BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXV, N. 137-138 - MARCH-JUNE 1993

C. GANTAR, M. MARCHI, R. SINCERI and R. VIDMAR

GEOPHYSICAL DATA PROCESSING IN THE ROSS SEA (ANTARCTICA)

Abstract. The procedures adopted by OGS, Trieste, in processing the navigation and the geophysical data acquired during the expeditions in Antarctica are illustrated and commented on. The quality of the results appears consistent with the state-of-the-art and well suited to their interpretation in terms of geology and tectonics.

INTRODUCTION

During the austral summers 1987-88, 1988-89, 1989-90, the Osservatorio Geofisico Sperimentale of Trieste (OGS) collected about 9600 km of multichannel seismic reflection data in the Ross Sea. Digitized navigation data, gravity and magnetic measurements were also acquired. The processing of these data was done at the OGS Computer Center and the procedures adopted were slightly different from those used in standard oil prospection. This paper describes the various steps performed and the modifications made to improve the results as far as computation time, and therefore cost, is involved.

NAVIGATION POST-PROCESSING

The first step in the computational flow of the data received on magnetic tapes from the ship was obviously the post-processing of the navigation data, which were recorded on separate reels and included position, depth, gravity and magnetic data from a single magnetometer, those from the gradiometer being recorded separately on the floppy disks of a personal computer.

During the first expedition (1987-88), navigation control was done with an INDAS V system (Berger et al., 1993) in which discrete fixes from the Transit satellite were integrated and interpolated by means of the data received from several dead reckoning sensors (logs and compasses).

In the following year, a more modern navigation system, the NAVDATA 3000, was installed and satellite fixes from GPS were added to the navigation control. Interpolation and forecast of the ship's course was done in real time by the software of the NAVDATA 3000 itself, in order to shoot at a predetermined interval and to steer along the chosen profile. However, a post-processing of the navigation data recorded on magnetic tape is still necessary since the system restarts at every interruption (of the flow in satellite information or when some other malfunction takes place), which causes jumps in the continuity of the tracks, which then have

Manuscript received, October 15, 1992; accepted, January 21, 1993.

OGS, Osservatorio Geofisico Sperimentale, P.O.Box 2011, 34016 Trieste, Italy

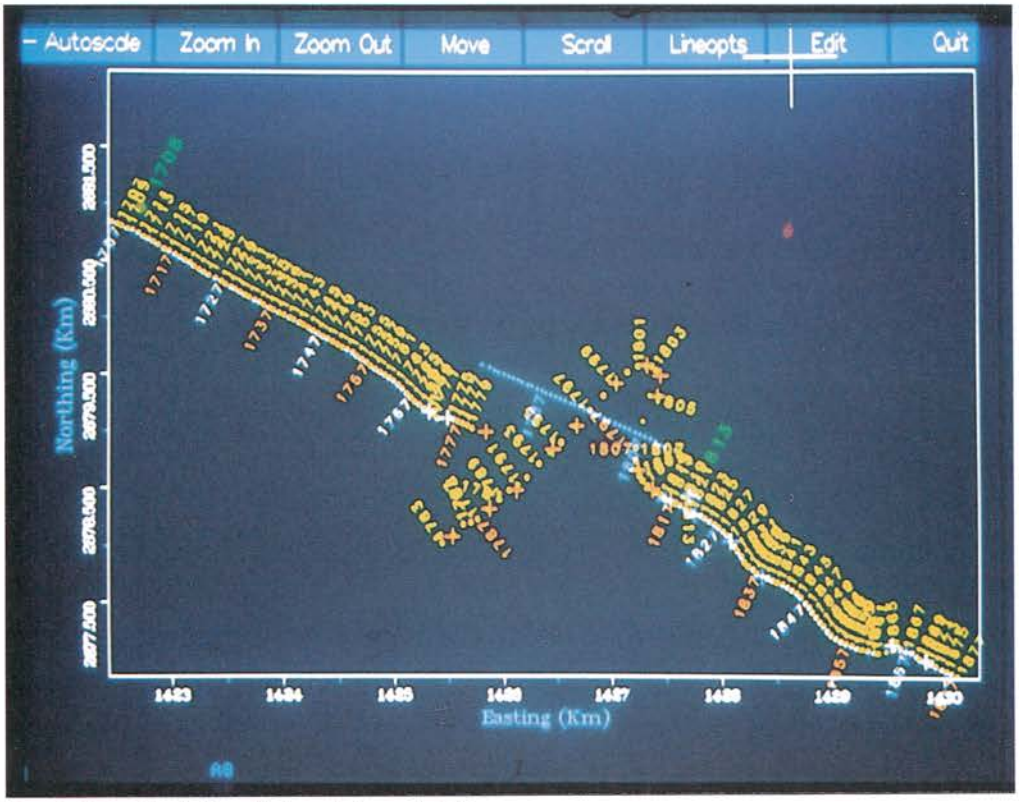

Fig. 1 - Example of video display of observed data.

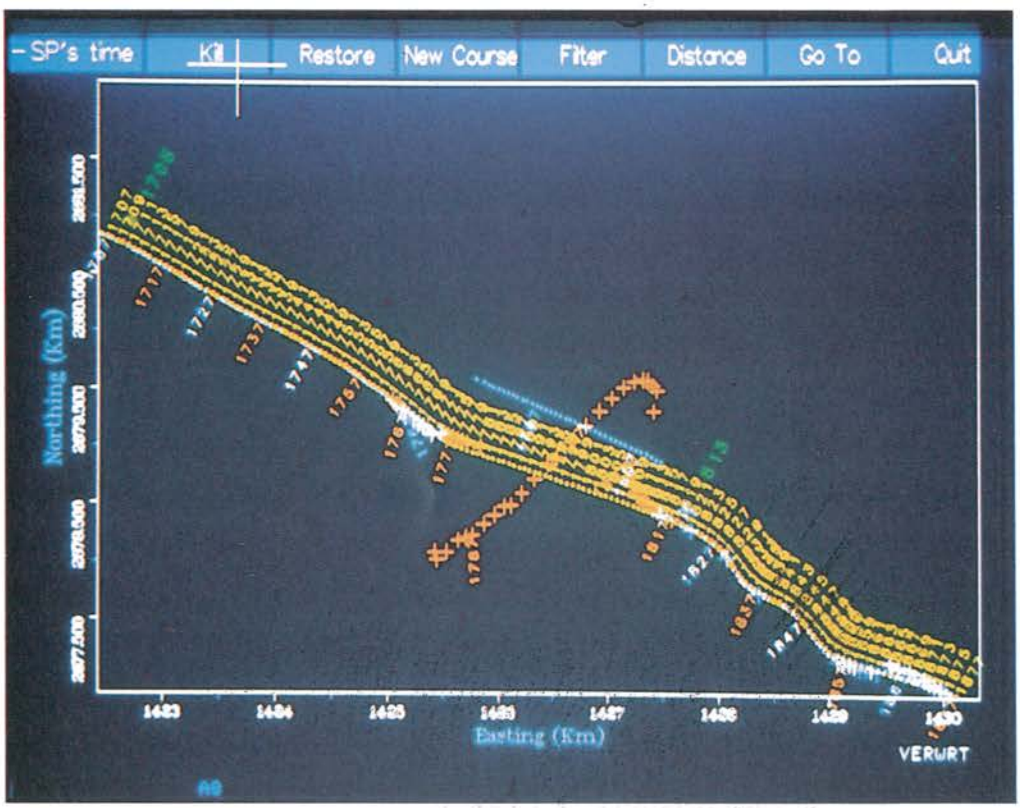

Fig. 2 - Example of video display with edited data.

to be reconstructed. Therefore, interpolation, despiking and a final filtering is necessary to output navigation data in a convenient format for their further use. Short period variations are controlled with dead reckoning from the sensors of the system, which are used to interpolate positions when GPS is missing as well as to individuate "jumps" in GPS sequences.

A final check of the quality of the recontruction is given by the gravity data, since the Eoetvoes correction is very sensitive to speed and course variations, and the corrected gravity must be uncorrelated with the Eoetvoes correction itself. The post-processing of the navigation data was performed by means of a software package (ND3P), written at OGS, designed to analyse, reprocess, complete and smooth the tracks of the ship. The same program picks out the potential field data collected along the profiles (gravity and single magnetometer data).

The magnetic gradiometer data, collected after the first cruise, were recorded with a separate system on the floppy disks of a personal computer.

The package ND3P has been written in FORTRAN 77 and consists of over 10,000 statements. The post processing-procedure involves two steps: the first imports the data from the field tapes, while the second permits interactive processing. This was done both to minimize use of the tape units and to allow future developments of the software.

The interactive program converts the geographical positions from the available positioning system into plane coordinates, plots them, and computes a 'most probable' course by merging the data with those supplied from the gyro compasses and the speed logs. The user can specify geodetic parameters, radiopositioning system parameters and rejection criteria to discard automatically the fixes which appear certainly wrong. While running the program, the user can view the fixes and the recomputed track on a graphic display, zoom in at different scales, choose display parameters and modify the track by discarding the fixes considered to be errors (Figs. 1 and 2). The whole editing sequence is recorded both on a logfile, and on a separate file which permits the recomputation of the same output in batch mode. Facilities to add new shot points to the existing sequence are provided to handle accidents where a malfunction may have generated the loss of data on tape. Renumbering of the shot points can be also done, to account for particular events.

Due to the extensive employment of satellite navigation, which was only Transit until 1989, and mainly GPS from 1991, the reference ellipsoid adopted in the navigation post-processing (as by nearly all other observers) was the WGS-72 with the following parameters:

$$a=6,378,135.000 \quad , \quad \frac{1}{f}=298.25989 \quad , \quad e^2=0.0066943178 \quad .$$

Eventually the GPS constellation was implemented and, at present, positioning may be achieved 24 hours a day: GPS represents therefore the future standard in positioning so that the WGS-84 reference ellipsoid is adopted in OGS maps (Gantar, 1993), with the following parameters (AIG, 1980):

$$a=6,378,137.000 \quad , \quad \frac{1}{f}=298.257222 \quad , \quad e^2=0.006694380023 \quad .$$

Changes from WGS-72 into WGS-84 may be carried out by simple transformation. However, at small scales (1:100,000 or smaller) there is no visible graphical difference between data computed with reference to one or the other, since the difference between the coordinates in the two systems is less than 10 meters. It should also be noted that the present accuracy of GPS technology implemented on board is of this same order of magnitude, and that the future target of $\pm$ 1 meter accuracy requires an inertial reference with pitch- and roll-control, a differental GPS technique, and a suitable software.

BATHIMETRY

Corrections to the observed depths taken with the echo-sounders callibrated for a sound

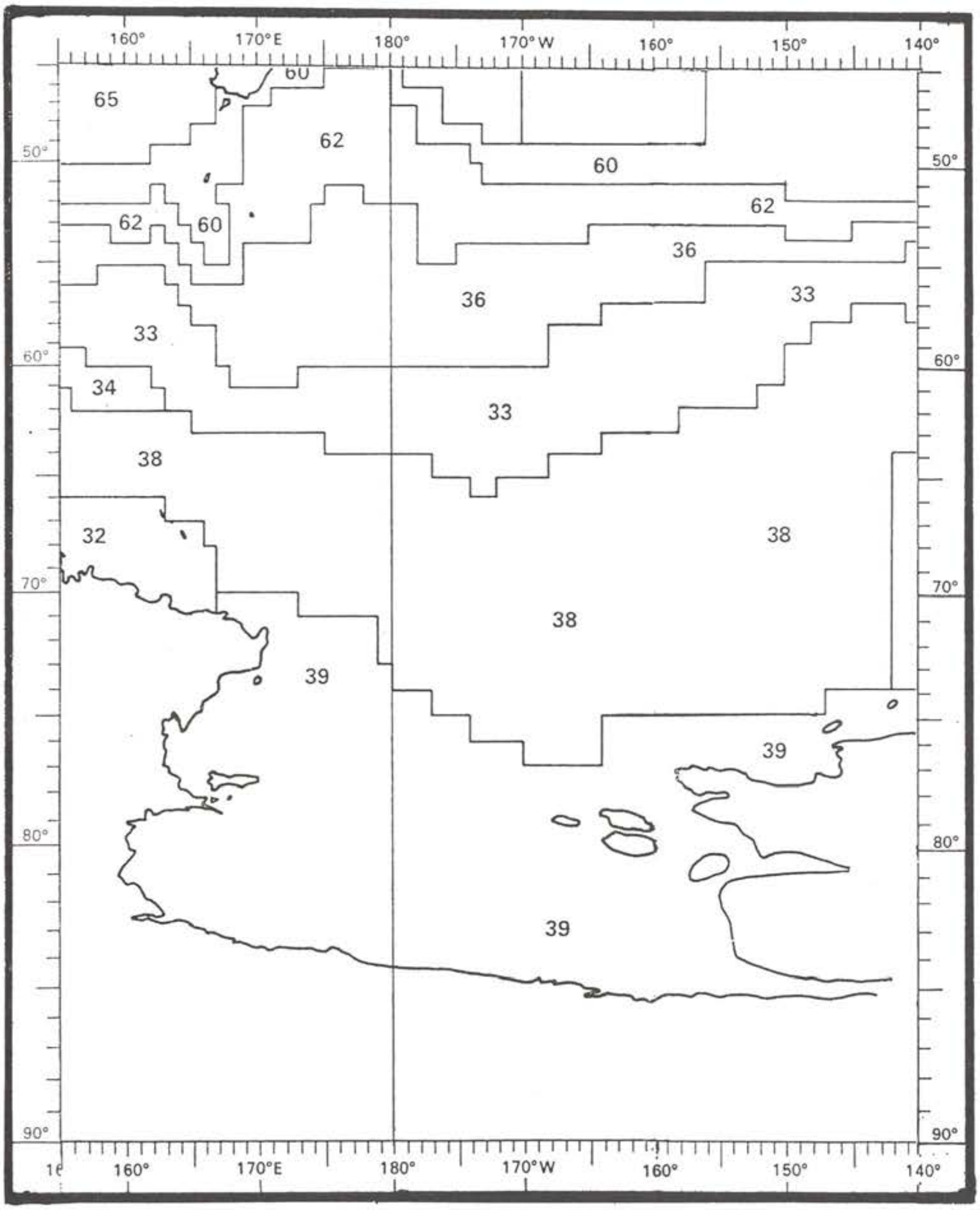

Fig. 3 - Boundaries of Carter's areas in Ross Sea and its environments.

velocity of 1500 m/s in order to account for actual velocity according to temperature and salinity are given in the tables edited by the Hydrographic Dept. UK (Carter, 1980, formerly Matthews, 1927), which cover all the oceans of the world and were recommended by and employed in the GEBCO charts.

When more oceanographic data for the Ross Sea are available, then new, possibly more accurate, corrections can be determined for this area. In the meantime, our data have been corrected according to Carter's tables from which, to simplify the computations, best-fit polynomial relationships were determined by means of least square approximations (residuals being within one meter) between observed (D_o) and corrected (D_c) depths, taken as absolute values.

Most of the area covered by the measurements considered in this paper is included in Carter's zone 39, while only the oceanic portion beyond the continental slope is in zone 38 (Fig. 3).

The conversion functions from observed (at 1500 m/s) to corrected depths may therefore be expressed as follows:

- zone 38:

$$D_c = +0.05 + 1.040235D_o - 2.449203E{-}5{-}D_o^2 + 1.592697E{-}8D_o^3 - 5.260440E{-}12D_o^4$$
$$+4.247543E{-}16D_o^5 + 1.258365E{-}19D_o^6 - 2.800149E{-}23D_o^7 + 1.591535E{-}27D_o^8$$

- zone 39:

$$D_c = +0.42 + 1.040144D_o - 1.183789E{-}6D_o^2 - 2.693007E{-}8D_o^3 + 2.600101E{-}11D_o^4$$
$$-1.125069E{-}14D_o^5 + 2.494195E{-}18D_o^6 - 2.793700E{-}22D_o^7 + 1.214320E{-}26D_o^8$$

The comparison of Carter's corrections for the zones 38 and 39 does not show large differences between the two zones: the greatest ones (up to 3 m) are present in the -400 to -1000 range, while for seas deeper than -1000, the differences are within ± 1 m. It is therefore questionable whether the subdivision into these two zones is really meaningful.

For comparison purposes only, new correction values have been determined from measured temperatures and salinities along the Victoria Land coasts and along the route to New Zealand (Fig. 4) by Italian observers. The provisional data used were simplified from those kindly communicated to us by G. Catalano. Great use was also made of the plots published by Artegiani et al. (1990), which give a generalized synthesis of the situation in the vicinity of Victoria Land and during the times when the Ross Sea is ice free. The velocity of sound in sea water as function of depth, and hence the corrections to the echo-sounder readings callibrated at 1500 m/s in order to get true depths, were computed by a specially devised program which receives in input the discrete pressure, temperature and salinity values logged at a station or averaged over a given area, and assumed representative for successive layers of seawater: this program interpolates at whatever chosen interval by computing the actual travel times according to the algorithms for the fundamental properties of seawater proposed as UNESCO/SCOR/ICES/IAPSO standards (Fofonoff and Millard, 1984).

These measurements were available for the Cape Adare area and at the Victoria Land latitude, taken during the ice breaking periods, but unfortunately not in other inner areas of the Ross Sea.

The assumed mean seawater parameters are shown by Fig. 5, and the computations gave the differences plotted in Fig. 6, and confirmed that the accuracy of Carter's corrections is satisfactory for the present needs, when only a general bathymetric picture is required. A better systematic determination of the thermosalinity distribution inside the Ross Sea area is however advisable to achieve a more accurate determination of the sound velocity in sea water, at least when more detailed surveys are being performed, especially in the areas where bottom circulation is present and where bottom topography is very uneven. It should be noted that Carter's tables are rounded to the meter and may not be smooth enough, a fact that may introduce rounding errors, as shown by the correlations of the differences in Fig. 6 (plots B,C,D), which indicate that the Italian data from relatively close locations are rather consistent. The different behaviour shown by the A,F and B,C,D groups puts into question the criteria adopted by Carter in the subdivision of his zones, since these differences are larger than those between Carter's zones 38 and 39 themselves.

GRAVITY DATA

The computation of observed gravity from the KSS31 gravimeter readings recorded at each shot point was done by applying the mean scale factor K=0.95319, determined from compari-

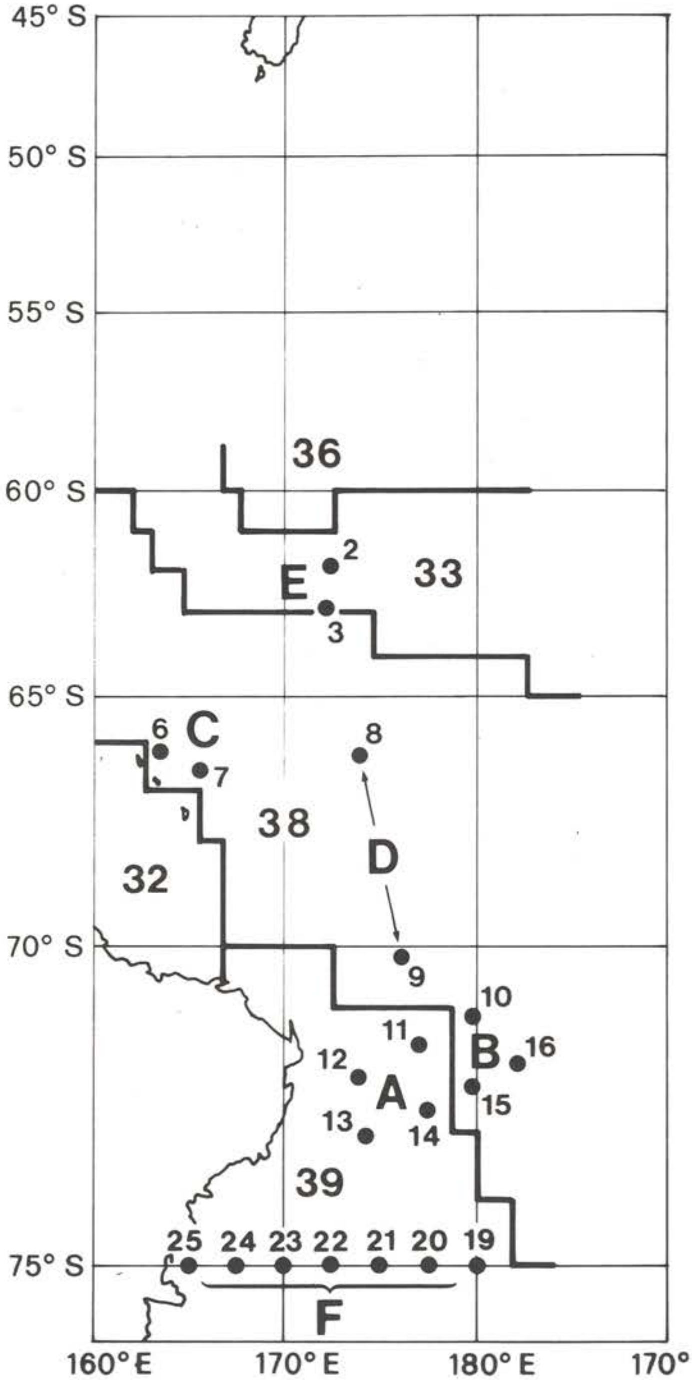

Fig. 4 - Location of temperature and salinity determinations (by the Italian expedition in 1989).

sons at the harbours (Gantar, 1993). The residual differences with the harbour base values were considered as linear drift and corrected as a function of time. Reference datum is given by the absolute gravity from connections to IGSN71 stations (Morelli et al., 1974).

The gravity values measured in motion were corrected for the Eoetvoes effect by means of the speed and course deduced from the successive positions of the ship, filtered to remove the rounding effects, and the free air anomalies were computed by comparison with the normal

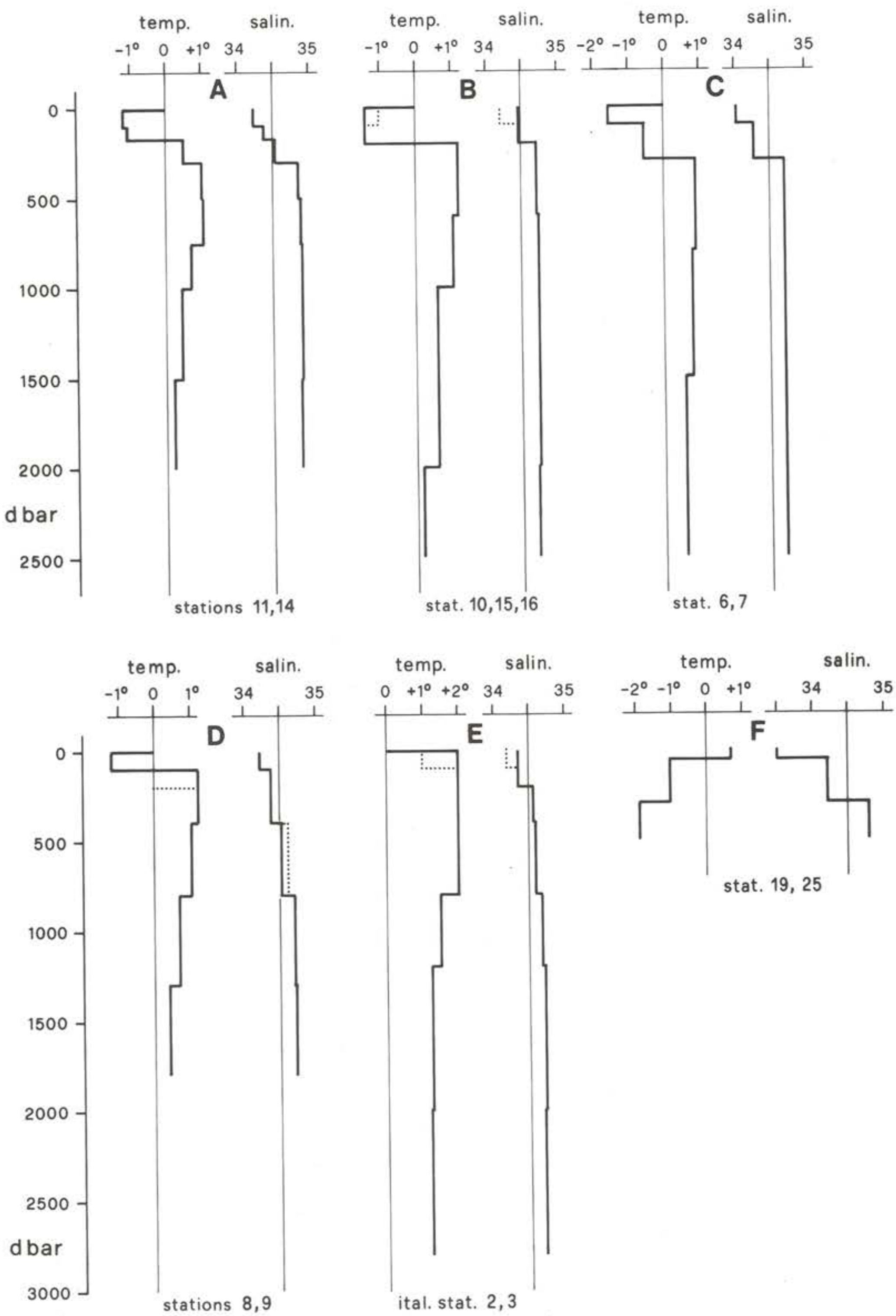

Fig. 5 - Temperature and salinity versus depth, averaged for successive layers from the Italian measurements located as in Fig. 4.

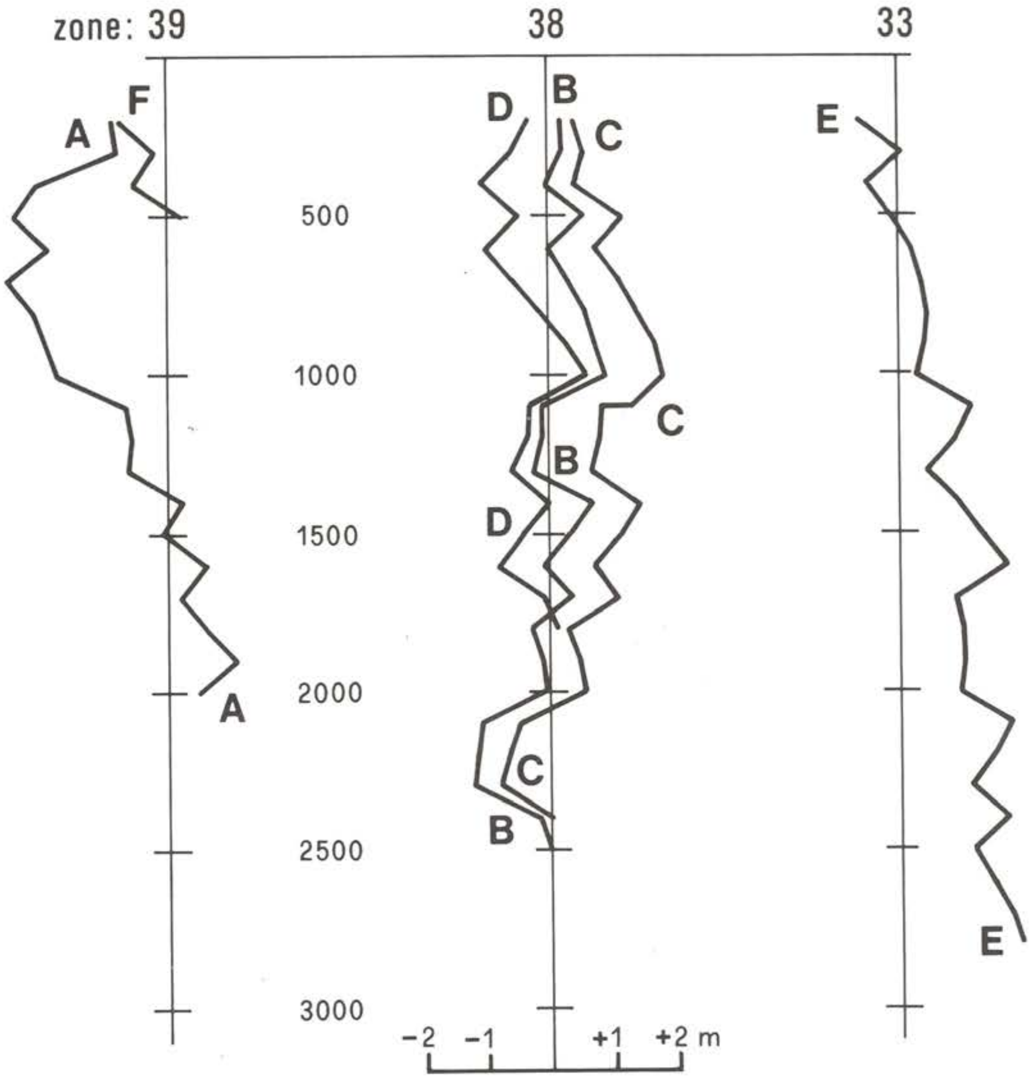

Fig. 6 - Comparison of the new computed sound velocity corrections (Carter's minus new ones).

gravity as given by Moritz (1980) with sufficient approximation to 0.1 mGal:

$$\tau_n = 978{,}032.68\ (1 + .0053024 \sin^2\phi - .0000058 \sin^2 2\phi)$$

MAGNETIC DATA

The measurements taken with the Geometrics G801 magnetometer were not corrected for diurnal variation, since the recordings made at Victoria Land base station do not cover all measurement periods. Moreover, this base site is rather far from the majority of the marine profiles, so that the recordings could be affected by unpredictable time lags with respect to the marine data, which therefore were reduced to anomalies by simply referring the observed data to the IGRF85. To illustrate the possible mean effect of the present time dependent variation, Fig. 7 shows the cumulative plot of the base station variations recorded in 1988 (16 days; Azzara, 1989, personal comunication): the marine measurements were taken after finishing the records at the land base.

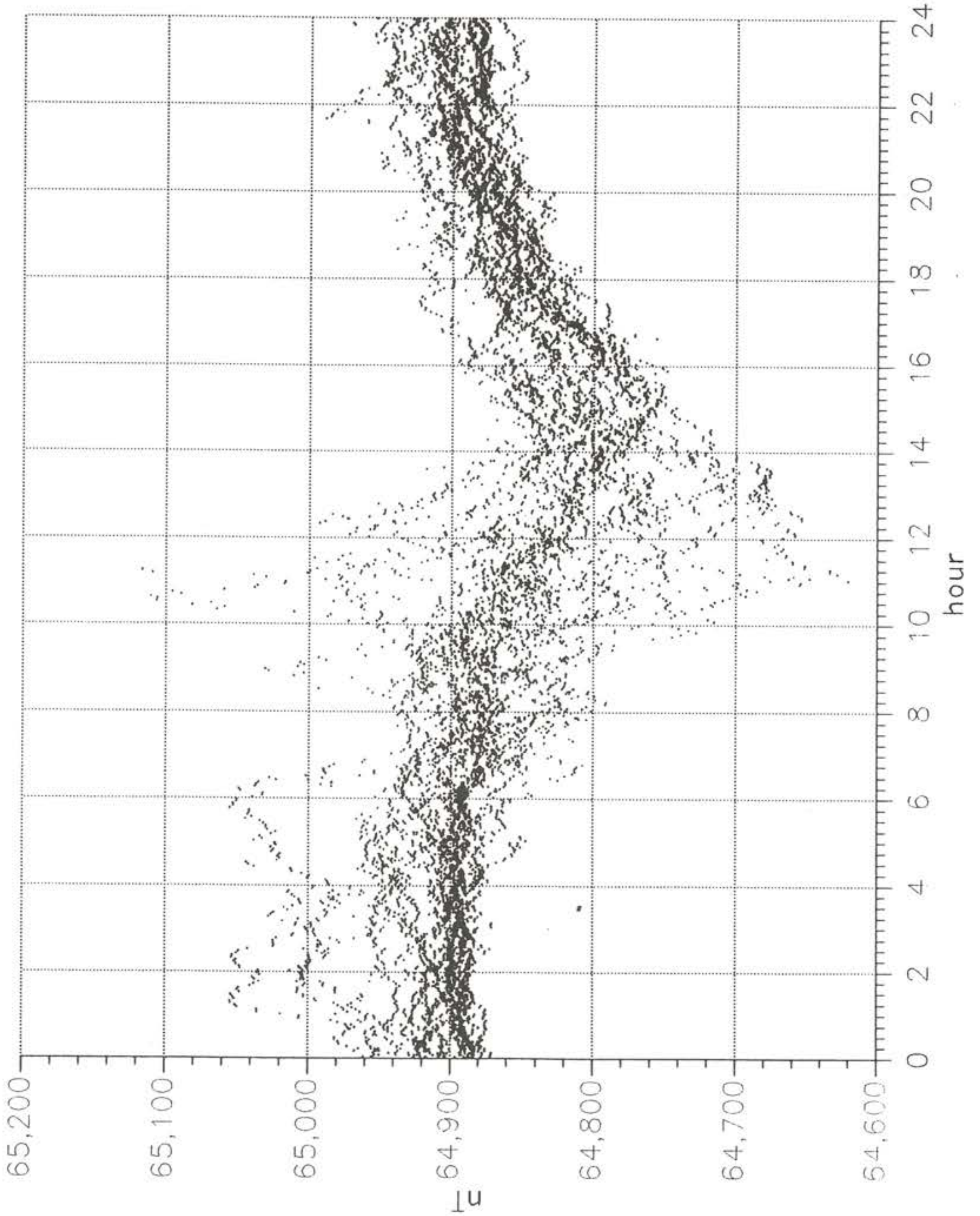

Fig. 7 - Cumulative time variations (from 1988 Terra Nova magnetic base station, 16 days of recording the total field).

The apparent anomalies introduced by neglecting the time dependent magnetic variations have wavelengths of more than 2000 shot points (and therefore over 100 km), and thus they do not interfere with the interpretation in terms of local intrusive or effusive events, unless significant short period variation are present.

SEISMIC DATA

When collecting data in hostile environments like the Antarctic seas, it is very advisable

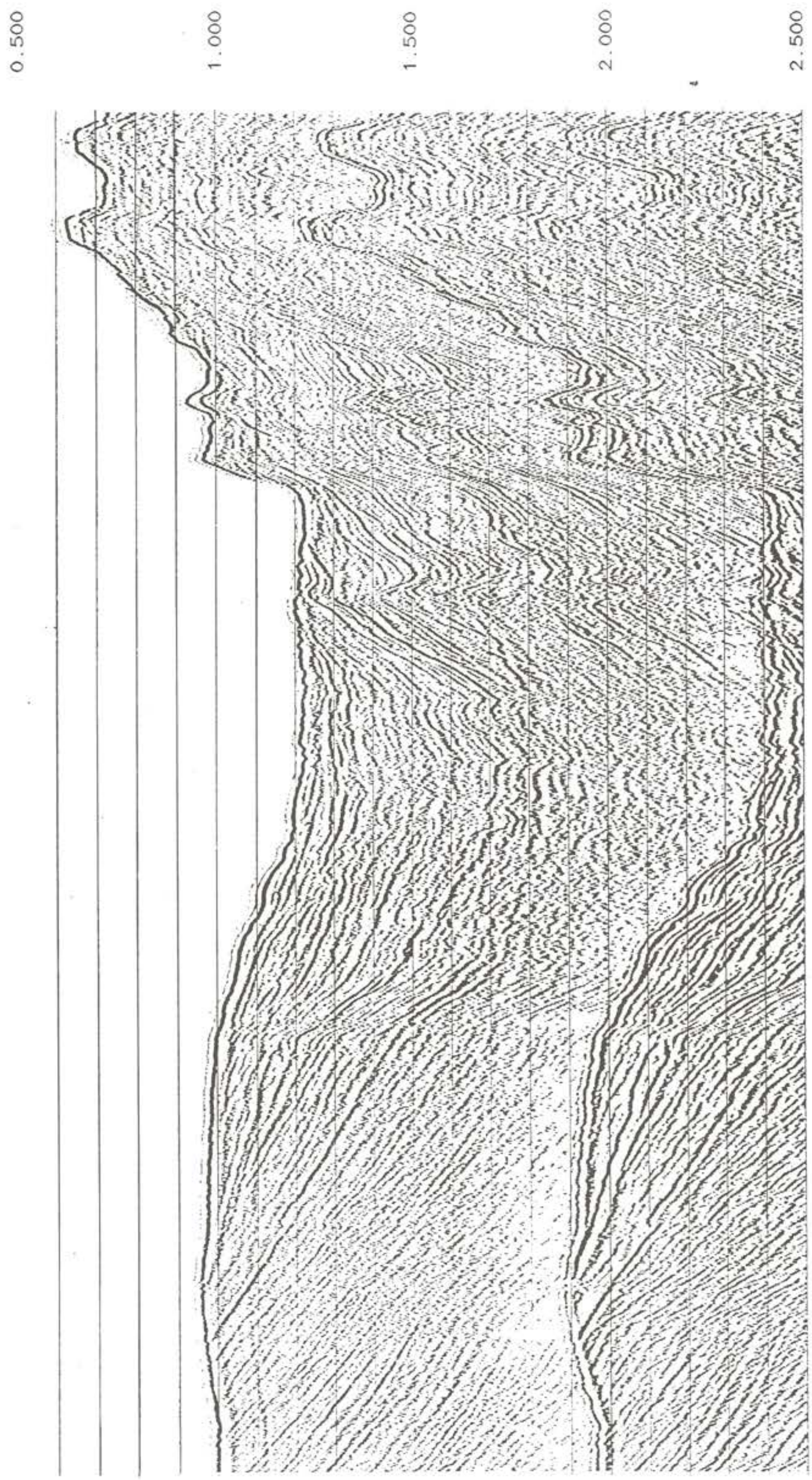

Fig. 8 - Very high definition near trace monitor used for shallow data display.

to record the largest possible amount of information with the greatest possible accuracy, since the cost of the magnetic tapes is negligible compared to the cost of the whole exploration. Thus we chose a 96-120 group streamer with a 25m group interval for recording the seismic data. The coverage was 1600-2400% in the first survey, 3000% in the second, and was increased to 6000% during the third due to the higher detail requested for that project, which was intended to survey some proposed drill sites. The sampling rate was 2 ms except for the second cruise when the recording was made at 4 ms due to the very long (16 s) seismic records.

Resampling and trace summing

The first step in the adopted processing sequence was to resample the data to 4 ms, because the main target was of regional size and resampling allowed a reduction in processing time and cost. For the same reason, a two adjacent trace summation was performed.

The preliminary tests showed that resampling, after anti-alias filter, leaves the frequency content of the seismic signal practically unchanged. Trace summation, on the contrary, shifts the spectrum towards the lower frequencies, especially for the shallower data (where moveout is greater).

The adopted procedure was therefore a compromise: trace summation was done to enhance deep events even though it reduces the definition of the shallow signals, and for focusing on the shallower data (Fig. 8), near trace sections were given to the interpreters, since they contain the very best detail for signals above the first multiple. We produced therefore near trace sections to 3 s with gain recovery, spike deconvolution, time variant filter and balance.

For the data of the third cruise, the above sequence was also applied, but with the addition of a differential moveout to the traces before summation. The program applies the normal moveout (NMO) correction for the mean offset of the two traces to both of them, adds the traces together and then removes the NMO. The only problem is to know the velocity function for computing the NMO. Velocity analysis is not possible since the operation takes place before sorting, but we can take into account the following points:

- differential moveout does not require great accuracy in the applied velocity function, as the moveout error is of the order of a few ms even if the velocity varies more than 500 m/s between the traces;
- moveout error is almost constant at a given time for different velocities;
- moveout error decreases as time increases at a given velocity;
- NMO stretching is close to zero for very near traces and therefore the frequency content changes very little after addition;
- the main factor affecting propagation velocity is water depth;
- previous experience on land data with array simulation and beam steering gave excellent results even when a single velocity function was used for the whole survey.

In our case, we had the velocity functions from the first two cruises in the Ross Sea and we could build a table of mean velocities from 250 to 3000 ms at two way time intervals of 250 ms (see Table).

We obtained good results even when we intentionally introduced gross inaccuracies to test the robustness of the method, and we intend to use this technique in the future for processing sequences requiring trace summation (Fig. 9).

Gain recovery

Amplitude decay due to spherical divergence and absorption must be recovered with a gain function. We used the following funtion:

$$gain_{dB} = 2.5\ t + 20 \log_{10} t$$

Furthermore, all traces were scaled to the same mean square amplitude.

Table - Velocity-time pairs used for differential NMO correction in the summing of two adjacent traces, Ross Sea.

	WATER BOTTOM 250 msec
V/T	1470/0.000 1510/0.250 1780/0.500 1880/0.750 2200/1.000 3100/1.500
	3350/2.000 3670/3.000 4000/4.000 4150/5.000 4500/6.000 4800/7.000
	WATER BOTTOM 500 msec
V/T	1470/0.000 1510/0.500 1750/1.000 2250/1.500 3000/2.000 3350/2.500
	3600/3.000 3750/3.500 3920/4.000 4200/5.000 4450/6.000 4700/7.000
	WATER BOTTOM 750 msec
V/T	1470/0.000 1510/0.750 1580/1.000 1950/1.500 2650/2.000 3150/2.500
	3450/3.000 3650/3.500 3800/4.000 4100/5.000 4350/6.000 4600/7.000
	WATER BOTTOM 1000 msec
V/T	1470/0.000 1510/1.000 1620/1.250 1750/1.500 2250/2.000 2750/2.500
	3050/3.000 3300/3.500 3450/4.000 4750/5.000 4000/6.000 4200/7.000
	WATER BOTTOM 1250 msec
V/T	1470/0.000 1510/1.250 1560/1.500 1800/2.000 2300/2.500 2650/3.000
	2870/3.500 3050/4.000 3170/4.500 3260/5.000 3450/6.000 3600/7.000
	WATER BOTTOM 1500 msec
V/T	1470/0.000 1510/1.500 1530/1.750 1580/2.000 1670/2.250 1800/2.500
	2300/3.000 2600/3.500 2750/4.000 2950/5.000 3100/6.000 3250/7.000
	WATER BOTTOM 1750 msec
V/T	1470/0.000 1510/1.750 1530/2.000 1560/2.250 1600/2.500 1670/2.750
	1860/3.000 2270/3.500 2570/4.000 2780/5.000 2950/6.000 3050/7.000
	WATER BOTTOM 2000 msec
V/T	1470/0.000 1510/2.000 1530/2.250 1540/2.500 1570/2.750 1600/3.000
	1700/3.250 1900/3.500 2300/4.000 2650/5.000 2770/6.000 2900/7.000
	WATER BOTTOM 2250 msec
V/T	1470/0.000 1510/2.250 1520/2.500 1530/2.750 1550/3.000 1590/3.250
	1670/3.500 1970/4.000 2220/4.500 2340/5.000 2500/6.000 2650/7.000
	WATER BOTTOM 2500 msec
V/T	1470/0.000 1510/2.500 1520/2.750 1530/3.000 1540/3.250 1580/3.500
	1670/3.750 1780/4.000 2050/4.500 2180/5.000 2340/6.000 2470/7.000
	WATER BOTTOM 2750 msec
V/T	1470/0.000 1510/2.750 1520/3.000 1525/3.250 1535/3.500 1570/3.750
	1650/4.000 1850/4.500 2010/5.000 2120/5.500 2190/6.000 2330/7.000

Quality control

Quality control was done on the first trace of every shot (near trace monitor) and on every sixtieth entire record (Fig. 10).

This check detects "dead" or noisy traces which must be rejected and allows an evaluation of the signal's overall quality and the seismic response of the surveyed area.

Sort and deconvolution before stack

After reordering into common depth points, a predictive deconvolution was applied using

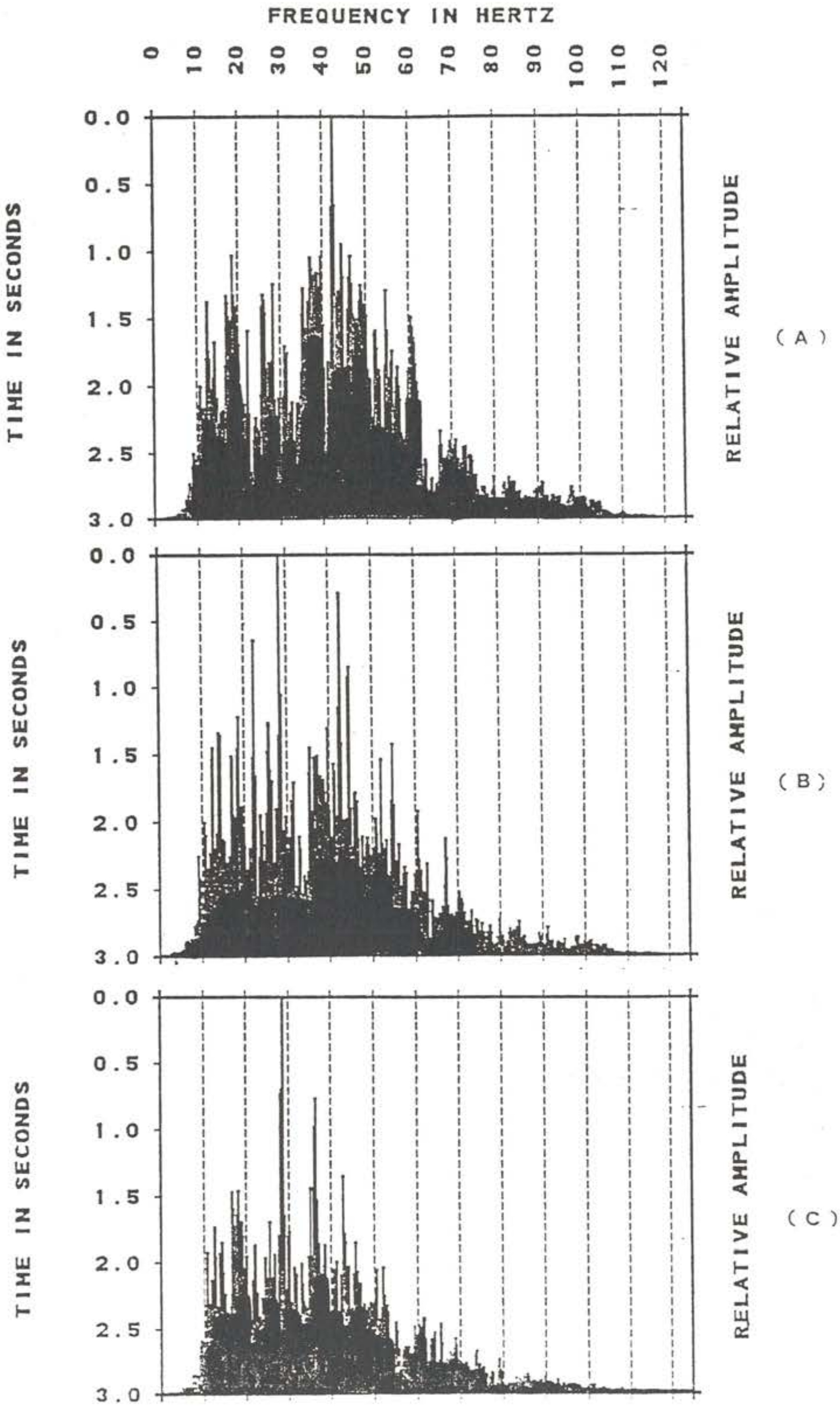

Fig. 9 - Frequency domain spectrum of field trace: a) unsummed trace; b) trace summed with differential NMO; c) idem without differential NMO.

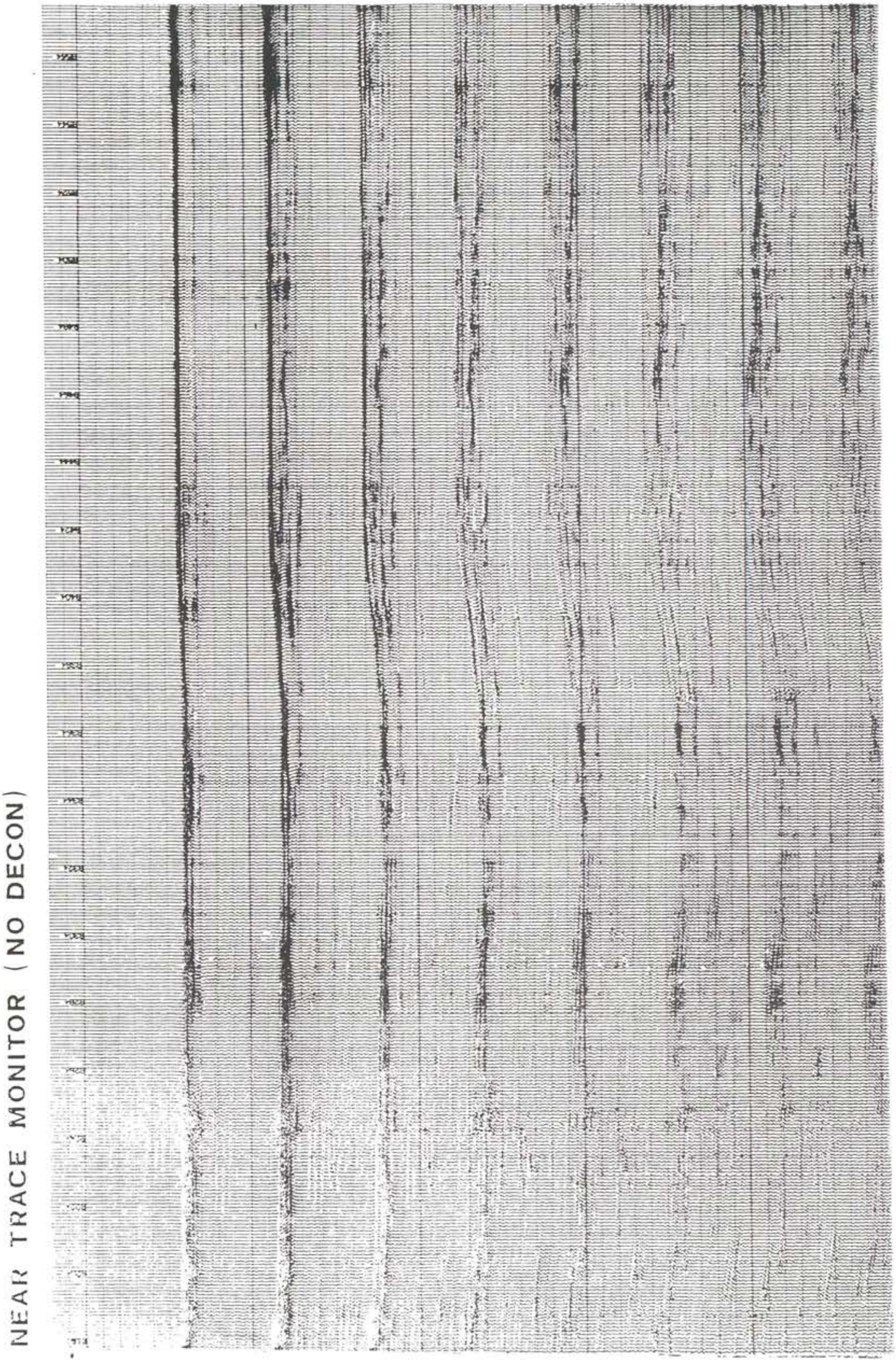

Fig. 10a - Quality controls from near trace monitor.

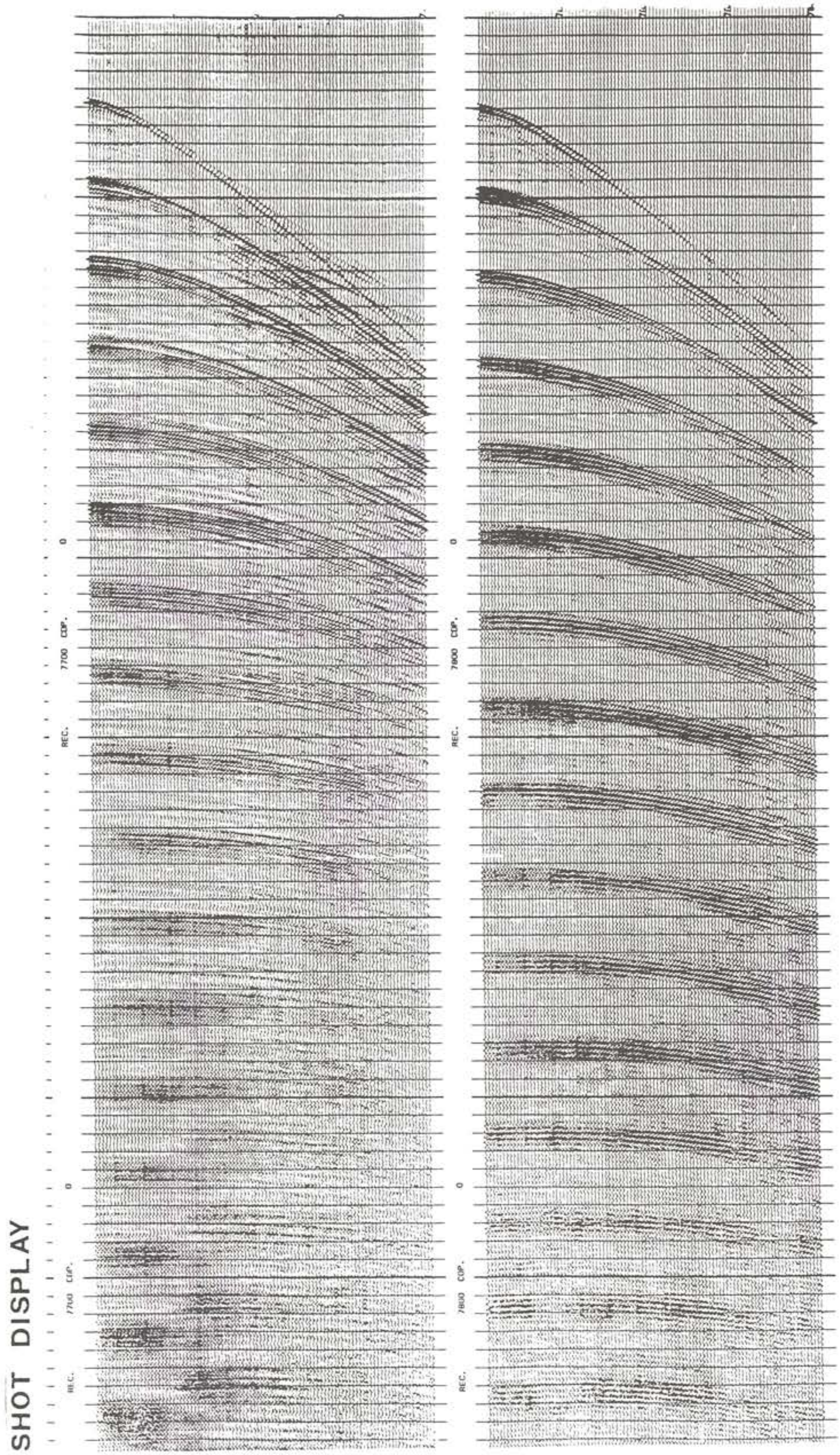

Fig. 10b - Quality controls from shot monitor.

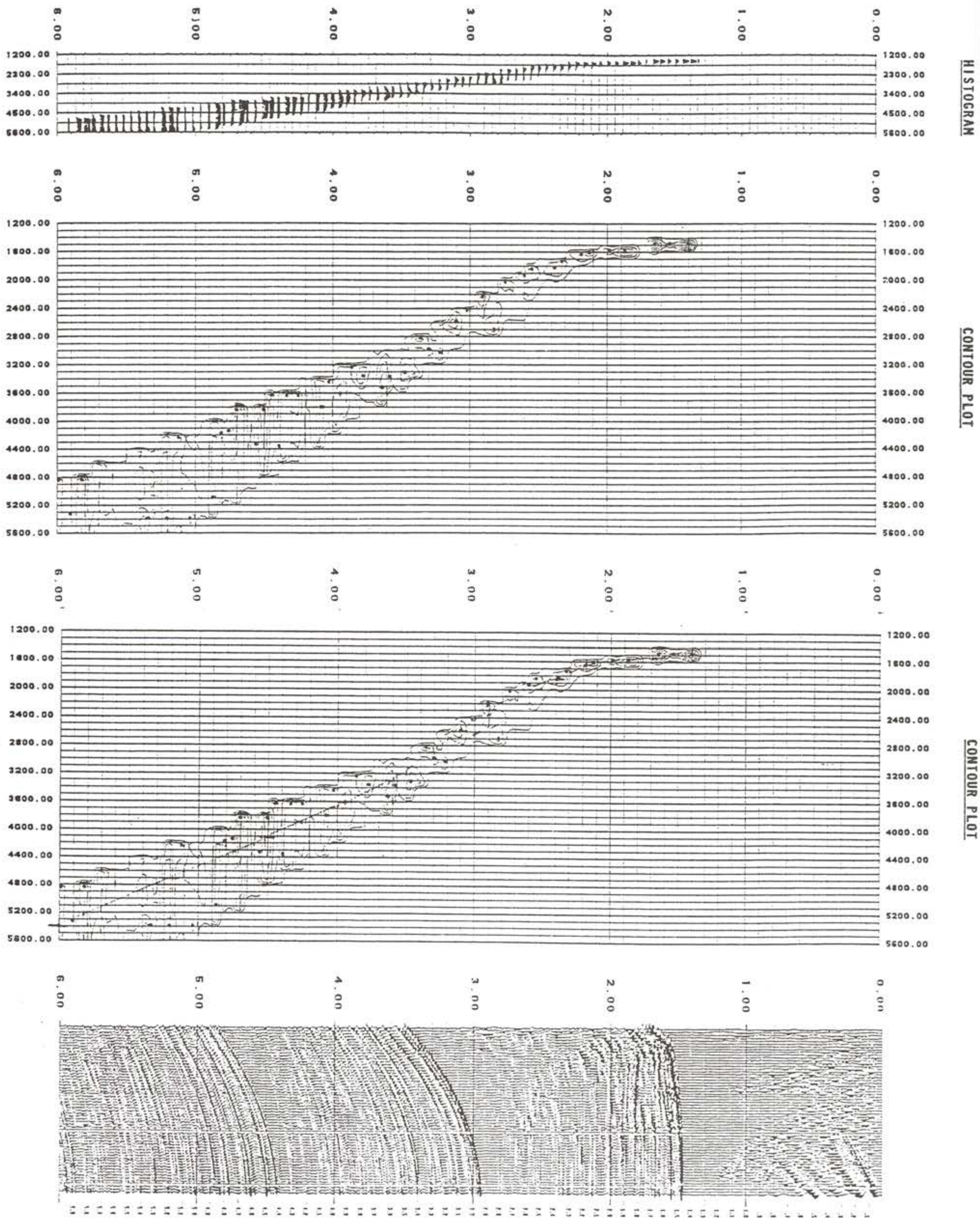

Fig. 11 - Velocity histogram and velocity function control on gather.

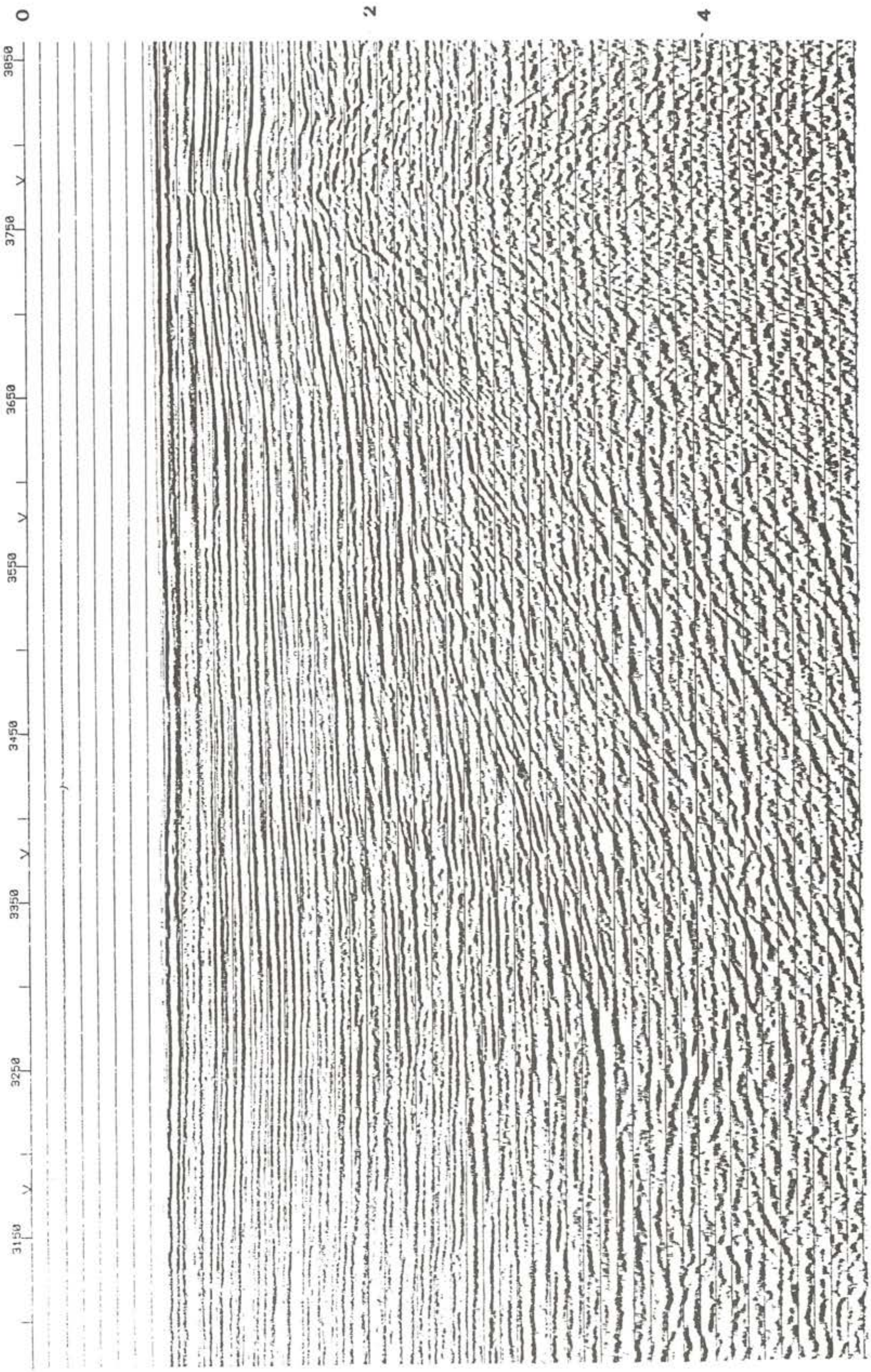

Fig. 12 - Example of Ross Sea line obtained using a weighted stack.

a 280 ms operator, with 8 ms prediction distance and 2% white noise added to the autocorrelation function. This operator was applied over two fixed length overlapping windows which automatically follow the sea bottom. Thus a partial reduction of the sea bottom multiples was obtained.

Velocity analysis

The main obstacle in velocity analysis is the very strong and numerous multiples which characterize the Ross Sea area. It is well known that within a seismic record the traces nearest to the shot, i.e., those with minimum moveout, do not give good discrimination between primary events and multiples, while traces with large offset have maximum moveout and yield an effective separation between them. To achieve the best results, we weighted the traces in proportion to their offset from the shot point (10% for trace 1 to 100% for trace 60), and applied an F-K filter (Fig. 11).

The next step was a quality control by application of the chosen velocity functions to common distance gathers. This operation is not very expensive in overall economy and allows both a verification of the accuracy of the function and any necessary trim in the range of some tens of m/s. A check of the interval velocities provides a final confirmation of the accuracy of the velocity functions, even at relatively large time values.

Multiples

Different procedures were applied in the processing of the data collected during the various cruises to tackle the problem of multiple reflections. Initially, we used a predictive deconvolution before stack, and a deconvolution after stack (DAS) which followed the sea bottom, with results which seemed good at that time (Yilmaz, 1987). Later tests suggested muting the traces nearest to the shot starting from just above the first multiple. The improvement was noticeable, but the method was difficult to apply in low coverage areas. Moreover, the reduction in near traces was harmful to the DAS, since it broke the periodicity of the multiples.

Finally, we adopted for the stack the same weight criterion that we had already used succesfully in the velocity analysis. The results obtained were good for a minimal increase in the processing time (Fig. 12) (Dadisman et al., 1990; Larter et al., 1990; Hardy and Hobbs, 1991). Moreover, trace summing respects better the periodicity of multiples and allows the use of a DAS with increased efficiency, even though in this case mute windows must be chosen with greater attention since we noticed spurious signal enhancements when using linear weights and non-linear (i.e. dog leg) mutes.

Time variant filter

From an analysis of the time variant filter scans, it was seen that the high frequency content near the sea bottom was spread with the multiples over the rest of the record. With the aim of revealing any deep primary events (which are usually characterized by low frequencies), the final filters were chosen to enhance the low frequencies.

Trace mix

The possibility of enhancing deep, sub-horizontal, low-frequency signals and the need for rejecting steeply dipping high frequency noise which was an obvious residual of multiple events suggested the use of a horizontal trace mix using three traces and two non-overlapping windows. The first window of one second length started at the first multiple and used weights of 5-100-5 percent, while the second window started just below the first with weights of 50-100-50 percent.

This technique enhanced the signal-to-noise ratio and the continuity of the horizons.

CONCLUSIONS

The acquisition and processing of different kinds of geophysical data carried out by OGS during the austral summers 1987-88, 1988-89, 1989-90 allowed an integrated study of the Ross Sea area (see other articles in this issue). In fact, it is known that some geologic features (such as volcanoes and diapirs) can be best identified only by following a multidisciplinary approach.

. A description of the standard processing steps in the seismic data was also discussed, paying particular attention to the water bottom multiple removal.

REFERENCES

Artegiani A., Azzolini R., Creazzo S., Paschini E. e Triggiani N.; 1990: *Oceanografia fisica.* In: Casazza G., Cervellati R. e Ramorino M.C.(eds) PNRA; *Rapporto sulla campagna antartica Estate Australe 1989-90*, PROGETTO ANTARTIDE, ANT 90/1 Rev.1, pp. 208-212.

Berger P., Fanzutti F., Gantar C., Marchetti A., Nieto D. and Persoglia S.; 1993: *Equipment data acquisition techniques employed by the Italian geophysical exploration in Antarctica performed by OGS - Cruises 1987-88, 88-89 and 89-90.* Boll. Geof. Teor. Appl., **35**, 299-323.

Carter D.J.T.; 1980: *Echo-sounding correction tables.* NP139, 3rd ed., Hydrogr. Dept., Min. of Defence, Taunton, 150 pp.

Dadisman S.V., Ryan H.F. and Mann D.M.; 1987: *Recording and processing procedures for multichannel seismic reflection data collected in the Western Ross Sea, Antarctica.* In: Cooper A.K. and Davey F.J., (eds); *The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea.* Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v.5B, pp. 17-26.

Fofonoff N.P. and Millard R.C. Jr.; 1983: *Algorithms for computation of fundamental properties of seawaters.* UNESCO Techn. Pap. in Mar. Sci., 44, 53 pp.

Gantar C.; 1993: *OGS maps for South circumpolar areas.* Boll. Geof. Teor. Appl., **35**, 291-298.

Hardy R.J.J. and Hobbs R.W.; 1991: *A strategy for multiple suppression.* First Break, **9**, 138-144.

Larter R.D., Cunningham A.P. and Hardy R.J.J.; 1990: *A sea floor multiple problem in multichannel seismic reflection data acquired on the Antarctic continental shelf: its causes and treatment.* In: Cooper A.K. and Webb P.M. (eds): Overview and Extended Abstracts. Int.Workshop on Antarctic Offshore Acoustic Stratigraphy (ANTOSTRAT). USGS Open File Rep. 90-309, pp. 187-194.

Matthews D.J.; 1927: *Tables of the Velocity of Sound in Pure Water and Sea Water for use in Echo-sounding and Sound-ranging.* HD282, first edition, 30 pp.

Moritz H.; 1980: *Geodetic Reference System 1980.* In: Mueller I.I. (ed): The Geodesist's Handbook 1980. IUGG-AIG, Bull. Geod., **54**, pp. 395-405.

Yilmaz O.; 1987: *Seismic Data Processing.* SEG, Tulsa, 526 pp.

Yilmaz O.; 1989: *Velocity-stack processing.* Geoph. Prosp., **37**, 357-382.