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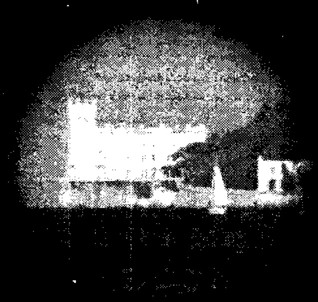

preprint

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United Nations Educational Scientific and Cultural Organization
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CRUSTAL STRUCTURE BENEATH DISCOVERY BANK IN THE SOUTH SCOTIA SEA FROM GROUP VELOCITY TOMOGRAPHY AND SEISMIC REFLECTION DATA

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Abstract

Bruce, Discovery, Herdman and Jane Banks, all located along the central-eastern part of the South Scotia Ridge (i.e., the Antarctica-Scotia plate boundary), represent isolated topographic reliefs surrounded by relatively young oceanic crust, whose petrological and structural nature is still the subject of speculations due to the lack of resolving data.

In the Scotia Sea and surrounding regions negative anomalies of about 3-4% are reported in large-scale group velocity tomography maps. The spatial resolution (~500 km) of these maps does not warrant any reliable interpretation of such anomalies.

A recent surface wave tomography in the same area, performed using 8 broad band seismic stations and 300 regional events, shows that in the period range from 15 s to 50 s the central-eastern part of the South Scotia Ridge is characterized by negative anomalies of the group velocities as large as 6%. The resolution of our data set (~300 km) makes it possible to distinguish an area (centered at 61°S and 36°W) with a crust thicker than 25 km, and a shear wave velocity vs. depth profile similar to that found beneath the northern tip of the Antarctic Peninsula and southern South America.

Rayleigh and Love wave dispersion curves are inverted in the period range from 15 s to 80 s to obtain shear wave velocity profiles that suggest a continental nature of Discovery Bank.

The continental-type crust of this topographic relief is in agreement with the interpretation of a multi-channel seismic reflection profile acquired across this rise. Peculiar acoustic facies are observed in this profile and are interpreted as thinned and faulted continental plateau.

The boundaries of the negative group velocity anomalies are marked by a high seismicity rate. Historical normal faulting earthquakes with magnitude around 7 are localised between the low velocity anomaly region in the eastern South Scotia Ridge and the high velocity anomaly region associated with the surrounding oceanic crust. The depth of the events and the large seismic moment suggest the presence of continental lithosphere.

1. Introduction

The Scotia Sea region is floored mainly by oceanic crust, and is bounded on the north and south by the system of shallow banks, islands and submarine ridges belonging to the North and South Scotia Ridges (NSR, SSR). These morphostructural elements mark the present-day South America-Scotia and Antarctica-Scotia plate boundaries, along which the relative strike-slip movements between the plates involved are accommodated. The Scotia Sea has evolved over the past 40 Ma by extension behind an east-migrating subduction zone, similar to the presently-active South Sandwich margin (see Barker et al., 1991, for a comprehensive geological and geophysical review).

Although the proposed gross geological structure and evolution for the entire Scotia Sea is commonly accepted, significant uncertainties still remain which preclude precise reconstructions of the evolution of key areas of the Scotia Arc. In particular, the nature of some elevated areas (Bruce, Discovery, Herdman and Jane Banks), located to the east of the South Orkney Microcontinent (SOM, see Fig. 1), the largest continental fragment of the entire Scotia Arc region, is unknown. These restricted areas are more elevated than normal ocean floor, and may be fragments of continent (as are some components of the Scotia Arc), thinned by extension, or elements of island arc or remnant arc.

Dredging across Discovery Bank (DB) yielded arc tholeiites radiometrically dated at 12-20 Ma. On this basis, Barker et al. (1984) interpreted this fragment as a former part of an intra-oceanic island arc ancestral to the present South Sandwich Arc. Volcanic rocks dredged from Jane Bank (JB), which is separated from the eastern SOM by the upper Oligocene Jane Basin (King and Barker, 1988), are chemically similar to the low-K tholeiite series which characterize the South Sandwich Arc (Barker et al., 1984). The peculiar double-ridge crest with a flanking trough characterizing JB, forced the interpretation that it represents an in-situ remnant of the arc and upper fore-arc of an intra-oceanic arc produced by subduction of the South American oceanic lithosphere (Barker et al., 1984). Magnetic anomalies within the northern Weddell Sea, located south of the Scotia Sea, become younger northward (Barker et al., 1984), suggesting ridge-crest subduction. It has been proposed (Barker and Hill, 1981; Barker et al., 1982) that such collisions could have controlled changes in the rate, direction and location of back-arc extension. The age estimated for the collision (earliest Miocene), according to Barker et al. (1984), is close to the onset of N-S spreading in the Central Scotia Sea, which supports earlier speculation that ridge crest-trench collisions have triggered the main changes in the mode of Scotia Sea evolution. However, the collision over the entire 200 km length of JB, which is fundamental to this hypothesis, cannot be assessed on the basis of the available marine magnetic data: they represent a relatively limited data set and cover only a narrow region.

The morphological and petrological data described are, at present, the only available information which guided the interpretation proposed to date. In this paper, we describe the results of surface wave tomography inversion and the interpretation of a multichannel seismic reflection profile to contribute relevant information about the nature and structure of the restricted elevated area of DB.

2. Seismicity

The entire SSR may be classified as a transtensive plate boundary, which combines extension and transcurrent motion; its tectonic regime is described by Pelayo and Wiens (1989) using source mechanisms determined from P and SH waveforms inversion. The events show strike-slip and normal faulting mechanisms. DB is a high-seismicity region. The largest event (May, 6, 1962, M 7.0) is located within a northeast-trending trough to the east of DB (Pelayo and Wiens, 1989). The event was preceded by a series of smaller events, including a magnitude 6.5 event in 1961. The exceptionally high seismicity rate (Pelayo and Wiens, 1989) of the trough is evidenced by a number of events which occurred in this region, and recorded before 1960, including two magnitude 7 events. A much smaller, normal faulting earthquake occurred farther to the southwest, along the trend of the trough. Other events, located along the southern part of DB, show strike-slip focal mechanisms and presumably represent the relative motion between the Scotia and Antarctic plates. According to Pelayo and Wiens (1989), the normal faulting events associated with the trough occur in a region of extension that connects two transform segments along the Central-eastern SSR.

One may attempt to interpret this region as a typical oceanic ridge-transform zone, but several aspects of the seismicity suggest that the tectonism may be more complex. The depths of the events (> 20 km, according to Pelayo and Wiens, 1989, see Fig. 1) and the large seismic moment indicate that the mechanism of extension more closely resembles diffuse rift zones or pull-apart basins in relatively cold continental lithosphere, than organized mid-ocean ridge spreading (Pelayo and Wiens, 1989). Since the installation of our permanent broad band seismic stations and some FDSN stations in the Scotia Sea region, there has been no meaningful event close to the Eastern South Scotia Ridge (ESSR) to increase the available information.

3. Group velocity measurements and regionalization

New regional surface wave propagation data (Fig. 2), recorded by 8 permanent broad-band seismic stations (three of them from our regional network, managed in collaboration with the Instituto Antarctico Argentino, see Vuan et al., 1997), are used to infer the lithospheric structure across the Scotia Sea and surrounding areas. These data cover periods between 15 s and 80 s and provide information about the crustal and upper mantle structure down to depths exceeding 50 km. Data analysis is done in two stages: (1) 2-D tomographic images for different periods are used for the construction of sub-regional dispersion curves; (2) average shear wave velocity profiles for well defined sub-regions are determined by nonlinear inversion of the sub-regional dispersion curves.

The tomography has been carried out using the Bakus-Gilbert formalism (Ditmar and Yanovskaya, 1987; Yanovskaya and Ditmar, 1990). Fig. 3 shows the Rayleigh wave group velocity map at 40 s. Low velocity anomalies in the group velocity sketch out the locus of present-day plate boundaries.

The shear wave velocity models, inferred from tomography by Vuan et al. (2000), are in general agreement with the global model CRUST5.1 (representing a compilation of refraction seismic experiments (Mooney et al., 1998)), except in two sub-regions where the crust appears to be much thicker than previously believed. The anomalous sub-regions (Fig. 3) are the Bransfield Strait (BS), located at the northeastern tip of the Antarctic Peninsula, where high temperatures in the upper crust are found due to active volcanism and rifting phenomena, and the ESSR, including DB, that represents the subject of this study. Regional tomography maps showing in detail BS, ESSR and the other sub-regions in the whole period range, can be found in Vuan et al. (2000).

Homogeneous high density path coverage and acceptable errors in the measurements are observed from 15 s to 50 s. Tomographic maps are also calculated for periods from 60 s to 80 s, even if the path density is poorer than that estimated for short periods.

The maps displayed in Fig. 4 highlight the low velocity anomaly present at the ESSR. The negative group velocity anomaly, including DB, is clearly visible from 15 s (-3%) to 45 s (-5%) and can be associated with some well defined geologic and/or tectonic feature. The larger negative anomalies are seen at intermediate periods (20-40 s). Values exceeding -6% between DB and HB and nearby JB characterize ESSR at 40 s while smaller anomalies (-4%) are found for SOM and BB.

The estimation of the resolution (Yanovskaya, 1997) follows the method proposed by Backus and Gilbert (1968) for the 'averaging length' in 1-D inverse problems. The density of paths, the azimuthal coverage and the average path length control the resolution of the data set. The resolution or correlation length is around 300 km inside the low velocity anomaly, near DB (Fig. 5), while it deteriorates towards the periphery of the maps of Fig. 4. The Central Scotia Sea and the Weddel Sea are scarcely sampled by rays and the regions close to HB, JB and BB are poorly resolved. Due to the better path coverage and to the smaller errors in the group velocity measurements, the resolving power of Rayleigh wave data is higher than that of Love wave data, therefore, the anomalous zones in the ESSR, and especially DB, are better revealed by the Rayleigh data set.

The identified low velocity region and corresponding block (DB, Fig.4) (1) have dimensions that are comparable with the correlation length of the tomography, (2) present a clear signature on the maps, and (3) include most of the recent and the historical seismicity around 60° S. From these maps we can extract locally smoothed dispersion curves and compare them with the average dispersion curves obtained for other geological and tectonic features selected inside the Scotia Sea (Vuan et al., 2000).

The comparison between the curves shown in Fig. 6 reveals a continental dispersion curve for DB. This curve is quite similar to the average curves obtained for the tip of the Antarctic Peninsula (TAP) and the tip of South America (TSA) and fits well the average curve observed for BS. For periods above 40 s our group velocity values are consistent with the values found independently using teleseismic surface wave tomography by Vdovin et al. (1999) and Ritzwoller et al. (1996).

4. S-wave velocity models at DB

Here we invert locally smoothed curves obtained from the tomography for the portion of ESSR containing DB. The spatial resolution oversizes the extent of JB, BB and HB and we prefer to have a better ray path coverage especially for Love waves before considering possible structural models for these reliefs. To each regional dispersion relation we apply a non-linear inversion to obtain an average shear wave velocity model. The 'Hedgehog' method used, represents an optimized Monte Carlo search to find ranges of velocity/depth distribution which are consistent with the observations (Valus et al., 1969; Knopoff, 1972; Valus, 1972; Biswas and Knopoff, 1974; Panza, 1981).

Our lithospheric model is represented by a set of parameters that describe the layer thicknesses, the velocities and densities. Each parameter may be fixed, independent or dependent. Fixed parameters are not perturbed during the inversion and are assumed to be well constrained and/or insensitive to the observations. Independent parameters are those for which acceptable models are sought taking into account the resolving power of the data (Panza, 1981) and dependent parameters maintain a fixed relationship with the independent ones.

In our inversion the shear wave velocities and thicknesses of some layers are retained as the only independent parameters. The parameterisation is consistent with that used in CRUST5.1; the lithosphere is formed by 8 layers: 1) ice, 2) water, 3) soft sediments, 4) hard sediments, 5) upper crust, 6) middle crust, 7) lower crust and 8) upper mantle. We select 7 independent parameters representing the shear wave velocities of the layers 5, 6, 7, 8 and the thicknesses of layers 5, 6, 7. The choice of the independent parameters is made taking into account the resolving power of the available data with respect to shear wave velocities of the CRUST5.1 models.

The accepted models satisfy two conditions: (a) the computed group velocity curve at any given period must lie within the uncertainty bounds of the observed data (0.09 km/s), and (b) the rms difference between the synthetic curve and the observed data must be less than 0.05 km/s.

Models inferred from Rayleigh wave data and from joint Love and Rayleigh wave data inversion are shown in Fig. 7a. and 7b, respectively. DB crustal models show a continental type crust thinner than that found for TSA and TAP models. The Moho is partially resolved by the joint inversion (Fig. 7b), and interpreted at a depth of about 25 km (Vs > 4.0 km/s). Upper mantle shear wave velocities range between 4.0 km/s and 4.4 km/s.

The shear wave velocity models found for DB are markedly different from the models inferred for the SSI arc (see Vuan et al., 2000). The SSI arc is characterised by a larger gradient in the S-wave velocity distribution with depth, than the models for the DB.

The joint inversion of Rayleigh and Love waves in the period range from 15 s to 80 s is consistent with isotropic models. Since different studies (e.g., Nishimura and Forsyth, 1989; Ritzwoller et al., 1998) show that especially in oceanic type environments velocity models determined from Rayleigh and Love wave data are different due to anisotropic properties of the crust and upper mantle, we may consider our result a further evidence of the continental character of DB.

5. Seismic reflection data

The only available seismic profiles in the studied region, which document the morphology and structure of DB and JB, have been acquired by the R/V *OGS-Explora* during the 1988/89 and 1990/91 Antarctic Campaigns (see Fig. 1). Considering the energy source utilized for the data acquisition (air-gun arrays of total volume of 45 liters), the interpretation of these data represents an independent contribution to the study of the nature of DB, focusing on the upper 6-8 km of the crust.

The most useful dataset for identifying the regional extent of DB is the satellite-derived bathymetric map (Smith and Sandwell, 1997; see Fig.1). DB elongates in a SW-NE direction, and it is separated from the BB by a 3000 m deep, 65 km wide basin, whose nature is completely unknown. The structural relationship with the Jane Basin, which physiographically represents the southwestern prosecution, is also unknown. The only available seismic profile crossing the DB is shown in Fig. 8. The rise is formed by two distinct highs, separated by a steep trough where the sedimentary cover has a negligible thickness. The shallowest water depth reached by the rise is 490 m, comparable to the water depths of most of the SOM. The north-western flank of the rise is gentler than the south-eastern one, and appears down-faulted by some direct faults, in a manner similar to a rifted continental margin. Some of these discontinuities reach the sea-floor, indicating present tectonic activity. Also, significant sedimentary features related to bottom-current activity are present. Here, the thickness of the stratified sedimentary cover ranges from 200 to 600 m. The southeastern flank apparently does not show the typical seismic facies of a rifted margin but more precisely appears as a volcanic margin, as testified by the numerous hyperbolae that mask in part the inner structure of the flank. The high reflectivity of most of the sea-floor and the relatively strong multiple, hide in part the identification of deeper events, with the exception of some weak reflections associated to stratification in correspondence of the two rises forming the DB. The significant elevation of the rise, the flat appearance of its south-eastern high, and the structure of its north-western margin all concur in describing the DB as a stretched continental fragment, once possibly part of the SOM and subsequently rifted apart during the transtensional mechanisms which characterize all the SSR development.

6. Conclusions

Many anomalous rises in oceans represent submerged continental fragments detached from stable continents or islands arcs, or basaltic piles formed by hot spots and spreading centers (Nur and Ben-Avraham, 1982). They may be unequivocally classified only on the basis of punctual measurements like drill holes, core records and dredging. Gravity data from satellite altimetry do not help to solve the nature of the submerged plateaus because as a rule they are isostatically compensated (Nur and Ben-Avraham, 1982). Seismic reflection data may help, in many cases, to determine the nature of these areas, often if combined with refraction measurements. When such information is scarce or not available, surface wave regional tomography in remote oceanic regions may highlight the nature of these unknown geological and tectonic features and represent a low-cost basis for planning future geophysical marine research.

The ESSR is still scarcely explored, and since the surrounding oceanic floor does not exhibit clear magnetic lineations (Barker, 2001), the information from regional surface wave tomography is the only one available to define the crust and upper mantle physical properties. The average path length (~1700 km) and coverage used in the regional tomography guarantees a spatial resolution (~300 km) which is comparable with the extent of the features we investigate and is much lower than that allowed by large-scale seismic tomography (~500 km).

From the simultaneous inversion of local Rayleigh and Love wave dispersion data, and in contrast with the interpretation based on morphological and petrological observations (Barker et al., 1984; King and Barker, 1988), we observe a thinned continental crust (~25 km) beneath DB. The inversion of both Rayleigh and Love average group velocity dispersion curves indicate that shear wave velocity models are able to fit the observations.

The continental origin hypothesis of DB is confirmed by a multi-channel seismic reflection profile. The significant elevation of the rise, the flat appearance of the highs, and the internal structure, all concur in describing the bank as a stretched continental fragment.

The large seismic moment and the depth of the events that characterise ESSR are consistent with a continental nature of the blocks. The mechanism of extension resembles diffuse rift zones or pull-apart basins (Pelayo and Wiens, 1989) and requires the presence of cold continental lithosphere although large normal fault events with considerable depth sometimes occur even in active and remnant island arcs.

None of the results discussed, if taken singularly, can be used to define the DB topographic relief as a remnant island arc or a continental fragment. However these results if taken into account as a whole strengthen the hypothesis that DB is a continental fragment once possibly part of the South Orkney micro-continent.

The recordings from a broad-band seismic station recently deployed at the South Orkney Island will improve substantially the ray coverage at ESSR and will help to answer to some of the remaining questions regarding the tectonic framework and evolution of this remote region.

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Figure captions

Fig. 1 - Bathymetry of the South Scotia Ridge from the database of Smith and Sandwell (1997). The main geological features are bounded by the –2000 m isobath: DB = Discovery Bank, JB = Jane Bank, HB = Herdman Bank, BB = Bruce Bank, SOM = South Orkney Microcontinent, ANT = Antarctic Plate, SAM = South American Plate, SCO = Scotia Plate, SAN = Sandwich Plate, SSR = South Scotia Ridge, NSR = North Scotia Ridge, ESSR = Eastern South Scotia Ridge, ESR = East Scotia Ridge. Historical events relocated by Pelayo and Wiens (1989) are represented by red stars. Events in the EHB catalog (Engdahl et al., 1998) are represented by yellow stars (depth > 15km) and by blue stars (depth < 15km). Multi-channel seismic reflection profiles are represented by red dotted lines.

Fig. 2 - Epicenter to station path coverage for 20s and 45s Rayleigh waves and Love waves. The path density in ESSR area (white rectangle) is larger than 20 paths per 1° x 1° cell.

Fig. 3 – Rayleigh wave group velocity tomography in the Scotia Sea region at 40s. Blues indicate faster than average, and reds slower than average, group velocity. Solid white lines mark the present-day plate boundaries. (BS = Bransfield Strait, ESSR = Eastern South Scotia Ridge, SOM = South Orkney Microcontinent, NSR = North Scotia Ridge, ESR = East Scotia Ridge, SS = Scotia Sea, WS = Weddel Sea, DB = Discovery Bank, JB = Jane Bank, HB = Herdman Bank, BB = Bruce Bank).

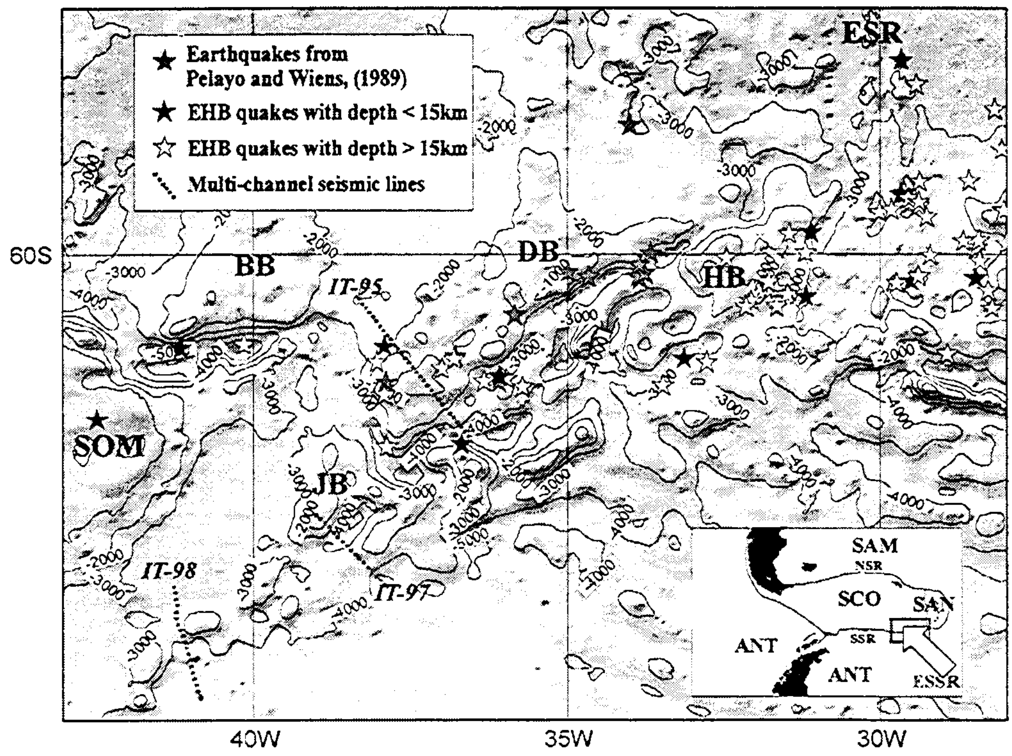
Fig. 4 – Rayleigh wave group velocity tomography in ESSR in the period range from 15 s to 45 s. In the whole period range negative anomalies are concentrated in DB and JB. Blues indicate faster than average, and reds slower than average group velocity. Historical events relocated by Pelayo and Wiens (1989) are represented by white stars, while black stars represent events in the EHB catalog (Engdahl et al., 1998) from 1964 to 1999.

Fig. 5 - Average resolution length in km for the study area at the same periods of Fig. 4 for Rayleigh waves.

Fig. 6 - Locally smoothed group velocity curves in the ESSR compared to the average group velocity curves obtained for other regions in the Scotia Sea and surrounding areas. Solid lines represent group velocity curves computed using CRUST5.1 model (Mooney et al., 1998), while the symbols identify the group velocity curves obtained with our tomographic study. TSA = Tip of South America, FP = Falkland Plateau, BS = Bransfield Strait, SS = Scotia Sea, SSI = South Sandwich Island arc, ESSR = eastern South Scotia Ridge, TAP = Tip of Antarctic Peninsula, SS51 = Scotia Sea from CRUST5.1, TSA51 = tip of South America from CRUST5.1, FP51 = Falkland Plateau from CRUST5.1, TAP51 = tip of Antarctic Peninsula from CRUST5.1. Crosses are the group velocity at periods greater than 50 s obtained by Ritzwoller et al. (1996) at ESSR.

Fig. 7 - Average shear wave velocity vs. depth models for ESSR are obtained inverting: (a) Rayleigh wave group velocity data, and (b) simultaneously Rayleigh and Love group velocity data in the range of periods from 15 s to 80 s. The ambiguity in the Moho depth determination is resolved by the joint inversion of Rayleigh and Love wave group velocities.

Fig. 8 - Seismic profile (unmigrated) IT-95 and line-drawing (see Fig. 1 for location) crossing the south-western part of the DB, which is constituted by two morphological reliefs flanked by a faulted margin to the NW, and by a possible volcanic margin to the SE.



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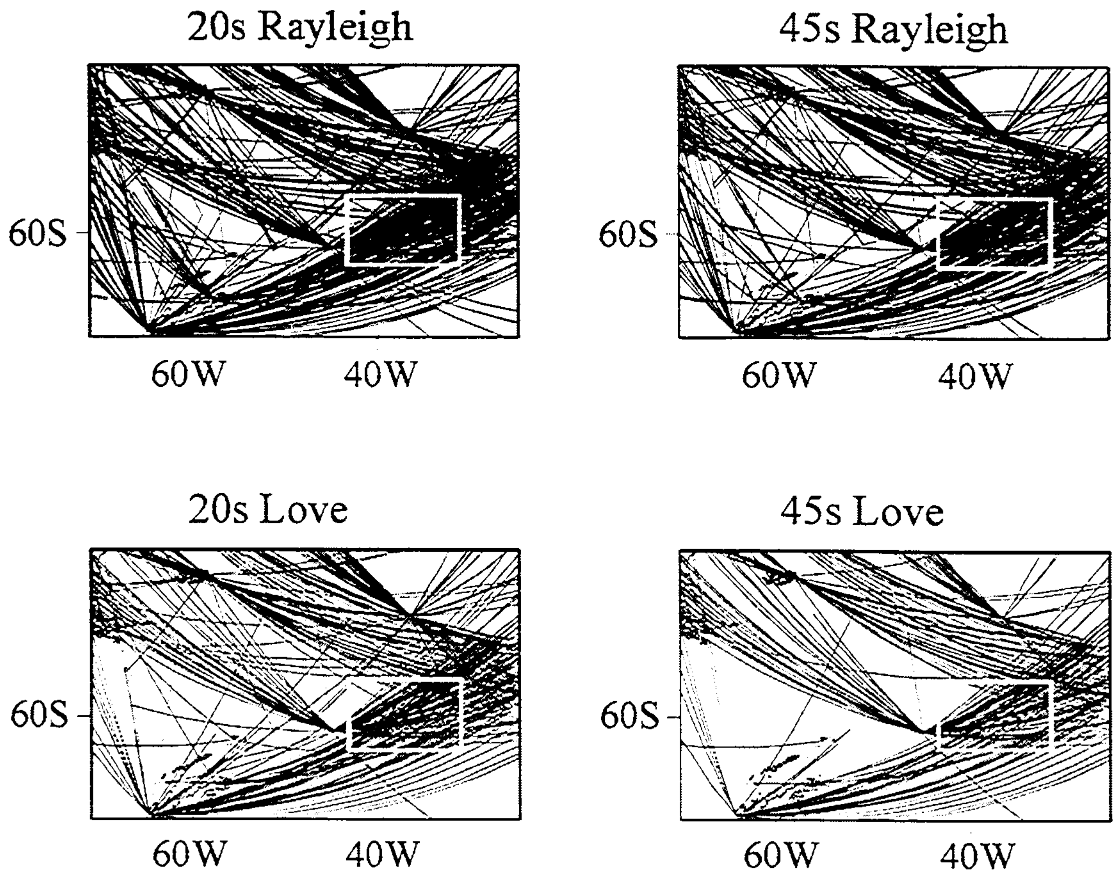

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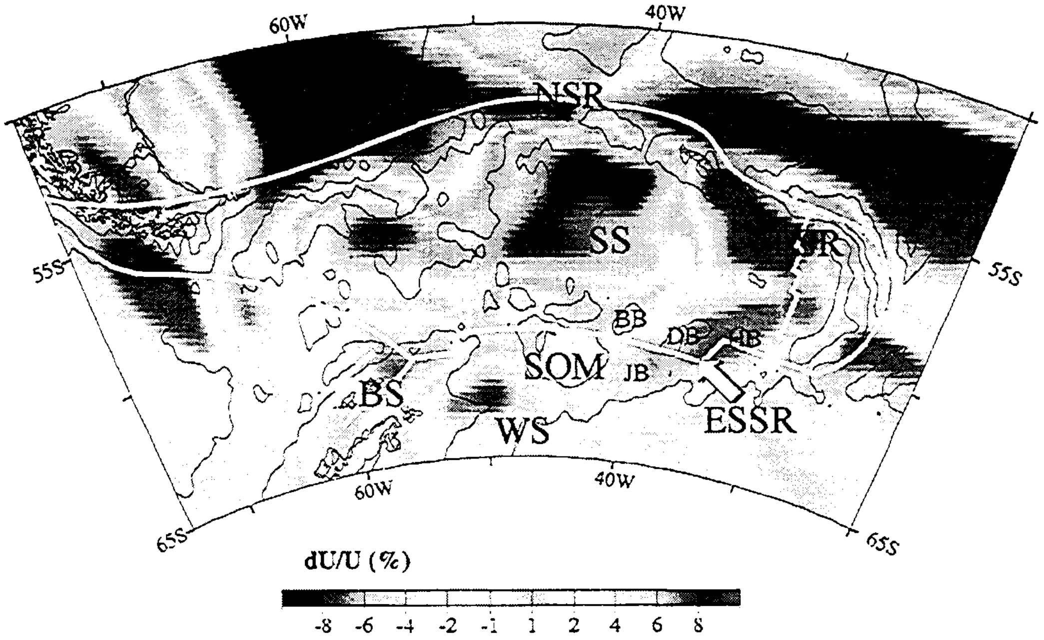

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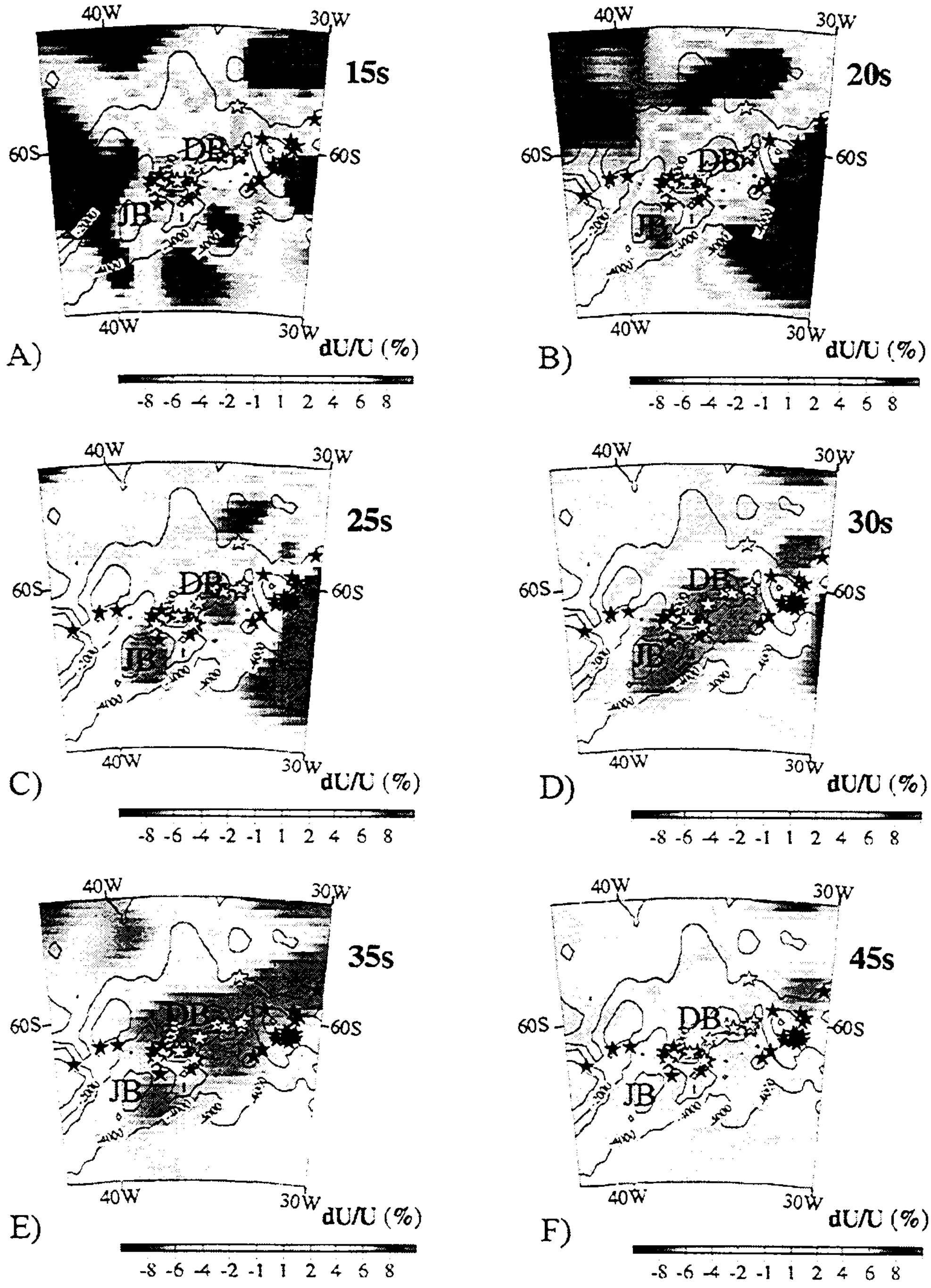

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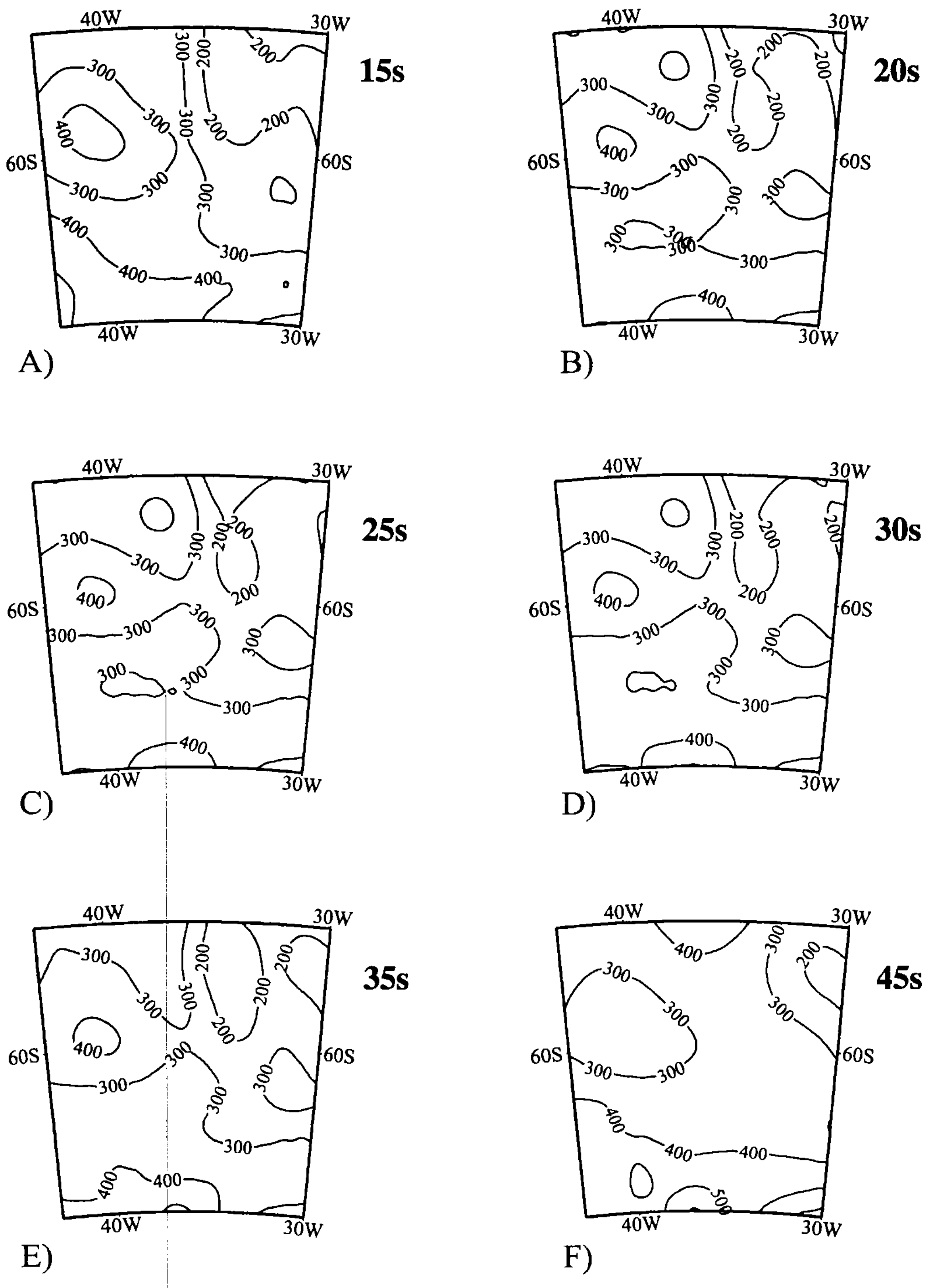

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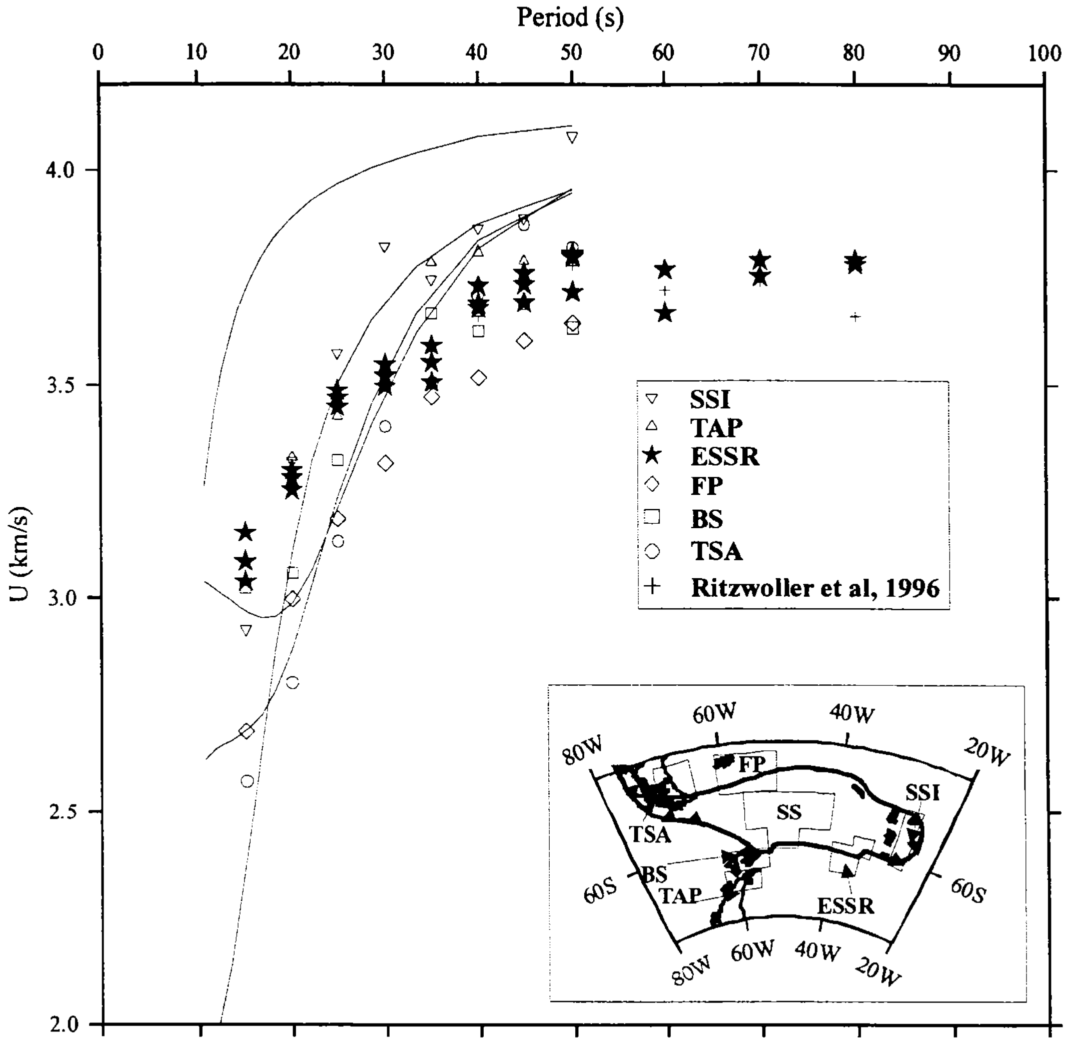

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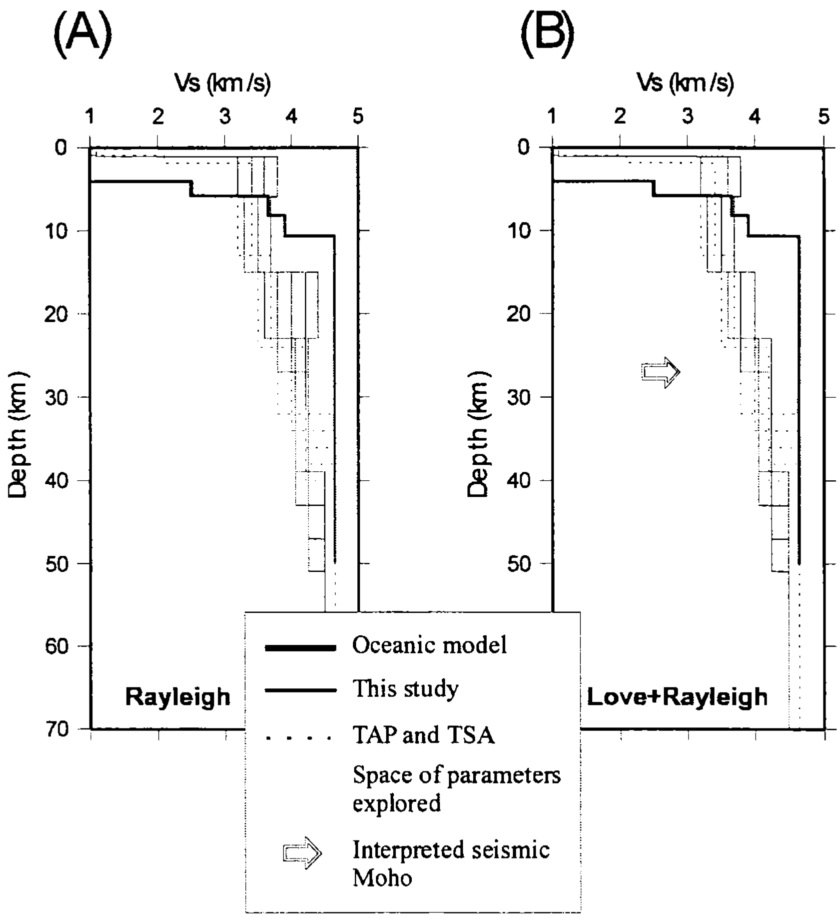
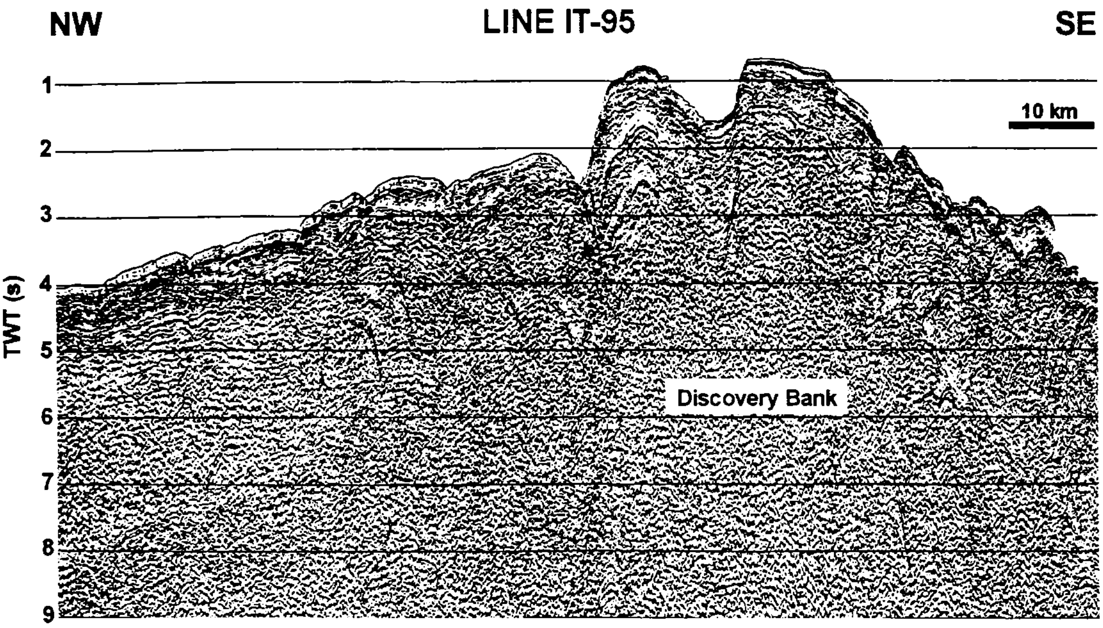
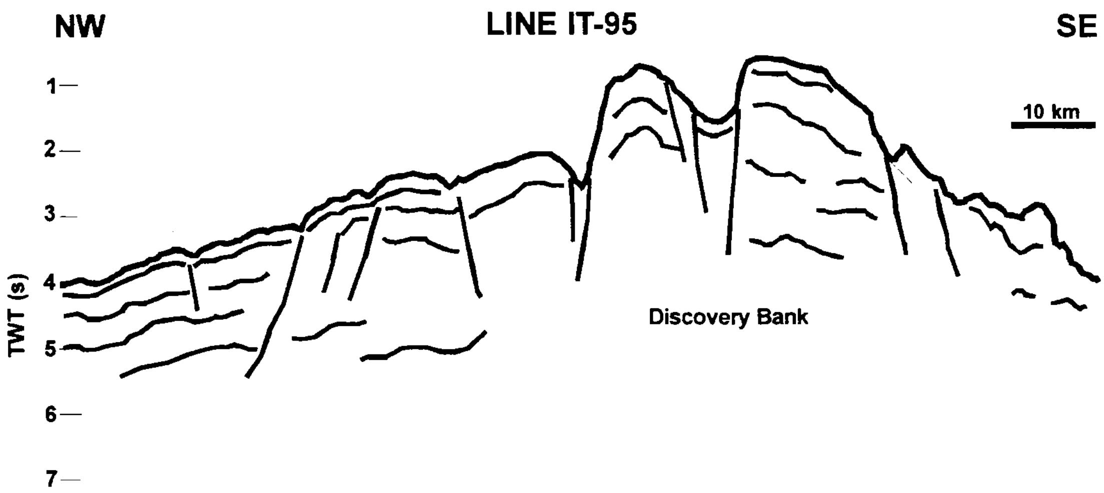
Fig. 6



Vuan et al.,
Fig. 7





Vuan et al.,
Fig. 8