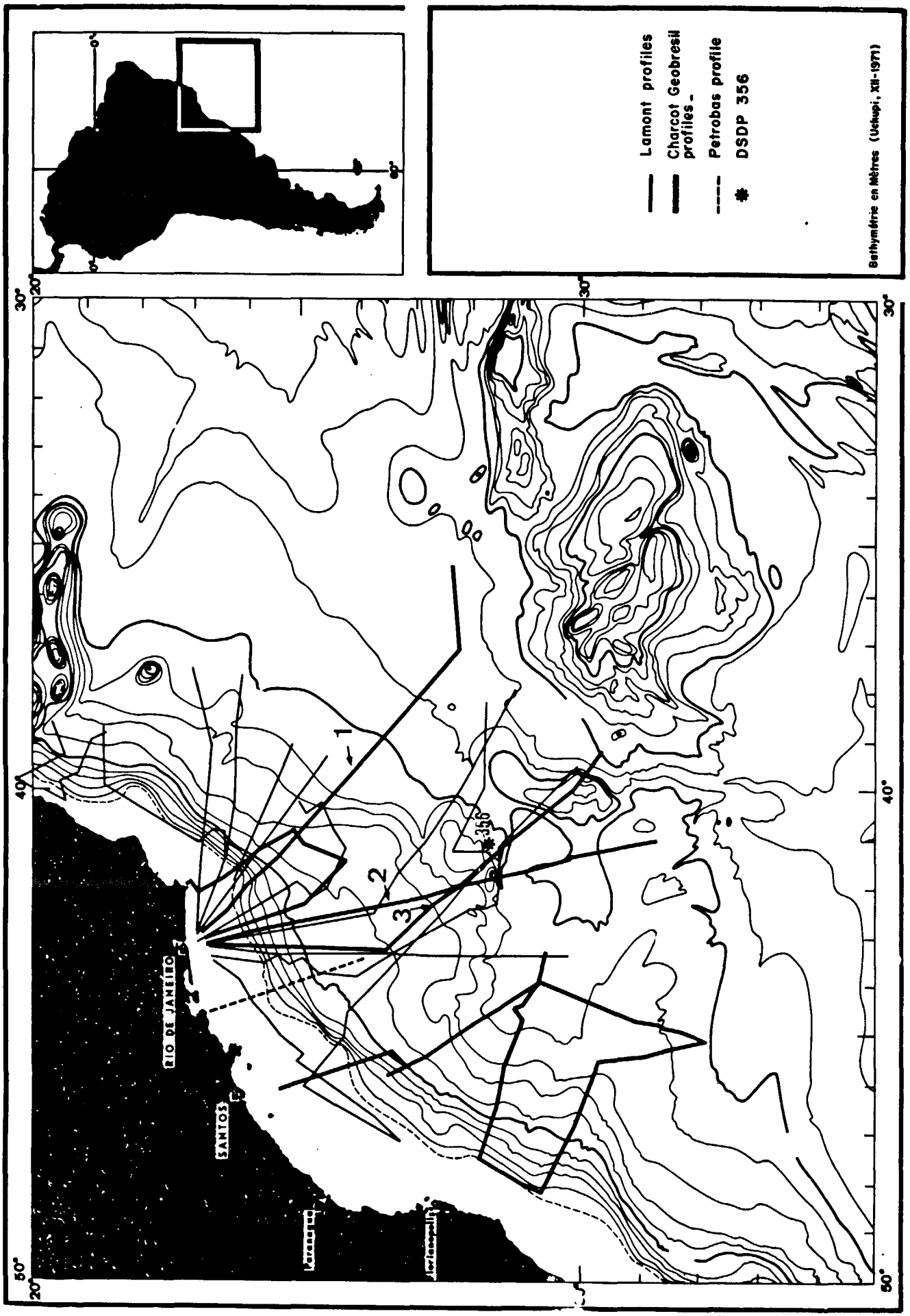


Fig. 1 — Index map of the surveyed area. In heavy black lines the track lines of the R. V. Jean Charcot across the southern Brazilian margin are indicated. The bathymetry is in corrected meters from Uchupi (1971).

a 5.1 to 5.6 km/s seismic layer, recorded beneath the marginal plateau, could represent the top of the seismic oceanic layer two. More recently Leyden and Nunes (1974) tentatively delineated a large diapiric area extending over most of the São Paulo Plateau. These authors propose a possible relationship, in Lower Cretaceous times, between this area and the well-known angolan diapiric marginal basin. The presence, at depth, beneath the São Paulo Plateau, of a probable Aption evaporitic sequence, is moreover strongly supported by unpublished wells, information obtained by Petrobras on the neighbouring continental shelf and quoted by Leyden and Nunes (1974).

This paper presents some new geophysical data, mainly deep seismic reflection profiles, obtained during the Geobrésil cruise of the R. V. Jean Charcot (1973) in this area. The geological structure of the São Paulo Plateau, including the presence of various and numerous deformations related to a deep evaporitic series, is inferred from these results and a brief comparison with the Angolan continental margin is made. Also, preliminary results from holes 356 and 364 of D. S. D. P. legs 39 and 40 (Perch-Nielsen, Supko et al., 1975; Bolli, Ryan et al., 1975) have brought new pertinent information.

BATHYMETRY AND MAGNETIC ANOMALIES OF THE SÃO PAULO PLATEAU

Although less detailed than the one of Butler (1970), the map of Uchupi (1971) indicates a complex topography in the area of the São Paulo plateau. Close examinations of two east-west projected profiles (figure 2) bring the following points:

— the marginal São Paulo plateau extends approximatedly 200 km, mainly between the 2 000 and 3 000 meters bathymetric lines;

— the São Paulo plateau does not appear to be continuously bounded, on its seaward side, by a steep scarp. Profile 1 shows on the contrary a progressive transition between the plateau and an almost flat continental rise, pierced by two important seamounts;

— numerous second-order topographic features exist particularly around 2 500 to 3 000 meters. On the average they are 5 to 10 km wide with an elevation of a few hundred meters;

— both the easternmost seamount (profile 1) and the marginal scarp (profile 2) border a relatively large depression (15 to 20 km wide and 200 to 300 meters deep), corresponding to the current-controlled Vema Channel or probable distributaries (Le Pichon and Ewing, 1971).

Thus, it appears that except for its unusual width between the 2 000-3 000 isobaths, this, area of the Brazilian margin is in all respects comparable to other areas of the South Atlantic continental margin, such as the Angolan margin for example. In this respect it is noteworthy that the profile 1 (of figure 2) is strikingly comparable to a profile across the Angolan continental margin published by Beck and Lehner (1974) including the presence, on the continental rise, of two large seamounts (see figure 11).

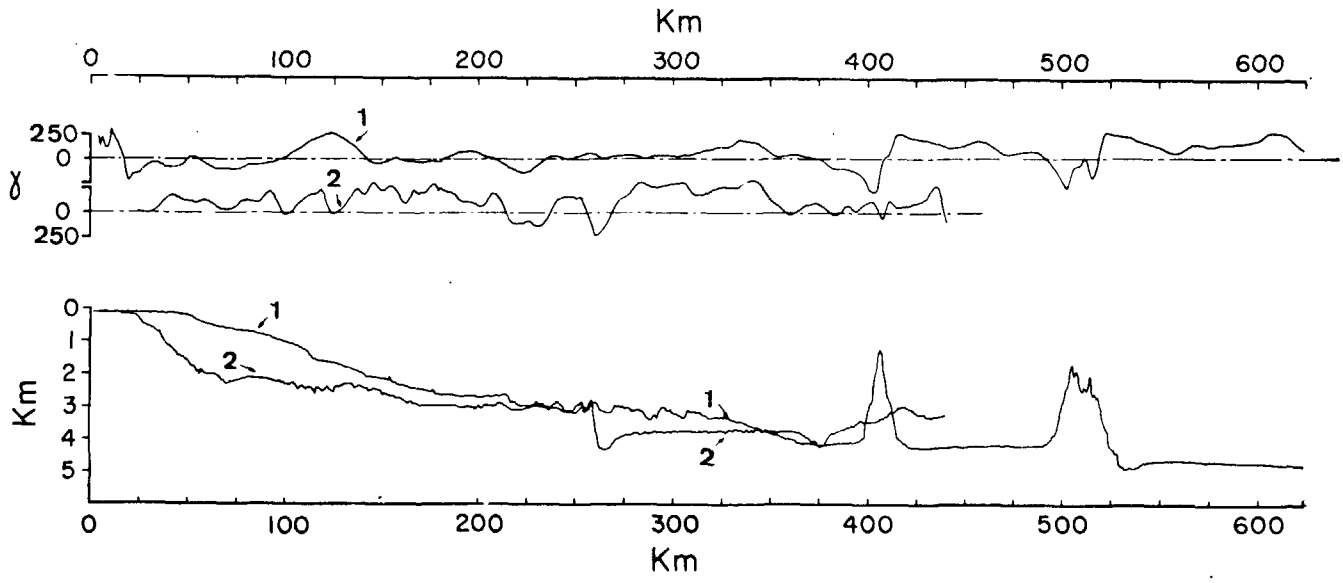


Fig. 2 — Two east-west projected bathymetric and magnetic lines across the southeastern Brazilian margin (indicated by 1 and 2 on figure 1). Note the prominent scarp (profile 2) and the two large seamounts (profile 1) as well as the numerous small bathymetric features along the São Paulo Plateau. Magnetic anomalies are relatively important over the whole surveyed area.

As indicated by the two east-west projected magnetic profiles of figure 2, the magnetic anomalies are relatively important (in the order of a few hundred gammas) over most of the São Paulo plateau. According to Leyden **et al.** (1971) and to our data, there is no apparent change in the magnetic pattern going from the deep oceanic area to the marginal plateau. This favors the hypothesis of an oceanic type basement beneath the plateau as already suggested by Leyden **et al.** (1971) and possibly confirmed by the recorded seismic velocities ranging between 5.1 to 5.6 km/s. This should also theorically allow, in further studies, to recognize here probable mesozoic magnetic lineations as it has been recently indicated along the south African margin (Larson and Ladd, 1974; Rabinowitz, in press), or suggested beneath the diapiric basin along the Angolan continental margin (Emery **et al.**, in press). Note also that, as on a profile shown by Leyden **et al.** (1971) (see their figure 4), the São Paulo scarp is underlined by a large amplitude magnetic anomaly, comparable to the ones recorded above the continental rise seamounts of profile 1.

SEISMIC REFLECTION PROFILES ACROSS THE SÃO PAULO PLATEAU

The figure 3 is an interpretation of a continuous seismic line running across the continental shelf just south of Rio de Janeiro and the abyssal basin just north of the Rio Grande Rise (see figure 1 for location). This section illustrates the general geological structure of the northern São Paulo plateau characterized by:

— a great thickness of relatively undisturbed sediments (in excess of 4 s D.T.T.) over the upper continental slope;

— a large area (approximately 180 km wide) of the São Paulo plateau, highly disturbed by deep anticlines and diapiric structures;

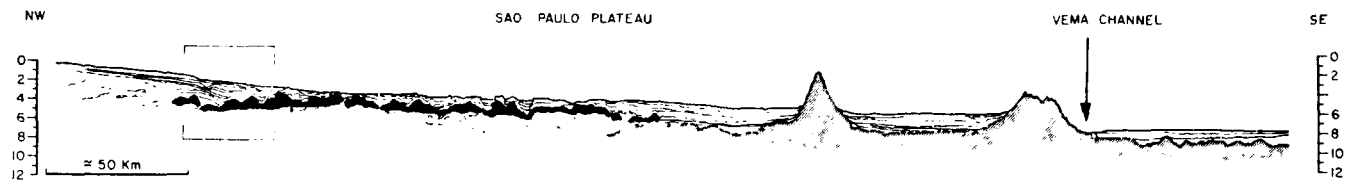


Fig. 3 — Regional profile across the São Paulo Plateau (profile 1 on figure 1). The evaporitic basin extends from the upper slope to water depth of 3 500 meters. Salt (in black) overlies a discontinuous series of reflectors probably representing non marine clastic rocks filling substratum depressions. The acoustic substratum (hatched) is seen only from the continental rise to the deep oceanic basin. It is interpreted to represent the top of the oceanic layer 2 and to extend beneath the São Paulo Plateau. The massive salt is overlain by probable albian dolomitic and calcareous limestones and by upper Cretaceous to tertiary hemi-pelagic, pelagic and terrigenous sediments as evidenced by DSDP result nº 356. The square indicates the segment of seismic profile shown on figure 5.

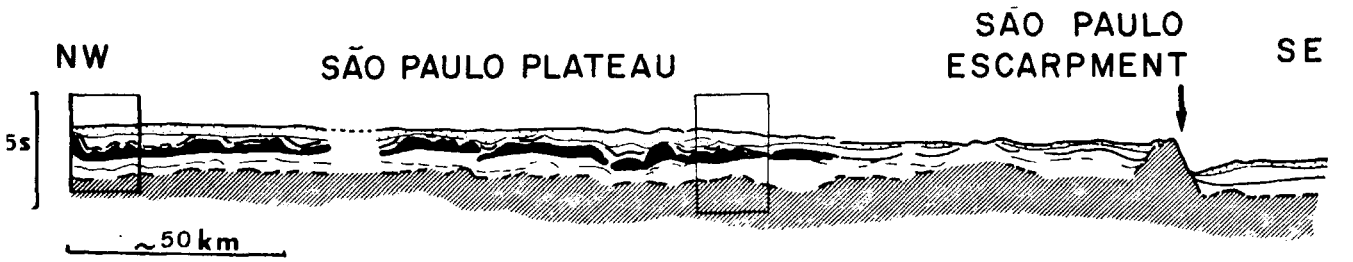


Fig. 4 — Interpretation of a seismic line run across the southeastern São Paulo plateau (profile 3 on figure 1). Same characteristics as for figure 3. Note the disappearance of the salt layer well before the São Paulo escarpment. Rectangles indicate the position of figures 6 and 7.

— on the contrary, except for the two seamounts, a relatively undisturbed continental rise with the exception of some small internal deformations probably related to fossil current actions;

- - beneath the continental rise as well as beneath the abyssal basin and partially beneath the São Paulo plateau itself, the presence of a strong and irregular reflective surface, from which originate the two previously described seamounts.

Except for a notable difference in penetration, most of these observations are compatible with those which can be made on the profiles published by Leyden and Nunes (1974) (see their figure 4). The Figure 4 represents an interpretation of a profile across the southeastern area of the São Paulo plateau, made in continuity with a profile published by Baccar (1970) (see figure 1 for the location). Note that, here also, the sedimentary blancket contains, at depth, numerous large scale undulations resting on a discontinuous and irregular series of reflectors. On this profile, the São Paulo plateau is bounded by a basement scarp, which from indications of a few other published bathymetric and seismic (Leyden **et al.**, 1971) profiles, seems to border the southern São Paulo plateau along a westerly trending direction. Thus, the southern area of the São Paulo plateau can be compared to the southern Voring plateau, feature which lies along the Norwegian continental margin and is bordered on its southern seaward side by the prolongation of the oceanic Jan Mayen fracture zone (Talwani and Eldholm, 1972).

The figures 5, 6 and 7 are examples of characteristic seismic reflection sections chosen to illustrate the details of the sedimentary cover and of its deformations.

In the area of the upper slope (figure 5) the sediment thickness reaches 4 s D.T.T., a value which agress with the ones indicated by Baccar (1970) further south. At least three distinct units can be described within the acoustic series -- an upper unit, thickening towards the shelf with a few strong reflections, continuous over the whole section, showing however some erosional traces such as a buried channel and lateral heterogeneities.

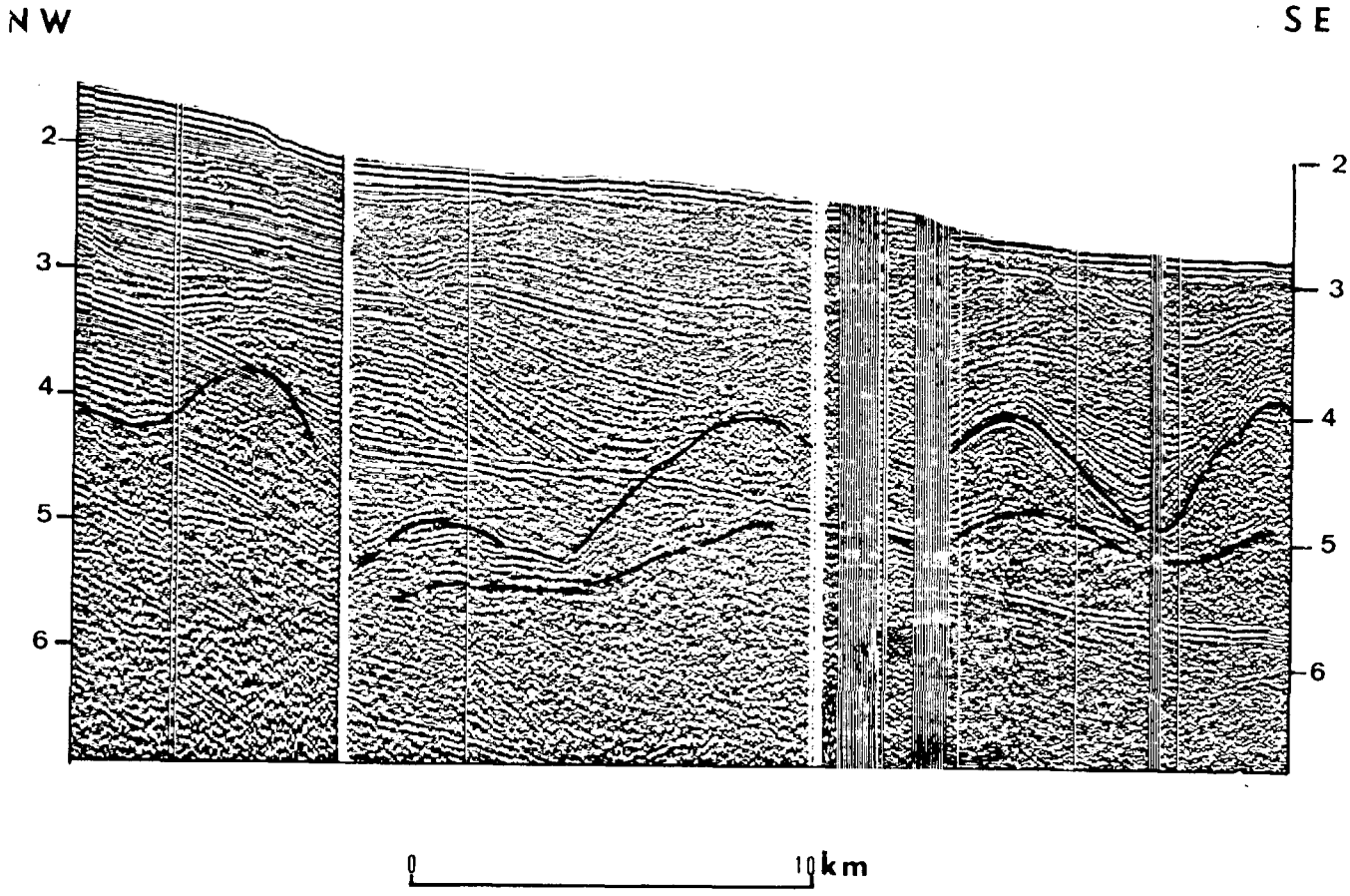
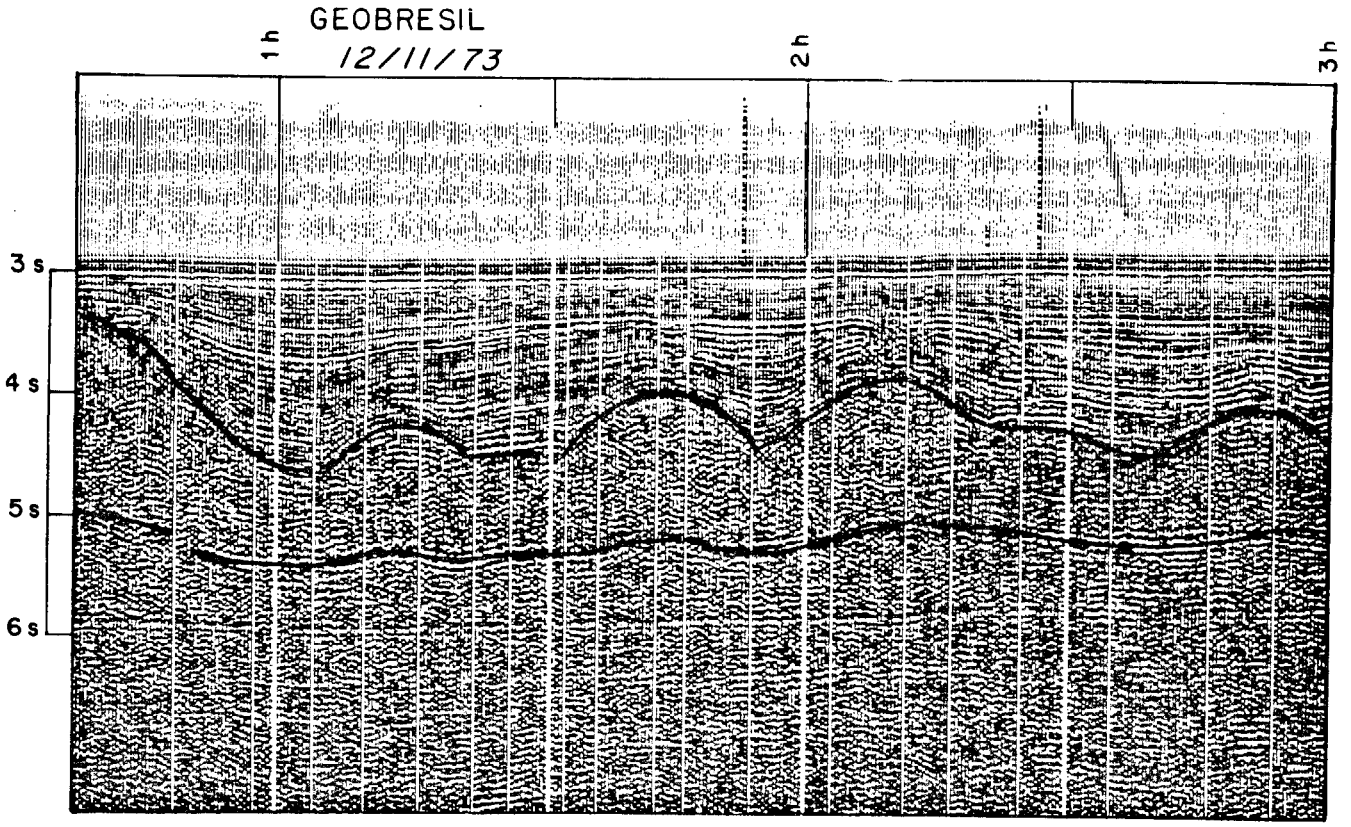


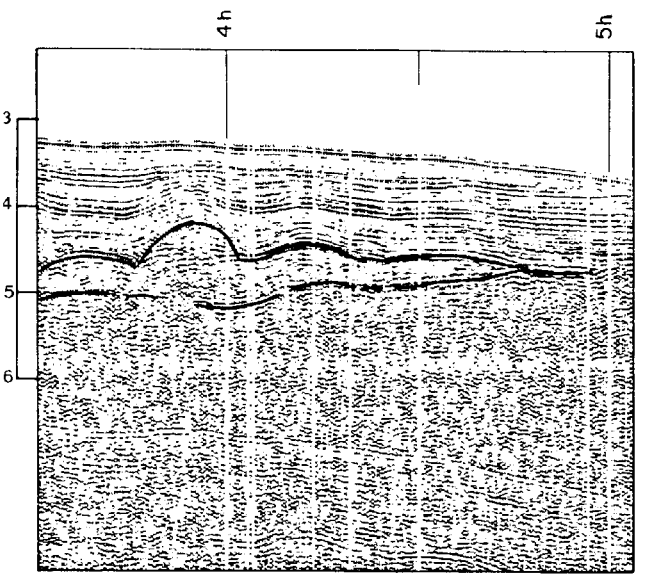
Fig. 5 — Segments of seismic profile across upper part of continental slope of the southeastern Brazilian margin, made using a watergun source. Note, below a thick and well-stratified sequence, (including a buried channel), numerous large anticlines, capped by a series of strong reflections, and underlined by a flatlying lower unit. Those anticlines are supposed to represent the undulated salt layer.



— a middle unit is strongly folded, particularly eastwards, where the anticlines are relayed by large diapirlike structures. This unit of variable thickness contains an irregular and acoustically poorly stratified sequence capped and floored by strong series of reflectors.

— locally, mostly eastward when the sedimentary thickness decreases slightly, a lower unit is apparent. It is made of a few, discontinuous but strong reflectors, indicating its probable sedimentary nature.

Figures 6 and 7 show an almost identical acoustic series to the one we just described but are of particular interest because they look exactly like sections recorded in western Mediterranean sea (Mauffret **et al.**, 1973; Biju-Duval **et al.**, 1974; Ryan **et al.**, 1973) (see respectively their figures 16, 3 and 3). In this last area, the undulated structures, proven to be flowing Messinian massive salt, are similarly capped by strong seismic horizons made of an alternation of marls and evaporites about 600 m thick. If such a comparison is valid, the anticlines illustrated on figures 5, 6 and 7 would then be made of massive salt sequences which could reach a thickness of 2 to 2.5 km. Such an interpretation agrees well with the thickness computed by Baccar (1970), in the order of 2 km, for a



Figs. 6 and 7 — Segments of seismic profile across the São Paulo Plateau. Same characteristics as for figure 5. These sections closely resemble profiles recorded in western Mediterranean sea (see Auzende *et al.*, 1970; Ryan *et al.*, 1972; Biju-Duval *et al.*, 1974).

The strong reflector, lying along the 5 s line and the deformed layer are inferred to represent the salt layer, while the series of reflectors closely capping the different structures may represent an alternance of evaporites including gypsum and dolomites.

mean velocity of 4.2 km/s. The figure 7 shows the progressive pinching out and disappearance of the undulated layer far before the São Paulo plateau scarp. On this section, the acoustically well-stratified upper unit maintains a quasi-constant thickness (in order of 1.5 s D.T.T.). Though discontinuous, the lower unit is easily detectable. Further east, it is directly capped by the previously mentionned strong reflectors. Near the São Paulo scarp, itself, the total sedimentary thickness averages 2.5 s D. T. T. of well-stratified sediments. A preliminary sonobuoy result obtained within this area (F. Avedik, personal communication) indicates beneath 0.7 s D. T. T. of unconsolidated sediments (mean velocity 1.87 km/s) a layer about 0.6 s D. T. T. thick, characterized by a velocity of 2.35 km/s. This should be compared to the result of D. S. D. P. drill hole 356 (Perch-Nielsen, Supko **et. al.,** 1975) (see location on figure 1) which has reached an albian marly, dolomitic and calcareous mudstone beneath 710 meters of an alternation of Upper Cretaceous to Cenozoic pelagic, hemipelagic and terrigeneous sediments and lead one to believe that the series of strong reflectors capping the undulations could partially correspond to Albian consolidated sediments.

PROBABLE NATURE AND AGE OF THE DIFFERENT ACOUSTIC UNITS

No new argument, except offshore unpublished wells informations, has become available to support the hypothesis of Butler (1970), Baccar (1970) and Leyden **et al.** (1971), mostly based on land geological evidences and seismic velocities analysis according to which salt could be present at depth beneath the São Paulo Plateau.

However, the similarities between seismic data presented in this paper and data from western Mediterranean sea where the sedimentology is known as well as the preliminary results of drill hole 356 (DSDP leg 39) strongly support the presence of a large evaporitic basin, at depth, beneath the São Paulo plateau. If this is correct, the age and nature of the São Paulo plateau sedimentary cover can be inferred as follows:

— an infrasalt series, probably of Lower Cretaceous age, seismically poorly defined, possibly made of coarse clastic deposits mainly terrigenous, identical to those described by Leyden **et al.** (1971) from bore hole data from wells drilled by Petrobras in the Espirito Santo Basin.

— an evaporitic series of Aptian age made of two main groups as in the Western Mediterranean: an upper one characterized by strong and continuous reflectors caping the deep undulations probably corresponding to an alternation of evaporites, gypsum and dolomites (note in this respect that hole 356 bottomed in albian calcareous and dolomitic mudstones). A second group, illustrated by the deep undulations and the diapiric features made of a massive flowing salt sequence. This last layer could reach as mentionned above, a thickness locally exceeding 2.5 km.

— an upper series that will be documented when detailed study of drill hole 356 will be available, is however shown by preliminary results to be made of Upper Cretaceous to Cenozoic deposits, including numerous hiatuses. It is most probable that these series had been exposed to one or several erosional periods as evidenced by the presence of numerous buried channels (see figure 5) previously described by Butler (1970). Towards the shelf, a few but strong reflectors, apparent within this series, may reflect lateral facies change comparable to those documented in Gabon or in Angola (Beck and Lehner, 1974; Driver and Pardo, 1974) and corresponding to carbonate platform built up.

GEOLOGICAL STRUCTURE OF THE SÃO PAULO PLATEAU

Figure 8 summarizes our thoughts concerning the geological structure of this area of the Brazilian continental margin. On this diagram the hatched area delineates the evaporitic basin using our data and other available data (Baccar, 1970; Leyden and Nunes, 1974). The southern limit of the diapiric zone is somewhat different from the one previously proposed by Leyden and Nunes (1974) since diapiric deformations are observed within the upper slope at the latitude of the city of Florianapolis. We distinguish in the evaporitic basin two different areas; a first one characterizes the upper slope where only deep salt anticlines, covered by at least 3 s D. T. T. of sediments are present (see figure 5); the second lies seaward of the upper slope and displays many piercing diapiric structures. This suggests, as supposed by many investigators for other evaporitic basins such as the northern gulf of Mexico (see Lehner, 1969) or the Angola (Renard and Mascle, 1974), a possible deep flowage of the massive salt sequence under the excessive load of continental slope sediments.

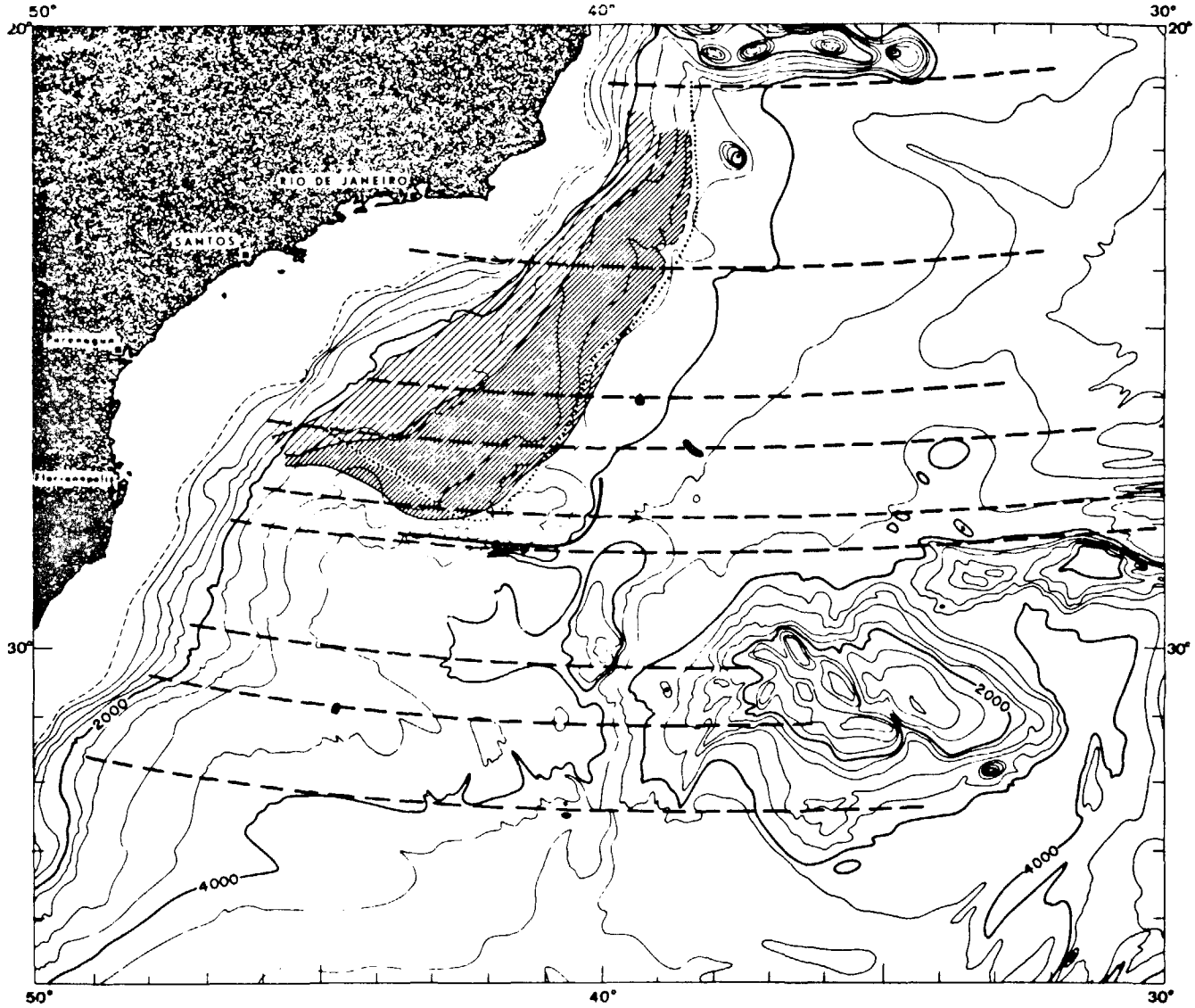


Fig. 8 — Outline of the general geological São Paulo Plateau structure. The area of the deep undulated sequence discussed and the area of diapiric structures are distinctly hatched. Dotted line indicate the limit of the diapiric zone as proposed by Leyden and Nunes (1974). Black dots represent seamounts discovered during this survey. Dashed lines correspond to early flow lines as deduced from the pole of Mascle and Sibuet (1975). Note that at least 9 early trends fit well with east-west bathymetric offsets in an area between 21° and 32° south.

On this figure we have also indicated the contour of the marginal scarp. (from Leyden and Nunes, 1974) as well as the different topographic seamounts discovered during our survey. A relatively good correspondence exists between the position of those different basement features and early south Atlantic opening flow lines as drawn from the pole given by Mascle and Sibuet (1975). It has been suggested by Francheteau and Le Pichon (1972) that two important early fracture zone trends, the «Novo Redondo fracture zone» and the 47° fracture zone, detected along the Angolan continental margin, may have their conterparts just north and south of the São Paulo plateau. However, as evidenced by the numerous east west bathymetric offsets we believe that several other early trends cut across the São Paulo plateau and consequently that the marginal scarp could correspond to a composite «en échelon» structure in a manner similar to the model proposed by Heyes and Ewing (1970) for the North Brazilian ridge. It should be stressed that many other probable early directions may be inferred from the east-west bathymetric trends visible south of São Paulo plateau and over the westernmost Rio Grande Rise. This suggests a possible relationship between the origin of the Rio Grande Rise and the presence of numerous and clasely spaced fracture zones.

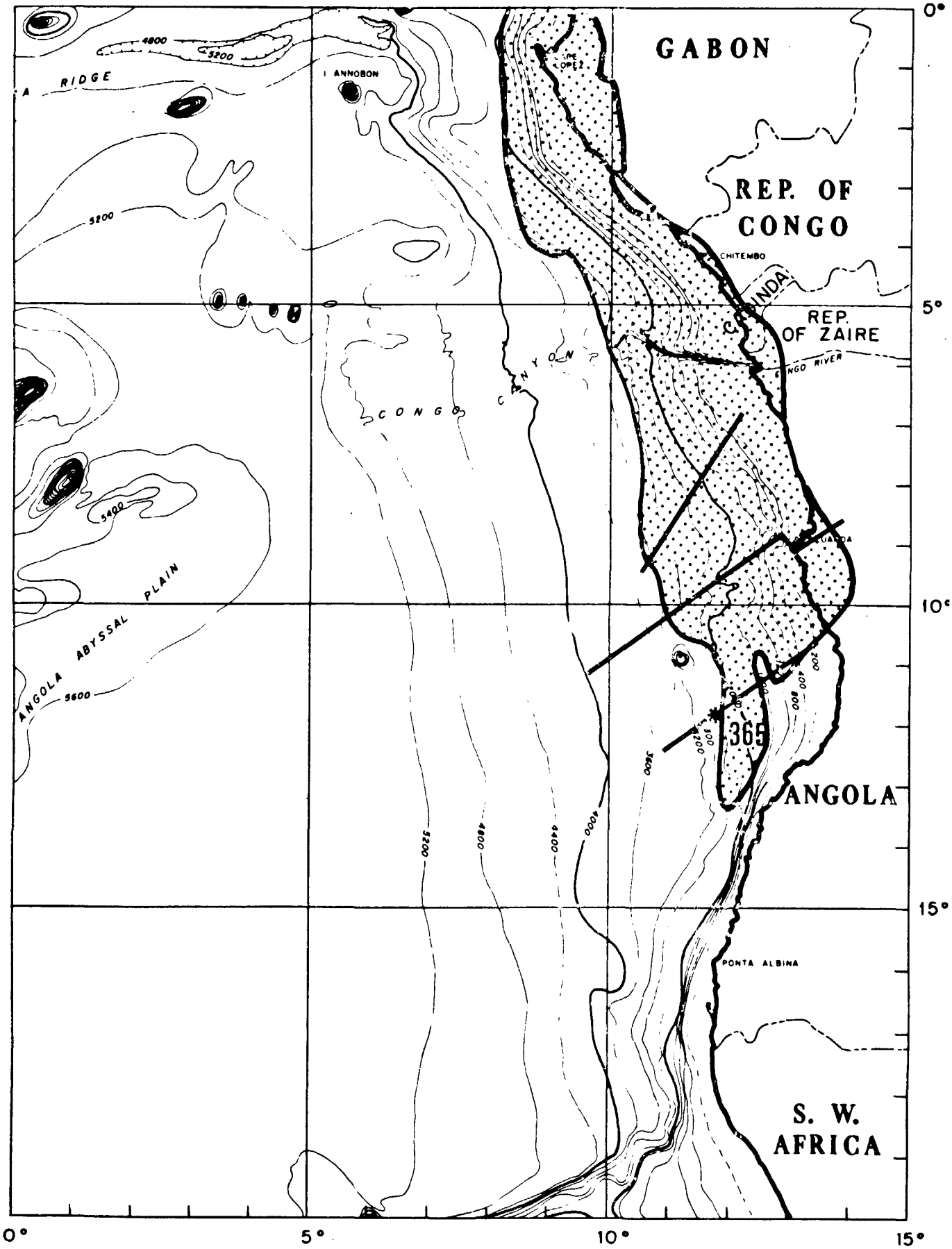


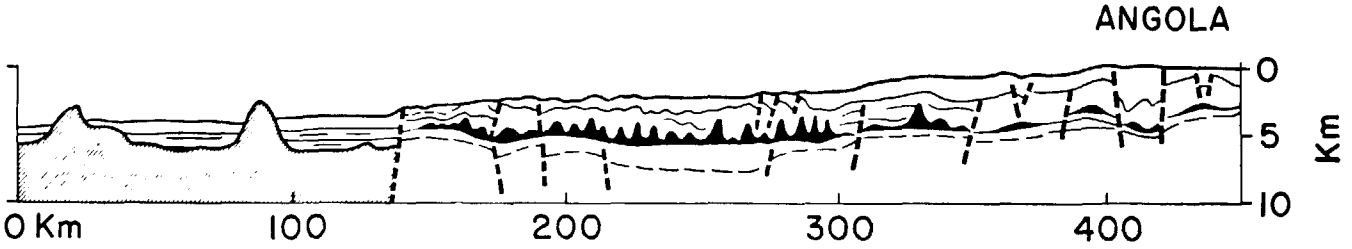
Fig. 9 — Map of the African diapiric basin lying along the continental margin of Angola to Gabon (in dotted). The bathymetry is in corrected meters from Uchupi (1971). Lines A and B indicate respectively the position of profiles illustrated on figures 10 and 11.

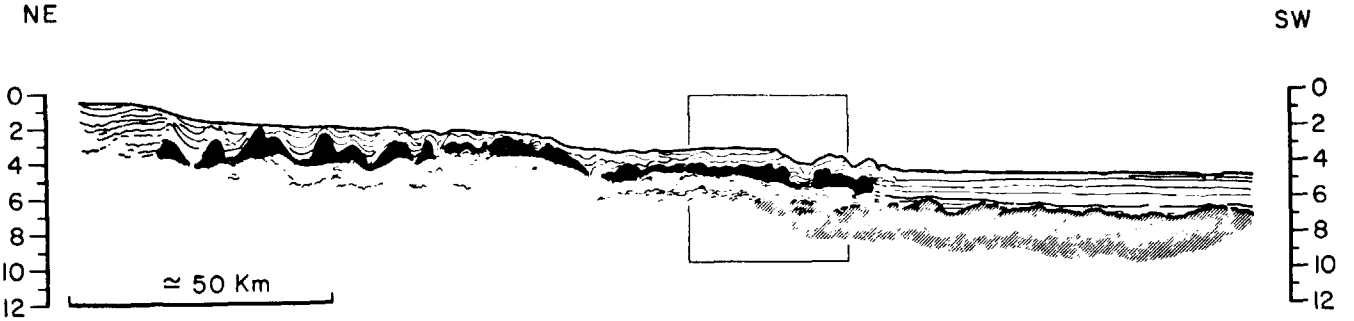
Finally note that the hypothetic prolongation of early trends beneath the São Paulo plateau is a good indirect argument in favor of the existence of an underlying oceanic crust as previously discussed. This would also indicate that the evaporitic sequences may well have been deposited on an oceanic crust as already suggested for part of the Angolan marginal diapiric field (Renard and Mascle, 1974).

COMPARISON WITH THE ANGOLAN CONTINENTAL MARGIN

As proposed by Leyden and Nunes (1974) on the basis of prerift reconstruction of the South Atlantic (Bullard **et al.**, 1965; Francheteau and Le Pichon, 1972) the Angolan continental margin and the present-day São Paulo marginal plateau may well have been portions of a large and unique evaporitic basin bounded to the south by the Rio Grande Rise-Walvis Ridge structural line, in lower Cretaceous times. If correct, this hypothesis leads to conclude that, at least during Cretaceous, both areas have been submitted to a similar geological evolution, and then that it is theorically possible to describe, on both sides of the south Atlantic, a comparable Cretaceous sedimentary history and geological structure.

The Angolan continental margin has recently been studied in several extensive papers, among them those of Rabinowitz (1972), Leyden **et al.** (1972), Pautot **et al.** (1973), Beck and Lehner (1973) and Emery **et al.**, (in press). We have shown, on figure 9, an up-to-date map of the Angolan evaporitic zone (from Emery **et al.**, in press) together with the position of two seismic lines illustrated on figures 10 and 11. The position of the recent D. S. D. P. drill hole 365 obtained just a few kilometers from one of these lines has also been indicated (Bolli, Ryan **et al.**, 1975). As evident from comparison between figures 3 and 10 or 11, the general structure of the Angolan margin is strikingly similar to the one we described for the São Paulo Plateau, including the presence of a thick sedimentary blanket covering the continent shelf and slope,





Figs. 10 and 11 — Two regional seismic sections across the Angolan continental margin. The figure 10 is an interpretation of a seismic line recorded during the Walda cruise (1971) of the R. V. Jean Charcot in this area. Note the close similarity with the São Paulo Plateau structure, including the different seismic units. There is no apparent basement scarp on this profile but figure 11 (from Beck and Lehner, 1974) offers a general section almost identical to the one we show on figure 3, including the presence of two continental rise seamounts. Beck and Lehner (1974) stop the oceanic basement just before the diapiric basin, but it is probable, as suggested by Renard and Mascle (1974) that the oceanic crust underlines part of the Angolan continental margin as moreover supported by the presence of possible mesozoic magnetic anomalies (Emery *et al.*, in press).

— In black, the salt layer.

— Hatched, the oceanic basement.

as well as the presence, at depth, of a highly disturbed zone (extending on about 120-150 km) resting on a poorly defined series, and covered by acoustically well-stratified sequences.
Note, in this respect, the surprising similarity between the seismic lines of figures 3 and 11, both including the presence of two large seamounts piercing the sedimentary cover in the area of the continental rise.

A study of a detailed seismic section obtained on the basis of the Angolan margin (figure 12) reveals that, as for the São Paulo plauteau, the sedimentary cover can be also divided in three main series. A lower one, made of poorly defined and discontinuous reflectors, about 0,5 D.T.T. thick rests on an acoustic basement; a middle series corresponds to an 1.5 s D.T.T. thick, highly disturbed layer, capped by a strongly reflective zone. Finally, the upper series consists of acoustically well stratified reflectors about 1.5 s (D.T.T.) thick. As mentioned above, hole 364 has been positioned close to this profile, (figure 9-12), it has allowed to sample the upper series as well as to strongly support the presence of a massive salt layer resting just below. According to Bolli, Ryan **et al.**, (1975) this hole bottomed in an Albian marly and calcareous chalk covering a few meters of Aptian dolomitic and sapropelic shales just covering the acoustic middle series. The upper series is of an alternation of pelagic, hemipelagic and terrigenous upper-cretaceous to cenozoic sediments.

On both areas of the continental margin of Angola and São Paulo plateau, there are thus strong presumptions that, below a Cenozoic to Upper Cretaceous cover, reflecting local variations of the terrigenous input and of the erosional processes, a comparable stratigraphic series does exist. From the preliminary indications of drill hole 356 and 364, we believe that the top of this stratigraphic series contains an alternation of Albian dolomitic and sapropelic layers indicating restricted conditions. This sedimentologic sequence could be quite analogous to the one drilled in western Mediterranean sea, which, closely caps the massive Messinian salt (D.S.D.P. leg 13, Ryan **et al.**, 1972). It is therefore probable that the middle term individualized in the acoustical column of both margins corresponds to a massive flowing salt layer of Aptian age resting on lower Cretaceous continental-derived sediments.

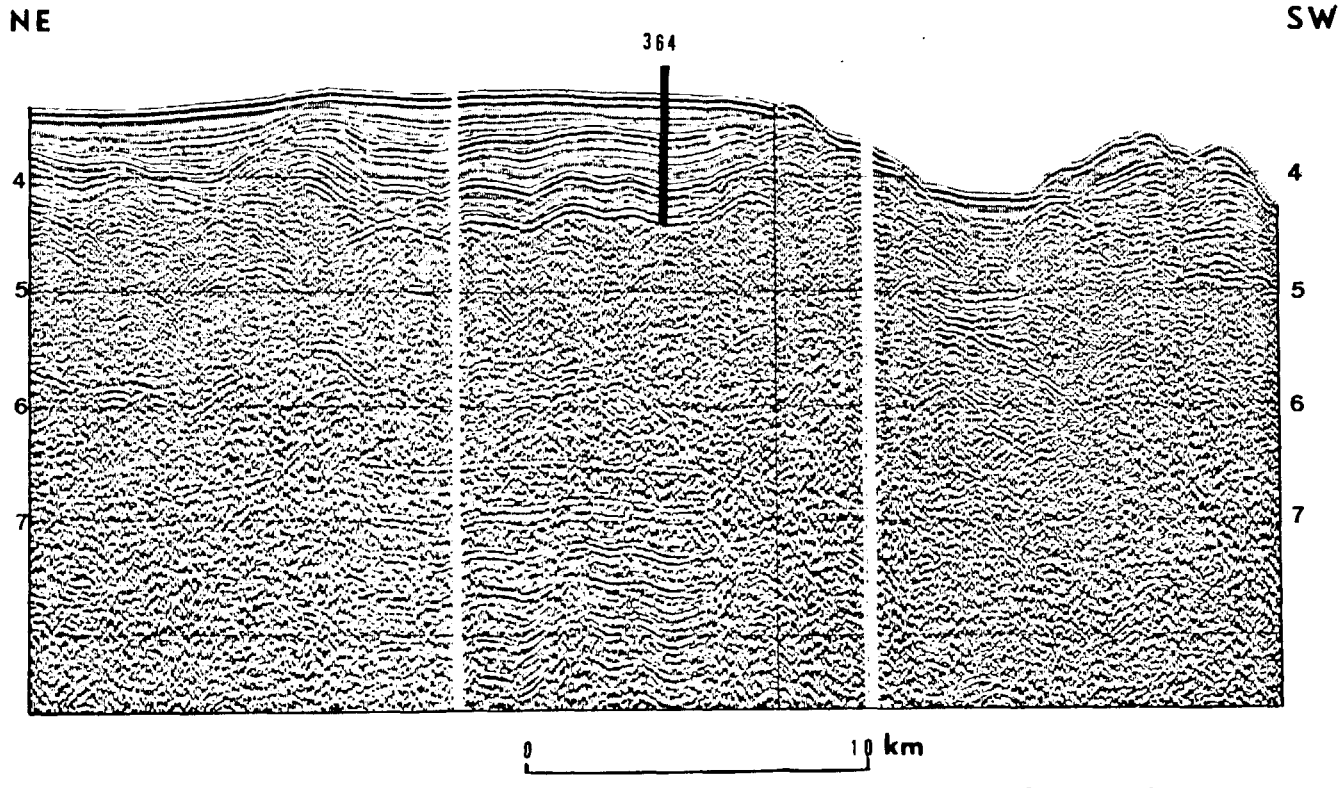


Fig. 12 — Segment of seismic profile across part of the Angolan continental slope (as shown by the square on figure 11). Drill hole 364 (DSDP leg 40) has been drilled close to this profile and has bottomed in an aptian dolomitic and sapropelitic mudstone. Note a disturbed layer just below the extremity of hole 364, believed to represent the massive salt. Discontinuous reflectors are still visible below this layer and may correspond to early cretaceous clastic deposits or to the proximity of the acoustic basements.

As for the Western Mediterranean sea, the nature of the basement of both areas is not positively established. It seems however most probable that the substratum is of oceanic type or corresponds at least to a highly injected and fragmented continental basement. In some respects the Lower Cretaceous to Cenozoic geological and sedimentological history of both areas, the São Paulo plateau and the Angolan margin may have been quite similar to the more recent, Oligocene to Quaternary, history of the western Mediterranean sea and the comparison of the D.S.D.P. results obtained in the three areas should be very instructive.

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