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SISTER 99: a seismic campaign to investigate the kinematics of South Tyrrhenian extensional regions

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Riassunto

In questo articolo, viene presentato il rapporto preliminare della crociera sismografica SISTER 99 che si è svolta nel Giugno 1999 nel Tirreno meridionale. Durante la crociera sono stati acquisiti più di 2400 km di linee sismiche con lo scopo di fornire una documentazione completa su segmenti crostali alla scala di chilometri. L'obiettivo primario di SISTER 99 è di definire la cinematica dei margini continentali tirrenici dell'Italia peninsulare sud-occidentale e della Sicilia settentrionale durante e dopo la fase di rift continentale. Questi margini delimitano l'area oceanica complessa del Vavilov e Marsili. Sono state acquisite linee sia parallele che sub-perpendicolari alla linea di costa in modo da documentare tutti i bacini sedimentari ed altre strutture tettoniche esistenti. Per l'acquisizione sono stati utilizzati un cannone GI ed uno streamer a 48 canali di cui solo 24 sono stati effettivamente impiegati. La registrazione è stata eseguita con due sistemi, StrataVisor della Geometrics e STM 96.

Praticamente in tutte le linee è stata ottenuta una penetrazione intorno ai 3-4 sec (tempo doppio) con una risoluzione sufficiente a descrivere i primi chilometri della crosta ed in particolare la geometria del basamento pre-rift. Questi aspetti sono visibili già nei profili monotraccia che sono stati elaborati a bordo immediatamente dopo l'acquisizione di ogni linea. SISTER 99 è stata anche un'ottima occasione per testare nuove configurazioni cannoni/idrofoni e per fare misure di magnetismo lungo le linee seguite.

La crociera SISTER 99 è frutto della collaborazione tra I'Istituto CNR Geomare Sud (Napoli) ed il Dipartimento di Tettonica dellaVrije Universiteit (Amsterdam) con la partecipazione fondamentale del Gruppo di Geologia Marina dell'Università di Palermo. Nello spirito di una collaborazione tra Università ed imprese, due geofisici di una una ditta olandese di prospezioni geofisiche sono stati ospitati a bordo contribuendo all'esecuzione di esperimenti tecnologici su sorgenti ed idrofoni. Studenti di varie istituzioni, tra cui l'Istituto Universitario Navale di Napoli, l'Università di Palermo, la Vrije Universiteit Amsterdam e la Technische Universiteit Delft hanno partecipato alla crociera fornendo un contributo molto importante al successo della crociera stessa.

Parole chiave: Mar Tirreno, bacini di retro-arco, margini continentali, sismica a riflessione.

Abstract

In this paper we report on the rationale, the development and the preliminary results of the oceanographic Cruise SISTER 99 which took place during June 1999 in the South Tyrrhenian Sea. A total of more than 2400 km of seismic lines has been acquired during the Cruise designed to image crustal segments several tens of kilometres to few hundred of kilometres long. The prime objective of SISTER 99 is to provide kinematic constraints on the syn-rift and post-rift evolution of the continental margins of SW peninsular Italy and N Sicily. These margins border the complex oceanic area of the Vavilov and Marsili basins. Lines were acquired both parallel and at high angle to the coast lines in order to image all sets of tectonic structures and associated sedimentary basins. We used a GI air-gun and a streamer with 48 channels, 24 of which were used for acquisition. Distance between groups and shot rate were respectively 50 and 25 m. Acquisition itself was performed with two systems, StrataVisor® of Geometrics and STM 96. Along most of the lines, we obtained a penetration up to 3-4 seconds (t.w.t.t.) with resolution good enough to provide a detailed image of the first kilometres of the investigated crust and, in any case, of the geometry of the pre-extensional basement. These features were clearly visible on the near-trace profiles produced on-board immediately after termination of each line. SISTER

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99 was also the occasion to test new receivers/air gun configurations and to perform magnetic measurements along the lines.

The Cruise was designed and executed in the frame of collaboration between the CNR Geomare Sud Napoli and the Faculty of Earth Sciences of the Vrije Universiteit Amsterdam. The Marine Geology Group of the University of Palermo also played a fundamental role for the success of the Cruise. In the spirit of an improvement of relations between academy and industry, two geophysicists of a Dutch seismic prospecting company also participated to the Cruise. Students from various institutions, namely the Istituto Universitario Navale Napoli (I), the Vrije Universiteit Amsterdam (NL), the Technische Universitet Delft (NL) and the University of Palermo (I), have also participated to the Cruise providing a significant contribution to its success.

Key words: Tyrrhenian Sea, back-arc basin, continental margins, reflection seismics.

The background of the Cruise and its rationale

A large body of data exists on the South Tyrrhenian (see, among many others, Fabbri *et al.*, 1981; Selli, 1985; Kastens,1988; Boccaletti *et al.*,1990; Mascle and Rehault, 1990; Patacca *et al.*, 1990; Sartori, 1990). A comprehensive summary of these observations is obviously beyond the scope of this Preliminary Report and only few general remarks will be here presented. Their main purpose is to highlight some poorly constrained issues rather than the remarkable knowledge available.

It is generally accepted that Tyrrhenian extension began in Tortonian times when the Sardinia-Corsica continental block ended its counterclockwise rotation away from Europe and stretching shifted from the Ligurian-Provençal ocean to the E of the Corsica-Sardinia block. In the Pliocene, crustal separation occurred and oceanic crust appeared in the Magnaghi/Vavilov area. Ocean accretion ended in the Late Pliocene and extension migrated to the SE causing a new zone of crustal separation and formation of oceanic crust in the Marsili basin. Extension is presently active not only in this area but also in large parts of S peninsular Italy (Amato and Montone, 1997). It is debated if this evolution should be associated with counterclockwise rotation of the Adriatic plate (Channel, 1996) or with SE-ward retreat of the Calabria subduction zone (e.g. Malinverno and Ryan, 1986; Faccenna *et al.*, 1997). The appearance of a complex area of oceanic crust in the central parts of the Tyrrhenian caused the formation of three continental margins, namely E Sardinia, N Sicily and SW Peninsular Italy. Extensional sedimentary basins (peri-Tyrrhenian basins of Selli, 1970) and other large-scale tectonic structures are present along these margins. These features contain the record of horizontal and vertical movements experienced by the continental crust surrounding the Tyrrhenian ocean and therewith the key to a complete, 3-D description of Tyrrhenian kinematics. In turn, this represents the necessary basis for further dynamic studies.

Despite this general knowledge, very important tectonic problems remain open, partly as a consequence of the limited number of available regional seismic lines, that is of lines crossing the entire continental margins. Two sets of tectonic issues were of particular interest to us:

The large scale structure of the Sicily-Tyrrhenian-Apennine system as imaged by the Gargano-Pantelleria refraction seismic line (Scarascia et al., 1994)

The re-processing of this older refraction seismic line (Fig. 1) has sparked a renewed interest in the topics touched by the line such as the crustal structure of the western part of Peninsular Italy and the relations between Apennine shortening/thickening and Tyrrhenian extension/thinning (Biella *et al.*, 1997). During these studies, the need was felt to integrate the seismic refraction data with other, more detailed information from the upper crust. Geological sections on-land reconstructed by E. Marsella and co-workers have provided such integration for the continental part of the line (e.g. Marsella *et al.*, 1995). Reflection seismic lines during SISTER 99 were designed to provide data from the marine part of the line.

The upper crustal structure of the continental margins surrounding the S Tyrrhenian Sea

Despite the abundance of data collected in the last decades, well-constrained images of

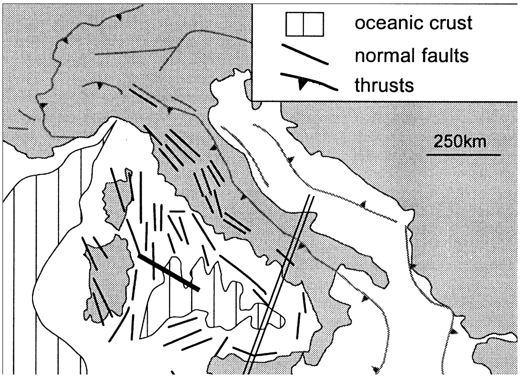

Fig. 1 - Schematic map of the Tyrrhenian Sea and surrounding regions. The thick black line indicates the trace of the profile across the E Sardinia margin discussed and modelled in Spadini *et al.* (1995 a and b). The double line shows the trace of the Gargano-Pantelleria refraction seismic profile (Scarascia *et al.*, 1994).

the top 3-5 km of the continental margins are still missing. Indeed, there is a striking contrast between the large amount of data at the basin to sub-basin scale and the paucity of regional information, i.e. of data at the scale of the margin. This limits our ability to constrain horizontal and, perhaps more importantly, vertical movements experienced by the margins during the last 10 Myr and thereby also to perform correct numerical modelling of rifting and post-rift. The best published regional lines are probably available from E Sardinia (e.g. Spadini *et al.*, 1995a, b and references therein). These same authors provided the first estimates of the amount of thinning and stretching of a Tyrrhenian passive continental margin. More recently, a regional seismic line has been acquired across the continental margin of N Sicily and has been used to derive kinematic quantities (Pepe *et al.*, 1999; Pepe *et al.*, in press). No comparable data are available from the W coast of peninsular Italy from Latium to Campania (Fig. 1). Furthermore, all along the continental margins from Latium to N Sicily, extensional basins and highs are found which are controlled by extensional faults running at high angle to the coast. The kinematics of these features is very poorly constrained thereby also preventing a comparison with the substantial orogen-parallel extension discussed by Ferranti and Oldow (1999 and references therein).

Imaging at the margin scale is also of primary importance in providing the "background" signal to more local investigations. This is the case, for instance, of studies of the tectonic and sedimentological evolution of the Gulfs of Napoli and Salerno which have been performed by Geomare in the last years (e.g. Sacchi *et al.*, 1994).

It was thus decided to launch a new seismic campaign with the goal of acquiring new regional seismic lines across the continental margins of the S Tyrrhenian Sea and thereby to image the top 3-5 km of the crust with high vertical and horizontal resolution. This scale is appropriate for the studies we wanted to perform since images of the sedimentary basins and of the basin-fill can be obtained. Additionally, SISTER 99 represents an improvement with respect to available lines which are mostly single-channel or low-resolution multichannel acquired by oil industry.

Already from the initial stages, it was clear to the initiators of the Cruise that this would be successful only if the acquired data could be transformed in geological profiles and tectonically modelled. For this purpose Geomare Sud and the Department of Tectonics of the Vrije Universiteit joined forces. Geomare Sud has been acquiring and interpreting seismic and other marine data from various parts of the South Tyrrhenian since years, mainly concentrating on the shallow geology of the Gulf of Napoli and of Salerno (e.g. Sacchi *et al.* 1994; Aiello *et al.* 1997). More recently, a multichannel regional seismic line has been acquired in collaboration with the Marine Geology Group of the University of Palermo, across the continental margin of North Sicily (Pepe *et al.*, 1999; Pepe *et al.*, in press).

The Faculty of Geology of the Vrije Universiteit and in particular its Department of Tectonics, has been carrying out tectonic studies in extensional regions since more than a decade integrating numerical modelling with field data. Since a couple of years, the Tyrrhenian Sea has become a very significant area of research for members of the Department producing new quantitative reconstructions of the evolution of the Sardinia and Sicily continental margins (e.g. Spadini *et al.*, 1995a, b; Pepe *et al.*, 1999; Pepe *et al.* in press).

The Marine Geology Group of the University of Palermo contributed to the success of the Cruise by providing very reliable, self-developed multi channel acquisition system and the regional geological knowledge of N Sicily.

The Cruise

The equipment used

At present, facilities and equipment by Geomare Sud allow for the acquisition of multi-channel, 24 to 48 channels seismic data allowing for an improved imaging of the continental margins.

The air production and delivery system - To compress the air needed by the GI gun, two large Bauer compressors worked together at an operating pressure of 200 bar for a total delivery of about 3000 l/m. The compressors feed an air buffer system made up of six cylinders with a capacity of 50 litres each. From the air buffer, the compressed air is distributed to the GI gun through a valve system designed to control air delivery and operating pressure.

The energy source - The energy source for all lines was a 210 cu.in. GI Gun (by SSI/SODERA) used in "harmonic mode" (Generator and Injector have the same volume of 105 cu.in.). Two of such guns were available on board to guarantee the continuity of the operations in case of malfunction.

The streamer - During SISTER 99 we used a 48 channels streamer. Its set up is shown in Fig. 2.

The acquisition system - Data acquired by the hydrophones were recorded with two systems. We used the Strata Visor NX of Geometrics Inc. and the STM 96 (Pepe, 1996) developed by one of the participants to the Cruise (F. Pepe). Strata Visor recorded 24-channels with a group interval of 25 m. STM 96 recorded 12 channels with a group interval of 50 m. Anti-alias analog filters of 300 HZ 48db/octava were applied to the seismic signals before sampling. Time rate and data lengths were respectively 1ms and 7-8 s (t.w.t.t.). Shooting was generated every 25 m. Therefore, the CDP spacing was 25 m and, for this reason, both acquisition systems recorded data with 1200 % coverage. Tab. 1 summarises parameters used during seismic prospecting.

Although the mentioned acquisition systems show very similar characteristic in the input procedures, they differ in the solutions adopted to store multichannel seismic data. StrataVisor NX was supposed to store seismic data in tape drives during acquisition using a Seg-Y format. However, problems were manifest already at the beginning of SISTER 99, because the system was not designed to handle rapidly the large amount of data produced by the high-resolution seismic line. The problem was solved by storing data on hard disk during acquisition, however requiring approximately 30 minutes for the transfer of each line from the hard disk to the tape.

The STM 96 system adopts a different method. Seismic data are transitorily stored on hard disk during acquisition using a binary demultiplexed format. This allows to roll-out seismic data in an auxiliary computer after acquisition, by using a network, in very short time (less than 5 minutes). To do this, an additionally computer was necessary during seismic prospecting to codify data in Seg-Y format and store it on CD-ROM.

Processing - On-board processing was limited to the production of single-channel profiles. By using the STM 96 system, near trace sections were produced immediately after acquisition. They were of crucial importance in providing information on data quality and guidance for further seismic prospecting. The following algorithms were running on STM 96 to perform data elaboration:
– edit of the traces
– D.C. removal
– gain analyses
– traces mixing
– band-pass filter
– time variant amplitude
– spherical divergence correction

Examples of the obtained near trace are show in the figures. More sophisticated processing was performed on few lines using the Geovecteur software package.

Immediately after the termination of the Cruise, more advanced processing of the acquired data has been started and is presently being carried out by scientists who participated to the Cruise in collaboration with the Technische Universiteit Delft (NL). This ensures an ideal co-ordination and coupling between the different stages.

Acquired lines

A total of >2400 km of seismic lines was acquired during SISTER 99 (Fig. 3). Lines were designed to form grids in front of the

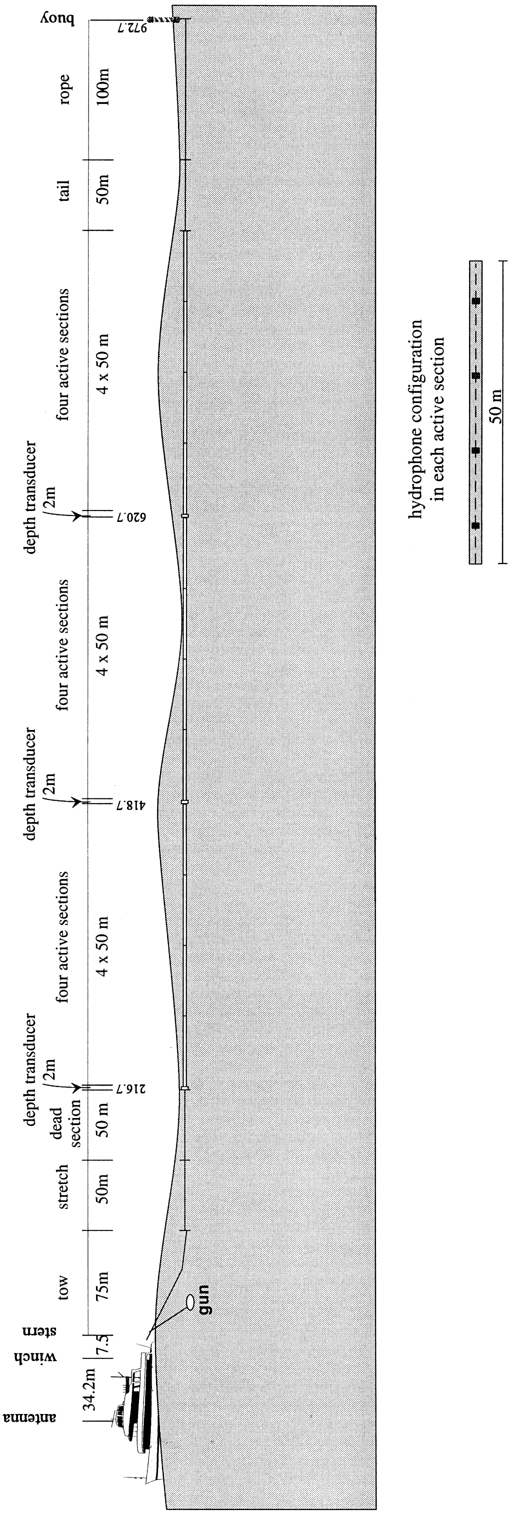

Fig. 2 - Configuration of the streamer adopted during SISTER 99. Other data: total # of channels 48; gun power 150 bar; shot interval 25 m; depth of gun 8 or 6 m.

Tab. 1 - Summary of configurations used during SISTER 99.

	StrataVisor NX	STM 96
Near Offset	175m	175m
Far Offset	750m	750m
Receiver distance	25m	50m
CDP distance	12.5m	25m
Shot distance	25m	25m
Number of channels	24	12
CDP coverage	12	12

peninsular coast of Southern Italy (Campania and Calabria) as well of N Sicily. In general, three lines parallel to the coast were acquired at variable distance from the coast itself. Transversal lines perpendicular to the coast were also acquired. Distance between such transverse lines was in the order of some tens of kilometres. Only little attention has been devoted to the oceanic crust areas which were beyond the scope of our investigation. Penetration was always good and well-constrained images of the pre-extensional basement as well as of the internal geometries of sedimentary basins has been achieved.

Technical evaluation

Despite the fact that a large part of the facilities and equipment available on board had been newly acquired, SISTER 99 was technically a success. The GI air gun, the streamer and the STM 96 acquisition system were the most reliable and effective parts of the equipment. Minor problems were caused by

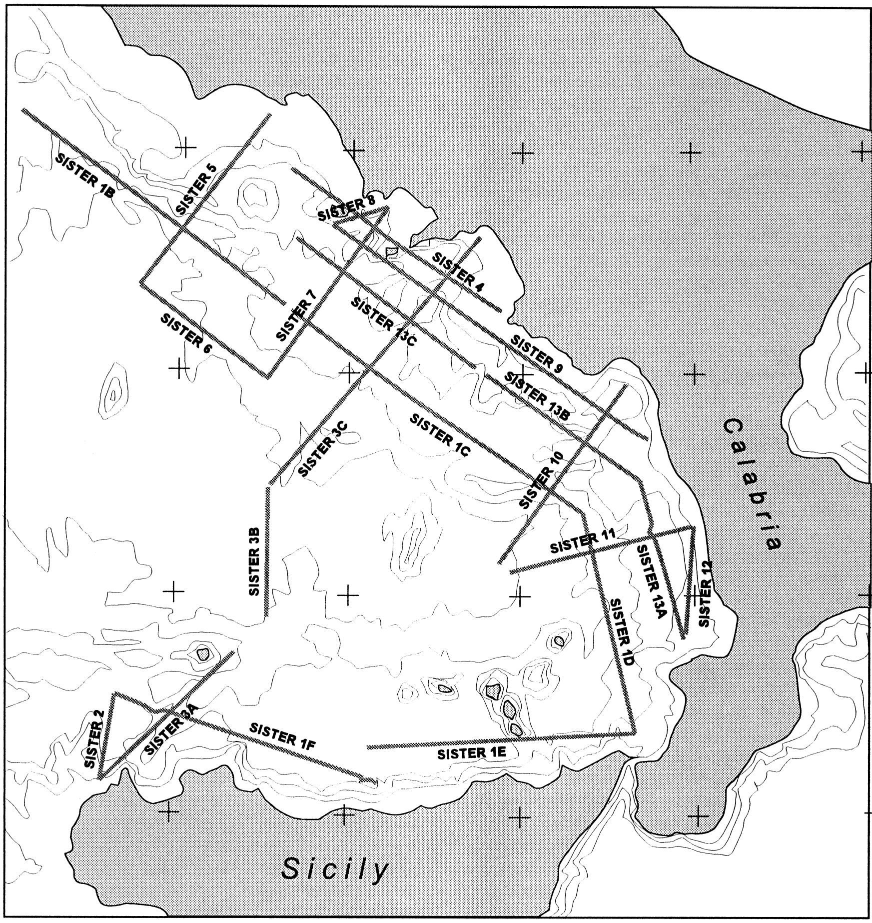

Fig. 3 - Map showing the traces of the lines acquired during SISTER 99

the air storage system furnishing air to the guns and by the StrataVisor acquisition software/hardware. All in all we consider these failures as "youth" phenomena which will be solved in the coming Cruises.

Preliminary results

Overall view

SISTER 99 has produced a very large quantity of data namely around 2400 km of seismic lines. In the large majority, resolution was very good and allowed for the imaging of sedimentary basins and of their internal geometry. This was the case also in the deep waters of the central part of the South Tyrrhenian. Profiles in shallow waters have strong and clear multiples, part of which will be removed during processing. The overall success is due to the satisfying functioning of the equipment, to the considerable engagement of all participants and to favourable weather conditions.

Some examples of results

In this section of the report we present some particularly interesting examples of the obtained data. The profiles we show are near-trace, single channel profiles, that is, a very preliminary and "brute" representation of the imaged objects. They are, however, quite spectacular and provide already interesting ideas.

Offshore Capri-Sorrento Promontory - Fig. 4 shows a ~20 km long segment of line SISTER 9 which runs in NW-SE direction offshore the Salerno Promontory and the island of Capri (see Fig. 3 for location). Two fault blocks with intervening sedimentary basins are beautifully imaged by this line. The two blocks are represented by fairly continuous, weak reflectors with a relatively large spacing. In accordance with the regional geology, there is little doubt that the blocks are formed by Mesozoic carbonates. The two blocks are both tilted to the NW in association with planar, SE-dipping normal faults. A further, similarly dipping normal fault must be present NW of the termination of the profile. Even the flat, partly erosive, tops of the two blocks are tilted documenting fault activity until very recent times.

Between the two fault blocks, a > 0.6 seconds thick package of Pliocene (?) to Pleistocene sediments is present which shows very regular, continuous and parallel beds. The SE-ward continuation of these beds is not preserved, but at least their lower part is likely to be age-equivalent to the more poorly structured sediments of the fault block top. The upper part of the well-bedded package, needs, on the contrary, to be deposited during and/or following normal faulting (creation of accommodation space).

To the SE of the central fault block, a sedimentary succession is imaged by the seismic lines which is subdivided in two parts. The lower part (> 0.7 seconds thick) is formed by weak and irregular reflectors describing a syncline. Sedimentation could partly be contemporaneous to the formation of the syncline. The upper package (~0.6 seconds thick) has very regular and continuos reflectors, horizontal and parallel to each other. It is evident that they were deposited following deformation and that they tend to smooth the pre-existing morphology.

While the well-bedded sediments in the SE are virtually undisturbed, those between the two imaged grabens are cut by a deep V-shaped valley, the Salerno canyon of the literature. The valley is fairly symmetrical and is located at mid-way between the two blocks rather than in the proximity of the normal fault. This suggests that the formation of the canyon follows the cessation of normal faulting and that it is therefore very young.

Offshore W Sicily: the Erice basin - The line shown in Fig. 5 is part of the SSW-NNE trending SISTER 2 line and images the Erice basin. The basin fill is formed by two major seismostratigraphic units separated by a distinct horizon of very strong reflections present over most of the basin. The overall appearance of this horizon suggests that it is formed by evaporites deposited during the Messinian salinity crisis, very common in the Tyrrhenian area (Fabbri *et al.*, 1981; Malinverno, 1981). The pre-Messinian succession is formed by a set of N-ward diverging reflectors indicating a quite asymmetric shape of the basin deepening towards the N. The evaporites are flat-laying and absent from the southernmost part of the profile. We interpret the evaporites to be re-sedimented bodies shed from the high area to the N of the Erice basin. The seismic units overlying the evapo-

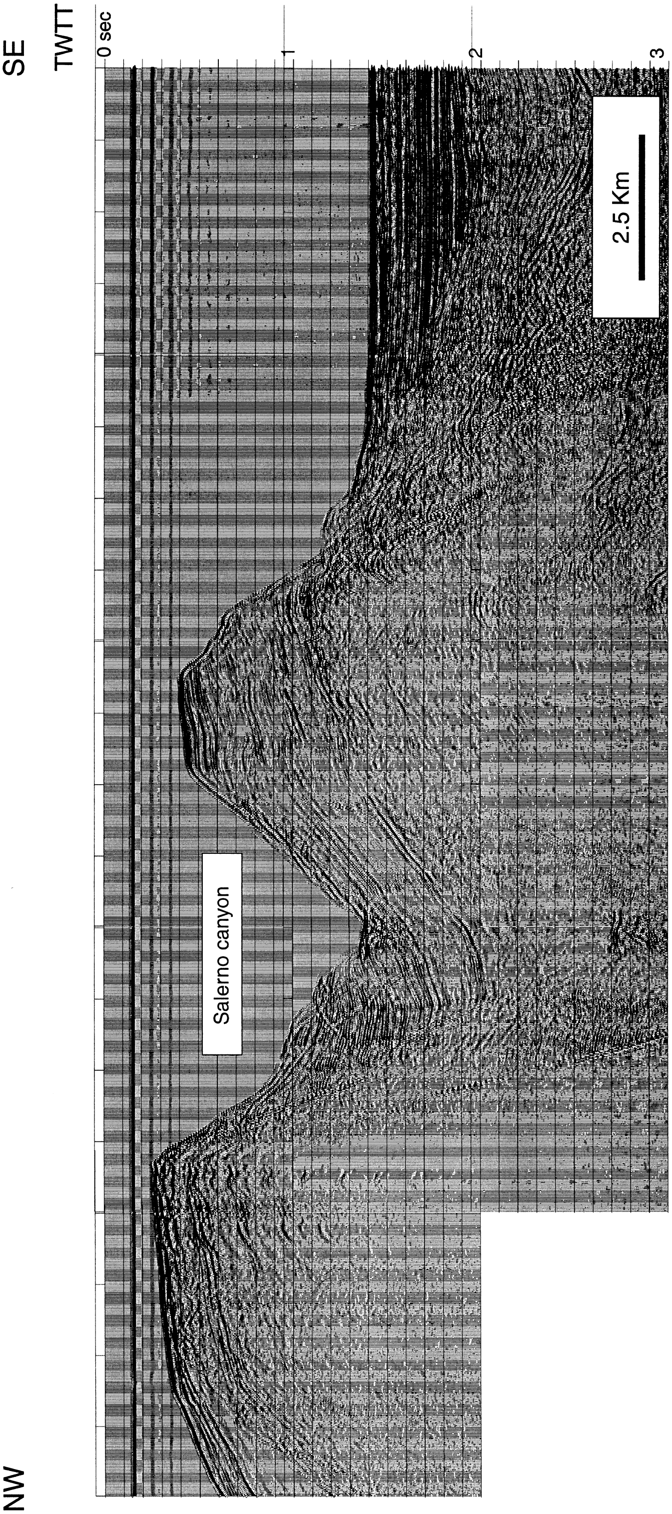

Fig. 4 - Offshore Capri as imaged by a segment of the line SISTER 9 (see Fig. 3 for location). The figure shown is a single-channel, near-trace profile.

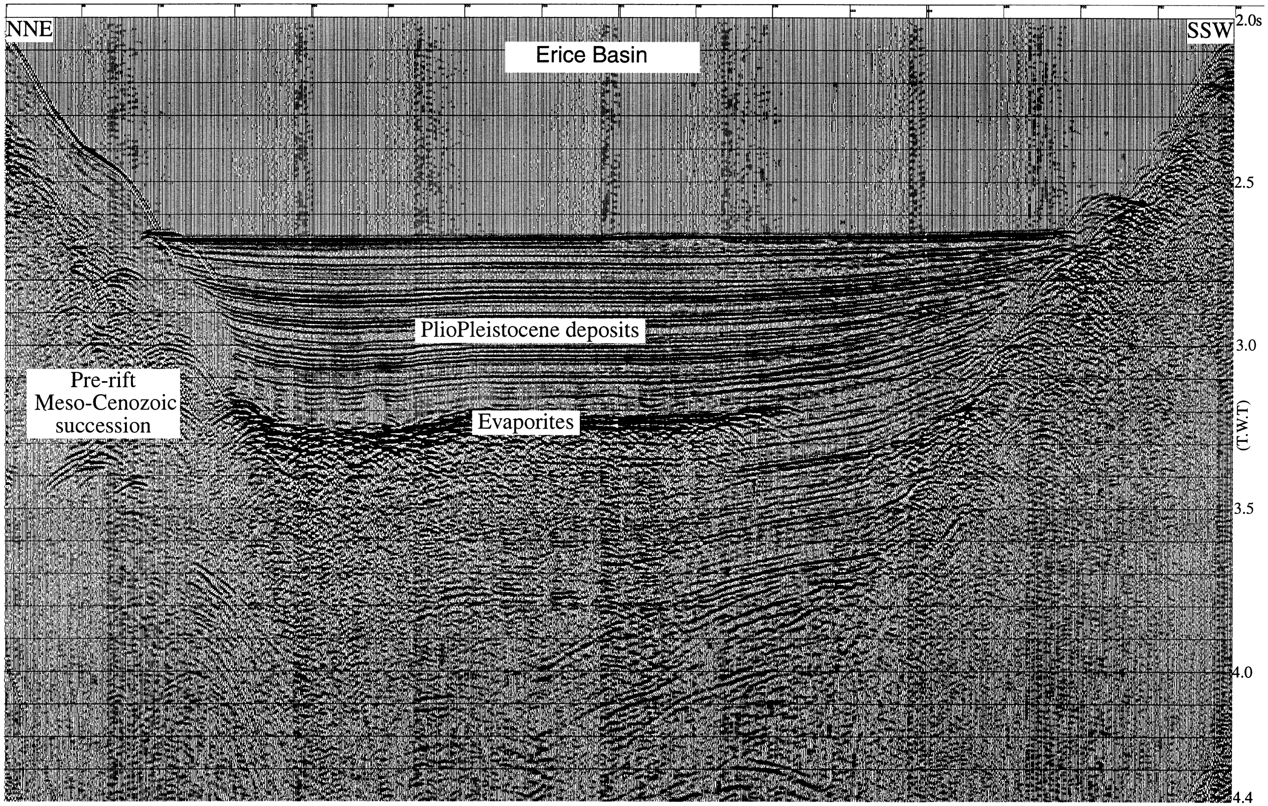

Fig. 5 - The Erice basin (N Sicily passive margin) as imaged by a segemnt of the SISTER 2 line (see Fig. 3 for location). The figure shown is a single-channel, near-trace profile.

rites is $\sim$ 0.5 s (t.w.t.t.) thick and formed by sub-horizontal parallel reflectors. It is basically post-tectonic and partially fills a pre-existing morphology.

Further projects

The justification and success of a campaign such as SISTER 99 lies not only in the quantity of acquired lines but, more importantly, in the ability of the participating groups to perform the complete processing and utilisation of the acquired data. In years of pronounced specialisation, such a goal can only be achieved through the collaboration of groups with different expertise. Consequently, lines successfully acquired during SISTER 99 will undergo a number of processing steps and then used to achieve the goals set for the Cruise, that is to constrain the kinematics and tectonics of the traversed continental margins.

The short term projects

The lines acquired by SISTER 99 are being processed during the writing of this note. Processing, is performed in collaboration with E. Verschuur of the Applied Physics Group of the Technical University Delft (Netherlands). Both data sets from STM 96 (12 channels) and from StrataVisor® will be analysed. Processing includes standard procedures (trace editing, resampling, bandpass filtering, NMO correction, CDP stack and Gain) and advanced procedures (predictive deconvolution, post-stack multiple removal and migration). The predictive deconvolution is deputed to suppress the reverberations. The multiple removal, based upon the predictions made on the basis of the wave equation (Verschuur, 1991), eliminates the surface-related multiples that constitute a major noise in marine data. The first results obtained show the reliability of the "advanced processing" to recover information from the data.

In a second stage, planned to be terminated in the first half of 2000, processed lines will be interpreted and depth-converted. Given the scale of the analysed geological objects and the regional goals of the project, the lack of wells should not jeopardise the successful completion of this stage. The end product of these short-term projects will be geological sections across and along the investigated continental margins.

At a more theoretical level, the data acquired are being used by Carmen van den Ijssel (Technical University Delft) in a project aimed at the removal and utilisation of multiples. The idea behind this study is to use multiples in updating focusing operators. Prestack migration can be described in terms of two consecutive focusing steps: focusing in emission and focussing in detection, in which the order of these focussing steps can be chosen arbitrarily. The related Common Focus Point (CFP) technology is described in Berkhout (1997a). Focusing operators are calculated in a data-driven way by iterative updating, using the principle of equal travel time. The latter method uses half the time difference between a CFP gather and a focussing operator as a correction to that focussing operator. The method proves to be robust. During the preliminary research of the CFP technology, the attention was directed to the use of primaries. However, when updating the operator, a limited part of the true operator was obtained. In particularly complex geologies, multiples illuminate the target focal point in different angles than primaries allowing for an extension of the aperture of the true operator.

Long-term developments

The obtained geological sections will form the starting point for a number of different, partly complementary projects.

The regional geology of the Salerno Gulf region. The goal of this project is to obtain a well-constrained reconstruction of vertical and horizontal movements in the Salerno Gulf region. This area is very important because NW-SE trending normal faults are found together with features associated with nearly orthogonal (extension such as the selegraben and its fault-bounded blocks with Tyrrhenian opening. SISTER 99 lines will be integrated with field studies and with unpublished seismic lines from the Salerno onshore.

Kinematics of continental margins formation. This project aims at the reconstruction of the kinematics of the continental margins surrounding the Tyrrhenian ocean. Timing and duration of fault activity will be ascertained and estimates for extension factors derived.

Kinematics of orogen-parallel extension in the Tyrrhenian offshore. Retrodeformation of obtained geological sections will be performed in order to derive quantities such as extension rate.

Numerical modelling of continental margins formation. Numerical modelling techniques will be applied to profiles at high-angle to the continental margins of the S Tyrrhenian Sea. These models will provide quantitative constraints on the overall extensional and thermal evolution as well as on the vertical movements experienced by the considered crustal segments.

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