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Geological studies of the eastern part of the Romanche transform (equatorial Atlantic): a first report

ENRICO BONATTI, YURI RAZNITSIN, GIOVANNI BORTOLUZZI, FRANCESCA BOUDILLON, GIOVANNI DE ALTERIIS, LUCA GASPERINI, MARCO GASPERINI, GIUSEPPE GIAQUINTO, MARCO LIGI, EMANUELE LODOLO, ALEXANDER MAZAROVICH, ALEXANDER PEYVE, MARCO SACCHI, SERGHEI SKOLOTNEV, VALERIJ TROFIMOV, NATALIJA TURKO, MICHAIL ZACHAROV, JEAN-MARIE AUZENDE, VASSILIOS MAMALOUKAS FRANGOULIS and ROGER SEARLE

Enrico Bonatti — Istituto per la Geologia Marina, CNR, Bologna, Italy; Dipartimento Scienze della Terra, Università di Pisa.
Giovanni Bortoluzzi, Luca Gasperini, Marco Gasperini and Marco Ligi — Istituto per la Geologia Marina, CNR, Bologna, Italy.
Yuri Raznitsin, Alexander Mazarovich, Alexander Peyve, Serghei Skolotnev and Natalija Turko — Geology Institute, RAS, Moscow, Russia.
Francesca Boudillon, Giovanni de Alteriis and Marco Sacchi — Istituto Geomare Sud, CNR, Napoli, Italy.
Emanuele Lodolo — Osservatorio Geofisico Sperimentale,, Trieste, Italy.
Valerij Trofimov — Krasnodar Experimental Group, Soiuzmorgeo Co., Krasnodar, Russia.
Valerij Zacharov —Vernadsky Institute of Geochemistry, RAS, Moscow, Russia.
Jean-Marie Auzende and Vassilios Mamaloukas-Frangoulis — Ifremer, Brest, France.
Roger Searle —Institute of Ocenographic Sciences, Deacon Laboratory, Wormley,, Godalming, Surrey, GU8 5UB, UK.
Giuseppe Giaquinto — Dipartimento Sc. Terra, Università di Napoli,, Italy.

Abstract

The Mid Atlantic Ridge is intcrsected by a number of long—offset transforms in the equatorial region. The longest is the Romanche (offset ~ 950 km) located close to the equator. The St. Paul transform (offset ~ 400 km) is located about 180 km to the north, the Chain transform (offset ~ 300 Km) about 180 km to the south.

Multibeam and magnetometric surveys as well as high resolution multichannel seismic reflection experiments and rock and sediment sampling were carried out during a recent expedition to the eastern part of the Romanche transform. This field work is part of PRIMAR (Russian Italian Mid Atlantic Ridge Project). a collaboration for the study of mid ocean ridges between the Russian Academy of Sciences and the Italian CNR (National Research Council).

A detailed morphobathymetric survey of a limited area at the eastern ridge/transform intersection (RTI) suggests that the axial segment of spreading approaching the transform loses a well defined morphotectonic signature. An overall oblique trend prevails, probably resulting from a number of short *en-enchelon* ridge segments. No well defined nodal deep was observed. An aseismic rift valley was observed about 80 km west of the present RTI, suggesting a ridge jump to the east sometimes within the last 5 my. A markedly alkalic magmatism has been recently active near the RTI. These data suggest that the axial system of spreading approaching the Romanche transform from the south is sluggish and not well established, possibly due to a relatively «cold» upper mantle thermal regime below.

Major positive topographic anomalies, reaching over 4 km above the predicted thermal contraction level of the crust. are found on the transverse ridge opposite the eastern RTI. Seismic reflection profiles and bottom samples indicate that shallow reliefs on the crest of the transverse ridge are wave-eroded blocks of oceanic lithosphere that formed islands between 10 and 5 my ago and subsided since then at rapid (~ 0.2 mm/y) rates. Their summits are now covered by originally shallow water reef-lagunar carbonate caps, whose thickness ranges from 200 to 400 m.

An aseismic valley is observed to the north of and subparallel to the presently active transform valley. The active and inactive valleys merge near the eastern RTI. The inactive valley can be traced westwards as a continuous feature up to about 150 km from the western RTI. It is probably the trace of a former location of the Romanche transform boundary, that became inactive between 8 and 10 my ago. It appears. therefore, that the Romanche ridge/transform geometry has changed significantly through time. with ridge jumps that have increased the length of the transform offset and migration and the reorientation of the transform boundary.

Transpression and transtension due to changes in the ridge/transform geometry and to a non-straight transform boundary are probably the major cause of vertical crustal motion responsible for the topographic anomalies of this area.

KEY WORDS: Equatorial Atlantic. Romanche Fracture Zone. Bathymetry. Reflection Seismics. Vertical Tectonics.

Introduction and background

The Equatorial region of the Atlantic Ocean is geologically peculiar. The axis of the Mid Atlantic Ridge (MAR) is broken in short (< 200 Km), roughly N-S, segments that are separated by several long offset (> 300 km), E-W transforms. This is clearly seen in satellite radar altimetry elaborations (Fig. 1) or in maps of distribution of earth-quake epicenters (Fig. 2). The largest of the transforms is the Romanche (offset ~ 950 km) located very close to the equator. The St. Paul transform (offset ~ 400 km) is located between l° N and 2° N i.e., roughly 180 km north of the Romanche. About 180 km south of the Romanche we find the Chain transform (offset ~ 300 km). Each of these transforms has a strong topographic signature, generally with a deep transform valley parallelled by prominent transverse ridges. These transverse ridges constitute major topographic anomalies relative to the thermal subsidence curve of the oceanic lithosphere. The topographic signature of each of these major transforms can be traced outside the ridge/ridge offset, and can be shown to extend as fracture zones from one side to the other of the Atlantic (Fig. 1). Given the above, the equatorial Atlantic may be considered a large latitudinal megashear zone that crosses the ocean from coast to coast.

The Romanche transform is the longest active transform of the entire mid ocean ridge system (Heezen *et al.*, 1964). SEASAT gravity imagery (Haxby, 1987) shows that the Romanche fracture zone can be traced across the equatorial Atlantic from an offset of the Gulf of Guinea continental shelf to an E-W branch of the North Brazilian Ridge on the American side (Fig. 1). Thus, the Romanche probably originated as a continent/continent transform at the time of initial rifting of the protoAtlantic.

The Romanche is characterised by a deep, roughly E-W valley flanked on both sides by two prominent ridges and by a system of secondary parallel troughs and ridges (Heezen *et al.*, 1964; Gorini, 1977; Chermak, 1979). If we assume a constant ridge/transform geometry and an average spreading rate of 1.75 cm/year (one way) both N and S of the transform, the offset represents about 50 my. The assumed spreading rate is derived from plate kinematic reconstructions of Cande *et al.* (1988). The shallowest depths are reached in the narrow transverse ridge flanking the northern side 0f the transform, east of about l8° W. This constitutes a major topographic anomaly that rises up to 4 km above the level predicted by the thermal contraction depth age law (Bonatti and Chermack, 1981; Bonatti *et al.*, 1993). With the assumptions defined above the crust affected by the topographic anomaly ranges in age roughly from 35 to 55 million years. Previous work has indicated that the summit of the transverse ridge was above sea level up to about 5 my before present and subsided since then at a rate one order of magnitude faster than the plate thermal subsidence rate (Bonatti *et al.*, 1979; Bonatti and Chermak, 1981).

We report in this paper the first results of an expedition carried out on the eastern part of the Romanche transform by the research ship «Akademik Nikolay Strakhov» of Moscow's Geology Institute of the Russian Academy of Sciences. This expedition (S-13) was part of PRIMAR (Russian Italian Mid Atlantic Ridge Project), a long range collaboration between the Russian Academy of Sciences and the Italian CNR (National Research Council) for the study of mid ocean ridges. The expedition took place in the period November 1991-January 1992. The field work consisted in multibeam and magnetometric surveys of selected areas at the eastern ridge/transform intersection (RTI) as well as multichannel high-resolution seismic refIection experiments and rock and sediment sampling.

Methods

The ship's position was determined with a GPS NAVSTAR satellite navigation system. Morphobathymetry was obtained with a Hollming Echos 625 multibeam system, consisting of 15 (12.5 kHz) beams covering a swath of seafloor roughly 2/3 water depth in width. Rock and sediment sampling were carried out by conventional dredging and coring methods.

Seismic reflection data were obtained using a Sodera GI gun as sound source. It operated in harmonic mode configuration, with the capacity of 105 cubic inches for the

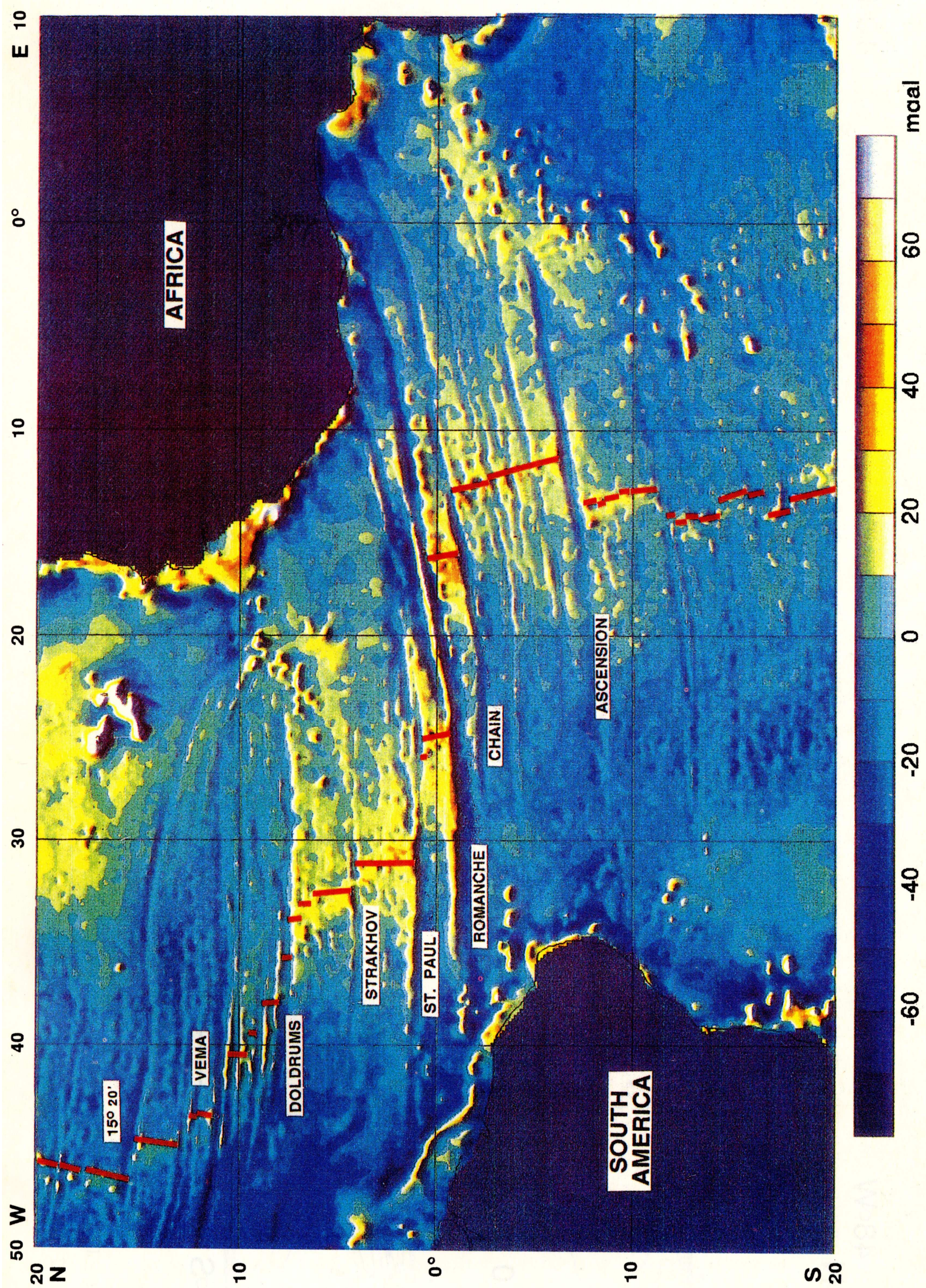


Fig. 1 - Seasat and Geosat gravity imagery of the equatorial Atlantic, compiled by W.F. Haxby (1989). The trend of the Mid Atlantic Ridge axis and of the major fracture zones has been superimposed.

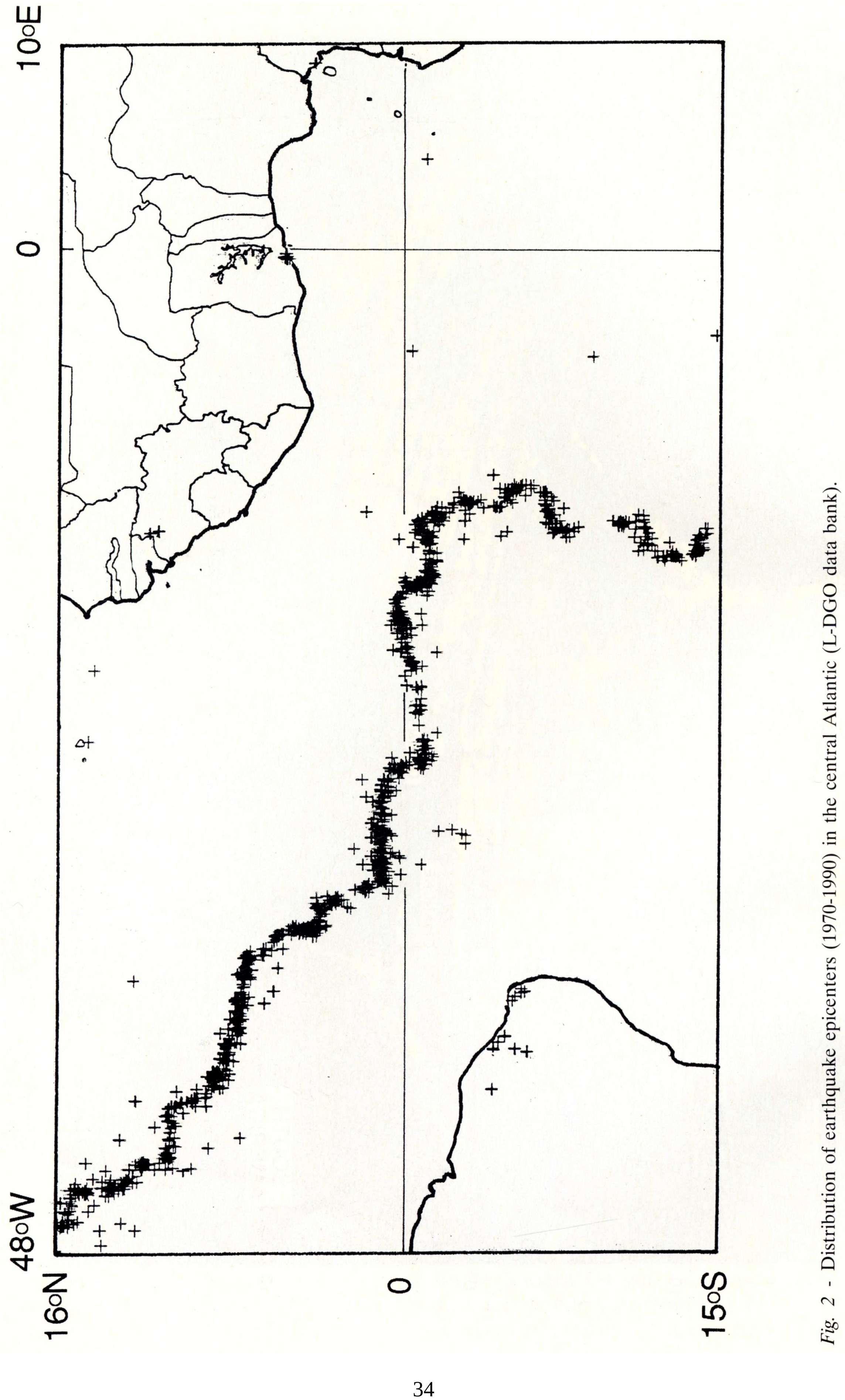


Fig. 2 - Distribution of earthquake epicenters (1970-1990) in the central Atlantic (L-DGO data bank).

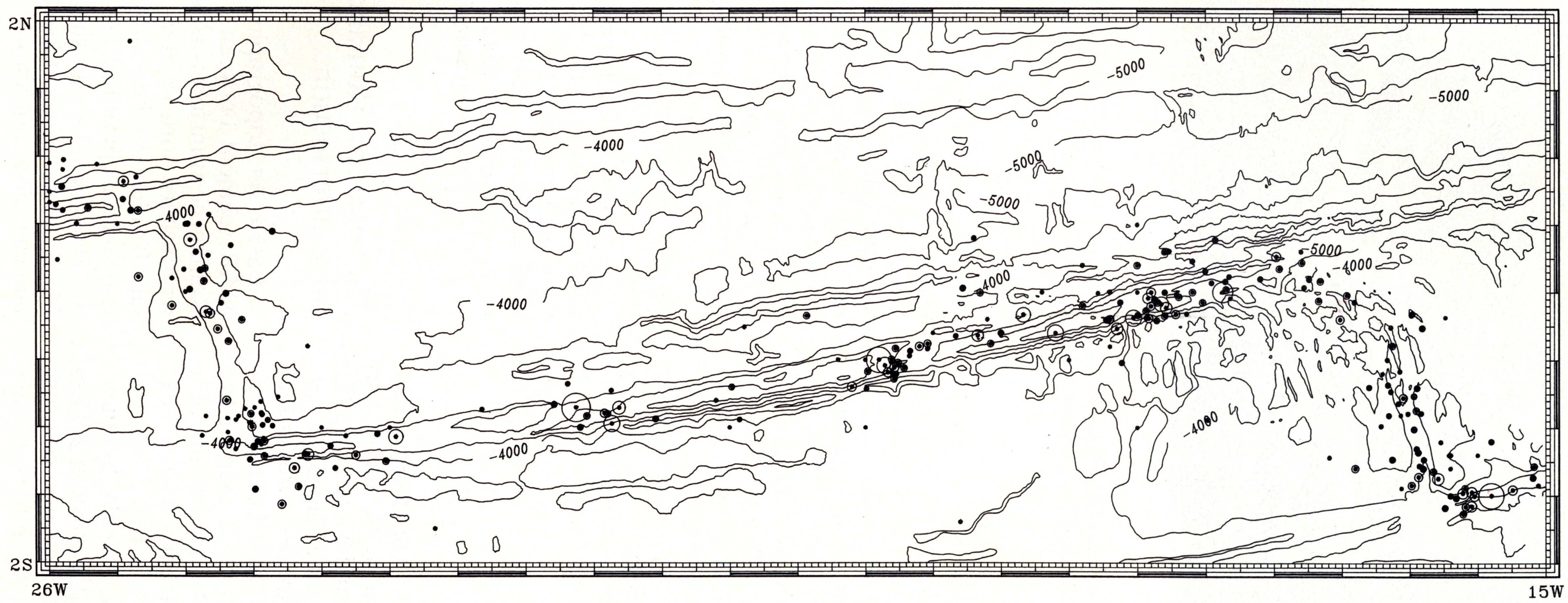


Fig. 3 - Simplified bathymetric map of the Romanche area, based on data by Heezen *et al.* (1964), Gorini (1977), Chermak (1979), Honnorez *et al.* (1992), Monti and Mercier (1991), Searle *et al.* (1993) and our own data. Earthquake epicenters (L-DGO Data Bank 1970-1990) are superimposed.

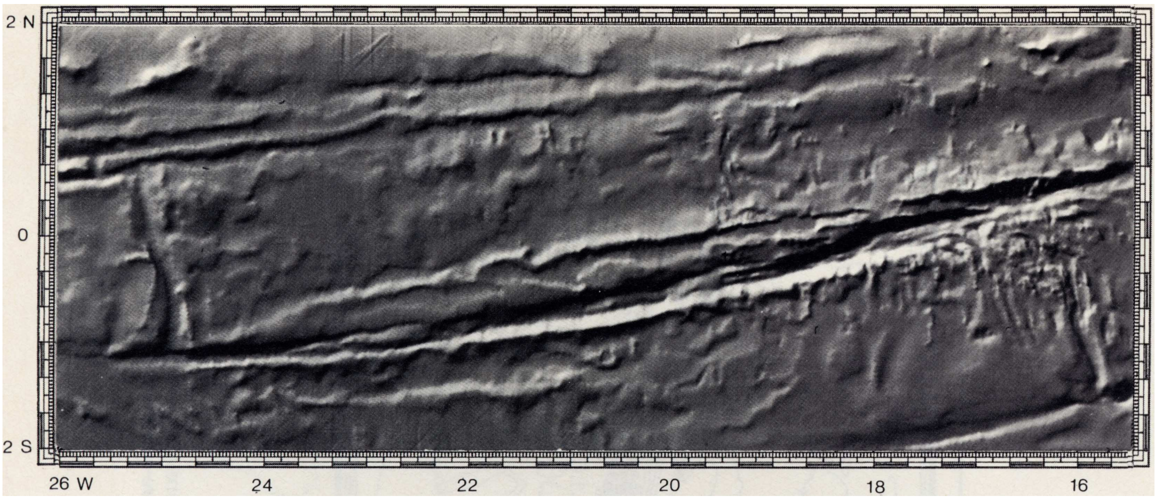


Fig. 4 — Shaded relief map of thc Romanche transform region, derived by bathymetric data. Shaded relief map was obtained assuming illumination from NW 45° over the horizon. Horizontal resolution is l km, no vertical exageration. Mercator projection at 0°.

generator as well as for the injector, at the pressure of 2000 psi. The receiving streamer, made by Teledyne, employed 24 channels (each with 20 hydrophones) spaced 25 m apart. Seismic source and nearest channel were spaced 150 m apart. Shot interval was 50 m, allowing six fold coverage. Digital acquisition was carried out with a Geometrics ES2420, with a sampling rate of 1 ms., record length of 11 s. and an antialias filter of 180 Hz. Seismic data have been processed at the Institute of Marine Geology of the C.N.R. of Bologna using an industry-standard package (DISCO) made by CogniSeis.

Morphobathymetry

A synthesis of available bathymetric data from the Romanche region, including our own and those of Monti and Mercier (1991), Honnorez *et al.* (1991) and Searle *et al.* (1993) is presented in simplified form in Fig. 3. These bathymetric data have been processed using the software PLOTMAP (Ligi and Bortoluzzi, 1989) to produce a shaded relief map of the Romanche region (Fig. 4). The results of a close-spaced survey of a limited area near the eastern RTI is shown in Fig. 5. Of the many features shown by these maps, we note that: (a) the eastern RTI is not well defined morphologically, contrary to the western RTI (where, however, data coverage is not as good); (b) a more or less continuous aseismic valley is observed to the north of the active transform valley. The aseismic valley merges into the active valley near the eastern RTI; (c) the transverse ridge rises prominently on the northern side of the transform, reaching its maximum relief in an area opposite the eastern RTI; (d) the active transform valley, defined on the base of earthquake epicenters, in not straight but has a few bends in its orientation.

Bathymetric data from Monti and Mercier (1991), Searle *et al.* (1993) and from this work were digitized, merged and edited at IGM-CNR of Bologna (Bortoluzzi and Ligi, 1986, 1987, 1988). After processing with a regular-gridding program, the maps of Figs. 3, 4, 5, 6, 7 were produced (Ligi and Bortoluzzi, 1989).

The eastern Romanche transform/ridge intersection.

Based on topography, the axis of the MAR segment between the Chain and the Romanche transforms is well constrained in its southern portion. Here a well formed axial rift valley can be clearly identified, where earthquake epicenters are clustered (Figs. 2, 3). However, the northern portion of the MAR, close to its impact against the Romanche, does not show a clear topographic

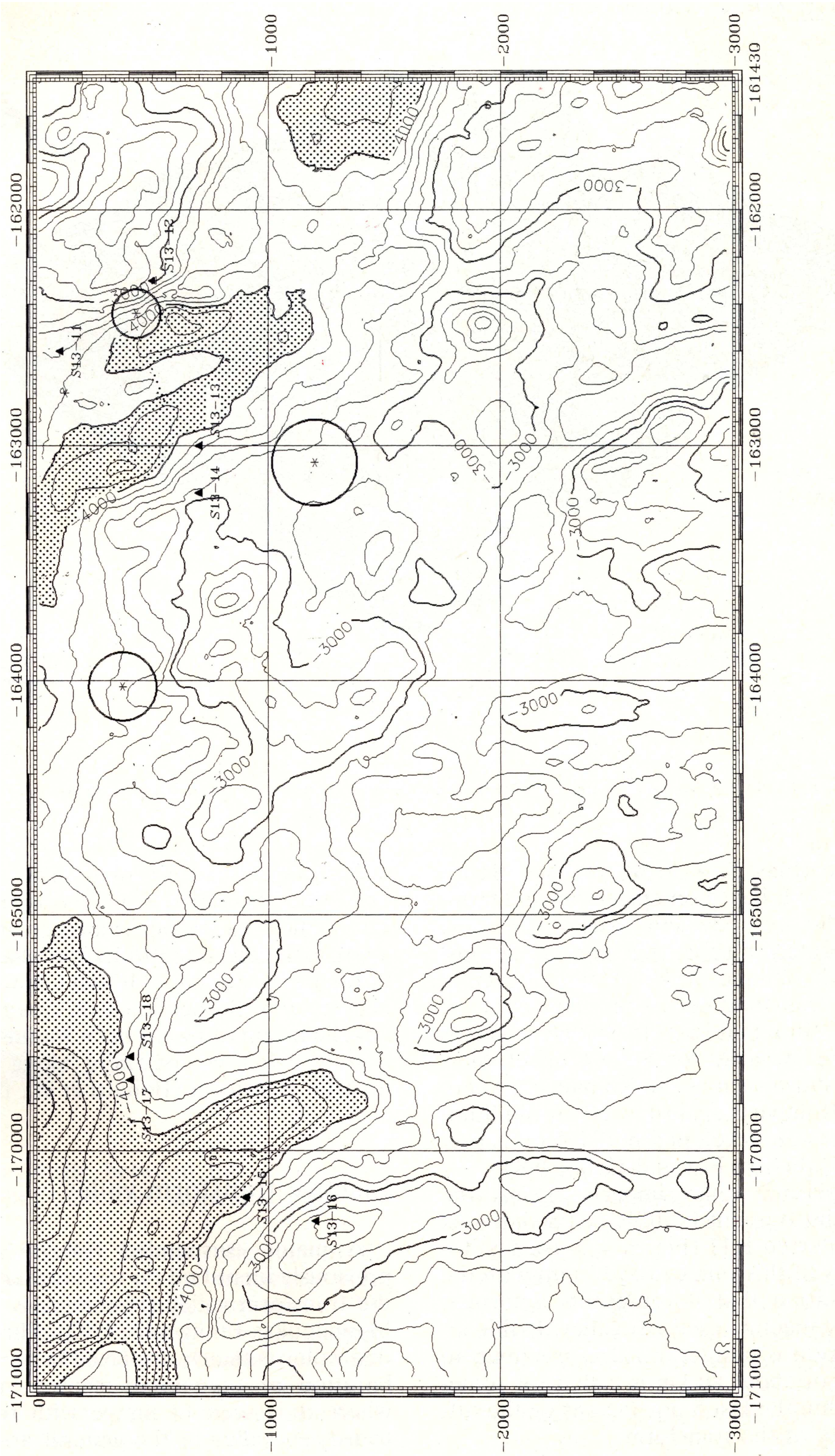


Fig. 5 - Detailed bathymetric map of an area close to the Romanche eastern RTI. Areas deeper than 4000 m are shaded. Circles indicate earthquake epicenters.

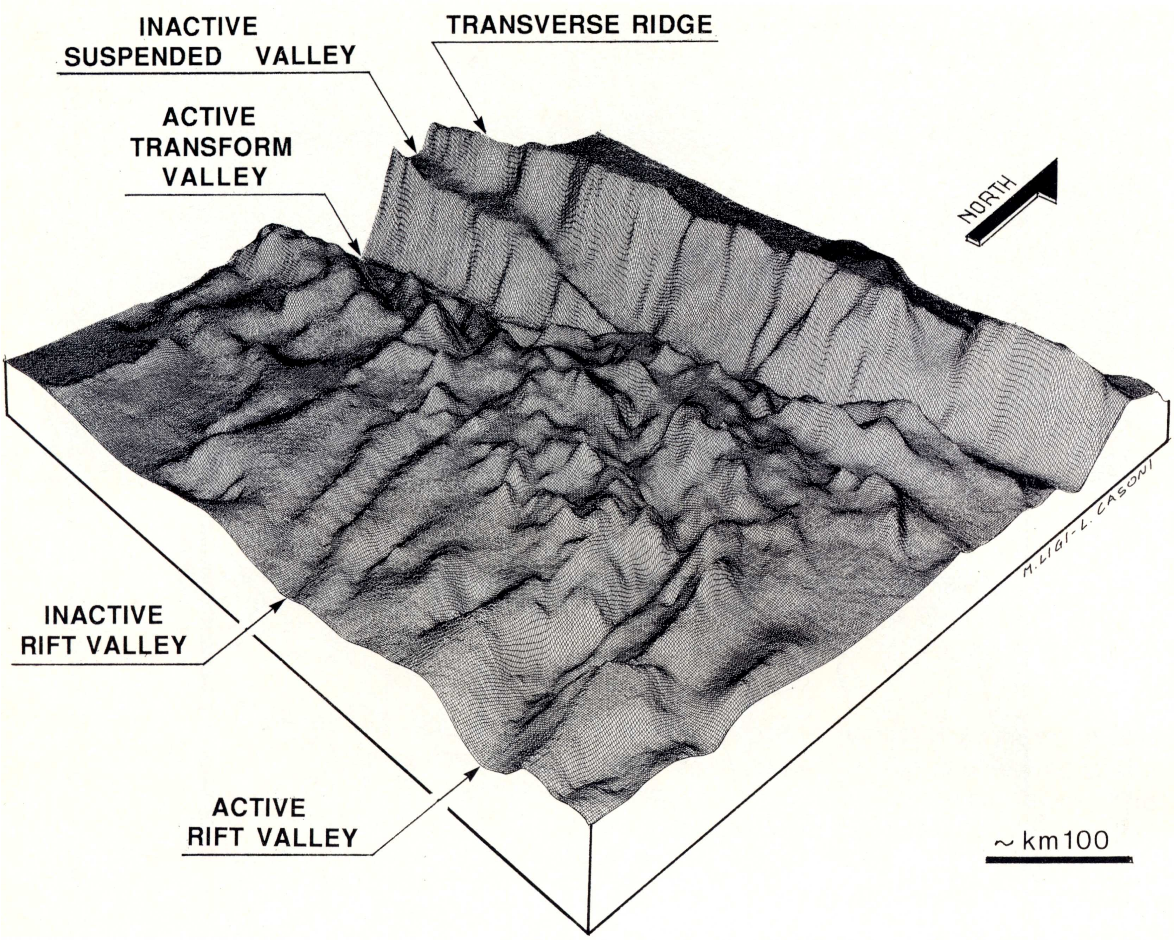


Fig. 6 — Three-dimensional view of thc Romanche transform eastern intersection. View from SE.

signature (Figs. 3, 4, 5, 6). Oblique trends are observed. Based on epicenters and topography the presently active axis of spreading is fragmented in short segments, some possibly with oblique strike. The intersection with the transform occurs probably at about l6°30’W. No nodal deep is observed. This is surprising, because for a long offset, slow slip transform such as the Romanche, where the MAR impacts against ~ 50 my old lithosphere, a well developed nodal deep is predicted by theory (Fox and Gallo, 1984).

An aseismic valley impacts against the Romanche at about l7°l0’W, *i.e.*, 80 km west of the inferred RTI (Fig. 3, 4, 5, 6). The topography of this valley is consistent with the interpretation that it represents a former, presently inactive axial rift valley. If this interpretation is correct, a ridge axis jump to the east of about 80 km is called for sometime within the last 5 my, increasing the offset length of the transform.

Petrological studies of basaltic and gabbroic rocks sampled from the eastern RTI area indicate a widespread magmatism with a strongly alkalic affinity, in contrast to normally prevaling MORB compositions (Peyve and Sushevskaja, in preparation). Alkalic magmatism has been found to be relatively common elsewhere along the Romanche transform (Bonatti *et al.*, 1979).

Inactive transform valley

A major «suspended valley» has been previously identified on the northern wall of the transform valley (Honnorez *et al.*, 1991; Mamaloukas-Frangoulis, 1992). This suspended valley is clearly displayed in the 3-D elaboration of topography shown in Fig. 6, where it is seen to merge with the active transform valley in the general area of the

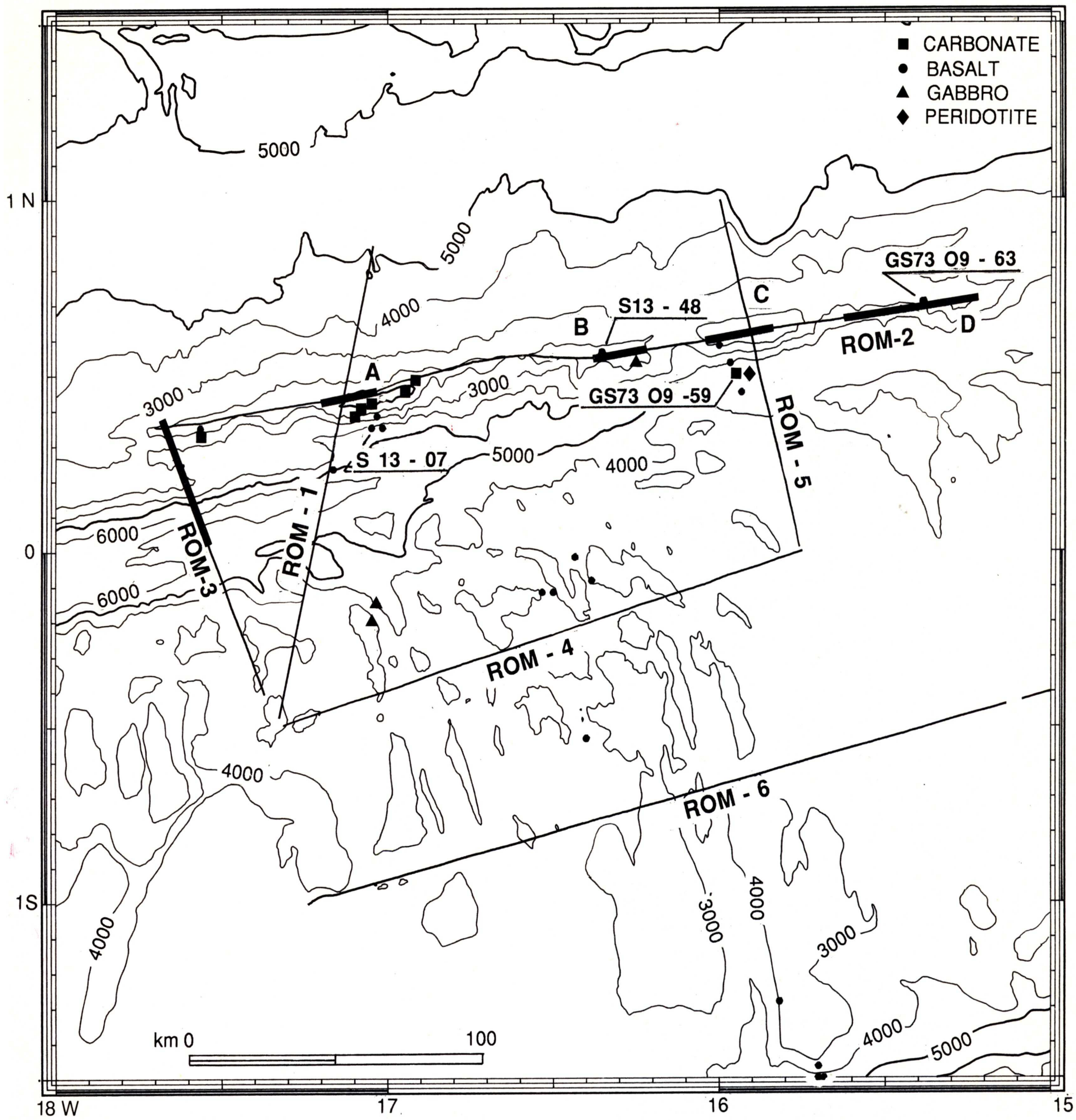


Fig. 7 — Tracks of seismic reflection profiles carried out during Cruise S-13. The portions of the profiles shown in Figs. 8, 9 and 11 are marked with 21 thicker line. Sites where rock samples were recovered are also indicated, with different symbols for different rock types.

RTI. The angle between the active transform valley and the suspended valley is about 10°.

A roughly N/S seismic reflection profile across the summit of the transverse ridge and the suspended valley at about 17° W (ROM3, Figs. 7, 8) shows that the suspended valley contains a sediment pile about 500 msec. or ~ 450 m thick (assuming sound velocity of 1.8 cm/sec). Moreover, the basement below the suspended valley appears to be affected by sets 0f low angle listric faults and smaller antithetic faults dipping in the opposite direction, suggesting N-S extentional tectonics.

It is important to note that the suspended valley can be traced as a continuous feature westwards for several hundreds kms, up to about 150 km from the western RTI (Fig. 3, 4). A possible interpretation is that this aseismic valley represents the trace of a former location of the Romanche transform boundary. Given

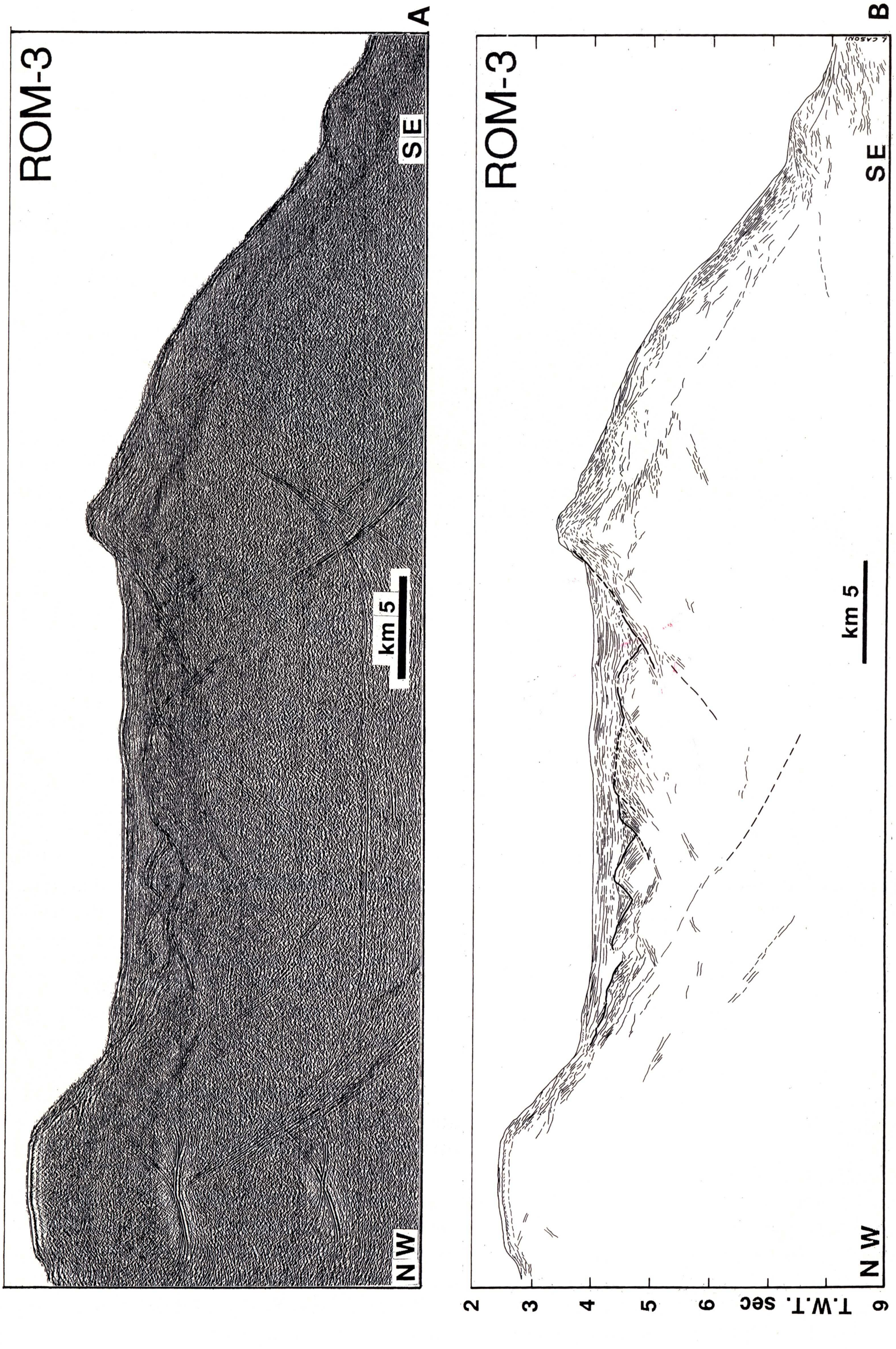


Fig. 8 - Portion of seismic reflection profile ROM-3 showing the summit and the southern slope of the transverse ridge, including a section of the suspended valley. **A**, migrated time section; **B**, interpreted line drawing. Location of this profile is shown in Fig. 7.

that this inactive valley appears only about 150 km from the western MAR segment (Fig. 3, 4), and assuming a one way spreading rate of 1.75 cm/y, we estimate that the valley ceased to be an active transform boundary between 8 and 10 my ago.

The Romanche northern transverse ridge

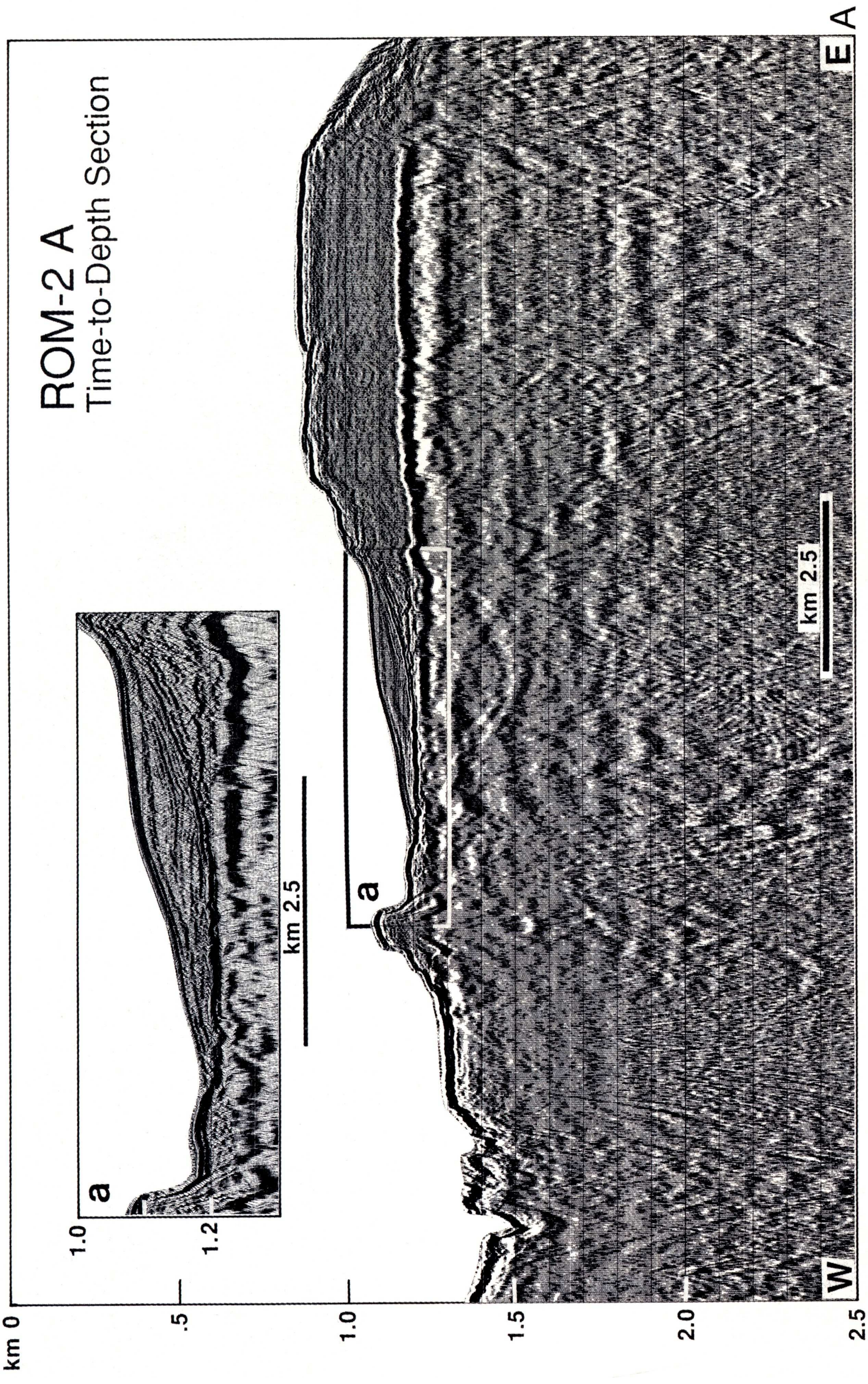
Fracture zone transverse ridges, (*i.e.*, ridges flanking slow-slip transforms and partly also their inactive fracture zone extensions) can be major topographic features (Bonatti, 1978). The transverse ridge running on the northern side of the Romanche transform valley becomes particularly prominent in the eastern portion of the transform offset. The shallowest (< 2000 m below sea level) stretch of this transverse ridge is located roughly opposite the eastern RTI (Fig. 3, 4, 5). As noted by Honnorez *et al.* (1991) and Mamaloukas-Frangoulis (1992), the transverse ridge appears to be asymmetric in N/S sections, its N-facing slope being less steep than the S-facing one. Moreover, the S-facing slope is interrupted by the suspended valley described in the previous section. The suspended valley deepens towards the E and merges with the presently active transform valley at about the longitude of the eastern RTI. The shallowest (< 2000 m) portion of the transverse ridge displays a number of flat-top reliefs elongated roughly E-W. We identify them from W to E as reliefs A, B, C and D (Fig. 4). Samples were obtained from different sites on the transverse ridge during this and previous expeditions. A seismic reflection line was run roughly E-W along the crest of the transverse ridge (line ROM-2, Fig. 7) and three lines were run roughly normal to it (ROM-1, ROM-3 and ROM-5, Fig. 7).

Reliefs A, B and C show similar characteristics. Their summits range from a maximum of 930 m to a minimum of 1200 m below the sea level. A prominent more or less horizontal reflector is observed in all the three reliefs (Fig. 9 a-b). No clear reflections were detected below this horizontal reflector. Above this reflector transparent, stratified unit is observed. This unit was sampled, and was found to consist in all the three reliefs of shallow water limestones in reef and lagunar facies displaying evidence of subaerial exposure (Bonatti *et al.,* 1979, 1993). Emersion as islands of these reliefs sometime in the past is confirmed by the recovery of ventifact basaltic pebbles from relief A by Honnorez *et al.*, (1992) and from relief C by us. Seismic reflection profile over relief A (Fig. 9a) shows what appears to be a sunken atoll, with a carbonate platform, a lagoon prograded by sediments and a fringing reef.

We propose the following interpretation of the seismic and lithological data. The units below the horizontal reflectors consist of blocks of oceanic crust and upper mantle. These lithospheric blocks were uplifted and their tops reached above sea level. Subsidence followed. Erosion and wave truncation flattened the summit of the blocks at sea level during subsidence. Shallow carbonate banks, reefs and lagoons were implanted on the horizontal, erosional surfaces of the lithospheric blocks. These carbonate caps were exposed above sea level during minor reversals and oscillations of sea level and of the vertical motions of the lithospheric blocks. Overall subsidence continued, the carbonate reef formations sank rapidly and ceased to grow, up to the present situation when the tops of the reliefs lie between 1 and 1.5 km below sea level. This sequence of events is illustrated schematically in the cartoon of Fig. 10. Some time constraints of these events can be provided by paleontological ages that were obtained on carbonates sampled from the shallow water reef/lagunar limestone unit capping relief A (Bonatti *et al.*, 1979).

Age determinations, based on planctonic Foraminifera and on Stylophora sp. corals, date the shallow water carbonates sampled from relief A at the Miocene-Pliocene boundary, about 5 1 1 mybp. Assuming the summit of the relief was at sea level at that time, and that sea level at the end of the Miocene was within 50 m of present day sea level (Shackleton and Kennett, 1975), an average subsidence rate of 0.2 mm/y can be estimated. This rate is one order of magnitude faster than the thermal subsidence estimated for 50 my old crust (Bonatti *et al.*, 1979; Bonatti and Chermak, 1981).

The easternmost relief of our survey on


ROM-2 A
Time-to-Depth Section
a
1.0
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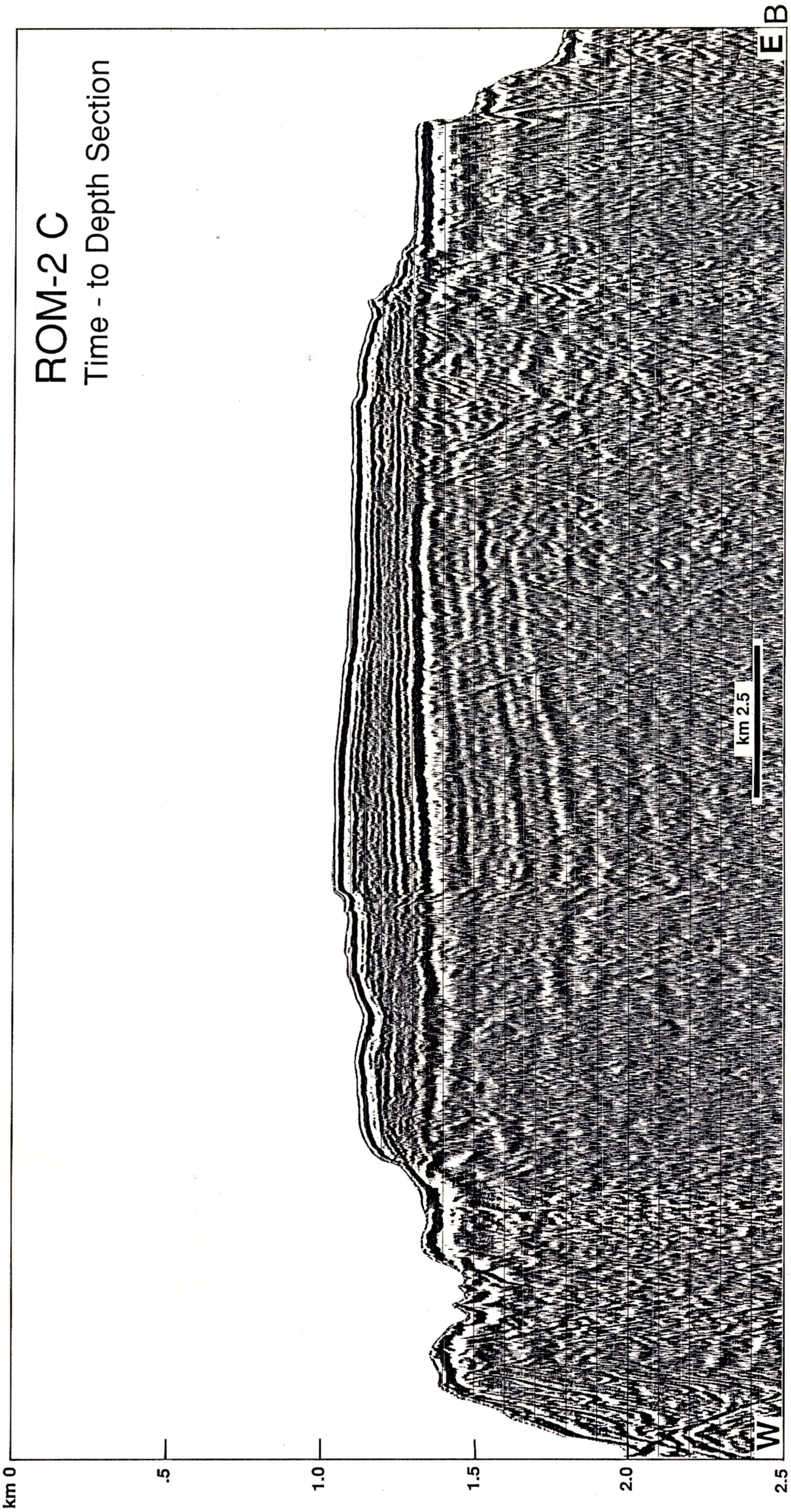

Fig. 9 - **A**, portion of seismic reflection profile ROM-2 over relief A and **B**, over relief C. Location of these profiles is shown in Fig. 7.

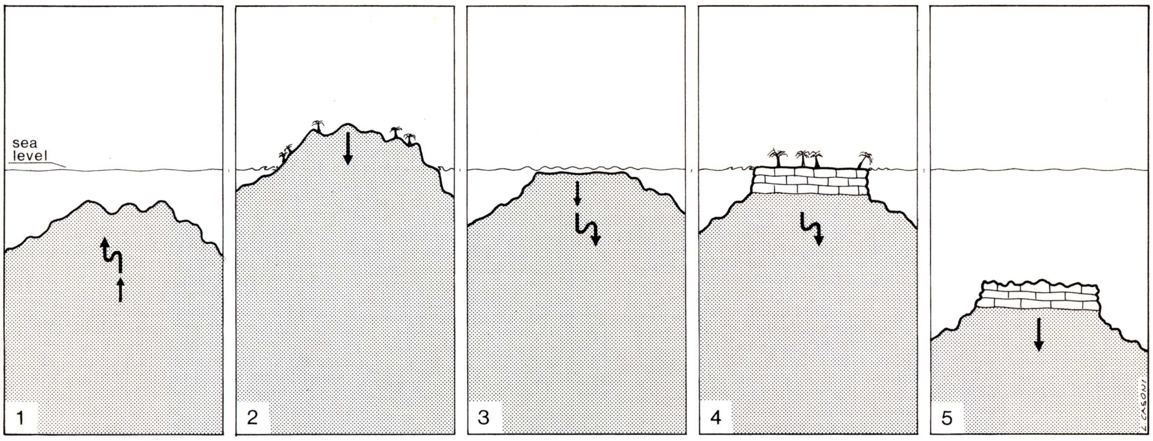

Fig. 10 — Cartoon illustrating a possible model of vertical motions on the transverse ridge giving rise to islands.

the transverse ridge (relief D) has a seismic signature very different from that of reliefs A, B and C. It lacks a carbonate cap and shows reflectors down to about 8 sec (Fig. 11). Igneous basement was not reached, and this stretch of transverse ridge appears to consist of a thick (~ 4 km) pile of sedimentary rocks affected by folds and overthrusts. An interpretation of this profile must wait for additional processing and for study of samples recovered from this area.

Discussion

Non-steady-state ridge/transform geometry — A first analysis of the results obtained to date indicates that the MAR/transform geometry in the Romanche area might have changed considerably through time. Two types of changes are suggested by the data: (a) migration and reorientation of the transform boundary and (b) migration or jump of the MAR axis segment impacting against the transform.

The migration and reorientation of the transform boundary is suggested by the presence of the aseismic valley running subparallel to and on the northern side of the presently active transform valley. We have mentioned in a previous section of this paper that the inactive valley might have represented the active transform boundary prior to about 8-10 my ago.

A jump to the east of the eastern ridge segment, suggested by the presence of an aseismic former rift valley ~ 80 Km west of the present RTI, might have taken place about < 5 My ago, thus increasing the offset length significantly. This might be the last of a series of events that have nearly doubled the length of offset of the Romanche trans-form since the opening of the Atlantic, when the «proto Romanche» probably acted as a continent/continent transform.

Non straight transform boundary — If we assume as a first order approssimation that the Romanche transform boundary presently runs along the deeper part of the seismically active transform valley, the boundary appears not to be straight. It shows a number of kinks and bends that change the overall orientation of the transform from about E-W in its western part to WNW-ENE in its eastern part. This change in orientation is confirmed if we consider the trace of the transform boundary identified by Belderson *et al.* (1984) and Searle *et al.* (1993) based on GLORIA data. A non straight transform boundary may determine zones of transpression and of transtension along the transform boundary, as indicated schematically in Fig. 12.

Vertical tectonics and the origin of the transverse ridge — An analysis of possible factors responsible for the development of the large topographic anomalies observed along the Romanche transform zone has been carried out elsewhere (Bonatti *et al.*, 1993).

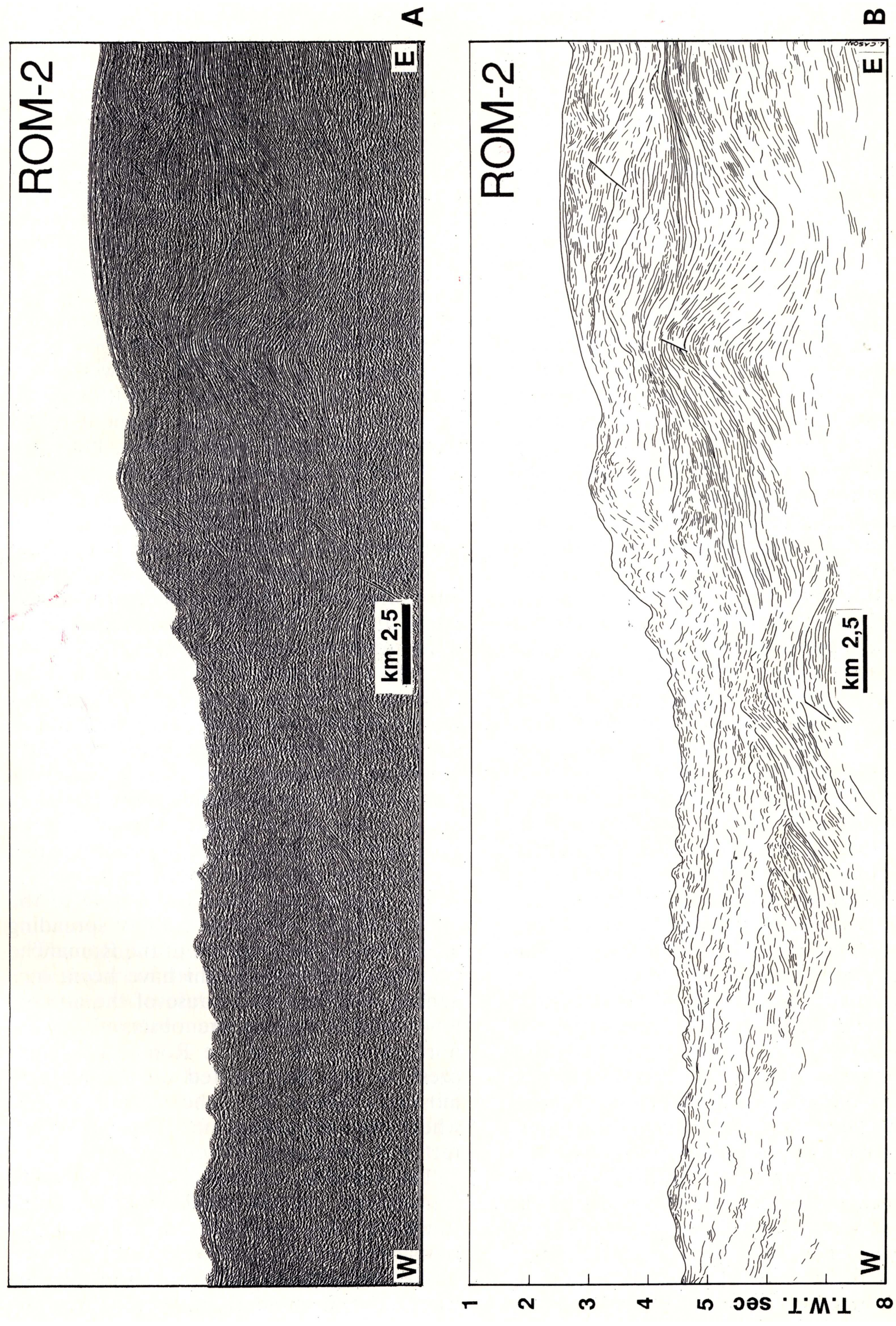

Fig. 11 - Portion of seismic reflection profile ROM-2 over relief D. **A**, migrated time section; **B**, line drawing. Location of this profile is shown in Fig. 7.

Briefly, one possibility is that the transverse ridge is a constructional, volcanic structure. However its elongated, narrow morphology is quite untypical of volcanic structures. Only at one site on the southern slope of the transverse ridge across the RTI, fragments of fresh-looking basalts were sampled, raising the possibility that some volcanism might have spilled over on the transverse ridge from the MAR axis across the RTI. However, basalts recovered elsewhere from several sites on the upper slopes are strongly altered, consistently with their being part of ~ 50 My old crust originally formed at the western MAR axis. The recovery of lower crustal gabbros and upper mantle peridotites on the slopes of the transverse ridge as well as its morphology suggest that this feature is not a constructional volcanic structure but an uplifted sliver of oceanic lithosphere.

A number of processes related directly or indirectly to the thermal structure of the lithosphere adjacent to the transform can contribute to the vertical motions. Horizontal conduction of heat from the hot ridge axis to the old cold plate across the RTI can cause swelling and uplift of the old lithosphere (Langseth and Hobart, 1976; Louden and Forsyth, 1976; Chen, 1988). It has been estimated, however, that for a long-offset, slow slip transform such as the Romanche this effect may cause a few hundred meters uplift at the most (Chen, 1988; Bonatti *et al.*, 1993). Shear frictional heating occur in a long offset transform but cannot contribute significantly to the required uplift (Chen, 1988). Lithospheric flexure due to the thermal contraction of the aging and cooling plate may cause uplift adjacent to the transform that will not be over ~ 200 m (Parmentier and Haxby, 1986).

Hydration of the mantle ultramafic rocks may take place below 500° C due to sea water penetration into crust that is highly permeable and of reduced crustal thickness near the RTI. The consequent decrease of density of hydrated upper mantle may cause uplift in the first few million years of spreading away from the RTI. However, dehydration and subsidence will occur when the old lithosphere is reheated upon transiting across the other RTI. Thus, dehydration-induced subsidence works against reheating-induced uplift when the old lithosphere transits opposite the RTI (Bonatti *et al.*, 1993).

All these factors taken together can account for no more than about‘20% of the up to ~ 4 km uplift inferred for portions of the Romanche transverse ridge.

It has been recognised for a long time that adjacent blocks in continental strike-slip terrains can either converge or diverge, with important structural consequences (Wilcox *et al.*, 1973; Christie·Blick and Biddle, 1985). Anomalous topography can result from vertical tectonic movements of upper lithospheric slivers, due to transpressional or transtensional events related either to non straight transform boundaries, or to changes in the direction of spreading and consequent reorientation of transforms, as well as to transform migration connected with longitudinal propagation of ridge segments (Menard and Atwater, 1967; Bonatti, 1978; Bonatti and Crane, 1982; Karson, 1986).

Transpression due to clockwise changes in the direction of motion of the plates adjacent to right-lateral transforms such as the Romanche, Vema and Kane is probably particularly effective in inducing vertical tectonics (Bonatti, 1978; Tucholke and Shouten, 1988).

In addition, based on GLORIA data, showing a non-straight Romanche transform boundary, portions of the lithospheric plate on the northern side of the transform are likely to impact against the boundary determining a transpressional regime (Fig. 12). Conversely, estension should prevail in some areas along the southern margin of the transform boundary (Fig. 12), possibly with a tendency for pull-apart basins to form.

We suggest that compression due to the oblique impact of the direction of spreading against the eastern branch of the Romanche transform boundary might have been, in a general way, the main cause of the anomalous uplifted lithosphere observed on the northeastern side of the Romanche. Compression was documented on the easternmost relief (relief D) of the transverse ridge, where the thick sedimentary deposits are affected by folding and overthrusts.

The geometry of Fig. 12 implies areas ol transtension on the southern side of the transform close to bends in strike of the transform boundary.

We can further speculate that in the area where the suspended valley (*i.e.*, the old

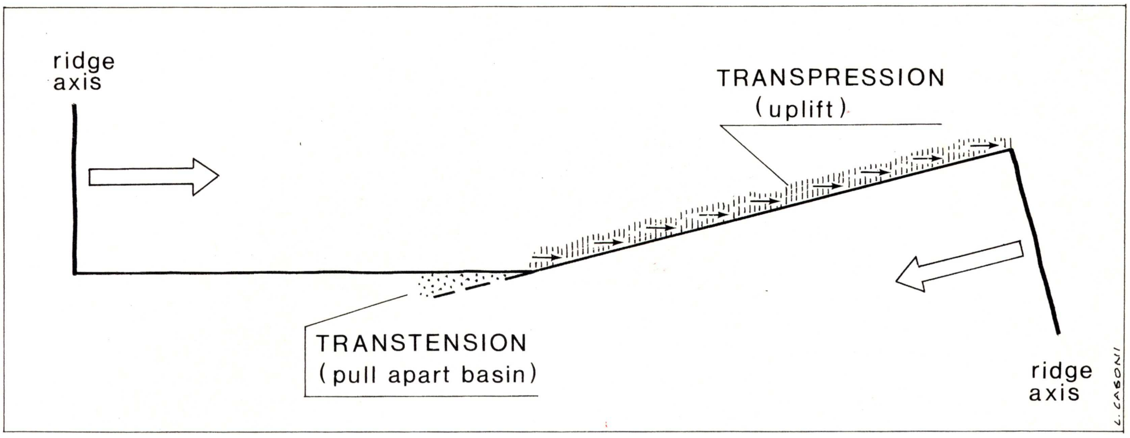

Fig. 12 — Schematic and simplified model indicating that transpression and transtension can develop due to a bend in the transform boundary.

transform) merges with the presently active transform, the tectonic regime changed to transtensional about 5 mybp. The «Vema Depth» (Heezen *et al.*, 1964), an ultradeep (> 7.5 km below sea level) sediment free basin at about 18°30'W along the transform valley, is probably a pull apart basin that formed as a result (Fig. 12). At the same time reliefs A, B and C, that 5 mybp were located close to the confluence of the old with the new transform, started to subside. Another event that probably occurred around 5 mybp is the eastward jumping of the MAR axis at the eastern RTI by about 80 km to its present position.

Conclusions

The complex geotectonic situation on the eastern part of the Romanche transform and the complex evolution in time of this situation will require much more field work to be unravelled.

The Romanche functioned as a large transform throughout the evolution of the equatorial Atlantic. Although the offset length was probably smaller in the past, this situation makes it very probable that transpressional and transtensional events occurred throughout the history of opening of the equatorial Atlantic, leading to intense vertical motions of lithospheric blocks and intermittent emersion of islands of tectonic origin. The tranverse ridges bounding the equatorial transforms, resulting from such vertical motions, can be traced from one side of the Atlantic to the other. Drilling on one such transverse ridges on the south American margin (north Brazilian Ridge) ended at the base of a sediment pile in Eocene reef limestones (Bader *et al.*, 1970), suggesting that the transverse ridge was at sea level at that time.

The presence of elevated ridges and islands across the equator has had probably important consequences for deep cold water circulation between the south and the north Atlantic; for sedimentation, both in terms of calcium carbonate dissolution (strongly affected by deep cold water circulation) and transport of terrigenous matter; for faunal migrations, that might have been made possible to some extent by the presence of islands even after the separation of Africa from south America.

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