Evaluation of Geological Hazards in the Seas around Italy: Earthquakes, Tsunamis and Submarine Slides

Scientific Coordinator: Andrea Argnani

Introduction

Italy is located within a tectonically young area where geological processes like earthquakes, volcanic eruptions and intense erosion of mountain ranges are fairly common. These processes, however, can be hazardous when they affect adversely humans and their activites. Sites of potentially hazardous geological processes occur also in the marine areas around Italy, and the present program aims at identifying the tectonic features located at seas that present such hazard potential.

The risk evaluation of a geological event depends upon factors such as density of population and kind of manufactures in a given area; however, a good knowledge of the tectonic setting within which the event originates and of how the effects can propagate in time and space is also required. In this respect, understanding the tectonic setting of the marine areas where recent seismic activity occurs can contribute to a better evaluation of geologic hazards.

Within this frame, unit **IGM1** aims at investigating the neotectonics of the Eastern Sicily Escarpment, a seismically active region which has not been adequately studied so far. Unit **IGM2** aims at investigating the relationships between earthquakes and sedimentary instability in the central Adriatic Sea. Any aspect that can be related to tsunamis is then handled by unit **UNIBO**, which if performing numerical modelling of tsunamis generated both by fault ruptures and submarine landslides.

In addition, an informal workshop between the participants to the GNDT project "**Design and development of monitoring and alarm networks in high seismic risk marine areas- First development of a node in Eastern Sicily**" (Coordinator Laura Beranzoli) and unit **IGM1** has been organised in order to share relevant pieces of information obtained from eastern Sicily offshore. In particular, the preliminary seismological registrations from the marine station offshore Catania could contribute to better locate the active faults in the marine area.

SUB-PROJECTS

1) Location and characterisation of tectonic structures with seismogenic and tsunamigenic potential along the Eastern Sicily slope

Local coordinator: Andrea Argnani

Geological Setting

The narrow and steep Eastern Sicily Escarpment connects the narrow shelf of Sicily with the deep Ionian basin. This morphologic feature has a known tectonic origin (Scandone et al., 1981; Casero et al., 1984), and is the site of intense seismic activity, reported both in historical catalogues and recent instrumental records. The destructive earthquakes that stroke several times Catania, Messina and the towns of southern Calabria are almost certainly due to tectonic feature located at sea (Bianca et al., 1999). Furthermore, the largest tsunamis that affected the coasts of Italy, with waves as high as 13 m originated in this region (Tinti, 1991; Piatanesi & Tinti, 1998). One additional aspect of interest concerns the relationships between tectonic activity along the Malta Escarpment fault system and Mt. Etna volcanic activity (Hirn et al., 1997).

Objectives

Recently acquired morphobathymetric data have shown in this area the presence of sea floor scarps likely related to active faulting. The fault system, however, is rather complex and the structural architecture is only loosely known. Multichannel seismic profiles have been acquired along the Eastern Sicily Escarpment but they were aimed at some specific problems such as the definition of the crustal structure from the coastal area to the Ionian basin (STREAMERS, Hirn et al., 1997 e CROP Mare, Catalano et al., 2000) or the understanding of the crustal geology of the area adjacent the Mt. Etna volcano (ETNASEIS, Cernobori et al., 1996).
IGM proprietary and published seismic profiles show the presence of fault scarps and fault-controlled sedimentary basins with strata that record growth geometry. The fault maps so far published, however, are based on rather sparse seismic grids (Hirn et al., 1997; Bianca et al., 2000) and morphobathymetric data, acquired by IGM within the Italian "Progetto Strategico" (1996), support only partially the mapped extent and direction of faults offsetting the sea floor.
In order to contribute to hazard assessment and risk evaluation, a regional survey was planned and carried out to obtain a more detailed mapping of the tectonic structures. The acquired seismic grid is dense enough to overcame the spacing bias that affected previous studies.

Cruise MESC 2001

The study area covers about 2 squared degrees and the proposed MCS survey, carried out from July 27 to August 16 2001 onboard of the R/V Urania of CNR, has led to the acquisition of c.a. 2500 km of seismic profiles. Profiles are about 5-mile spaced over the Malta Escarpment whereas a larger spacing has been kept in the Ionian plain. MCS profiles will be interpreted to define the architecture of the fault system which contains the seismogenic structures. The high resolution Chirp sonar profiles, recorded along with MCS, should allow evaluating the neotectonic activity of the structures. Data acquisition has been carried out using a 48 channel Teledyne streamer, with 12.5 m group interval, and a Sodera G.I. gun in harmonic mode (105 + 105 c.i.). Shot interval was 50 m giving a coverage of 600 %. Seismic adata have been processed using a standard sequence up to time migration, using the software Disco/Focus by Paradigm.

During this cruise we have also put attention on the basal portion of Mt. Etna volcano which extends offshore. The topographic gradient of the Malta Escarpment may play a role in controlling the evolution of the volcanic edifice (McGuire, 1996) and a relationship between fault activity along the Malta Escarpment and volcanic activity of Mt. Etna has also been suggested (e.g., Hirn et al., 1997).

In addition, we have investigated the NNW-SSE-trending Salina-Vulcano alignment (Barberi et al., 1974; Lanzafame and Bousquet, 1997), in the Aeolian Islands. This line of volcanoes are located along the northern prolongation of the Malta Escarpment and it is of interest to understand if a regional tectonic feature like the Malta Escarpment played a role on the growth and activity of the Vulcano, Lipari and Salina volcanic edifices.

Preliminary results

The fault system characterising the Eastern Sicily Escarpment appears well imaged on seismic profiles and presents some additional complexity when compared to the previously published structural maps (Cernobori et al., 1996; Hirn et al., 1997; Bianca et al., 1999; Nicolich et al., 2000).

The simplified structural map of the eastern Sicily slope and adjacent regions illustrates the location of the neotectonic features with respect to the Malta Escarpment. The mapped structures lie all on the accretionary wedge of the external Calabrian Arc which is encroaching the Malta Escarpment at the latitude of Siracusa. With the exception of the Alfeo Seamount, which trends NNE-SSW, most of the structures present a NNW-SSE orientation that recalls the trend of the Malta Escarpment. The extensional faults located at the eastern end of the deformed belt present features indicative of, more or less pronounced, contractional rectivation. In one instance a reactivated extensional fault passes southward to a broad uplifted region where evidence of extension are lacking. On the other hand, the westernmost extensional fault system, located above the Malta Escarpment, does not present any contractional rectivation.

The Malta Escarpment represents the dominant morphological feature of the surveyed area and appears as a steep eastward-sloping surface partly onlapped by the flat laying sediments of the Ionian basin. Offshore eastern Sicily the Malta Escarpment can be divided, for sake of description, into two portions with different tectonic structures (Argnani and Bonazzi, 2002; Argnani et al., 2003).

a) The segment of the Malta Escarpment extending north of Siracusa is characterised by the presence of NNW-SSE-trending east-dipping extensional faults located along the morphological escarpment and a few km east of it. Moving south along the eastern Sicily slope, the previously mentioned western extensional fault system dies out rapidly. The recent deformation of this sector is located about 20-30 km east-wards of the morphologic slope and is characterised by a broad area of uplift, trending NNW-SSE, apparently bounded by reverse faults. The recent activity of this uplifted feature is documented by the growth geometry displayed by the adjacent sediments.

b) The Malta Escarpment does not seem affected by recent faulting in the segment south of Siracusa. In this part a thick package of reflectors is visible underneath the slope and continues undisturbed further east-ward, underneath the chaotic units of the external Calabrian Arc. Limestone samples attributable to this package of reflectors have been dredged along the southern scarp of the Alfeo Seamount, presenting Jurassic microfossils and pelagic facies (Rossi and Borsetti, 1977).

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2) Deformation of the Adriatic late-Holocene prodelta deposits through fluid escape processes

Local coordinator: Fabio Trincardi

Introduction

The project focusses on the Central Adriatic area to define:

a) the favouring factors that make a sediment body potentially unstable; special emphasis is on the stratigraphic setting of the units that fail and the morphology of resulting mass-failures or soft-sediment deformations;
b) the triggering mechanisms that are needed to destabilise and set into motion a section of unstable sediment in a more or less catastrophic way;
c) the recurrence of such events since the last glacial maximum up to recent and modern times.

Among the favouring factors, one should consider the role of the late-Quaternary sea-level cycle in dictating where, on a margin, sediment accumulates at the highest rate and sediment bodies reach the maximum thickness; increasing evidence proves the importance of short-term climatic fluctuations in causing dramatic increases in sediment flux potentially leading to sediment instability and failure.

Subproject Submarine Slides

The objectives of this subproject (restricted to the Adriatic area because of consistent budget reductions) are summarised as follows:

a) Determine the distribution of slide deposits or other kinds of soft-sediment deformation that occurred since the last glacial maximum, when sea level was 120 m lower than today;
b) Determine distribution and age of faults and other tectonic structures that may have been active during the same interval;
c) Define the areas of highest sediment accumulation rates during the last glacial maximum, the following sea level rise and the modern high stand (i.e.: the last 5.500 years);
d) Study the morphology of deposits affected by possible deformation accompanied by limited, if any, horizontal displacement; this goal can be achieved through the acquisition of very-high-resolution multibeam bathymetry data.

This report includes two parts: the first reviews the evidence for tectonic deformation and sediment failure through seismic-stratigraphic investigations of Quaternary regressive units; the second part reviews all evidence of sediment deformation and failure from the modern (late-Holocene) high stand progradational wedge through the analysis of morphobathymetric, high-resolution seismic and sediment property data.

Sediment failure, mass transport and tectonic deformation during the late Quaternary

Ultra-high resolution seismic profiles allow recognise shallow and small-scale features resulting from tectonic deformation during the last few hundreds of thousands of years in the Central Adriatic. Detailed stratigraphic reconstructions define a succession of depositional sequences that originated in response to Quaternary glacio-eustatic cycles, each characterised by a fourth-order (100 ky ca.) cyclicity (Trincardi et al., 1996; Trincardi and Correggiari, 2000). Four Pleistocene depositional sequences record the interval between ca. 450 ky and are largely composed of regressive deposits recording overall sea level fall conditions. These sequences are older than the last glacial maximum (LGM), corresponding to Oxygen Isotope Stage 2, and the late-Quaternary (ca. the last 20 ky) trasngressive and high-stand record (Cattaneo and Trincardi, 1999). Multi-proxy analysis of marine cores, accompanied by tephro-chronology and 14C dating, allow define precisely the age of key surfaces bounding the four regressive sequence and provide a tool to determine the intervals of growth of the tectonic main structures: anticlines, synclines and high-angle normal faults.

<u>*Sediment deformation and failure affecting the late Holocene mud wedge*</u>

On the Adriatic continental shelf the late Holocene highstand mud wedge (HST) prograded under the influence of major rivers, after the attainment of the present sea-level highstand (about 5.5 cal kyr BP). The thickness distribution of the HST reflects the location of major deltas on the western side of the basin and the geostrophic circulation, which prevents more uniform sediment dispersal toward the center of the basin. Very high sediment accumulation rates (1 cm/year) resulted in a total thickness of the late-Holocene HST up to 35 m thick. Gas impregnation is common in the topset region and occurs at very shallow levels (a few meters) below the sea floor. This thick and rapidly-deposited mud wedge is affected by sea floor and subsurface undulations and/or mud reliefs over a consistent portion of its extent. Our goal is to determine if, and to what extent, these features can be attributed to sediment deformation and failure of limited displacement. The difficulty in interpreting the origin of these puzzling features is becoming increasingly evident in many areas and several Authors suggest a mixed origin where localized sediment failure is accompanied by upslope growth and migration of large-scale bedforms through the activity of bottom currents. The study of these features is particularly relevant in the case of a prodelta environment (as in the Adriatic) because if sediment deformation plays a role it is clear that it is necessary to evaluate the associated potential risk for coastal towns and infrastructures. This is a complex problem requires an integrated use of seismic reflection profiles, high-resolution swath bathymetry and sediment properties. Our work in the GNDT project contributed new and complementary data to those that have been acquired under the COSTA project funded by the EU. In particular, the GNDT project allowed the acquisition of key morpho-bathymetric information through two high-resolution multi-beam bathymetric surveys (using a Simrad EM3000 multibeam) in two representative areas (150 km^2 and 190 km^2 offshoree Ortona and Vieste, respectively) characterized by contrasting thickness and deformation styles of the late-Holocene mud wedge.

In sections perpendicular to the coast, the late-Holocene mud prism shows an overall progradational geometry and a basinward downlap termination above a thin basal unit recording condensed deposition between 5.5 and 3.7 cal. kyr BP, in turn floored by a regional downlap surface (the maximum flooding surface, mfs). The sediment affected by deformations is entirely muddy and variations of amplitude in the seismic reflectors and/or seismic wipe-outs evidence the presence of shallow gas (likely methane), often trapped in very shallow levels or at the top of the thin basal condensed unit. Both high-resolution CHIRP-sonar profiles and seafloor images (multibeam and side scan sonar surveys) show that: all the evidences of deformation

occur only where the basal unit of the HST is disrupted and affected by geometries that are consistent with fluid escape processes. This relationship suggests that the basal surface acted as a weak layer for sediment failure; elongated mud-reliefs occur in areas where the HST prograding wedge decreases in thickness towards deeper waters. The mud reliefs (either buried or exposed at sea floor) are elongated features that have an acoustically transparent core on seismic profiles and do not appear random in spatial distribution. These reliefs occur in water depths greater than 70 m in two main stratigraphic settings (Fig. 1): a) seaward of main depocentres (35 m) of the late-Holocene mud prism, in areas characterised by shore-parallel seafloor crenulations and on a basal surface sloping seaward typically less than 0.2° (offshore Ortona); or b) seaward of areas of thinner late-Holocene sections but relatively steeper gradient (> 0.5°) on the basal surface; the increase in basal gradient is caused by the occurrence of buried basement highs (offshore Vieste). The two swath-bathymetry surveys revealed (Fig. 2): 1) a non-random distribution of the reliefs in plain view (most seem to be disposed in elongated stripes that are perpendicular to the regional contour); 2) an orientation of most of individual relief crests in a direction subparallel to the regional slope. Complementary seismic-stratigraphic and core data from the same areas show that only mud is encountered within, at the base and below the late-Holocene HST; geotechnical properties on the basal weak layer are extremely variable and consistent with the role of this surface as a mobilization horizon. These reliefs can best be explained as fluid-escape features related to one or repeated events of sediment mobilization. After they form, these features act as obstacles to bottom currents flowing parallel to the coast and depositing mud preferentially on the upcurrent flank of the reliefs. Very precise (century-scale) stratigraphic studies indicate that the observed features formed before the onset of the Little Ice Age but it is not yet clear whether the reliefs formed in one or more generations.
Increasing attention is being paid worldwide to the kind of features studied in the Adriatic. The Adriatic study area offers the advantage that these features occur in shallow water and are therefore better resolved on high-resolution seismic profiles (50 cm vertical resolution) and swath bathymetry (1-5 m grid resolution). The mud reliefs described on the Adriatic shelf are not commonly observed on continental margins for two possible reasons: 1) the reliefs develop as a transitional deformation that is removed anywhere a more thorough downslope translation takes place; 2) if occurring in deeper waters, these features are hardly resolved, because of limited spatial resolution on conventional seismic surveys, and would appear as a set of overlapping diffraction hyperbolae.

3) Modelling of tsunamis

Local coordinator: Stefano Tinti

The research activities of the second year of the three-year project of the Research Unit of the University of Bologna (**UNIBO**) regarded two distinct phases conducted side by side: the former concerning simulations of tsunamis induced by earthquakes, the latter on tsunamis induced by landslides.

As regards the first issue, two historical tsunamis have been taken into account: the 1905 Calabrian tsunami and the 1693 Eastern Sicily tsunami. The analysis of the 1905 Calabrian tsunami has been completed. The earthquake caused more than 550 casualties and about 300,000 homeless. The tsunami was not disastrous, but large enough to produce effects that were seen along the Calabrian coasts and in the Tyrrhenian part of the Messina Strait. As for many other earthquakes associated with marine or near-shore sources, the identification of the genetic fault with traditional seismic methods is problematic and numerical simulations of tsunamis can expectedly give a significant contribution. The results have been illustrated in a paper (Piatanesi and Tinti, 2002). In our analysis three possible sources taken from the known active seismogenic faults have been considered, namely the Vibo Valentia fault, the Lametia fault and the Capo Vaticano fault. These faults cause exclusive or predominant subsidence of the sea floor and consequently an initial depression of the sea surface. Tsunami propagation has been performed through a hydrodynamical model of the University of Bologna. The results achieved so far show that Lametia fault can be ruled out as the responsible source since it generates a sea perturbation that is too weak. On the other hand a clear discrimination between the two remaining faults cannot be made because both are capable to produce a sizeable tsunami that fits most, though not all, historical observations. Although the agreement between computed and observed data is not full, it is believed that a clever tuning of the source parameters is a remedy sufficient to improve or even to eliminate discrepancies. An important finding of the studies on the Calabrian tsunami concerns what has be learnt on the propagation characteristics of the South-Tyrrhenian basin. From simulations it comes out that, irrespective from fault orientation, a considerable amount of wave energy produced in the Gulf of St.Eufemia is trapped in a narrow coastal band and propagates northward. Conversely, southern coasts are partially protected by Capo Vaticano. Further, the Aeolian islands are observed to act as a screen preventing the westward propagation of the tsunami and protecting the Palermo (Sicily) coastlines. Moreover, the tsunami does not enter significantly the Messina Strait, since the northern entrance is narrow and low-depth, determining back-reflection rather than transmission of tsunami waves.

Simulations of the 1693 case are being performed on finite-element grid that has very fine resolution near-shore in order to study the effect of the waves in the coastal belt, with special attention to the bay of Augusta, that was greatly affected by the tsunami. The genetic fault that has been used is the one that was proposed in the GNDT project Catania, but very soon also the faults identified by the marine survey carried out within the present project by the **IGM1** unit will be considered. Indeed, the main focus of the undertaken tsunami research pointed more to the propagation aspect of the waves toward the coast and to their interaction with the today's breakwaters and jetties bordering the harbour of Augusta rather than to their generation offshore. The preliminary numerical results show the sheltering effect of the breakwater on the tsunami waves, which is partially unexpected since what is known from experience on Pacific ocean tsunamis is that the harbour breakwaters are effective in sheltering from the short wind waves but inefficient against tsunamis. Therefore this finding deserves further investigations.

According to the project programme, the research focussed also on the tsunamigenic earthquake in the Messina Straits. Simulations of the 1908 tsunami confirm the results of our previous studies, that is the tsunami source cannot be confined within the straits: the earthquake fault compatible with tsunami data is bnger than the fault deduced in studies of the '80s on the basis of earthquake data.
These results have been presented in the ESC General Assembly that was held in September 2002 in Genoa and in a scientific paper (Tinti and Armigliato, 2003).
The second phase concerns the study of tsunamis generated by landslides and requires developing a code based on a Lagrangian approach to describe the dynamics of the landslide body. The **UNIBO** unit made use of a 1D code developed in recent years. In the second year the research undertaken in the first year has been continued: this research has extended the 1D code to 2D cases, that is to cases where the transversal scale of the body is not negligible compared to the longitudinal size. The analysis of the Vajont case history (1963) has been continued: the slide mass has been partitioned into a 2D matrix of blocks, instead of a 1D chain of blocks, interacting each other, and a code solving the equations of motions in a local curvilinear co-ordinate system has been implemented, that, beyond the basal friction, takes also care of the water resistance: this term had effect for the Vajont body that displaced disastrously the water mass contained in the Vajont reservoir, and is also important for landslides generating tsunamis in the sea. Simulations with the 2D code are under development. Results concerning the Vajont slide simulations have been presented at the EGS XXVII General Assembly in Nice, 21-26 April 2002 (Tinti et al., 2002).

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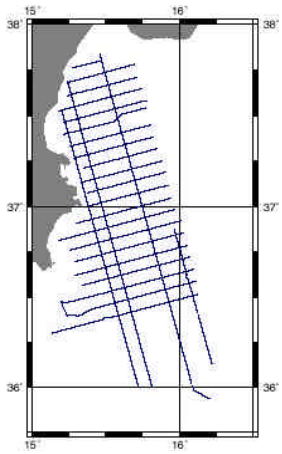
Conclusion

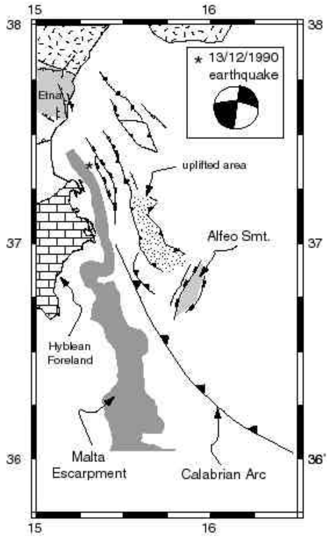
The work carried out so far by unit **IGM1** has allowed to better define the nature and geometry of the fault system along the Eastern Sicily Escarpment (Argnani and Bonazzi, 2002; Argnani et al., 2003). The picture that emerges is rather different from what previously described in the literature and the quality of the data will allow a more accurate seismo-tectonic characterisation of the region. The analysis of seismic data is continuing and we are preparing maps of the thickness and base of both the Plio-Quaternary sedimentary cover and of the sediments that show syn-tectonic growth within the basins. This will allow to outline the sedimentary depocentres and to identify the most active segments along the faults. In addition, to check the effect of a more realistic fault geometry, a simplified scheme of the fault system of the Malta Escarpment has been used by the unit **UNIBO** to input a revised modelling of the 1693 earthquake and tsunami. The faults of the previous modelling (Piatanesi and Tinti, 1998) were, in fact, only loosely constrained. The modelling work is currently ongoing.

Aspects of deformation and failure affecting late Holocene sediments in the Central Adriatic have been addressed by unit **IGM2**, with particular attention to the role played by the escape of fluids and to their morphological expressions.

Unit IGM1 - Figures



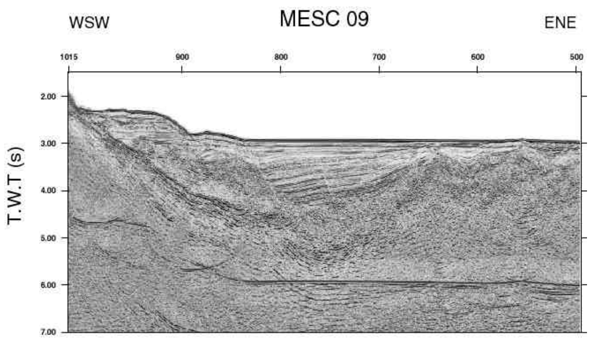
a)



b)

a) Map of seismic profiles acquired during the MESC 2001 cruise along the eastern Sicily escarpment.

b) Simplified structural map along the eastern Sicily slope and adjacent regions. Random dashes indicate the outrcopping Calabrian Arc terranes, whereas the foreland units outcropping in the Hyblean region are represented with brick pattern. Lines with ticks or black rectangles represent extensional faults, whereas lines with black triangles are thrusts and reverse faults. Contractional reactivation occurred where extensional and thrust symbols are present along the same line. A morphologic relief of up to 3 km is accomplished across the Malta Escarpment. Inset shows the focal mechanism obtained for the 13 December, 1990 earthquake (Giardini et al., 1995; Amato et al., 1995).



Example of migrated seismic profiles crossing the eastern Sicily escarpment from west to east. Note the east-dipping extensional fault system and the related half graben basin filled by sediments.

Unit IGM2 - Figures

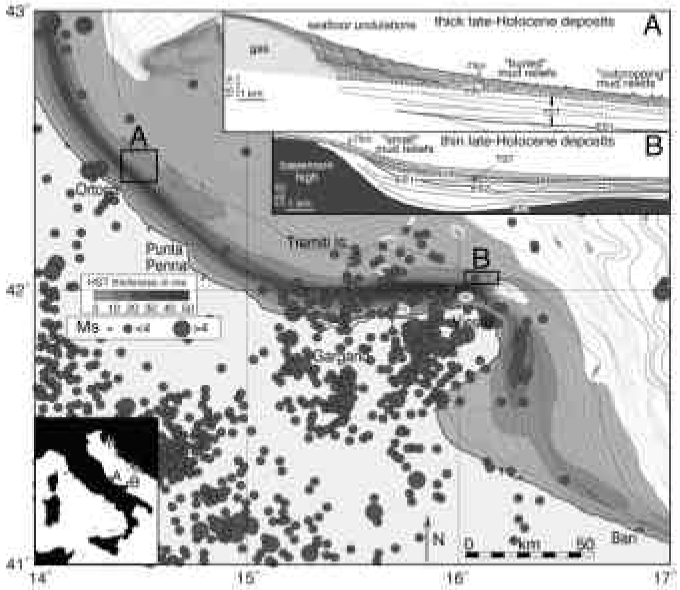


Figure 1. Shore-parallel thickness distribution of late-Holocene mud wedge. Epicenters in historical times (1000-2002 AD) http://emidius.mi.ingv.it/. Insets A and B depict contrasting geologic setting of the two areas where mud reliefs form at the base the HST shown in Figure 2.

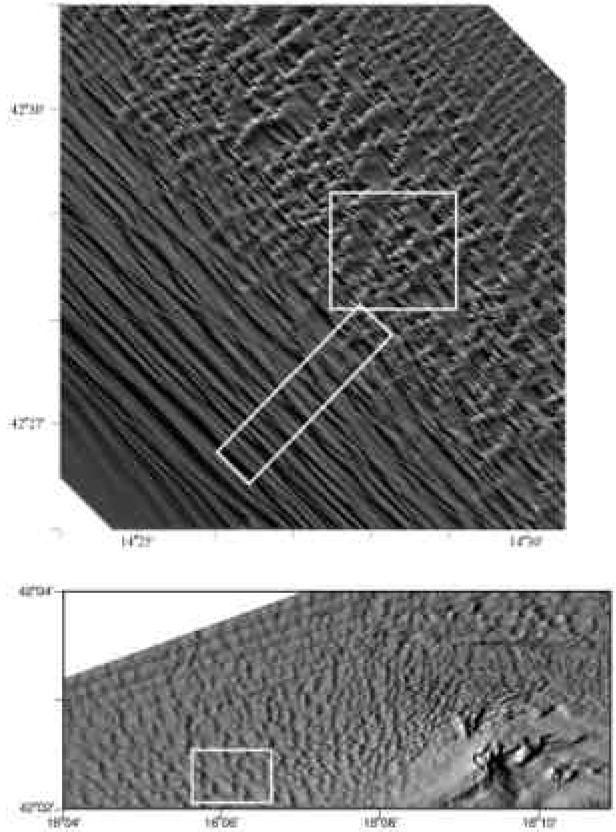


Figure 2. Swath bathymetry from EM3000 surveys offshore Ortona (A, upper) and Vieste (B, lower). In both areas, relief size decreases seaward. A): preferred NE-SW orientation of relief clusters seaward of contour-parallel undulations (low left corner). B): preferred N-S orientation of relief clusters with contour-parallel crests becoming increasingly evident towards the east around a basement high (low right corner) located NE of Gargano Promontory.