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Cenozoic Tectonic Evolution of the Northern Antarctic Peninsula (TENAP Project)

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ABSTRACT

During the austral summer 1996-97, an offshore-on land wide-angle seismic experiment was carried out along two 400 km long crustal transects across the northern tip of the Antarctic Peninsula (running parallel on either side of the Hero fracture zone) and along a third 200 km long tie-transect on the Pacific margin of the Peninsula, as part of the Cenozoic Tectonic Evolution of the Northern Antarctic Peninsula (TENAP) project, an Italy-Argentina bilateral cooperation supported by the *Programma Nazionale di Ricerche in Antartide* (PNRA) and the *Direccion Nacional del Antartico* (DNA).

We used 15 broad-band portable seismic stations on land and 8 ocean-bottom seismographs (OBS) offshore. Seismic energy was provided by the *R/V OGS Explora*, operating a 60.5 liter air-gun array in "single-bubble" mode and firing along the Pacific portion of the transects. Air-gun shooting was performed twice along the transects: first for the wide-angle seismic experiment, with a 250 m shot interval into OBSs and land stations, and second for the multichannel seismic (MCS) recording, with a 50 m shoot interval. Logistic and scientific support for the land operations was provided from the argentinian bases on the Peninsula; the icebreaker *Almirante Irizar* supported the activities on the coastal areas and on the islands. Seismic energy was received from crust and upper mantle up to offsets of more than 200 km on the Weddell side of the Peninsula.

Recent deformation along the trend of the Hero fracture zone (HFZ) was observed on the continental margin of the AP, close to its west coast.

TENAP OBJECTIVES

TENAP is a bilateral research project between the *Programma Nazionale di Ricerche in Antartide* (PNRA), Italy and the *Direccion Nacional del Antartico* (DNA), Argentina for the study of the deep structures of the northern tip of the Antarctic Peninsula (AP) by means of seismic refraction and wide-angle reflection investigations, integrated by field geology and geophysical observations. TENAP is organized as a multidisciplinary cooperation between Universities and research Institutions in Argentina and Italy, with the contribution of the Earth Resources Laboratory-MIT, USA.

The northern AP is an interesting and rare example of an elongated, narrow continental block bounded by an active (or recently extinct) Andean-type margin, on the Pacific side, and by a passive continental margin, since Mesozoic time, towards the Weddell Sea ocean basin. The present geodynamic setting of the Pacific shows major changes across the Hero fracture zone (HFZ) margin alignement. The subduction at the South Shetland Trench, the active South Shetland volcanic arc, the Bransfield Strait back-arc basin extension, the seismic and volcanic activity, northeast of the HFZ, contrast with an extinct plate boundary to the southwest, where the age of the ridge crest-trench collision increases southwestard, from 4 to about 50 Ma. On the Weddell Sea side of the AP, the James Ross and Larsen Mesozoic back-arc basins are interested by relevant Pliocene alkaline volcanism (James Ross Is. volcanic group and Seal Nunataks); this volcanic activity could likely indicate extensional or transtensional stress regime in the area during Pliocene.

The TENAP program focuses on crustal and subcrustal structures of the Pacific and Weddell Sea continental margins of the Graham Land, including the magmatic arc that formes the AP cordillera. The major targets are the changes along the present/paleo- plate boundary of the western AP; in particular, the limited extent of the Bransfield Strait back-arc basin, the role of the HFZ, the effects of ridge subduction at the paleo-trench, and the Cenozoic crustal deformation and processes associated with these changes. In the above mentioned areas we have the following specific objectives:

- *on the Pacific margin*: the regional mechanisms of margin deformation, the ridge-crest subduction, the back-arc extension and subsidence by defining Cenozoic tectonic structures (*e.g.*, faults, unconformities, basement topography, accretionary prism, volcanic intrusions) and the deep crustal and sub-crustal structures (crustal thicknesses, sub-Moho velocities, subduction dip, slab-free regions), which are investigared using MCS, wide-angle reflection and refraction (OBS) seismic experiments, seismic tomography, bathymetry, gravity and magnetic measurements;
- *across the Antarctic Peninsula*: the deep crustal structures underneath the magmatic cordillera, the extent and characteristics of the deep magmatic rocks, uplift and erosion of the magmatic arc, which are investigated by collecting geological, GPS, gravity, magnetic and wide-angle reflection and refraction seismic data (using three component portable broad-band seismic stations and the seismic stations at Base Esperanza and Palmer Station). The seismic instruments also record local seismicity and teleseismic events; their analysis can contribute in determining the AP crustal and sub-crustal structure.

It was also planned to collect data on the Weddell side of the AP to study the structure and formation mechanisms of the Weddell Sea margin, the Ross and Larsen back-arc Mesozoic basins, and the puzzeling cenozoic magmatism along the eastern AP margin.

The investigations on the Pacific margin and across the AP were successfully carried out during the 1996-97 field experiment, whereas those on the Weddell Sea margin of the AP could not be performed because of too many icebergs and broken sea ice flowing northwards.

FIELD OPERATIONS

Geological and geophysical investigations were carried out from the beginning of December 1996 to the beginning of March 1997 and required a quite strong organizing and logistic effort. The Italy-Argentina bilateral cooperation for the TENAP project worked out fairly well.

The activities schedule was as follow:

- December 1996: instrumentation shipping to Marambio Base by C-130, deployment of 10 portable seismic stations in the coastal areas and on the islands around the AP, with the support of the icebreaker *Irizar*, field measurements and observations in the area of the seismic stations;
- mid January/mid February 1997: offshore-on land wide-angle seismic experiment, geology and geophysics on land, logistic support from *OGS Explora* offshore, helicopters and Twin Otter from the Argentinian bases on land;
- end of February/beginning of March 1997: recovery of 7 portable seismic stations in the coastal areas and on the islands of the Pacific side, with the support of the icebreaker *Irizar* and of the ship *Castillo*.

The field investigations were focused along two 400 km long crustal transects, running parallel on either side of the HFZ alignement, and crossing orthogonally the AP and its Pacific margin. A third 200 km long crustal transect, intersecting at a right angle the other two, was run on the Pacific continental margin; its northeastern part enters the Bransfield Strait. The transects are labelled in figure 1 as I, II and B. The transects I and II continue across the AP with the land seismic stations; in correspondence of the AP cordillera there is a gap in instruments coverage of about 60-70 km. The experiment included refraction and wide-angle seismic reflection, gravity, magnetic and seismological measurements both offshore and on land along the three transects, MCS along the marine portion and field geology and GPS measurements on the land part. The energy was provided by a 60.5 liter air-gun array, arranged according to the innovative "single bubble" technique (Avedik et al., 1993; Avedik et al., 1995; Avedik et al., 1996). This technique consists in the sequential firing of different size air guns in the array, synchronizing the guns output on the first low-frequency/high energy bubble pulse, instead of on the primary pulse (Fig. 2). In this way we can obtain a source with a higher strength in the low-frequency band (0-32 Hz), thus providing better penetration in the crust.

The "single bubble" firing was provided twice along the Pacific part of the transects (Fig.1): during the first run the shot interval was 250 m for the refraction and wide-angle seismic recordings (OBS and land stations), whereas during the second run the shot interval was 50 m for the MCS recording. Bathymetry, gravity and magnetic data were also acquired along the marine part of the transects.

The seismic energy was recorded by Ocean Bottom Seismographs (OBS) offshore and by broad-band portable seismic stations on land (Fig. 1): 8 OBS were deployed twice in 16 positions, 7 portable REFTEK stations were deployed on the Pacific coast and islands and 8 on the Weddell Sea side. Twelve Reftek stations recorded properly, some of which working without inspection for about 50 days; three stations on the Pacific side missed part of the data because of various technical problems and inspection impossibility during the experiment. Three OBS were lost.

The *OGS Explora* operations were carried out between January 12 and February 2, 1997. We first run transect II deploying 8 OBS and shooting into OBS and land stations, and later shooting again into the MCS streamer. The transects I and B were operated both in once, deploying 8 OBS and firing twice as for transect II. The OBS had three component geophones and were recording continuously at 64 Hz, storing the data on a 2 Gb hard disk. The battery pack could power them up for up to 8-10 days of continuous recording. The MCS streamer was 3 000 m long, 120 channels,

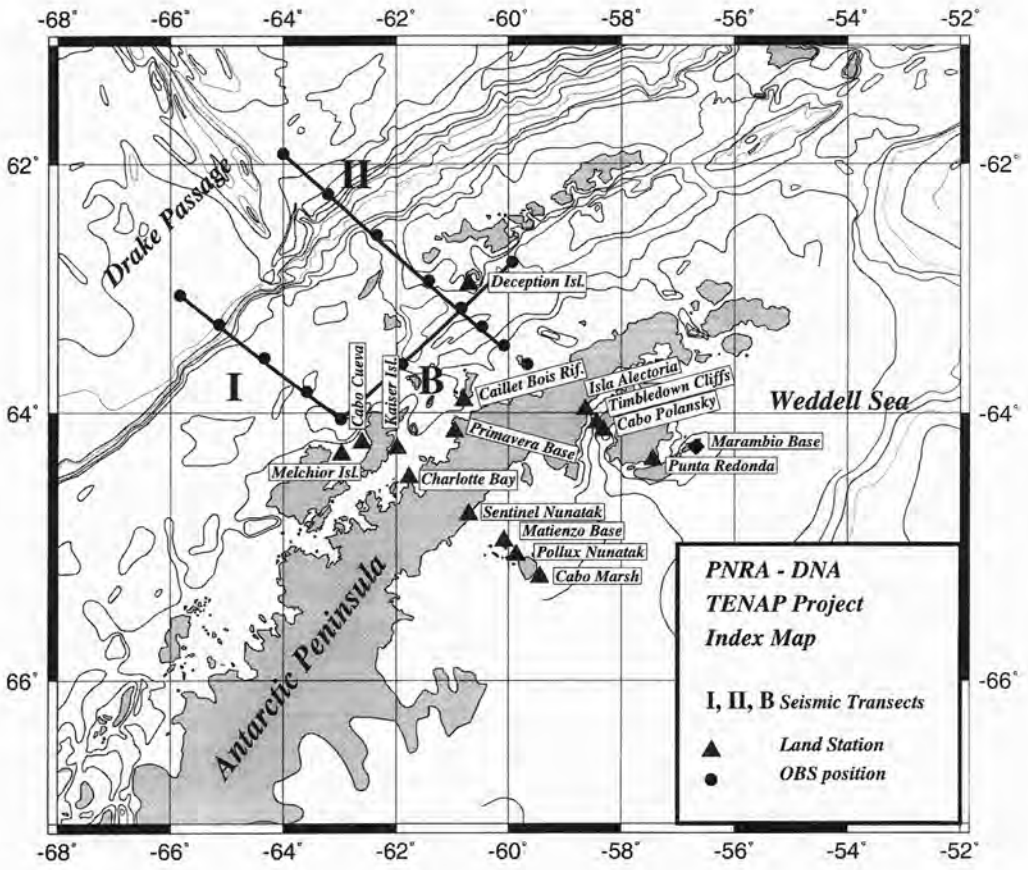

Fig. 1 - Index map of the TENAP Project seismic experiment.

25 m intertrace distance, working at 12 m depth and at a speed of 4 knots. MCS data were recorded with a sampling interval of 4 ms over a 16 s record length.

The operations on land were carried out from November 96 to mid March 97, supported by aircrafts from the Marambio Base and by the icebreaker *Almirante Irizar*. The seven portable seismic stations on the Pacific side of the AP, deployed in December 1996 using helicopters and boats from the *Irizar*, were recovered in March 1997 by the same icebreaker with the help of the ship *Castillo*. The seismic stations on the Weddell Sea side were deployed by the *Irizar* at Matienzo Base, Pollux Nunatak and Cabo Marsh, in December 1996 too. The four land stations near Marambio Base were deployed by helicopters by mid January 1997. All the eigth Weddell Sea land stations were recovered by helicopters from Marambio base, at the end of February 1997. All the land stations had GPS time receivers, solar panels, three component geophones and were recording continuously at 50 Hz, storing the data on a 2 Gb hard disk.

Gravity and GPS measuremens were taken at each seismic station and also in nearby locations (about 30 measurement). The gravity measurements were taken with two LaCoste & Romberg mod. D instruments, whereas navigation was provided by a Trimble differential GPS system, integrated with an auxiliary Trimble GeoExplorer II differential receiver. A local gravity and GPS

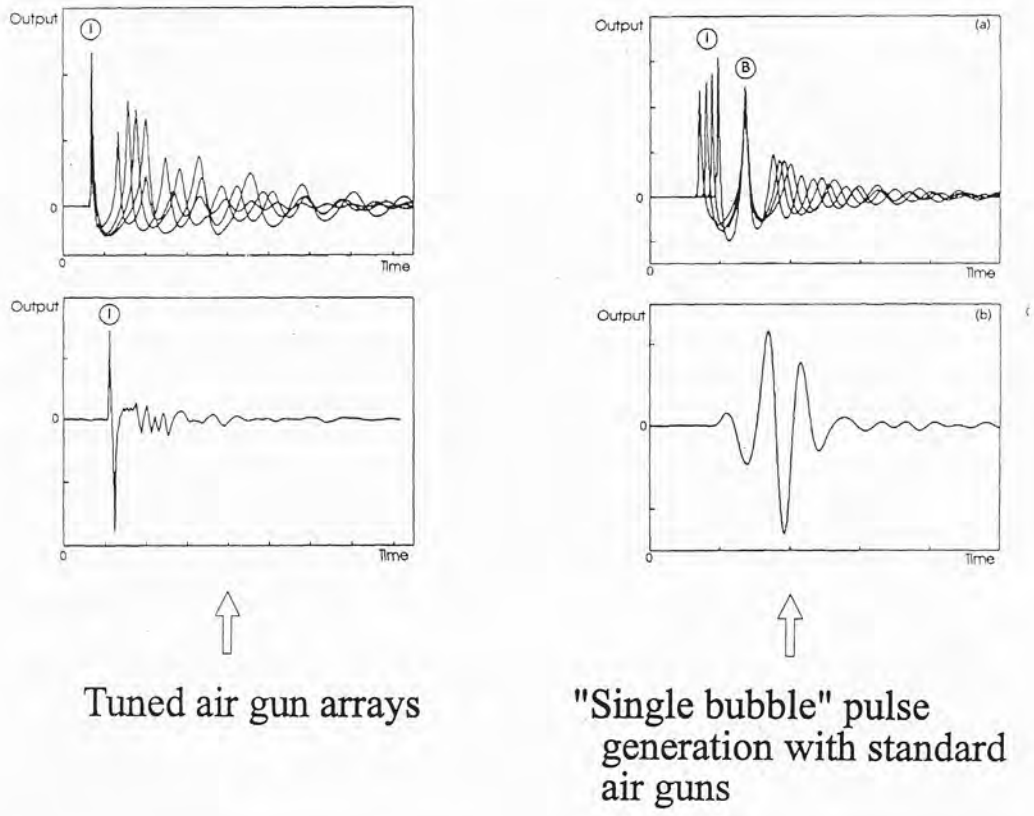

Fig. 2 - Air-gun array seismic signature: comparison between tuned air-gun arrays syncronized on the first pulse (I) and air-gun arrays syncronized on the first "bubble pulse" (B) (from Avedik et al., 1993).

network was established at the Marambio base, in order to compare the measurements taken with the two different instruments. The local network was based on two geodetic points available at both ends of the Marambio runway; one of them has also a gravity measurement linked to Buenos Aires.

Field geology was particularly concentrated in two key areas, such as Isla Alectoria and Sentinel Nunatak, that represent the contact area between the western border of the J. Ross and Larsen back-arc basins, respectively, and the AP, consisting of Permo-Triassic basement (Isla Alectoria) and mesozoic magmatic arc (Sentinel Nunatak). In these two specific areas there was very little work done before.

DATA QUALITY AND PRELIMINARY RESULTS

The quality of the TENAP geological and geophysical dataset has not been yet fully assessed; however some tests performed on parts of the data show a generally good to very good quality.

The field geology observations and the preliminary laboratory measurements on the collected samples have the potential to reconstruct some of the deformation phases which affected the western border of the James Ross and Larsen back-arc basins. Isla Alectoria faces directly the Cretacic deposits representing the J. Ross basin infill. The lithology consists of low-grade schists

probably belonging to the Trinity Peninsula Group. A sub-vertical NNW trending crenulation cleavage is the main foliation, affecting the previous metamorphic foliation (green-schist facies, clorite zone), with the developement of shear bands. NW faults cut the metamorphic rocks; some faults show oblique displacenment. The youngest deformative event seems to be represented by the NE trending joints and faults,

Sentinel Nunatak metavolcanics (on the Weddell Sea side of the southern transect) are characterised by a well developed sub-vertical NE trending fracture cleavage (very low-grade metamorphism) and outcrops of basic dike intrusions; these rocks probably belong to the Mesozoic magmatic arc sequence. A NNW joint system affects the whole metavolcanic-magmatic sequence and represents the youngest deformative event. One oriented sample of metavolcanic rock shows clasts and fenocrysts with characteristic sigmoidal structures. The developement of such kinematic indicators, when confirmed by further analysis on the other samples, together with the regional sub-vertical fracture cleavage, could indicate transpressional stress regime.

The gravity data collected on the Pacific side of the AP are among the few ones presently available in the area, whereas the ones on the Weddell Sea side well complement the relatively dense data coverage performed by the British Antarctic Survey and the data recently acquired by the IAA-DNA. Gravity profiles along the two transects crossing the AP will be missing anyway the portion corresponding to the cordillera mountain range. Gravity ground measurements are here extremely difficult to obtain, as well as an accurate elevation model for the topographic correction.

The seismic dataset constitutes the largest amount of new data acquired by the project. More than 16 000 shots were fired into the OBSs and land stations and about 700 km of MCS lines were carried out; the majority of these data has still to be analysed and processed. The quality of MCS, checked underway onboard, seems quite good. On the other hand, only a few tests have been done on OBS and land stations data. Figure 3 shows the MCS image of two of the more interesting structures along the transects, such as the South Shetland trench northeast of the HFZ (Fig. 3a) and a small sedimentary basin, next to a structural high, located along the HFZ alignement, on the Pacific continental shelf, close to the AP coast. This latter feature is a wedge-shaped asymmetric basin with at least one second TWT of deformed sediments. The reconstruction of the seismostratigraphic sequences should be able to provide the timing of the deformation phases.

A quality control on the OBS data has shown clear energy arrivals and relatively low-amplitude environmental noise. Figure 4 shows an OBS seismic section with coherent energy arrivals at offsets greater than 100 km. The OBS data will complement the MCS record, providing a good velocity vs. depth function. Integrating OBS and land stations data, with the seismological observations we should be able to provide a 2-D tomographic image of the crustal and upper mantle structures across the whole AP.

With regard to the land seismic stations, we preliminarly analyzed only the seismic data recorded by the four stations located on the Weddell Sea side of the northern transect. Three of the four stations show clear energy arrivals from the air-gun shots on the Pacific side. Figure 5 shows a common receiver gather (Vred = 8 km/s) as recorded at Cabo Polansky. Strong energy arrivals from the upper mantle are clear up to a source-receiver offset of over 200 km.

One preliminary but important result of the seismic experiment is the recording of the seismic energy, produced by the "single bubble" air-gun array on the Pacific side of the AP, by the stations located on the Weddell Sea side, at offsets larger than 200 km. This means that the seismic energy propagating through the crustal and upper mantle structures, beneath the AP margin and AP itself, could be recorded at large offsets, despite the not excellent environmental conditions.

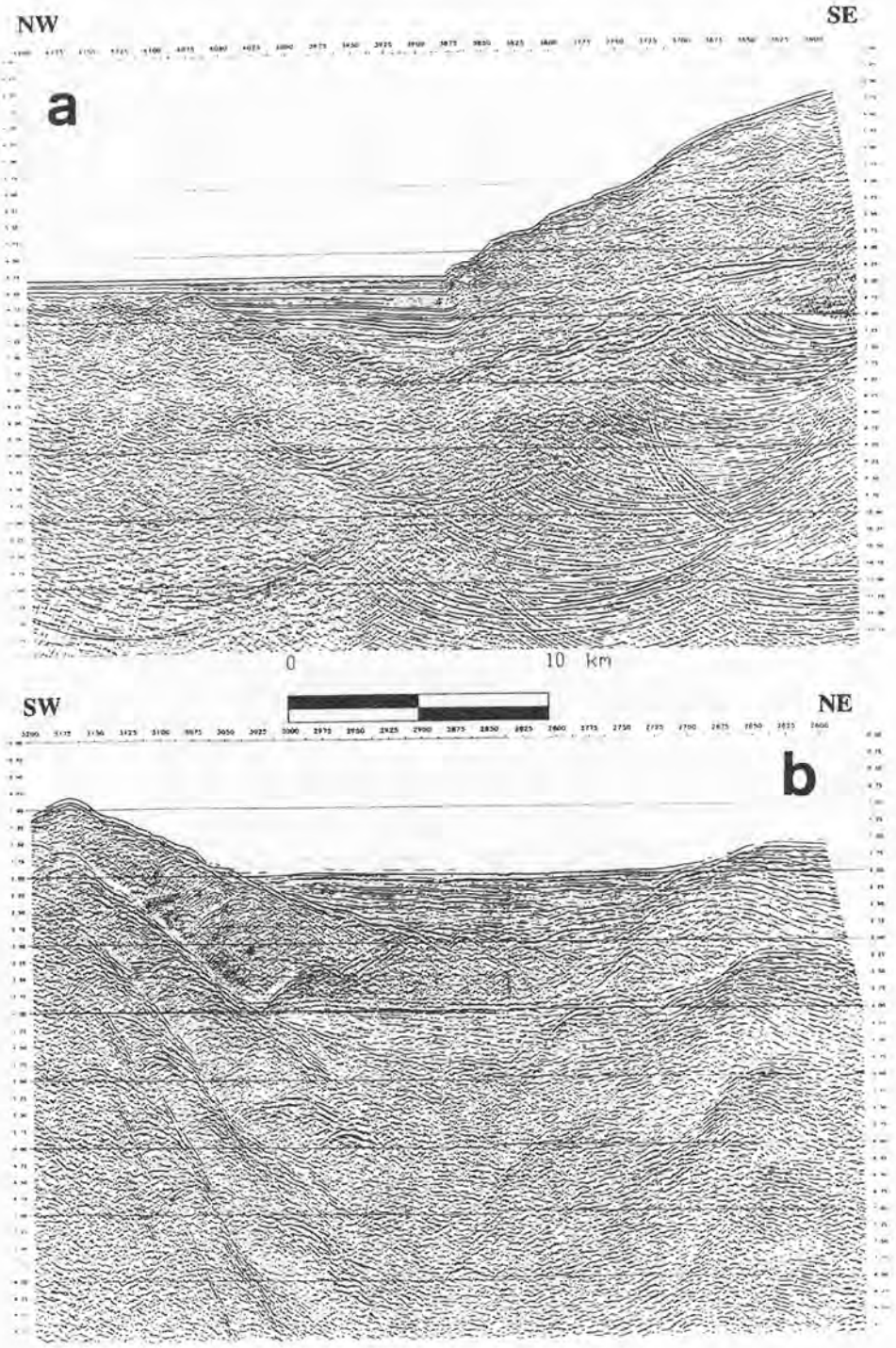

Fig. 3 - Preliminary MCS stack sections imaging the South Shetland trench along transect II (*a*) and the central part of transect B in correspondence of the HFZ alignement (*b*).

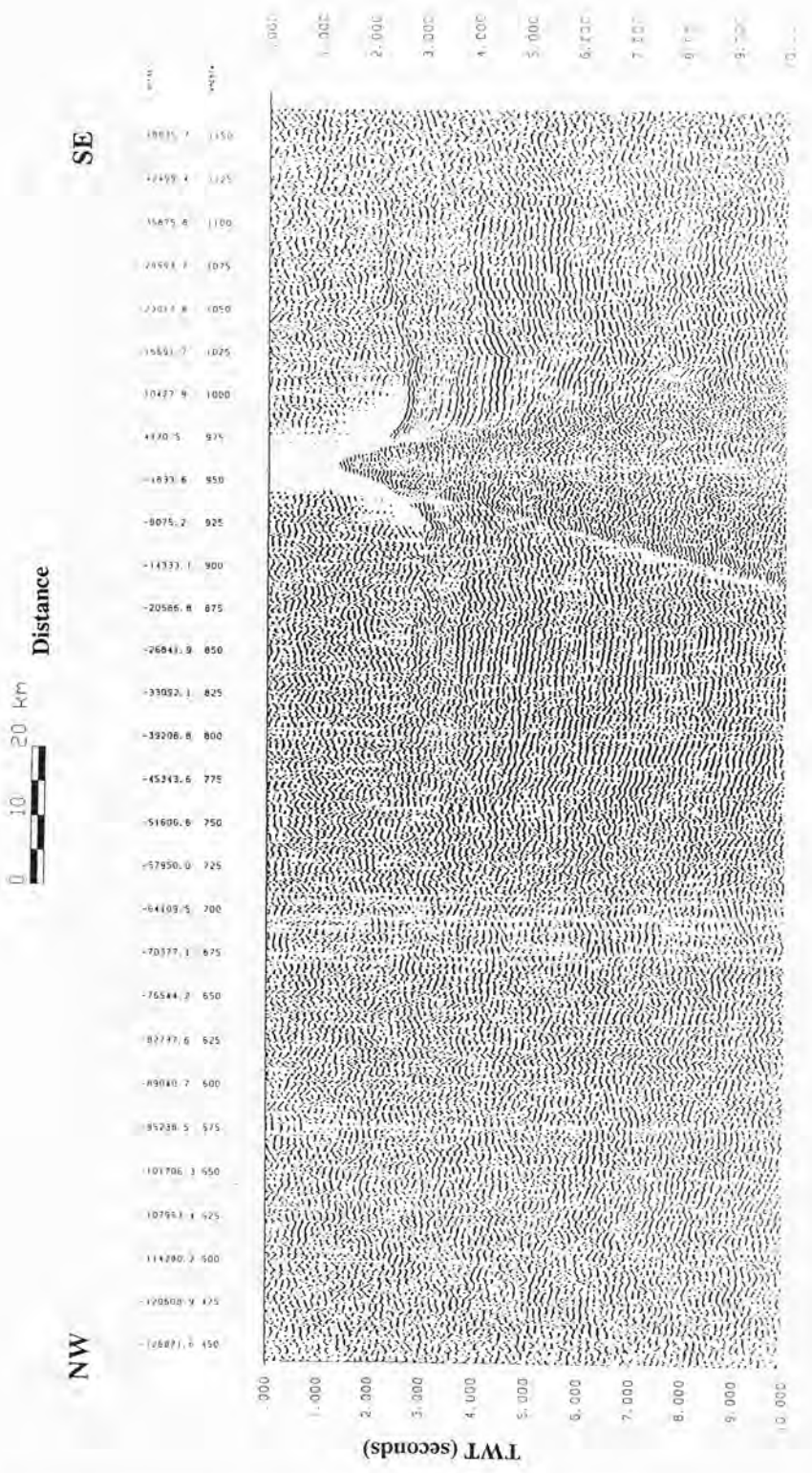

Fig. 4 - Preliminary travel-time section (6 km/s reduction velocity) of the seismic energy fired along transect II and recorded by the OBS deployed at the crossing between transect II and transect B.

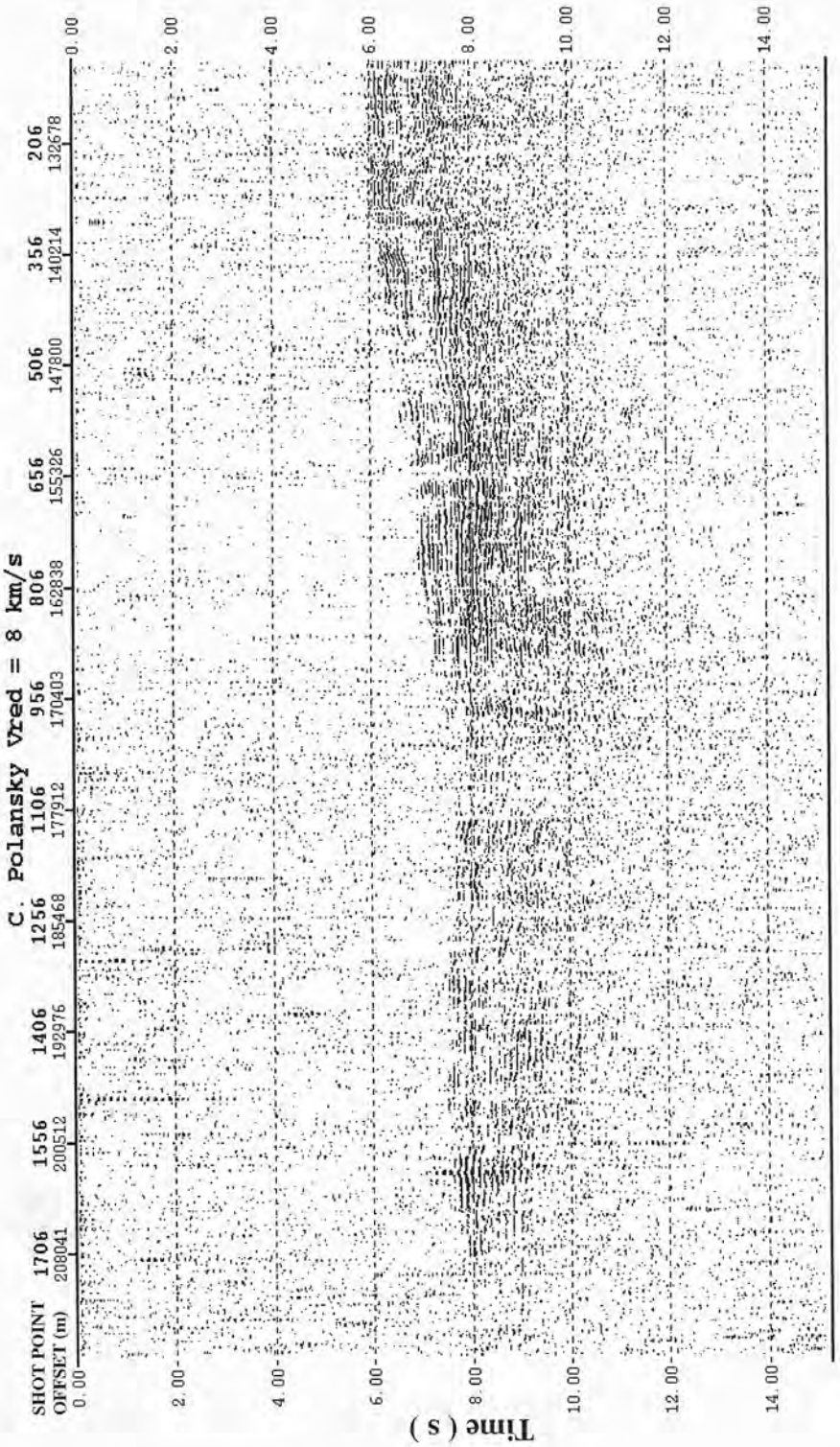

Fig. 5 - Common receiver gather (Vred = 8 km/s) recorded at Cabo Polansky.

The preliminary scientific evaluation of the TENAP dataset is extremely positive: we believe that the results will meet the project objectives, despite the fact that we could not extend the seismic experiment through the Weddell Sea margin of the Peninsula.

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