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Planning, acquisition and processing of the CROP seismic data: a few comments

Progettazione, acquisizione ed elaborazione dei dati sismici CROP: alcuni commenti

BERTELLI L. ([1]), MAZZOTTI A. ([2]), PERSOGLIA S. ([3])

Abstract - The procedure adopted for the field acquisition and processing of the CROP seismic reflection data is described briefly, including the criteria followed for both the marine surveys and the land profiles during the planning phases, and the relevant acquisition parameters and processing sequences. In the planning phases, the choice of profile path, energy source and source locations (for land acquisition), had the greatest impact on the final results. In the field acquisition phase, the performance of regular tests, the development of accurate QC procedures and, especially in the latest acquisitions, the timely update of the acquisition parameters to respond to changed surface and/or geological conditions, allowed the project to acquire seismic data that are as close as possible to the optimal parameters, within the available budget, and to obtain seismic data of a generally satisfactory quality. The criterion followed during the processing of the huge quantities of data was always to avoid overly complicated processing sequences, and to limit them to the time domain, so as to achieve interpretable seismic sections in the structural and geometric sense. The profile shown in this Atlas were not subjected to any complicated "lithologic" processing, directed at correlating the amplitudes and phases of the reflected signals directly with lithological or petrophysical features.

KeyWords: CROP Project, seismic data, acquisition, processing.

Riassunto - Descriviamo brevemente l'evoluzione delle modalità di acquisizione e di elaborazione numerica dei dati sismici a riflessione del Progetto CROP e illustriamo, sia per i dati marini sia per quelli terrestri, i criteri che hanno guidato la progettazione, l'acquisizione e l'elaborazione. Per ciò che riguarda la fase di pianificazione, fra i vari parametri da selezionare, la scelta del percorso del profilo, il tipo di sorgente di energia, l'ubicazione delle locazioni di energizzazione (per le linee a terra) sono stati quelli che hanno prodotto un maggiore impatto sul risultato finale. Nella fase di acquisizione dei dati in campagna, la realizzazione di test accurati, la messa a punto di procedure di controllo di qualità e, in special modo per le acquisizioni più recenti, l'aggiornamento in corso d'opera dei parametri in risposta a variate condizioni superficiali e/o geologiche, hanno consentito la registrazione di dati sismici generalmente di buona qualità nei limiti del budget disponibile.

La successiva elaborazione della grande mole di dati ha sempre seguito il criterio di applicare sequenze di elaborazione non eccessivamente complicate, esclusivamente in dominio tempi, e mirate all'ottenimento di sezioni sismiche interpretabili essenzialmente in chiave geometrica e strutturale. Nessun tipo di elaborazione sofisticata, tesa alla realizzazione di immagini con indicatori petrofisici o litologici è stata applicata ai profili che sono contenuti in questo atlante.

Parole Chiave: Progetto CROP, sismica a riflessione, acquisizione, elaborazione

([1]) Novak AGIP A/S, Travbaneveien 3, P.O. Box 101, Forus, N - 4064 Stavanger, Naway.
([2]) Dipartimento di Scienze della Terra – Sezione geofisica, Università degli Studi di Milano, Via Cicognara 7 - 20129 Milano, Italy.
([3]) Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - OGS, Borgo Grotta Gigante 42/c - 34010 Sgonico (Trieste), Italy.

1. – INTRODUCTION

Italy and the Mediterranean area in general are characterised by highly complex and heterogeneous geological settings. As a consequence of the extremely variable geological characteristics of the areas interested by the profiles of the CROP Project, the acquisition parameters and the field acquisition and processing phases assumed a fundamental role. As a general rule the seismic techniques applied in oil and geothermal exploration can also be used to investigate deep crustal targets, but the objectives of deep crust exploration by seismic NVR techniques are such as to require specific solutions. The early stages of the project obviously included an extensive study of reports on previous projects in the United States and Europe.

Among the objectives of the CROP Project was the acquisition of about 8740 km of marine profiles in shallow and deep waters around the Italian peninsula, in both compressional and extensional structural domains, and in the presence of sea floors of variable morphology and acoustic characteristics. The project also included about 1250 km of on-shore profiles across the Apennine and Alpine orogenes and several vast alluvial plains. Again, some very different problems had to be faced, from the presence of shallow or outcropping volcanic rocks that limit the transmission of seismic waves, to the abrupt lateral succession, often within the same spread-length, of "high-velocity" and "low-velocity" outcropping lithologies that caused problems in the computation of field static corrections.

The wide variety of characteristics of the areas under study, the many logistic and environmental problems and the obvious budget limitations, led to the creation of a permanent team of specialists responsible for planning, implementing and monitoring all the seismic operations. This team (CROP Acquisition and Processing Group), composed of members of the sponsoring institutions, had to plan, steer and optimise the seismic operations, and at the same time, keep within the available budget. The authors of this paper are the former (A.M.) and current (L.B.) co-ordinators of this team, and the project leader (S.P.) of the national research institute that acquired the majority of the seismic data of the CROP Project.

After presenting the main criteria adopted in the data acquisition processing phases, we then discuss separately the planning, acquisition and processing of the land and marine seismic profiles. More detailed descriptions can be found in the references cited in the introductory notes to the profiles.

2. – ON-SHORE CROP-PROFILES. PLANNING, ACQUISITION AND PROCESSING STRATEGIES.

After the planning and acquisition of the first profiles, in cooperation with ECORS-CROP (France) and NFP-CROP (Suisse) and with the support on the Italian side of CNR only, the Italian joint venture CNR-AGIP-ENEL became operational in 1989, with the acquisition of the CROP 04 profile crossing the Southern Apennine Chain. From then on, the seismic data acquisition and processing phases have been planned well ahead of the actual field operations. Very fruitful collaboration developed with the geologists and the geophysicists responsible for the subsequent data interpretation and other scientific activities and with their work groups. This enabled us to plan acquisition and processing strategies on the basis of both geological and geophysical criteria, and consequently to define profile locations, acquisition parameters and processing sequences that are an optimum compromise between geological needs and objectives, and geophysical requirements.

One area of crucial importance, where this cooperation has been most effective, was in the choice of location of the field profile. Althought the grid of lines and each single profile follow criteria of structural geology and geodynamics, the actual location of the seismic line in the field was defined on the basis of geophysical factors. This has often meant that the location of the profile had to be shifted many kilometres from its original site. Another important field of interaction was in the definition of an optimal stacking and/or migration velocity field in the processing phase. The combined input of geological information available a priori and the various tools of velocity analysis played a significant part in our achieving such satisfactory results, especially in the most difficult areas.

As a general rule, these were the steps followed in the preparation of a profile. All the available geological and geophysical data, and any other information on the areas interested by the profile, were collected and studied. These include previous seismic lines, well logs, geological surveys and interpretations.On the basis of this information, a field acquisition strategy was drawn up, in which we defined the main acquisition parameters, such as energy source, spread characteristics and coverage. Wherever possible, the pre-established field parameters were tested in suitable test sites along the profile. All the land profiles (CROP 04, CROP 03, CROP 18, CROP 11, CROP 01/TRANSALP) were subjected to a preliminary detailed scouting in the field to determine the optimal path of the seismic line, to identify the difficult areas and the location of expanding spread and large offset experiments or any other specific test that might be needed. In some cases, the acquisition parameters were also tested by applying ray tracing and seismic modelling techniques to existing deep geological models in the computing centres.

The results of these preliminary geological and geophysical studies have been published in a number of special issues of local scientific journals. The relevant references can be found in the description notes of each profile.

During the actual field acquisition, adequate quality control procedures were systematically applied. A first, quick processing in the field was carried out for all the profiles up to the production of a preliminary stack section. The day-by-day quality control of the field records meant that we could modify our technique as necessary. The bore-hole depths and explosive weights were frequently adjusted in this way, as were the Vibroseis energy parameters. The sponsoring institutions, and AGIP in particular, provided expert field supervisors who monitored all the operations both in terms of data quality and time/cost issues. In the case of the land profiles, they often had the unenviable task of helping the head of the seismic team in his contacts with the local authorities. The innumerable permits that have to be obtained from the central and local authorities are time-consuming, so this job had to be started soon after scouting in the field. Because of the significant quantities of dynamite used for each shot, considerable care was taken in contacts with land owners and local authorities, especially in critical locations such as natural parks, densely populated areas, and areas with archaeological remains such as Etruscan tombs, historical sites and monuments.

In the seismic processing phase, different sequences have been applied to the various profiles as a function of their different characteristics and problems. In general, the objective was to apply optimal, industry standard, sequences of processing operations to remove the (often large) noise components and to provide the interpreters with fair-to-good seismic sections, and all within the time and cost limits of the CROP Project. A major problem due to the presence of significant noise, especially at high recording times, was the possibility of creating artefacts or false events during processing operations. In order to limit this extremely undesirable effect, we either avoided any operations aimed at enhancing of the lateral continuity of the data, or applied with a very careful setting of the processing parameters and checked the results for the presence of possible artefacts. Operations such as "pre-stack dip scan", "lateral coherency enhancement", "radial predictive filter", "coherency stack" and others are therefore not common in our processing sequences. All the multi-channel pre-stack or post-stack operations, from "F-K filtering" to "time migration", were also applied to the data with special care.

All the processing sequences, both for the marine and land data, were focused on the production of the best stack section and, in some cases, time-migrated sections possible, but in a time and cost-effective way. Our aim was always to obtain the best possible indications about the geometry and morphology of the buried structures and not to derive reliable indications about the lithological/petrophysical properties of the reflectors. Thus, the issues of true amplitude preservation and wavelet processing have generally not been addressed. Phase and amplitudes were instead processed by standard robust statistical methods.

The following tables (Tables 1a and 1b) summarise the operative parameters applied in the acquisition of the various deep crust profiles of the CROP Project.

The energy source in both the Western and Central Alps was a fleet of 5 vibrators, essentially because of the difficulty in using large drilling devices n the narrow mountain valleys. Actually, dynamite was also used to produce very low coverage seismic sections along the profiles, which were processed by means of the velocity fields derived from the profiles energised with the vibrators, and mainly used as a reference for the very deep reflectors. An explosive source was also used to highlight reflectors along the borders between Italy, France and Switzerland. In the case of Italy, two seismic recording systems (one master and one slave) and a radio link were used for the co-ordinated shots and recordings along the two sides of the border at high altitude. Because of problems in radio communication between the seismic systems, pre-synchronised clocks were used on the French/Italian border.

The CROP 04 profile was also acquired using truck-mounted vibrators and an explosive source to produce a secondary, low-coverage control section. This was the first deep crust reflection profile to be acquired in the Apennines, and was performed with an acquisition configuration derived from previous CROP Projects in the Alps. The number of channels was increased from 120 to 240, thus doubling the coverage to 120, and the station interval was kept at 80 m.

The results obtained in this survey (see specific note in this Atlas) demonstrated that the station interval was too large, the Vibroseis energy produced was not satisfactory and the very long spread characteristics (more than 19 km for the active part) were not worth using and were also too expensive. Consequently, the on-shore profile CROP 03 was acquired using an explosive source, 192 active chan-

Table 1a – *CROP On-shore profiles (vibrators source).*
– Profili CROP a terra (sorgente vibroseis).

Year - profile/s		**1986 CROP-ECORS Western Alps**	**1988 CROP Central Alps**	**1989-90 CROP 04 Southern Appennines**	**1998-2000 CROP 01 (part of TRANSALP)**
N° of n. profiles		1	2	1	1
Area (from - to)		Valle dell'Orco (Serrù Lake – S.Giorgio Canavese)	Spluga Pass - Colico and S.Marco Pass -Zogno	Southern Appennines (Acropoli-Barletta)	Eastern Alps (Italian part of the Munich –Treviso profile)
Total length	Km	65	51	172	300
N° of active channels		120	120	240	360
Stations interval	M	80	80	80	50
Coverage		60	60	120	120-90
N°of vibrators		5	5	5	4-5
Vertical stacking		8	8	12	8
Sweep length	Sec	50	50	40	28-36
Frequency (from - to)	Hz	10-40	10-40	8-40	8-60
Recording time	Sec	25	32	20-25	18-20
Shot interval	M	2.400	4.800	2.400	4.500
Dynamite charge	Kg	50 – 75	50 – 200	100	90
Coverage		2	1	4	2
Note					Seismic data were also acquired along fixed transects orthogonal to the main seismic profile. Each of those consisted of 240 active seismic stations, at 80 m spaced-spacings.
Main Contractor		**O.G.S.**	**O.G.S.**	**O.G.S.**	**Geoitalia, THOR**

nels and a station interval reduced to 60 m. The maximum accepted lateral offset of the shot stations was reduced with respect to the CROP 04 profile and the continuous control of data quality further improved. These changes provided better results and again demonstrated the importance of detailed planning prior to the acquisition survey and of extensive real-time quality control.

The positive results obtained with the CROP 03 profile also provided valuable information for determining the parameters of CROP 18 profile, shot in 1995 in the Southern Central Tuscany and crossing the most important geothermal area of the Italian peninsula. CROP 18 was acquired in two separate transects (CROP 18/a and CROP 18/b) utilising the same basic recording parameters of the CROP 03 profile. Two wide-angle expanding-spread experiments were also performed, with a maximum spread length of 42 and 45 Km, respectively, providing as good quality data as the main NVR profile.

The concepts adopted in planning the CROP 03 and CROP 18 profiles were also taken into account during the preparation and execution of CROP 11, the longest deep crust profile acquired on land in Italy until now. This profile was acquired over a period of four years, because the funds came from a number of different sources. This long period meant that the data acquisition strategy along the various parts of the profile, from the Tyrrhenian to the Adriatic Seas, could be based on a comprehensive analysis of the known geology, on the seismic data acquired and processed until then, and on a detailed scouting for more convenient shot locations. The operative parameters were modified accordingly, changing the station intervals (40 and 60 m), shot intervals (160 and 180 m) and coverage. Specific lithologic situations were addressed by expanding-spread acquisition and large offset experiments.

A higher degree of complexity characterised the subsequent deep crust profile CROP-TRANSALP, acquired from Munich to Treviso, the Italian part of which constitutes CROP 01. The TRANSALP Projects is a European multi-disciplinary research programme for investigating the Eastern Alpine orogenic

Table 1b – *CROP On-shore profiles (explosive source).*
– Profili CROP a terra (sorgente esplosiva).

Year - profile/s		**1987 CROP -ECORS Western Alps**	**1987 CROP -NFP/20 Mt. Rosa**	**1988 CROP Central Alps**	**1992-93 CROP 03 Northern Apennines**	**CROP 18/a CROP 18/b Nothern Apennines**	**1995, 1999 CROP 11 Central Apennines**
N° ofn. profiles		1	1	2	1	2	1
Area (from - to)		Gran Paradiso National Park	Ayas Valley	Intelvi Valley – Porlezza and Brembilla Valley - Roncola	Torre Civette (GR) – Casteldimezzo (PS)	S.Giovanni delle Contee - Guardistallo	Marina di Tarquinia – Vasto
Total length	Km	22	20	32	230	116	265
N° of active channels		150	150	120-192	192	192	192
Stations interva	M	80	80	80	60	60	40-60
Shot interval	M			4.800	180	180	160-180
Explosive charge	Kg	30 – 300	30	70 – 140	30	30	30
Coverage		1	1	1	32	32	24-32
Sampling interval		2	2	2	2	2	2
Recording time	sec	25	45	32	25	25	25
Notes		Synchronized shots across the border (18 in Italy) and seismic recording systems in Italy and France	Synchronized shots across the border (6 in Italy) and seismic recording systems in Italy and Switzerland	Along one line, synchronized shots across the border	Expanding spread- type and large offset experiments	Expanding spread- type and large offset experiments	Expanding spread- type and large offset experiments
Main Contractor		**O.G.S.**	**O.G.S.**	**O.G.S.**	**O.G.S. Geoitalia and Discovery G.S.**	**Discovery G.S.**	**O.G.S., Geotec and Ismes**

processes by partner institutions from Italy, Austria and Germany (see the specific note in this Atlas). Deep NVR seismic profiling formed the core of this study, which is accompanied by a set of additional specific projects. The Italian CROP Group actively co-operated with Austrian and German groups to set up project planning in all the different phases. The main TRANSALP data acquisition was divided into three different campaigns, in 1998 and 1999; for the first time a continuous, ~ 300-km long section was gathered, including the orogen at its broadest width as well as the two adjacent Molasse basins.

Seismic reflection data were mainly acquired with the Vibroseis technique, with four heavy vibrators (total peak force of up to 872 kN) in a split and asymmetric spread configuration of 360 receiver channels. The maximum offset on the vibrator main line was about 12 km. The channel spacing of 50 m and a source spacing of 100 m resulted in an average 90-fold common-midpoint (CMP) coverage. The vibro-point parameters adopted were a linear sweep with a sweep frequency of 8- 60 Hz and 12 sweeps for each VP. The total sweep length was 48 sec (30 sec of sweep plus 18 sec of listening time). Again, in order to ensure that seismic penetration went deep enough below the crustal root, the Vibroseis technique was accompanied by explosive sources (charges of 90 kg in 30-m deep boreholes) at large intervals of about 5 km for gathering low-fold (2- fold) but high-energy deep sections. The spread configuration in this case was off-end, which means there was on average one shot-point every 4.5 km.

The seismic reflection profiling was also accompanied by passive cross-line recording (7 cross-lines of about 20 km length each) for three-dimensional control, and by passive recording using a wide-spread three-component stationary network listening to all seismic sources in wide-angle configuration for velocity control. For more than nine months another network recorded continuously any local and global earthquakes for tomography and earthquake studies.

A field quality control (QC) system was available to the team and preliminary QC and data processing was carried out daily. As a general observation the acquisition results confirmed our previous experience on the Alpine crustal profiles. The Vibroseis acquisition provides good quality data up to 8-10 seconds of recording time. At deeper levels energy penetration is problematic and explosive records may supplement the Vibroseis data for a better interpretation. Processing of the Vibroseis reflection data followed basically the well-established common-midpoint (CMP) stacking scheme and post-stack depth migration used in oil and gas exploration and was performed separately by the Italian and the Austrian-German groups. The explosive seismic data were also handled separately. The main objective was to image the lower crust, including the crust-mantle boundary ('Moho' discontinuity).

3. – OFFSHORE CROP-PROFILES. SOME ASPECTS OF THE MARINE SEISMIC ACQUISITION AND PROCESSING.

NVR off-shore data acquisition offers several technical advantages over the on-shore technique. In NVR crustal acquisition the seismic energy reflected by the acoustic interfaces of the lower crust or of the crust-mantel border is negligible. Therefore, all the experiments to define the deep crustal structure show a low signal-to-noise ratio at high reflection times. Increasing this ratio is the most important target of the geophysical team. A quiet environment, such as that off-shore, will help to increase the S/N ratio. In off-shore acquisition, moreover, we can use powerful energy sources with a good repetitivity and maintain a good coupling with the surrounding medium. Other advantages of marine acquisition include the possibility of achieving long, rectilinear profiles with a homogeneous distribution of the spread geometries as well as of the subsurface coverage. Both characteristics are, of course, more difficult to achieve in the on-shore acquisition where the surface layout frequently has a slalom-type geometry that creates dispersion in the subsurface CDP distribution as well as a lack of homogeneity in the surface parameters, due to the lateral displacement or suppression of shot-point positions. Another important factor in marine acquisition is the absence of any low velocity layers close to the spread, which reduces to a minimum the problems linked to near-surface static corrections. The near-surface homogeneous conditions also provide a better lateral balance of the recorded seismic amplitudes compared to the on-shore profiles, where near-surface conditions are frequently responsible for deterioration in recorded data.

The economic benefits of marine acquisition are also important. The average cost of the marine CROP profiles is about 1/30 that of the on-shore profiles, which clearly explains the large quantities of recorded off-shore profiles (about 8000 km) compared to those on-shore (about 1100 km).

However, there are also some well-known technical drawbacks in marine NVR data acquisition, which may severely affect the recorded data quality and the interpretability of the final sections.

The most serious technical problem is the presence of high-amplitude multiple reflections generated at sea-bottom and at strong acoustic interfaces below this. These problems are of an order of magnitude higher than in the equivalent on-shore profiles. The typology of the multiple events present is vast and complex. In addition to the-double time multiples, there may also be energetic multiple reflections such as peg-leg multiples, which are difficult to remove or attenuate. In some of the marine CROP profiles (Central and Southern Tyrrhenian Sea) attenuation of the multiple reflections posed a serious problem and required complex time-consuming processing operations. In the Tyrrhenian area the 1st order multiple often overlaps the reflection from the Moho discontinuity; separation of the two events was a delicate task for the processing analysts. Other areas with complex peg-leg multiples included parts of the profiles recorded in the Ionian Sea and in the Channel of Sicily. Another complex area was the off-shore Iblean platform, where the multiple events are high-amplitude refracted waves generated by the high-velocity acoustic interface lying at or just beneath the sea-bottom. Another technical problem is that of a reduced spread length. In the on-shore acquisition we had no limitations, and could use offsets as large as we required, but when the off-shore profiles were being acquired it was difficult to achieve an offset over 6 km with a single vessel. This has an impact on the resolution of the velocity analyses and on the possibility of separating multiple from primary reflections at the widest offsets.

Another technical aspect that had to be dealt with is the recording length of the marine profiles. To achieve a recording length of more than 20 sec some compromises had to be reached between shot interval and profile coverage, as it is impossible to reduce vessel speed below 4 knots without compromising the hydrodynamic balance of the recording streamer. This issue becomes particularly important in areas where recording lengths of over 20 sec are needed to image the geological targets. In the CROP MARE this problem arises only in the Calabrian Arc area, where recording lengths had to exceed 30 sec. The compromise adopted was to double the SP interval and reduce accordingly the subsurface coverage. Special expe-

Table 1c – *Marine profiles.*
– Profili CROP a mare.

Year - profile/s		**1988 CROP-ECORS Western Mediterranean Sea**	**1991 CROP MARE 1**	**1993-1994-1995 CROP MARE 2**
N° of profiles		1 10 24		
Area		Western Sardinia	Ligurian, Tyrrhenian and Ionian Seas	Tyrrhenian, Ionian and Adriatic Seas, and Channel of Sicily
Total lenght	Km	205	3.410	5.225
N° of channels		120	180	180
Hydrophone interval	m	25	25	25
Streamer lenght	m	3.000	4.500	4.500
Pops interval	m	50	50	50
Air gun total volume	l	82	80	80
Coverage		30	45	45
Recording time	sec	16	17-20	17-30
Notes		Continuation of an ECORS marine profile	The energizations at sea were also recorded on land in Sicily	The energizations at sea were also recorded on land in many different sites
Main Contractor		**O.G.S.**	**O.G.S.**	**O.G.S.**
Research vessel		OGS-Explora	OGS-Explora	OGS-Explora

riments were also run, in which a two-pass ship recording was made on the same location, the first pass with recording time from 0 s. to 21 s. and the second pass with the recording device "on hold" from 0 to 19 sec and recording from 19 to 40 sec.

Finally, in correspondence to several seismic profiles at sea, on-shore profiles were recorded with low-frequency geophone stations, using an air gun source (see the specific note in this Atlas). Again a compromise had to be reached between the SP interval, recording time and subsurface coverage.

All the NVR profiles of the CROP MARE Project have been recorded by the OGS on the vessel R/V OGS-EXPLORA during two separate campaigns, CROP MARE I (1991) and CROP MARE II (1993, 1994, 1995). The acquisition parameters are similar to those utilised for hydrocarbon prospecting and are listed in Table 1c.

The main differences with respect to commercial parameters were the higher recording times (17-18 sec), the use of a powerful source with an areal configuration, and a source signature such us to provide a low-frequency enriched spectrum. The streamer was analogic, with a maximum length of 4500 m and 25 m group interval. To ensure a low-frequency oriented spectrum the cable depth was kept at 12-14 m and the low-cut filter left open as much as possible (3.5 Hz).

The processing procedures were based on experience gained during processing of the marine seismic reflection data in oil/gas exploration. The approach used in the CROP MARE NVR data is also similar in several ways to that used in other crustal projects, e.g. the BIRPS Project. However, attenuation of the different types of multiple reflections was one of the most important aspects of CROP MARE data processing.

The processing strategies and relative parameters were defined jointly by AGIP, CNR and ENEL during meeting of the Acquisition and Processing Teams, and based on a series of scheduled tests. The data were processed by the OGS, ISMES and, in part by AGIP, following the same general indications provided by the CROP Technical Committee. The seismic data processing was mainly aimed at obtaining seismic time images of the subsurface that evidence the deep structures without neglecting the shallow geological setting. All effort was made to improve the S/N ratio. The most common noises on the data were acquisition noises, such as those connected with tugging of the streamer, and external noises from other vessels and multiples. As in the land data processing, forcing operations, which could have distorted the real image or created artefacts, were avoided so as to achieve a reliable picture of the subsurface geometries. In general we adapted the processing sequence to the different geological domains surrounding the Italian peninsula, which trigger different NVR responses at the crustal level. Four main domains were defined: the Tyrrhenian, Ionian, Adriatic and Sicily Channel. In each of them, specific problems had to be addressed and the processing parameters and sequences were changed accordingly. In general, the applied processing sequences consisted of the following main steps: quality control, gain recovery, trace sum (optional), deconvolution, CDP re-ordering, velocity analysis (CVS), NMO correction, muting, multiple reflection attenuation, array simulation (optional), weighted stack, F-K filtering (optional), horizontal mixing (optional), time-variant filter, and equalization.

Many different algorithms were tested for attenuating the multiples of the sea-bed reflections. The chosen methodology is based on a median filter: the multiple reflections of the sea-bed are flattened by applying an appropriate velocity function. A median filter then removes the aligned multiple reflections by assuming that, at a constant time, only one or two samples of the real signals are affected by the multiples. The data are then inverse NMO-corrected by using the same velocity functions. This method proved to be easy and efficient, although dependent on sea-bed conditions. Where the latter are particularly rough, the diffractions that also appear in correspondence to the sea-bed multiples make it difficult to determine a correct velocity function and to remove the multiples.

The attenuation of intra-bed multiples and diffractions is, in general, more complex than the attenuation of sea-bed multiples. A modelling algorithm based on the discrete Radon transform was tested but, due to high variability in the velocity of diffracted signals, the resulting models were laterally unstable and produced numerical noises. The application of dip move-out corrections proved to be insufficient, and eventually an array simulation in the common-shot domain was preferred. The number of mixed traces and the applied weights were carefully chosen along the profiles by also considering the dips of the reflectors. The good results compensated for the effort expended in this time-consuming procedure.

The weighted stack also mad a contribution to reducing the multiple reflections, which, in the traces near the source, are less sensitive to NMO corrections. An F-K filtering was applied after the stack to reduce the dipping noises caused by the tails of any diffraction hyperbolas that were not completely removed.

A weighted and time-variant lateral trace mixing was also applied, to further reduce diffracted signals and multiple reflection residuals at high two-way times. The processing steps mentioned above were applied when necessary, and fine tuned by evaluating their efficiency in reducing multiple sea-bed reflections, intra-bed reflections and other organized noises.

Again, no special processing was performed for lithology and/or petrophysical informations.

4. – FINAL COMMENTS

In Tables 1a, 1b and 1c it is clear that an evolution occurred in the choice of operative parameters, mainly for on-shore profiles, due to technical developments in the seismic data acquisition systems and a constant improvement in the organization of the seismic crews. The number of active channels increased from 120 to 240 and 360; the coverage increased from 60 to 120 (up to 32 when using dynamite); the recording methodology was modified from the usual straight or crooked line to an expanding spread and large offset experiment, and even to complex large crossing listening transects with complementary shots at their ends. A second improvement occurred as a result of processing and QC of the seismic data directly in the field. We passed from the simple record displays and brute-stack sections of the first CROP profile in the Western Alps to the complex processing sequences applied during the CROP 11 transect from the Tyrrhenian to the Adriatic Seas. The latter approach permitted us to make a constant quality control of the operative parameters, which were optimised and modified five times along the seismic line.

The acquisition techniques and the processing sequences applied to the CROP seismic data represent, within the available budget, stake-of-the-art industry standards for the production of interpretable 2D seismic sections. A number of other acquisition and processing options, however, have not been tested, along with many alternative sequences. Specific segments or specific lines of the CROP project may benefit from re-processing operations aimed at solving particular noise problems, thus increasing the final quality of the seismic image. Entire fields of seismic processing have not been touched: one of these is the depth migration of the seismic data, which also entails the perilous issue of estimating the optimal velocity field, and brings the seismic data onto the "geologically natural" space-depth scale instead of the "space-time" scale of the present sections. Another field of study is the extraction of lithological or petrophysical indications from the CROP seismic data, which would require specific processing efforts and, possibly, matching with borehole information.

There is a lot more that can be done in this field, and room for improvement.