REPORT AND PRELIMINARY RESULTS OF POSEIDON CRUISE P336:
CRESTS - Cretan Sea Tectonics and Sedimentation,
Heraklion, Heraklion, 28.04. - 17.05.2006.
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Preface

The expedition P336, termed CRESTS (=CREtan Sea Tectonics and Sedimentology), takes the German research vessel R/V Poseidon into the Cretan Sea for the first time. Main reason for this regional target is the exceptional role of the area of Crete as an exhumed forearc-high in a compressional tectonic setting. CRESTS aimed to study sediment stability along the northern slopes of the island of Crete and adjacent basins of the Cretan Sea in the north. The study area is bordered by the volcanic arc of the Aegean islands, which themselves represent slope instability hazard here. The scientific party gathered experts in the fields of geophysics, geology, geotechnics, and modeling of geosystems, largely from RCOM and University of Bremen, and additionally from ETH Zürich, Switzerland, and HCMR, Greece.

The main interest in the area arises from the fact that the Cretan Margin is an ideal natural laboratory to study a variety of neotectonic and sedimentary processes, which include

- (micro)seismicity and active extensional faulting,
- large-scale transpressional movement,
- rapid sedimentation and turbidites, and
- episodic submarine landslides.

In addition, we aimed to identify potential sites of active fluid venting, which are probably linked to the deep-seated faults of the exhumed Cretan forearc high.

In a broader context, the cruise P336 stands in a line of investigations in the entire Hellenic subduction zone. This area is predestined for researchers interested in active convergent margins, mostly because the subduction zone processes are accentuated here due to the indentation of the Libyan promontory south of Crete. So far, a lot of research has been dedicated to the region south of the island, especially the Ionian and Herodotus basins and the Mediterranean accretionary complex. This included national and international seagoing campaigns with various objectives, one of which was the highly successful ODP drilling leg 160. The island of Crete itself has further been considered a target for onshore ICDP (= International Continental Drilling Program) drilling. However, the Cretan Sea, which is situated between the Aegean islands and the island of Crete, represents the landwardmost portion of the forearc, but was so far neglected as a research target. With CRESTS, we now wanted to address some of the open questions of this portion of the highly dynamic collisional setting between the African and Eurasian plates.
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1. Abstract

Cruise P336 CRESTS with R/V Poseidon studied the eastern portion of the Cretan Sea, north of the island of Crete, Greece. This area of the eastern Mediterranean Sea represents the northernmost portion of the forearc region of the Hellenic subduction zone, located immediately south of the volcanic island arc (Aegean islands of Santorini, etc.). Owing to the rather complex tectonic history with Crete having been exhumed from about 20 km depth to its present day’s position, the geodynamic as well as mechanical environment is rather complex. Crete is currently extending in both E-W- and N-S-direction, with a lot of microseismicity, neotectonic movements, and mass wasting as a result.

Landslide processes, turbidites, and other consequences of slope instability were the aim of this RCOM expedition into two subbasins of the Cretan Sea, the Heraklion and Kamilonisi basins. An area of approximately 2450 km2 was surveyed in a multi-methodological approach, using multibeam swathmapping, seismic reflection systems (3.5 kHz and 16-channel seismics), in situ measurement of strength, pore pressure and heat flow, and gravity coring for laboratory studies on board and onshore. The various measurements can be separated into 6 small study areas A-F, which included the western slope of the Heraklion Basin (area A), the eastern margin of that same basin (area B), a tectonic high termed “Horseshoe structure” (area C), a large landslide complex at the NE’ Cretan Margin (area D), a small, but steep landslide scarp structure further east (area E), and a deep site in the Kamilonisi Basin in the east (area F).

Preliminary results of cruise P336 are here wrapped into the following statements. All aspects will be deepened by more detailed post-cruise research.

A large number of landslides and other mass wasting deposits has been identified on seismic reflection profiles. The materials recovered have relatively high porosities (ca. 60% on average), but otherwise lack direct evidence of amalgamation.

Depositional events such as Sapropels S1, S3, or the Minoan volcanic eruption cause strong deviations in most physical properties (MSCL core logger) and are harder than their surrounding sediments.

The Horseshoe structure shows anomalously high thermal gradients, suggesting tectonic activity at depth. Sediment cores fail to explain or hint towards the nature of this feature.
2. Introduction

The population of active convergent margins is blessed with repeated large subduction thrust earthquakes, landslides, and other threats for human life, ecosystems and infrastructure. Given that 60% of the Earth's population lives within the frontal 50 km of the coast, enormous scientific and economic efforts are hence undertaken to shed light on the processes responsible for such ocean margin geohazards. Given the highly dynamic setting and complexity of collision zones, many processes are still poorly understood. Amongst the shortcomings in understanding collision zones such as the eastern Mediterranean, the temporal variation of deep-seated processes as well as their manifestations at shallower levels is the emerging key question. This addresses both landslides and other mass wasting deposits, and sites of fluid venting, possibly being of deep origin.

The Hellenic Subduction Zone (HSZ) in the Eastern Mediterranean Sea represents a mature collision zone where African crust is thrust beneath Eurasia (Fig. 1). As a consequence, a wide backstop area of partly old accreted strata (marine), partly HP/LT rocks (exhumed island of Crete as forearc high; Altherr et al., 1982), an extensional submerged landward forearc (Cretan Sea), and a volcanic arc and backarc basin (Aegean Sea) evolved (Le Pichon & Angelier, 1979). Since many scientists from different fields have identified the HSZ as a promising research target, both seismic onshore and offshore networks (Harjes et al., 1997; Meier et al., 2004; Bohnhoff et al., 2006) and deep-sea cables (e.g., NESTOR) already exist. As a result, many research initiatives within the EU ‘HERMES’ project as well as observatory science programmes (e.g., ‘ESONET’ Network of Excellence) focus on the HSZ. Scientific drilling has been carried out earlier (e.g., ODP Leg 160; Emeis et al., 1996) and has also been proposed for the near future (e.g., Kopf et al., 1999). Most of the targets neglect the Cretan Sea so that an initiative by combining offshore (IODP = Integrated Ocean Drilling Program) and onshore/shallow water (ICDP) targets have been proposed (Zoback & Emmermann, 2006; Kopf & Bohnhoff, 2006).

The CRESTS expedition focuses on two main achievements:

1. Study of slope instability and related geohazardous processes at the northern Cretan Margin and, to a lesser extent, the slopes of the Aegean volcanic islands;

2. Acquisition of site survey information for ICDP Glad800 drilling, or alternatively, IODP MSP[G1] (i.e. mission-specific platforms) drilling in the area.
While the first is one of the key targets in Research Area C of RCOM Bremen, the latter ties the research carried out with R/V Poseidon to international initiatives on an European and global scale.

Fig. 1. Schematic map of the Eastern Mediterranean Sea and surrounding land masses where Africa and Eurasia collide. Red box shows the P336 study area (see also Figure 6).

If we regard the Eastern Mediterranean, the most prominent feature is the arcuate, up to 200 km wide, 1500 km long Mediterranean Ridge accretionary complex south of the island of Crete. The island acts as an abutment, or backstop, to the accreted strata, and comprises a stack of nappes of variable lithologies (for details, see e.g. Altherr et al., 1982; Fassoulas et al., 1994). Mechanically, the situation is rather complex, because Crete is extending in both E-W- and N-S-direction, being potentially landslide prone because of its neotectonic movements and frequent micro-earthquakes. Landsliding occurs along the steep to moderately inclined slopes north (i.e., study area of cruise P336) as well as south of the island.

Landslides are one of the most immanent hazards in the Cretan Sea, both triggered by the tectonic movements of the Cretan block in the south (e.g. Chronis et al., 2000a, 2000b) and flank collapse of volcanic islands in the N (e.g. Dominey-Howes et al., 2000). Although the inherent mechanisms and factors governing slope stability and submarine landslides are known, their temporal and spatial variability is poorly understood. In fact, the exact trigger mechanisms of
only a few submarine landslides are known with certainty (Mienert et al. 2003). In general, submarine landslides occur due to an increase in loading on a slope, which may in turn lead to an increase in shear stress, relative to shear strength. Possible trigger mechanisms for submarine landslides include sea level change, high sedimentation rates, oversteepening of the slope gradient, wave activity (especially during storm events), gas hydrate dissociation, pore pressure increase, tsunamis, and earthquakes. Since several of the above triggers may apply for the Cretan Margin, one of the key objectives of cruise P336 CRESTS was to shed light on the sedimentary and tectono-physical environment using geophysical, sedimentological and in situ methods.

3. Scientific objectives

Expedition P336 using R/V Poseidon aimed to carry out a multidisciplinary investigation with a group of European geoscientists including geophysical data acquisition (seafloor mapping, seismic reflection), sediment coring, in situ CPT, and heat flow measurements across the northern Cretan Margin. The scientific motivation for the proposed work is best outlined with respect to the understanding of parameters controlling sediment physics, and ultimately geohazards such as landslides and other mass wasting events. The two main players in weakening a fault as to where it may slip are weak mineral phases and excess fluid pressures. While the first are mainly restricted to the clay mineral group (with the weakening being enhanced by their preferred fabric alignment), the latter may originate from various processes in nature that cause net water release, or water influx into a system. These include basically all geological settings onshore and offshore, and are as diverse as mineral transformation reactions (clay minerals, opal-quartz reactions, etc.), diagenesis, hydrothermal alteration, lateral flow, mud volcanism, tectonic/tidal/sedimentary/glacial loading, weathering processes, or rapid sediment accumulation.

During P336, we followed a multi-methodological two-phase approach:

In a first step, we used multibeam swathmapping and different seismic reflection methods to identify landslide and mass wasting deposits.

Based on these data, we aimed to characterise these deposits by in situ measurements and sampling/laboratory methods in a second step. The first included Cone Penetrating Testing (CPT), where pore pressure and sediment strength are obtained, and sub-surface heat flow measurements, whereas the latter were gravity coring and laboratory studies on board (sedimentological description, petrography, physical properties).
Finally, shore based studies will include additional geotechnical physical property testing, pore water geochemistry, and possible dating of the mass wasting events.

4. Geological setting

4.1. The Hellenic subduction zone (HSZ)

The Eastern Mediterranean hosts one of the most prominent retreating convergent margins worldwide that was capable to generate M>8 earthquakes (e.g., 365 AD, western Crete) and exhaustive volcanic eruptions (e.g., 1170 BC, the so called Minoan eruption of Santorini volcano) in historic times. The Hellenic collision system is an ideal natural laboratory to study subduction-collision that is well recorded over the past ca. 35 million years. Many manifestations of the ongoing collision are directly linked to the Alpine orogenesis, which terminated in the Miocene (Mercier et al., 1979; Le Pichon & Angelier, 1979; McKenzie, 1978). The geodynamic processes included an intermittent stage of micro-continent collision between about 30 and 20 Ma, followed by break-off of the subducting slab, trench roll-back, and incipient collision with the passive African margin today (Fig. 2; e.g. Thomson et al., 1998).

![Fig. 2. Schematic cross section of the Mediterranean Sea with the Eurasian Margin in the N and the African passive margin in the S. See text. Modified after Kopf et al. (1998).](image)

The island of Crete represents a horst structure developed within the last 5 million years in the central forearc. Owing to its evolution, it comprises of various diagenetically or metamorphically altered sequences of primarily sedimentary origin (Fassoulas et al., 1994; Kopf et al., 1999). As a result of the above mentioned stack of thrust nappes of the Pindos and Gavroro units (diagenesis to low-grade metamorphism), which are underlain by the HP-LT rocks of the Phyllite-Quartzite-
and Plattenkalk units, a km-thick sequence of rock is accessible at various levels (e.g. Avigad & Garfunkel, 1991; see Figs. 2, 3). Both rapid exhumation of thrust sheets to form the Crete forearc high and the extreme thinning of the frontal part of the upper plate continental crust are believed to have been accommodated by southward retreat "roll-back" of the downgoing slab for up to ca. 19 Ma (Thomson et al., 1998). Extensional tectonics has migrated southwards with time, and now affects the southernmost part of the backstop off Crete (Fig. 2). The transition from extension at the leading edge of the overriding plate (Cretan forearc), to compression in the backstop setting is particularly important as it remains unclear how the two, apparently paradoxical, processes of extension in the upper part of the forearc and compression along the converging plate interface are coupled.

![Diagram](image)

**Fig. 3.** Schematic overview of the evolution of the late Neothethyan ocean until now.

The Pindos ocean finally closed, driving allochthonous units over the Gavrovo platform unit; 35-40 Ma bp; B) the Gavrovo unit carbonate platform was accreted to the base of the overriding thrust stack and the Phyllite-Quartzite and Plattenkalk units began to be overthrust; ~30 Ma bp; C) Phyllite-Quartzite and Plattenkalk units were subducted to c30 km depth and metamorphosed to high pressure; begin of subduction of Neotethys; 20-25 Ma bp; D) Exhumation of PQU and Plattenkalk at ~19 Ma bp; beginning accretion of the Mediterranean Ridge was initiated. Modified after Kopf et al. (1999).

On Crete, frontal accretion and underplating was active whilst the hinterlandward part of the stack was detached, unroofing metamorphic rock in the process which had been at >30 km depth beforehand (i.e., Phyllite-Quartzite- and Plattenkalk units). After slab breakoff, buoyant sedimentary units underthrust the nappe pile of Crete along a shallow-dipping detachment fault, associated with tectonic uplift and formation of a forearc high which then acted as an initial
'rigid' backstop to sediment being offscraped from the Neotethyan seafloor (Fig. 3). Plate kinematic reconstruction suggests trench "roll-back" and accretion of a wide accretionary prism at the leading edge of the Eurasian Plate, whilst the forearc of Crete underwent extensional deformation during the Neogene.

**Fig. 4.** Geodynamic situation in the HSZ: A) Compressional (W) and transpressional/oblique subduction along the deformation front south of Crete; B) overall geodynamic situation around Crete and its vicinity. Note the extension in both N-S- and E-W- direction despite the general situation of an initial continent-continent collision.
To its south, the main features are shown in Figures 2 and 5, i.e. the North African passive margin in the S, a broad accretionary complex (~100-120 km) overriding it, and its backstop domain (~80 km width) just south of the forearc-high (Crete). The backstop domain, also known as “Inner Ridge” of the broad Mediterranean Ridge accretionary complex (Fig. 5), is strictly speaking a depression (i.e. forearc basin). It is part of the so called “Hellenic Trench” (comprising the Plini and Strabo “Trenches”), a sediment-starved suture where the accretionary wedge is backthrust over the Inner Ridge strata (Camerlenghi et al., 1995; Chaumillon & Mascl, 1997; Kopf et al., 2003).

In the N, Crete is bordered by the Cretan Sea, the moderately active volcanic arc (e.g. Santorini and adjacent islands), and the Aegean Sea back-arc basin. Fluid venting, sometimes from great depth and with enigmatic geochemical signatures, is known from both the distal accretionary complex south of Crete (e.g. Deyhle & Kopf, 2001; Kopf et al., 2001) as well as the Cretan Sea north of the island (Fitzsimons et al., 1997; Georgopoulos et al., 2000). Back-arc volcanism and spreading are moderate now, however, evidence of volcanism and extension are found throughout the marine realm north of Crete (see Chapter 4.2). The volcanic arc corresponds to the southern part of the Cyclades Plateau and sills, which separate the Northern and Central from the Southern Aegean subbasins. The southern Aegean Basin, or Cretan Sea, is the largest of these depressions (e.g. Giresse et al., 2003).
4.2. The Cretan Sea

The geological structure of the Cretan Basin (Greece) is ultimately linked to the Alpine orogenesis (e.g. Le Pichon & Angelier, 1979). It is a depression with various topographic lows or subbasins, separated by ridges of variable height and strike. From W to E, they include Myrtoon Basin, main Cretan Sea, and eastern Cretan Sea subbasin. The so called Kamilonisi basin is the deepest basin in the east, located south of the Cyclades plate and volcanic chain, and reaches up to ca. 2500 m water depth (Fig. 6; see also Stavrakakis et al., 2000).

Fig. 6. A) Map showing Cretan Sea sub-basins (shaded area shows region for which research permission was obtained); B) Cretan Sea bathymetric chart with the location of the working areas during cruise P336.
The main extentional phase of the Cretan basin occurred between Late Miocene and Pliocene whilst during the Late Pleistocene experienced only minimal extension phenomena (Macle & Martin, 1990). Tectonic movements still occur today, as indicated by recent seismicity and volcanic activity throughout the area (McKenzie, 1978). Geomorphologically, the Cretan Basin is an elongated depression, trending E–W; it is bounded to the north by the Cyclades Plateau, a relatively shallow (500 m) complex of islands, and to the south by the island of Crete (Fig. 1). Water depths are generally larger than 1000 m with localized deeper (ca. 2500 m) subbasins located in the eastern part of the study area (see shading in Fig. 6a). Cruise P336 focused on the Kamilonisi basin in the east and Heraklion basin in the west (Fig. 6). The south Cretan Sea has been extensively surveyed in terms of geological structure, tectonism and associated sedimentation processes during a series of research cruises carried out by the research vessels Meteor, Shackleton, Rift, Urania, Sonne and Aegaeo. The results of these surveys have been published by Jongsma (1975), Bartole et al. (1983), Anagnostou et al. (1987), Rossi et al. (1986, 1988), and Yelnikov (1990). They confirm not only the highly active tectonic setting (e.g., Lykousis et al., 1995; Perissoratis & Papadopoulos, 1999), but emphasized the variability of the hydrological and sedimentary processes (e.g., Chronis et al., 2000a; Lykousis et al., 2002; Giresse et al., 2003). On a more general level, our results will also be tied to scientific deep drilling during earlier DSDP (Deep Sea Drilling Project) expeditions (e.g. Hsü et al., 1978).

Geophysical studies in the Cretan Sea revealed relatively steep slopes of up to 4° (Chronis et al., 2000b). Still, in places, hemipelagic sediments are accumulated in shallow and mid-slope regions. Owing to the high relief and rapid sedimentation, some of these slopes are potentially unstable (e.g. Manakou & Tsapanos, 2000). Chronis et al. (2000a, b) found evidence for young landslide and mass wasting events in the youngest portion of the sedimentary succession (e.g. Fig. 7; see also their Figs. 3 and 5). On the other hand, Chronis et al. (2000b) also state that often, the continuous slope-parallel reflectors are not significantly disturbed by the syn-sedimentary faults in the area. These authors further interpreted abundant blankening in their hydroacoustic sections as zones of free methane gas.
There has been a number of paleoceanographic and sedimentological studies on the lithologies accumulating in the Cretan Sea recently (Chronis et al., 2000b; Giresse et al., 2003). From sediment cores taken in the entire Cretan Sea, four hemipelagic lithostratigraphic units in the glacial to Holocene sediments were identified (Aksu et al., 1995; Geraga et al., 2000; Giresse et al., 2003). From top to bottom, they are

1. yellowish brown bioturbated muds,
2. grey mud, mottled and bioturbated,
3. greyish, brownish to olive grey mud, >2% C\textsubscript{org}, no bioturbation, and
4. yellowish grey clayey mud, slightly bioturbated.

Units 1, 2 and 4 are further characterised by high carbonate contents of up to 60%, often as authogenically formed Mg-calcite clasts and nodules of mm-diameter (Giresse et al., 2003). The third unit coincides with an anoxic event that caused deposition of sapropel 1 (S1), which is dated to 9600 to 6400 a BP (Giresse et al., 2003). This distinct layer comprises high contents of organic matter, in places exceeding 3% (see Emeis et al., 1996). Sapropels are generally a good marker since they have a dark olive gray to black colour and a wide distribution over both the Eastern and western Mediterranean Basins (see Emeis et al., 1996; Zahn et al., 1996; Cramp & O’Sullivan, 1999). The S2 deposition in the Eastern Mediterranean is dated to has occurred between ca. 23 and 55 ka BP depending on source of the study (Muerdter et al., 1984; Lourens et
al., 1996; Kroon et al., 1998; Emeis & Sakamoto, 1998). The S3 event, which is often the second sapropel layer (since S2 is missing), is dated ca. 81 ka BP. Sapropels deeper than S3 are not expected to be recovered by the gravity corer used during cruise P336 (see Ch. 5.7 below).

The mean rate of sedimentation during the Holocene has been estimated to be >15-20 cm/ka from box- and push core samples (Chronis et al., 2000b). Based on the assumption that the prominent reflector in the seismic profiles represents the base of the Holocene (18 ka), the sediment accumulation ranges around 83-250 cm/ka on the inner and mid-shelf, and 10-35 cm/ka at the outer shelf. Lower values were found by both Geraga et al. (2000; 9-10 cm/ka) and Giresse et al. (2003; 10.7 cm/ka). For deeper burial, 3.5 kHz profiles have been used to date the Pleistocene sediments (Chronis et al., 2000b).

Similar to these paleoceanographic events, there are other distinct time markers in the area. The most prominent ones are arguably the abundant ash deposits from the volcanic islands, which are particularly reliable during historic times. For instance, the very prominent “Minoan” eruption of the Santorini volcano, Thera island, has been dated to be 3370 years BP (Pichler & Friederich, 1976). Since the volcano erupted violently for several days, causing a collapse of its entire central and southern portion, a huge deposit has been postulated for the SE’ sector relative to the island. In fact, Giresse et al. (2003) cored the event successfully in 5 out of 7 push cores (see their Fig. 4). The several cm-thick layer comprises black to light grey, sand- to gravel sized components of rhyolitic to dacitic composition. In other places in the Cretan Basin, ash layers of similar composition have also been related to the Thera event (Keller et al., 1978; Warren & Puchelt, 1990). The layer has also been recovered during other eastern Mediterranean campaigns in various places (refer to Halbach et al., et al., 1994; Aksu et al., 1995; de Rijk et al., 1999; Geraga et al., 2000).
5. Methods

5.1. Multibeam Swathmapping

(I. Kock, M. Reichelt, S. Krastel-Gudegast)

_Echosounder_

During the P336 cruise, the ELAC _SEABEAM 1050_ multibeam echosounder was used for a continuous mapping of the seafloor. The echosounder consists of several units: (i) a transmit and a receive transducer array is fixed in a Mills cross below the keel of the vessel; (ii) a preamplifier unit contains the preamplifiers for the received signals; (iii) the transducer unit contains the transmit and receive electronics and processors for beam-forming and control of all parameters with respect to gain, ping-rate and transmit angles. Furthermore, the system monitors via serial interfaces the ship’s motion, such as roll, pitch and heave, external (GPS) time and vessel position. A high performance PC is used as an Operator station. The Operator station processes the collected data, applies standard corrections, displays the results, and logs the raw data to internal or external disks.

_SEABEAM 1050_ uses a frequency of about 12 KHz with a whole angular coverage sector of up to 150° (75° per port-/starboard-side). One ping is sent and the receiving signal is formed into 191 beams by the transducer unit through the hydrophones in the receiver unit. The beam spacing can be defined as equidistant or equiangular, or a mix of both. Running the system in full 150°-configuration the system maps a swath of roughly 4-5 times the water depth. The ping-rate depends on the water depth and the runtime of the signal through the water column. Depending on the state of the sea, an opening angle of 60-70° was used, restricting the coverage to a max. 14 km wide swath to gain a more continuous spacing of beams on the ocean floor. The spacing within these limits was controlled automatically by the echosounder system.
5.2. Water Sound Velocity (CTD)

(S. Stegmann)

To convert the recorded travel times into depth several water velocity profiles were obtained with the shipboard CTD and entered into the operator SUN workstation. During the cruise data handling of the bathymetric data was done by the ship’s system administrators. Each beam was corrected for ray bending using the appropriate sound velocity profile and the ship’s motion and were finally stored with GPS position. To generate maps the data were averaged using the nearest neighbour gridding algorithm of GMT (Wessel & Smith, 1991) and displayed with the GMT mapping software. However, data were not edited for bad beams. Final data editing of the data has to be done in a post-cruise phase.

Fig. 8. CTD on board R/V Poseidon returning from deployment.
To obtain information about the distribution of the water masses along the Iberian coast a CTDOS (Conductivity, Temperature, Depth, Oxygen, Salinity) profiler combined with a rosette water sampler (24 Niskin bottles, 1 l volume, HydroBios) was used at one site at the beginning of cruise P336 (Fig. 8). Main reason was to determine the influence of saline, warm Mediterranean waters on the echosounder and geophysical acquisition systems (e.g., for the conversion of the recorded ELAC travel times into depth values).

5.3. 3.5 kHz profiling

(S. Krastel-Gudegast, I. Kock, M. Reichelt, M. Strasser, M. Thölen)

A conventional 3.5 kHz system was used during Poseidon-Cruise P336 for imaging the uppermost part (10s of meters) of the sedimentary section. Four transducers were mounted on a catamaran (Fig. 9), which was towed on the port side of the vessel (see Ch. 5.4.2). The transducer was connected with a Geoacoustics GeoPulse Transmitter 5430a via a cable. The transmitter generated a pulse with a frequency of 3.5 kHz. The pulse cycle was generally two except for the first few lines, where a pulse cycle of four was chosen. The shooting rate was 1 sec for water depths up to ~700m, 2 sec for water depths between ~700m and 1450m, and 3 sec for water depths > 1450m.

The incoming signal was processed by a Geoacoustics GeoPulse Receiver. The data were filtered with a band pass (2 kHz – 5 kHz) and the gain was adjusted to the signal strength. The analogue data were recorded by a DAT-Recorder together with the trigger and the GPS-signal. An Octopus 360 Sub-bottom processor was used for visualisation and digitizing of the incoming signals. Due to the limited penetration of the signal into the sediment, only a small depth window close to the seafloor is displayed and recorded.

The depth window was chosen by setting the sweep length and delay. The sweep length was 200ms during the entire cruise, while the delay was adjusted to the water depth. The selected time window was also digitized with a sampling rate of 24 kHz. The digitized data were recorded in SEGY-format on a DAT-Recorder. The processed data were plotted on a printer for immediate date control and evaluation. The main tasks of the operators are system and quality control and the adjustment of the upper limit of the reception window.
3.5 kHz data were generally collected along all the seismic lines. As data quality strongly depends on the sea state, we did not deploy the system between the evening of May 3rd and the morning of May 5th due to strong winds. Hence no 3.5 kHz data were collected for the seismic profiles GeoB06-140 to GeoB06-153 (see Ch. 6.3 below).

5.4. Seismic reflection

(S. Krastel-Gudegast, N. Kaul, B. Heesemann, I. Kock, M. Reichelt, M. Thölen)

With the high-resolution multichannel seismic equipment of Bremen University, small scale sedimentary structures and closely spaced layers can be imaged on a meter scale, which can usually not be resolved by means of conventional seismic systems. During R/V Poseidon Cruise P336, a Mini-Generator-Injector (GI) airgun with reduced chamber volume (2 x 0.25 l, 50-500 Hz) was used as seismic source. Data were recorded with a 101-m-long 16 channel
streamer with 8 hydrophones per group and a channel distance of 6.25 m. Figure 10 gives an outline of the system setup as it was used during R/V Poseidon Cruise P336.

![Seismic system setup during cruise P336.](image)

Fig. 10. Seismic system setup during cruise P336.

**Seismic Source and Compressors**

During seismic surveying, the Mini-GI-Gun was towed at the port side approximately 12.5 m behind the ship's stern (Fig. 11). The gun was connected to a bow with the Mini-GI-Gun hanging on two chains 30 cm beneath. An elongated buoy, which stabilized the guns in a horizontal position at a water depth of ~70 cm, was connected to the bow by two rope loops. The Injector was triggered with a delay of 20 ms with respect to the Generator signal, which basically eliminated the bubble signal.

Air was provided by two portable KAP14 Bauer compressors, which provided 380 l/min of air each. The Mini-GI-Gun was shot at an air-pressure of ~140-150 bar. The shooting rate was 8 seconds. The ship speed during seismic profiling was ~4 kn resulting in a shot-point distance of ~17 m. The geometry of source and receiver systems during the measurements is shown in Figure 11.
The reflection seismic data are obtained using a 101-m-long streamer. It is a 16 channel unit built by Teledyne Exploration Co. in 1993. The system comprises four parts, a 101 m active length, a 25 m stretch section, a 120 m tow leader, and a 75 m deck leader (Fig. 12). Only 12.5m of the tow leader were in water during cruise P336. The active streamer section is separated into 16 groups with 8 hydrophones each. Within one group the hydrophones are 0.78 m apart building a 6.25 m long unit. The whole unit is stored and operated from a manual winch midship of R/V Poseidon. Tail rope is 20 m. The distance between the sips stern and the midpoint of the first channel is ~ 48.5 m.

**Streamer**

![Fig. 11. Deck and seismic gun setting during cruise P336.](image1)

![Fig. 12. Schematic sketch of the seismic acquisition configuration](image2)
Data acquisition systems

The data of the 101-m-long streamer were recorded by means of a 60-channel Geometrics Strataview, which allows a maximum sampling rate of 0.25 ms at 24 bit resolution. Only 16 channels were recorded during the cruise. The seismograph allows online data display (shot gather) and data storage on internal hard disc in SEG-2 format. Data were recorded with a sampling rate of 0.25 ms over an interval of 2 seconds. Pre-amplifiers were set to 48 dB; low cut filter to 15 Hz and the anti alias filter to 1 kHz.

The internal discs allowed data storage for about 32h of seismic profiling. Thereafter it was necessary to download the files from the hard disc. This was achieved using the software package ‘roundup’, which converts the individual SEG-2 files in one SEGY file and writes the data to a DLT-tape via an SCSI-interface.

Trigger unit

The custom trigger unit used controls seismic source and acquisition systems (see Streamer). The unit is set up on an IBM compatible PC with a Windows NT 4.0 operating system and includes a real-time controller interface card (SORCUS) with 16 I/O channels, synchronized by an internal clock. The unit is connected to an amplifier unit and a gun amplifier unit. The PC runs customized software that allows us to define arbitrary combinations of trigger signals. The PC was additionally used for logging of GPS-data.

Data processing

For an immediate evaluation of data quality, brute stacks of the GI-Gun data were produced for each multichannel seismic line. Processing was done with the Vista software (Seismic Image Software Ltd) on a Laptop. The field traces 1-4 were chosen for the brute stacks due to a good signal to noise ratio of these traces. The data were filtered with a wide band pass (55/110 – 600/800 Hz) and thereafter simply summed up. These images were used for preliminary analyses of the seismic data.
5.5. Heat flow measurements

(N. Kaul, B. Heesemann)

*Heat Probe and Shipboard Operation*

On cruise P336 a temperature gradient probe (Fig. 13) from the University of Bremen, *Meerestechnik und Sensorik* was used to obtain temperature gradients with miniaturised autonomous temperature data loggers (MTL, Fig. 14; Pfender & Villinger, 2002). Five MTLs were attached at 0.7 m intervals to the strength member of the probe plus an additional one to monitor the water temperature above the weight stand.

Parameters of autonomous temperature data loggers:

- **Instruments:** 1854144C, -147C, -161C (damaged), -162C (damaged), -165C (lost), -167C, -190C, -191C, -192C, -193C, -194C (damaged)
- **Sample rate:** 1 sec
- **Recording length:** 18:03 h potential maximum
- **Spacing:** 0.7 m @ 0.78, 1.48, 2.18, 2.88, 3.58 m below the head

Measurements are made in so-called ‘pogo-style’, performing many penetrations in a row at small distances. Each penetration is carried out by raising the probe some hundred meters above the sea floor from the previous penetration, slowly moving the ship to the next penetration site, and letting the wire angle become nearly vertical before dropping the probe into the sediment for the next penetration. Once the probe is in the bottom, it is left undisturbed for 7 minutes to gain equilibrium temperature. For the penetration spacing used in this survey, transit between penetration points lasts about 20 – 45 minutes, a recording cycle in the sea floor is 7 minutes, yielding a rate of about 0.5 – 1 hour per penetration. Transit speed is governed by the trade-off between keeping the wire angle small and minimising the time between penetration points.
Winch speed during payout and retrieval of wire is 0.8-1.2 m/s. The initial penetration velocity is generally 1.2 m/s. Total weight of the instrument is app. 600 kg. Deployment of the instrument is amid ship on the port side (Fig. 13), employing a beam crane and one assistance winch. This procedure ensures safe operation even during medium sea state and minimum interference due to the ship’s vertical movement during station work. On R/V Poseidon three deckhands are necessary during deployment and three during operation since the heavy-duty winch employs one operator and two deckhands for assisting smooth spooling. Control of bottom contact is solely by load plotter. The load signal is clearly identifiable as paid out cable is less than 1000 m and cable weight is moderate. Cable diameter is 13 mm.
To achieve spatially high resolution of heat flow determinations, penetrations were usually positioned between 400 and 1000 m.

**Heat flow data reduction**

Processing temperature data includes calibration of thermistor sensors, calculation of sediment temperatures and temperature gradients, correction for probe tilt during penetration, and calculation of thermal conductivities when applicable. While the 7-minute wait is not long enough for the sediment temperatures to return to equilibrium after the frictional disturbance of penetration, it is long enough to extrapolate to an equilibrium temperature with a high degree of precision. Each temperature-time series, from each thermistor, is extrapolated to an equilibrium temperature by the program T2C (Hartmann & Villinger, 2002). Because the calibration of each thermistor by the manufacturer is only good to 0.1°C, a secondary calibration is applied. In this case it was performed in advance with reference to a high precision thermometer (Brancker) to an accuracy of better than 5 mK. Tilt angles and sediment conductivities were not measured during this survey. Recovered material from gravity corers allows determination of thermal conductivities *in vitro*.

Fourier’s law of heat conduction in one-dimension shows that heat flow (Q) is the product of the thermal gradient (dT/dz) and thermal conductivity (k). If these terms are constant over the depth of the measurements then the calculation of heat flow is trivial. However if these values
are changing proportionately to each other, as is the case for a constant basal heat flux, then heat flow can be derived from Bullard’s (1939) relation given by,

$$\Delta T = Q \sum \Delta z_i / k_i,$$

Where $\Delta z_i$ is the thickness and $k_i$ is the thermal conductivity over the i-th interval. In this case heat flow can easily be calculated as the slope of the line given by the summation. To properly calculate the temperature gradient a correction for the penetration tilt angle is applied. In most cases the tilt angle is less than 10° and the tilt correction is modest. Thermal conductivities are sensitive to the sediment porosity over the depth range of the measurements. Thermal conductivities are summarized as harmonic means.

### 5.6. CPT Testing

(S. Stegmann, A. Kopf)

On R/V Poseidon Cruise P336, we used two RCOM free-fall CPT probes. Cone Penetration Testing (CPT) is an effective method for in situ measurements of these geotechnical parameters with one instrument (Lunne et al., 1997). Two different marine CPT probes measure sedimentary strength (tip resistance, sleeve friction), pore pressure, tilt and acceleration. Both CPT systems rely on an industry 15 cm$^2$ piezo-cone with the sensors at the tip and a pressure housing containing a microprocessor at the top. In addition, deceleration and tilt are monitored for vertical profiling of the penetrated sediment column. The lightweight (40-170 kg), shallow water (200 m depth) lance works completely autonomous with a volatile memory and battery package. The sturdier, deeper water (currently 2500 m depth, anticipated 4000 m depth) system uses both power and telemetry for real-time data transmission from the research vessel (here: Poseidon), although spare batteries accommodate for limited use in autonomous mode. In detail, please refer to the two chapters below.

**Instruments**

The lightweight free-fall CPT (FF-CPT) instrument for shallow marine use consists of an industrial 15 cm$^2$ piezo-cone and a water-proof housing containing a microprocessor, volatile memory, battery, and accelerometer (Fig. 15; see also Stegmann et al., 2006). Strain gauges
inside the probe measure the cone resistance and sleeve friction by subtraction. A single pore pressure port \((u_2)\) is equipped with an absolute 10 MPa pressure sensor. An inclinometer is used installed to monitor the penetration angle at +/-30° relative to vertical. An accelerometer provides information about the descent velocities and deceleration behaviour of the instrument upon penetration. It enables to calculate penetration depth during multiple deployments by integration. The aluminium pressure housing tolerates 2 MPa confining pressure (ca. 200 m water depth) and hosts the power supply and microprocessor. Frequency of data acquisition is variable, and has usually been set to 40 Hz during our tests. Binary data are temporarily stored on a Micro Flash Card and then downloaded to a PC. The two non-volatile battery packs available provide performance times of about six and twelve hours, respectively. The length of the lance may be varied from 1.5 m to a max. 6.5 m depending on what type of sediment is anticipated. The extension is accomplished by adding 1-m-long metal rods and internal extension data/power cables within them. The weight of the instrument thus ranges from ca. 45 kg to max. 110 kg. If deep penetration is desired, modular weight pieces (15 kg each) can be mounted to the pressure housing at the top of the instrument, then reaching a max. 170 kg. The instrument is deployed pogo-style and remains in the seafloor for about 5-10 minutes for individual measurements.

The deep-water CPT probe (short DW-CPT) is a sturdier version of the shallow water (short SW) FF-CPT. It has a length of 380 cm with a standard 15 cm² piezo-cone with strain gauges inside the probe measure the cone resistance and sleeve friction by subtraction (Fig. 16). Like the SW-CPT, it contains an accelerometer, tilt meter, and a microcontroller. Pore pressure ports at the cone \((u_1)\) and ca. 80 cm above the cone \((u_3)\) are connected to Validyne DP215 differential pressure transducers via stainless steel tubing. Pore pressure changes can be monitored over a range of 100 kPa with a resolution of ca. 10 Pa; the sensors are protected with valves if high
excess pore pressures are met. They are further used to bleed the tubing in case of gas is trapped inside, especially during the initial phase of deployment when the instrument is lowered through the water column.

The DW-CPT may be used in autonomous mode, where two batteries power a microcontroller, the sensors, and valves. In addition, it can be run with a Seabird Electronics (SBE36) telemetric system so that depth, tilt of the probe, and information from all sensors can be monitored on board the vessel. The SBE36 system with PDIM deck unit is schematically shown in Figure 17. It provides power and real-time data acquisition as well as control of the instrument via a attached PC with custom-programmed LabView control software. During P336, we used the DW-CPT with the telemetry control.
5.7. Gravity coring and sediment description

(M. Strasser, R. Schäfer, T. Alves)

In order to recover longer sediment cores, a gravity corer with tube lengths of alternatively 3 m, 4 m, or 6 m and a weight of approximately 1.6 tons was used (Fig. 18). Before using the coring tools, the plastic liners inside the steel tubes have been marked lengthwise with a straight line in order to retain the orientation of the core for subsequent paleomagnetic analyses.
Once on board, the sediment core was cut into 1 m sections, closed with caps on both ends and labelled according to a standard scheme (Fig. 19). By definition, the half core with the marked line was stored as archive half, while description, sampling, etc. was carried out on the remaining half.

**Sediment description and smear slide petrography**

Split gravity cores were photographed and described from a largely sedimentological standpoint. Grain size and composition of sediments were determined mainly visually using a simple hand-lens, HCl-testing and analyzing smear slides of dominant lithologies under a cross-polarizing microscope in accordance with Rothwell (1989). The size of grains was assessed based on Wentworth’s (1922) classification. The colour of the material was determined visually on board, but will be studied spectrophotometrically after the cruise on the Multi-Sensor Core Logger (MSCL).
For each core a composite one page core log sheet was compiled. It shows core photographs next to a graphical core log and gives information on redeposition-/event layers (i.e., sand layers, volcanic ash layers or clear evidences for mass movement deposits, such as mud clasts in muddy or sandy matrix, tilted beds and repetition of strata), bioturbation and the assigned lithological units in three different columns. The core log is combined with results from the fall cone penetration test (see below). A wide variety of features, such as sediment lithology, primary sedimentary structures, bioturbation, soft-sediment deformation, and coring disturbance is indicated by patterns and symbols in the graphic logs. A key to the full set of patterns and symbols used on the barrel sheets is shown in Figure 20. The symbols are schematic, but they are placed as close as possible to their proper stratigraphic position. All core descriptions are provided in the Appendix.
**Lithologies**
- Homogeneous to moteled yelowish brown (ochre) sandy to silty mud
- Faintly laminated grayish to yellowish brown (ochre) sandy to silty mud with little Corg content
- Motteled light (olive) gray to grayish sandy to silty mud
- Olive gray silty mud with higher abundance of dispersed volcanic material
- Dark olive gray silty mud with high Corg content (Sapropels)

**Lithological Boundaries:**
- Clear, sharp boundary within few centimeters
- Diffuse transition over several centimeters

**Symbols (Physical structures and lithologic accessories):**
- Sand layer
- Sand patch
- Dispersed sand
- Volcanic ash layer
- Pumice
- Pieces of carbonate concretions
- Fine grained black spots (high C-org)
- Mud clasts
- Slump folds
- Fault (normal)
- Cylindrical hole filled with sandy to silty mud with circular halo - fluid conduit?
- Cylindrical channel filled with sandy to silty mud - fluid conduit? or bioturbation?
- Cylindrical void / channel (? fluid conduit?)
- Void

**Biorurbation:**
- Weekly bioturbated
- Bioturbated / motteled - structurless
- Absent bioturbation / laminated

**Fossils**
- Coral (Caryophyllia)
- Mussel shell (??)

**Event Layer:**
- Clear evidence for redeposition event
- Assumed redeposition event

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**Fig. 20.** Key of symbols for barrel sheets of gravity core description.
5.8. Physical properties

(M. Strasser, M. Irving, S. Stegmann, A. Kopf)

During cruise P336, shipboard physical properties measurements were restricted to falling cone penetration tests on the working half of the core. Since no container with a Multi-Sensor Core Logger (MSCL) could be placed on board RV Poseidon, these measurements on the undisturbed archive half of the cores were carried out immediately after the cruise at RCOM Bremen. A description of the instrument is given below.

Cone penetrometer

The geotechnical properties along the sediment cores were determined according to British Standards Institutions (BS1377, 1975). A Wykeham-Farrance cone penetrometer WF 21600 (Fig. 21) was used for a first-order estimate of the sediment's stiffness. For the measurement, the metal cone was brought to a point exactly on the split core face. A manual displacement transducer was then used to measure the distance prior to and after release of the cone (i.e. penetration after free fall of the cone). Precision is 0.1 mm of displacement. The distances measured can then be translated into sediment strength (see Hansbo, 1957, and below).

Fig. 21. Falling cone penetrometer used on the split core surface.
The falling cone penetrometer with its defined weight (80.51 g) and geometry (30° cone) was used by Hansbo (1957) made a detailed study of the relationship between the cone penetration and soil strength. The undrained shear strength \( c_u \) can be calculated from the variables mass and tip angle of the falling cone, gravity \( g \), penetration depth \( d \) and the cone factor \( k \) via the “cone factor”. Wood (1985) calculated from fall-cone and miniature vane tests average values of cone factors (in our case \( k=0.85 \) for a 30° cone). The undrained shear strength can then be calculated using the equation \( c_u = \frac{(k \cdot m \cdot g)}{d^2} \).

Shore-based laboratory testing will include vane shear experiments as well as ring shear tests to obtain residual strength and rate-dependent frictional properties of the materials recovered.

**Multi-sensor core logger**

The *GEOTEK* MSCL device at RCOM Bremen combines three sensors on an automated track (see schematic diagram in Fig. 22). The P-wave velocity, gamma ray attenuation (bulk density), and the magnetic susceptibility were recorded, and from this data the fractional porosity and impedance were calculated. RGB images were also produced with a full color digital line scan imaging system. Magnetic susceptibility, bulk density, and line scan photography were generally measured on all cores.

**Magnetic Susceptibility**

Magnetic susceptibility was measured with a Bartington point sensor MS2 using an 80-mm internal diameter sensor loop (88-mm coil diameter) operating at a frequency of 565 Hz and an alternating field of 80 A/m (0.1 mT). The sensitivity range was set to the low sensitivity setting (1.0 Hz). The sample period and interval were set to 2 s and 4 cm, respectively, unless noted otherwise. The mean raw value of the measurements was calculated and stored automatically. The quality of these results degrades in XCB and RCB cores, where the core may be undersized and/or disturbed. Nevertheless, general down-hole trends are useful for stratigraphic correlations. The MS2 meter measures relative susceptibilities, which have not been corrected for the differences between core and coil diameters.

**Gamma-Ray Attenuation**

Bulk density was estimated for split core sections as they passed through the GRA bulk densiometer using sampling periods and intervals of 2 s and 4 cm, respectively, unless noted otherwise. A thin gamma beam from a Caesium-137 source with energies around 0.662 MeV is
passed through the core and the relative intensity of this beam can be used to measure the gamma density. These photons are scattered by electrons in the core and loose some of their energy.

![Fig. 22. Schematic of the Geotek Multi Sensor Core Logger (MSCL)](image)

To determine the gamma density the number of unscattered electrons is measured by counting photons with the same principle energy as the photon source. The gamma density of an aluminum billet of stepped thickness is used to obtain calibration equations to convert gamma density into actual density values.

**P-Wave Velocity**

The P-wave velocity is measured at 4 cm intervals and 2 s periods using two PWL transducers. The PWL measured P-wave velocity across the unsplit core sections. In order to determine the P-wave velocity, the PWL transmits 500-kHz P-wave pulses through the core at a frequency of 1 kHz. The transmitting and receiving transducers are aligned perpendicular to the core axis while a pair of displacement transducers monitors the separation between the P-wave transducers. Variations in the outer diameter of the liner do not degrade the accuracy of the velocities, but the unconsolidated sediment or rock core must completely fill the liner for the PWL to provide accurate results. During this measurement good acoustic coupling between the core liner and transducer is achieved by adding water to the contact points.
6. Preliminary Results

6.1. Multibeam Swathmapping

(I. Kock, M. Reichelt)

Multibeam bathymetry was gridded with the processing software HDPPOST from ELAC, which was installed onboard. Raw, unprocessed data is illustrated in Fig. 24.

Depth in the covered area ranges from 250m - 2800m below sea level. In the deeper parts of the Heraklion and Kamilonisi basins, the bathymetric chart delivered no indications of larger landslide phenomena. A curious feature in this part of the study area is the so-called ‘horseshoe’ structure at 35°54’N, 25°06’E (study area B; Fig. 23).

During the completion of several overview tracks, we discovered several features further along upslope, in the direction of the Cretan coast. We interpreted one large structure (study area D, Figs. 23, 24; around 35°30’N, 25°54’E to 34°54’N, 26°06’E) as one or more large slide scars. A smaller feature (Figs. 23, 24; 34°54’N, 25°36’E) may either be a slide scar or part of a canyon.

In total, multibeam bathymetry covered approximately 2450 km², where about ~300 km² are part of the ‘Horseshoe’ structure.

Fig. 23. Map of the research area of cruise P336 showing the main areas of interest, i.e. study areas A-F.
6.2. Water Sound Velocity (CTD)

(S. Stegmann, A. Kopf)

Only one CTD profile was run at the beginning of the cruise (see station list, Appendix). Data served to calibrate the Multibeam and other geophysical acquisition systems. The only crucial information gathered was the bottom water temperature, which serves to tie in the heat flow measurements (Ch. 6.5 below). Temperature was found to be stable at values around 14.5°C. Since all the other data are not meaningful with respect to the objectives of cruise P336 CRESTS, they are not presented here.

Fig. 24. Multibeam map of the study area illustrating the cover achieved during cruise P336.
6.3. 3.5 kHz profiling

(S. Krastel-Gudegast, I. Kock, M. Reichelt, M. Strasser, M. Thölen)

Owing to problems with digitizing the 3.5 kHz data on board, we can only present a few examples of the 3.5 kHz data collected during CRESTS. All data are reprocessed at the moment and will be available in digital form in due time.

Figure 25 shows a typical example of 3.5 kHz data in Working Area A (see also section 6.7). The 3.5 kHz data image a complex pattern of individual transparent units, which are characteristic for slide masses. The seafloor is characterized by a smooth surface except for a block at the northern end of the profile, which shows a hummocky surface (Fig. 25). The up to 7 m thick block itself is characterized by internal transparency. The hummocky surface in combination with internal transparency suggests that this block is a slide block. It seems that the uppermost transparent unit (Unit 1) pinches out at the edge of the slide block. The stratigraphic relationship between Unit 1 and the slide block, however, remains unclear. The block might belong to the uppermost Unit 1, but it also might represent an individual slide block. The thickness of Unit 1 varies between 1 m and 8 m. Unit 1 does not show any internal structures but acoustic transparency. Such a pattern is typical for a debrite though it might represent very homogenous hemipelagic sediments as well. Unit 1 is underlain by a second transparent package, which is imaged in the central part of the presented profile (Fig. 25). This unit shows very similar patterns as Unit 1, i.e. acoustic transparency without any internal structures. Two more transparent units are visible in the central part of the profile.

The overall seismic pattern suggests that we have stacked individual slide units building a slide complex. The presented profile (Fig. 25) is located at the deepest part of the basin north of Crete. This area serves as depositional center for submarine slides from the Cretan margin as well as from the volcanic island arc to the North.

Gravity cores taken across the slide complex aimed in coring different slide units. Penetration of all cores taken in this area was unfortunately very low (<50 cm). The cores do not show clear indications for redeposited material, but due to the limited resolution of the 3.5 kHz system, it is not possible to image thin (<50 cm) layers. An undisturbed drape of ~50 cm thickness on top of the transparent Unit 1 would not be detected by the 3.5 kHz system. Therefore the cored material might not be representative for the transparent units seen on the 3.5 kHz data.
Figure 25. 3.5 kHz profile crossing a slide complex in the basin north of Crete. Note that the profile is collected with a delay of 2240 ms. See Figure 31 for location.

Figure 26 shows an example of a 3.5 kHz profile collected on the margin north of Crete. The western part of the profile is characterized by overlapping hyperbolas, which are caused by a hummocky seafloor. Due to the large opening angle of a conventional 3.5 kHz echo sounder, closely spaced individual blocks on the seafloor are imaged as overlapping hyperbolas. In contrast the eastern part of the profile shows a very smooth seafloor with several very continuous, parallel sub-seafloor reflections (Fig. 26). The boundary between the hummocky and very smooth seafloor is very sharp. The western part of the profile represents undisturbed hemipelagic sediments. Penetration of the signal is up to 30 m. No sub-seafloor reflectors are imaged at the western part of the profile (Fig. 26). The hummocky terrain represents the surface of a major slide event. Owing to the limited vertical and horizontal resolution of the 3.5 kHz system resulting in overlapping hyperbolas it is not possible to visualize thin (<50 cm) drapes, which might be present on top of the hummock seafloor.
6.4. Seismic reflection profiling

(S. Krastel-Gudegast, N. Kaul, B. Heesemann, I. Kock, M. Reichelt, M. Thölen)

In total almost 1400 km of seismic lines were collected in the Cretan Sea during P336 (Fig. 27). Some typical examples are presented in the following section.

Profile GeoB06-129 crosses the basin north of Crete. A part of the profile is presented in Figure 28. A strong blocky reflector represents the acoustic basement. The seismic section can easily be separated in two major sedimentary units. The upper unit is characterised by continuous parallel reflectors with variable amplitude. The maximum thickness of this unit (almost 400 ms TWT, ~300 m) is found in the central part of the basin. The seismic pattern suggests generally undisturbed deposition of hemipelagic sediments. The higher resolution 3.5 kHz data, however, show local slide deposits in the basin (see Ch. 6.3, Fig. 25)
A major depositional unconformity separates the upper unit from a lower sedimentary unit. The sediments of the upper unit show onlapping onto a strong continuous reflector of the lower unit. The lower unit shows weaker amplitudes compared to the upper unit. The sub-parallel reflectors of the lower unit have a good to moderate continuity and show an undulating pattern. The undulating pattern indicates that this unit was tectonically deformed. However, the stress is not acting in present times because the reflectors of the upper unit are horizontally layered and not deformed.

The slope north of Crete also shows a very pronounced subdivision into two sedimentary units (Fig. 28). The upper unit is again characterized by very continuous well stratified high amplitude reflectors.
A very pronounced erosional unconformity separates the upper from the lower unit. The thickness of the lower unit is up to 250 m. The lower unit shows folded and faulted sub-parallel reflectors at the southern end of the profile. None of the faults reaches up to the upper sedimentary unit. In the central part of the profile the lower unit shows only weak reflectors which have a patchy structure. Some faults can be seen at the northern end of the profile. The strongly deformed sediment body with weak patchy reflectors might represent a major slump deposit but the folded and faulted sediments next to the almost transparent sediment body suggests that the internal structure is destroyed as a result of tectonic deformation.

It is interesting to note that profiles in the basin (Fig. 28) and on the middle slope (Fig. 29) north of Crete both show a deformed lower unit and a well stratified upper unit. This pattern shows that the lower unit was tectonically deformed during and after its deposition. The tectonics probably also caused large vertical movements causing a major hiatus which is documented as unconformities in the seismic sections. Following this hiatus, the upper unit was deposited, which consists of undisturbed hemipelagic sediments. No indication for major tectonic deformation is found in the upper sedimentary unit.
A different picture shows Profile GeoB06-134, which crosses the almost circular basin in the easternmost survey area (Fig. 30). The depth of the so called Kamilonisi basin is ~2250 m, which is significantly deeper than the Heraklion basin described above (Fig. 28). The basin fill is characterized by packages of high amplitude reflectors, which are separated by thin transparent layers. These thin transparent units probably represent slide deposits, while the hemipelagic background sediments are imaged as strong relatively continuous reflectors. The very steep flanks show numerous indications for slides and slumps. Some of these slides and slumps (and probably also slides and slumps from further upslope) reach the basin floor. Several faults can be identified in the basin. The fault offset generally decreases with decreasing sediment depth and none of these faults seem to reach to the sea floor. The basin itself is bounded by major faults.
Three areas were surveyed in detail during the cruise: A horseshoe-like structure (study area B; see Figs. 23, 31), and two slide areas on the northern margin of Crete (study areas D and E; see Figs. 23, 33, 6.4.10).
A seismic profile crossing the Horseshoe structure is shown in Figure 32. Most of the profile is characterised by parallel wavy reflectors with a good continuity. A 6 km broad elevated area is seen in the centre of the profile. The elevated area dips to the east and is bounded by a steep eastern flank and a gently dipping western flank. Both flanks are ~150 m high and seem to coincide with major faults. Several additional small offset faults are imaged at the western end of the profile. In the centre of the broad elevated area, a mound-like structure sticks out of the sea floor. On this profile the mound like structure has a diameter of ~600 m and a height of ~75 m. The bathymetric data, however, show that the mound is not circular but a curved elongated feature, which has a horseshoe-like geometry. The area beneath the mound-like structure shows an acoustic transparent zone with a diameter similar to the mound like structure. There are several possible explanations for the acoustic transparency. A hard seafloor and the steep morphology might scatter the energy at the seafloor and we are just not able to get enough energy into the subsurface for imaging the internal structure of mound like structure. The transparent zone, however, widens to the east with increasing depth, while the western boundary is almost vertical. If the observed acoustic transparency is caused by strong scattering at the seafloor only, one would expect near vertical boundaries on both sides. Hence this explanation is unlikely. Other explanations are very homogenous material without major impedance contrasts (e.g., mud) or strong signal attenuation due to the presence of free gas. From the seismic data alone we are not able to distinguish between these two possibilities, but both explanations suggest upward migration of fluids or gas from depth. This explanation is supported by higher heat flow values measured on top of the structure during the cruise (see Ch. 6.5). Similar features in the Mediterranean Sea and in the Black Sea have been identified as mud volcanoes or mounds. Cores taken in this area, however, do not show any indications for mud flows (see Ch. 6.7 below); therefore it is unlikely that this feature is a young mud volcano. The shape of the horseshoe like structure (see Ch. 6.1 above) and its large dimension is also atypical compared to other mound structures in the Mediterranean and Black Sea. An explanation of this horseshoe like structure needs to wait until all available data are processed and analysed.
Fig. 32. Brute stack of a part of Profile GeoB06-137 crossing the Horseshoe structure. Note that the profile is plotted in reverse direction. See Figure 31 for location.

A major slide was identified on the northern margin of Crete. Profile GeoB06-164 (Fig. 34) crosses this slide structure in a South-North direction. The northernmost part of the profile is characterized by well-stratified, undisturbed sediments. A major change of the seismic facies is seen around FFID 2650. A lens shaped body with a maximum thickness of almost 100 m extends for ~5 km up to FFID 2950. The internal structure of the lens shaped body shows a chaotic seismic facies, which is characteristic for slide deposits (study area D). No obvious headwall can be identified in the seismic data, but at the head of the slide the upper 20 m of sediments are missing and incorporated into the slide. The surface of slide is the relatively smooth. A strong very continuous reflector marks the base of the slide. The occurrence of some intact structures in the generally chaotic seismic facies of the slides suggests that the internal structure has not been totally destroyed and that the slide has not travelled very far. In the seismic data we do not see a hemipelagic drape on top of the slide deposits. Due to the limited resolution of the seismic system, thin drapes (<5 m), however, cannot be detected. Hence it is difficult to determine the age of the slide event.
The southern boundary of study area D is marked by a ~20 m high morphological step. North of this step, we see a much thinner chaotic sediment body, which extends up to FFID 3260. Several hummocks are imaged on this part of the profile. Such a pattern is also characteristic for a slide (study area E). Study area E ends at a morphological high where the slide came to a stop. The direct vicinity of the two slide units indicates a close relationship of both events. The study area D might have triggered a second event or the more mobile part of the slide disintegrates into a debris flow forming the thin chaotic layer with the hummocky surface. Profile GeoB06-133 (Fig. 35) crosses study area D in a West-East direction. A small channel levee system is imaged at the western end of the profile. The system sits on top of a reflector that comes up to the seafloor further to the west. Channel depth is only ~10 m but the levees are up to 50 m thick. The slide deposits reaches to the channel levee system at its western boundary. The chaotic internal structure of the slide including some intact features is very similar as described above for Profile GeoB06-164 (Fig. 34). The eastern boundary of the slide is located around FFIF 4800. The sediments east of the slide show a general undisturbed pattern with some small offset faults, which reach almost up to the surface. A thin (<20 m) drape does not seem to be affected by the faulting. The fact that the small channel levee system seems to have acted as barrier for the slide...
supports a relatively young age of the slide system. As the channel levee system is build on top of a reflector, which almost reaches the seafloor further to the west, it needs to be very young; otherwise a subsurface reflector would mark the base of the channel levee system. As the channel levee acted as barrier for the slide it must be even younger than the channel levee system. As already mentioned above, we want to point out, that layers <5 m cannot be detected by the used seismic system, which makes it difficult to give exact ages for the channel levee system and the slide.

Fig. 34. Brute stack of Profile GeoB06-164 crossing a slide on the northern Cretan margin. See Figure 33 for location.
Fig. 35. Part of the brute stack of Profile GeoB06-133 crossing a slide on the northern Cretan margin. See Figure 33 for location.

A second slope failure is found further to the west on the Cretan margin in study area E (Figs. 23, 36). This slope failure differs significantly from the slide described above.
**Fig. 36.** Track chart across a slope failure on the northern Cretan margin, study area E (Fig. 23).

Profile GeoB06-195 ([Fig. 37](#)) runs in a SE-NW direction and shows two very pronounced morphological steps. The bathymetric map (see Ch. 6.1) shows that these morphological steps are the sidewalls of an amphitheatre like scarp. The width of the scarp on this profile is ~2 km but it widens further downslope.

![Fig. 37. Part of the brute stack of Profile GeoB06-195 crossing an amphitheatre like feature. Note that the profile is plotted in reverse direction. See Figure 36 for location of the profile.](#)

**Figure 38** shows a closer look of the western sidewall. The sidewall is ~60 m high and has a slope gradient of >20°. Exact numbers can only be given after migration of the profiles. The well stratified sediments west of the scarp are cut at the sidewall and probably removed by a major slide. The sediments inside the scarp are characterized by a ~50 m thick chaotic to transparent seismic unit, which might represent slide deposits. Inside the unit, however, we see a significant
change from strong reflectors with a moderate continuity to a more transparent seismic facies further down. It is difficult to decide from the seismic data alone if the upper part of this unit is part of the slide deposits or if they represent hemipelagic sediments. Despite the very pronounced scarp no clear and continuous slide deposits were found on any seismic line.

Profile GeoB06-207 (Fig. 39) crosses the headwall and the area around the headwall in a SW-NE direction. Undisturbed well-stratified sediments are found upslope of the headwall. The headwall cuts the well-stratified sediments and has a height of ~50 m at this location. Directly beneath the headwall a relatively thin (<50 m) chaotic unit lies on top of well stratified sediments. This unit has a relatively smooth surface. About 4 km downslope of the headwall the chaotic unit thickens significantly to ~almost 100 m probably representing the main depositional area of the slide. This chaotic unit, however, cannot easily be traced between profiles and does
not seem to be a continuous feature. Hence it is difficult to determine the extent of the main depositional area of the slide. Profiles further downslope hit the very steep slopes of a deep basin and it might well be that the major parts of the slide material is transported much further downslope and deposited in the deep basin.

![Fig. 39. Brute stack of Profile GeoB06-207. See Figure 36 for location of the profile.](image)

### 6.5. Heat flow measurements

(N. Kaul, B. Heesemann)

Three main targets could be probed during this survey: i) one profile across the “Horse-shoe” structure within Heraklion basin (study area B; Fig. 23), ii) a seismically identified slump structure closer to the island (study area D; Fig. 23), and a scarp structure attributed a head and side wall of a slope failure (study area E; Fig. 23). This slid structure (area D) could be tackled with five transects to observe the edges of the structure, compared to its surrounding. Some of the results are given in Figure 40 (see also Table 1 for all heat flow locations).

A prerequisite for reliable temperature gradient measurements is a stable oceanographic situation which is usually not granted for water depth of 300 – 1000 m as encountered in the
working area. In most of the area the water sensor on the instrument indicates stable conditions at approximately 14.5°C except for a channel structure and its surrounding (see Chapter 6.2).

The determination of the geothermal heat flow requires the knowledge of the vertical temperature gradient and the thermal conductivity as a material constant. Values for the thermal conductivity were sampled after the cruise at core samples at distinct intervals (app. 0.1 m). As expected due to the vicinity to the coast, thermal conductivities show relatively high values (0.95 – 1.6 W/mK) with a regional mean of 1.06 W/mK. This is attributed to a high content of terrestrial input (i.e., quartz) and comparatively low amounts of pelagic debris.

![Fig. 40. Profile across the central “Horse shoe” structure, indicating high gradients of 140 and 160 mK/m on the top and app. 30 mK/m at a short distance. Order is from west to east. For location, see Fig. 23.](image)

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Tab. 1. Positions and nomenclature of temperature gradient measurements (HF).
6.6. CPT testing

(S. Stegmann, A. Kopf)

The DW-Lance as well as the SW-Lance has been deployed in the four geological areas B (East Side Western Basin), C (Horseshoe structure), D (Slide complex Cretan Margin), and E (Scarp Structure) (for location, see Figs. 23, 41). Depending on the swell, the lance was stuck in the sediment after the insertion for - in best case - about 10 minutes to observe the dissipation behavior of the insertion pore pressure and to define T_{50}, the time which is needed for a 50% decay of the maximum pore pressure and is therefore used as a first-order indicator for permeability. The described penetration behavior for both CPT-systems is done by using the sediment stuck to the lance after the measurement and recovery. So, in case of pogo-style deployment, it was not possible to detect penetration depth immediately because the CPT remained in the water column near the seafloor whilst moving the ship to the next position. In that case, the 2\textsuperscript{nd} integration of the vertical acceleration, which is stored during each measurement, can be used to calculate the penetration depth. This effort processing will be part of the post-processing and the actual missing information will be supplemented. As the DW-CPT mostly penetrated less than 0.7 m, the upper pore pressure sensor was still in the water column. Table 2 summarises, in addition to the frame parameter (position, penetration depth, duration), pore pressure data (insertion, T_{50}).

![Map of CPT deployments in the various study areas B – E. See text.](image)
Typical pore pressure features are combined in Figure 42. The “classical” pore pressure signal is represented by class 1 data (Fig. 42A), where an insertion maximum is followed by an exponential decay. Unfortunately, most of these measurements exceeded the upper limit of the differential pore pressure sensor in u1 position. Pore pressure feature of class 2 (Fig. 42B) is characterized by a significant peak, followed by a decay with later increase again. Based on previous pore pressure measurements in different locations, we interpret the peak as a result of a displacement of relatively stiff material, which generates first a peak and after that, an expulsion by the lance an evolution of the “undisturbed” insertion pore pressure. In this case, the later part of pore pressure evolution is used to define the insertion pressure and decay of the pore pressure signal. In contrast, the homogenous displacement of softer material may coincide with the “classical” pore pressure (class 1) evolution.

Tab. 2. CPT results acquired during P336. See also Figs. 41-43.
In the CPT data of the Cretan Sea it is not easy to identify a clear correspondence between a certain pore pressure feature and a geological structure (Tab. 2). The maximum penetration depth of the DW-Lance was 155 cm. Generally, the insertion pore pressure ranged between 13.5 kPa in the Horseshoe Structure (area C) and more than 77 kPa in the scarp area of a small landslide (area E), where T50 varies between 0.2 mins. on the Slide Complex (D) and 9 mins. in the East Side Western Basin (B) (Tab. 2).

The only study area where a significant number of tests were carried out with both the SW- and DW-instrument was area D (Figs. 23, 41). In the slide complex at the northeastern Cretan Margin (see seismic reflection line in Fig. 35), we measured along a transect with a high spatial resolution from the upslope undisturbed sediments downslope to the failed deposits (Fig. 43). In this area penetration depth varied between 40 cm and 155 cm, whereas penetration depth of about and over 100 cm was only reached in the undisturbed sediments in the south (Fig. 43B), where the background sediment (silty to sandy mud) dominates in the upper 120 cm (see Appendix 9.2, Core GeoB10426).

The deposits allowed us a penetration depth between 40 cm and 60 cm. In the same way, T50 varied between 5 and 6 minutes and indicates less permeable sediments in the upslope, whereas a gradient (downslope) can be observed to slightly more permeable material with T50 between 0.2 and 3 minutes (Tab. 2). In the EW-cross-section (GeoB position number 34-37, Appendix 9.1, Fig. 43A,C), however, lower permeability is observed.
The thickness of the sand to silty mud layer in the slide complex, which overlies the S1 sapropel is highest in the upslope area, and decreases downslope. There, the thickness of the slid deposits and the upper boundary of the S1 sapropel (~0.5 m, see Appendix 9.2 and Ch. 6.7 below) agree with the penetration depth of the CPT. The stiff sapropel may hence be too hard to allow penetration with the DW-CPT. Post-cruise shear tests are underway to shed light on the strength of the organic-rich layer in comparison to the dominant silty clays.

6.7. Gravity coring and sediment description

(M. Strasser, R. Schäfer, T. Alvez, S. Stegmann, M. Reichelt)

During cruise P336, 30 gravity cores of 0.1 to 5.67 m length were recovered in 6 study areas (A-F; see Fig. 23), totaling 70 m of core recovery (Figs. 44-45). It turned out to be difficult to core the hemipelagic sediments in the Cretan Sea and core recovery often was low and only few decimeters of core length could be retrieved. Estimations based on sedimentations rates, sapropel chronology and tephra chronology (see below) suggest that the longest section covers approximately the last 100 ka.
Fig. 44. Table and map summarizing the gravity coring information in study areas A-F.
Fig. 45. Compilation and simplified lithological profiles of all cores recovered in study areas A-F. See also text and Fig. 44 above.

**Sediment description**

Generally, sediments cored during the entire cruise are dominated by a mixture of pelagic oozes (nannofossils, foraminifera, pteropodes and flagellatae) with varying portion of clay, volcanic material (glass shards and pumice), fine grained terrestrial material (mainly feldspar and quartz), organic material, minor amounts of shell fragments (debris of bivalves, gastropods, serpulidae and benthic foraminifera) and, occasionally, carbonaceous clasts and nodules of mm-to cm- diameter. The facies are typically fine to medium grained and homogenous to mottled, with few identifiable sedimentary structures apart from bioturbation and distinct redeposition layers (see below). Bioturbation generally is moderate leading to a mottled appearance with few chondrites. The color varies from yellowish brown (ochre) in the upper part of the sedimentary section to light (olive) grey down-section, with distinct dark olive grey intervals.
**Lithostratigraphy**

Based on color, grain size distribution and organic material content the dominant hemipelagic lithologies could be assigned to the existing stratigraphic framework (Aksu et al., 1995; Geraga et al., 2000; Giresse et al., 2003) (see above). From top to bottom, they are

Unit 1: yellowish brown bioturbated muds,

Unit 2: grey mud, mottled and moderately bioturbated,

Unit 3: greyish, brownish to olive grey mud, >2% C$_{org}$, no bioturbation (Sapropel S1)

Unit 4: yellowish grey clayey mud, slightly bioturbated.

In the lower portion of Unit 1 we identified in several cores that the facies sometimes is faintly laminated and sediments have slightly higher organic contents. This section was assigned to Unit 1b and could potentially be related to a beginning stage of sapropelic sediment formation around 2000-1200 year B.P (Giresse et al., 2003). In 3 cores (core 19-1, 21-1, 24-1) another ~20 cm thick interval of dark olive gray silty mud with higher content of organic material was recovered (here assigned to Unit 5). Based on its stratigraphic position (Fig. 46) this layer is interpreted to correlate to sapropel S3 dated to have occurred between 81 and 78 ka BP (Muirdter et al., 1984; Lourens 1996; Kroon et al., 1998), while sapropel S2 (ca. 55 ka BP) is missing (see Ch. 4.2 above). The mottled light (olive) grey to greyish silty mud below this sapropel layer is assigned to Unit 6.

**Volcanic ash / volcanoclastic layers**

Volcanic ash / volcanoclastic layers represent an important minor lithology. Two prominent and few less distinctive layers of volcanic origin where identified.

*Z-2-Santorini event (3370 yr B.P.)*

The upper most of these two prominent layers was recovered in core depth between 0.2 and 1 meter below sea floor and ranges in thickness from few millimeters (only identified based on high content of glass shards in smear slides) and up to 20 cm (comprising black to light gray, sand to gravel sized pumice components). From its stratigraphic position and its peculiar
appearance it has here be assigned to correlate to the Z-2 ash layer related to the “Minoan” eruption of the Santorini volcano, Thera island, that has been dated to be 3370 years BP (Pichler & Friederich, 1976; Keller et al., 1978).

Fig. 46. Attempt to correlate marker intervals in core GeoB10419-1 with dated marker layers identified in other cores from the eastern Mediterranean Sea. Bold correlation lines indicate correlation with high confidence whereas dashed lines are rather speculative and entirely supported by initial shipboard observation. The resulting age model appears to be valuable since it satisfies published sedimentation rates (Geraga et al., 2000; Giresse et al., 2003), sapropel chronology (Muërdter et al., 1984; Kroon et al., 1998) and tephrachronology (Keller et al., 1978). However, future dating of P336 cores is needed to reliably constrain this model.
The Z-2 ash layer recovered in cores from deep basins (e.g., core 5-1) often comprises multiple stacked, normally and inverse graded mm to cm thick sand layers with an erosive base that is overlain by either coarser grained sediment composed mainly of light pumice gravels (as recovered mainly in study areas A, B, and C immediately south of the island of Santorini) or faintly laminated multiple brownish ash layers of only few mm thickness (as recovered in the Kamilonisi basin) (Fig. 47A and B). Smear slide analyses of the basal sandy material revealed not only volcanoclastic material but also variable portions of terrestrial material (mainly feldspar and quartz) and shell fragments (debris of bivalves, gastropods, serpulidae and benthic foraminifera) indicating not only a volcanic source but also that a considerable amount of shallow water material was mobilized and transferred to the deep basin. The stacked turbidite succession furthermore indicates that sediment was not transported during one single pulse but instead involved a series of closely spaced events or, perhaps, pulses within a single mass flow event. Speculatively, this could be related to volcanic shore collapses, submarine mass movements on the volcanic flanks and/or to tsunami waves in the Cretan Basin triggered by the final volcanic collapse.

**X-1 Hellenic volcanic event (~80 ka B.P.)**

A second prominent few cm-thick volcanoclastic event layer containing black, up to 5 mm big, pumice pieces was identified immediately above sapropel layer S3 in core (core 19-1, 21-1, 24-1). From its facies this layer is interpreted to correspond to a major volcanic event in the Hellenic area similar to the historic “Minoan” eruption and – based on its stratigraphic position – could correlate to the X-1 Hellenic ash layer identified in other core from the eastern Mediterranean (Keller et al, 1978).

**Other volcanic ash layers**

Throughout the sedimentary section few intervals where identified that comprise higher abundance of mainly black (presumably mafic) dispersed volcanic material, suggesting the occurrence of tephra layers that have been disrupted by bioturbation after deposition. In Figure 46 an attempt was made to – speculatively – correlate these intervals to known volcanic ash layers (Keller et al. 1978).
Core photographs showing: a) + b) Z-Z Santorini event layer. a) multiple stacked, inverse and normally graded volcanic sand and pumice layers. b) multiple stacked, inverse and normally graded volcanic sand layers that are overlain by faintly laminated multiple brownish ash layers. c) graded, brownish gray sandy layer with erosive base. d) + e) sediment deformation structures. d) normal fault, e) tilted beds and sedimentary folds. f) reworked carbonate crust clasts covered with serpulid tubes g) well preserved deep water coral test (Caryophyllia, probably C. calva). h) + i) special sedimentary structures: cylindrical tubes (bioturbation or fluid conduits?), h) open cylindrical tubes (3cm in diameter), originally filled with soupy sandy to silty mud “extruded” during core cutting, i) vertical channel filled with soupy sandy to silty mud.

Fig. 47. Collection of core photographs (see description above plate).
The resulting age models appears to be a valuable solution satisfying published sedimentations rates (Geraga et al. 2000; Giresse et al. 2003), sapropel chronology (after Kroon et al., 1998) and tephra chronology (Keller et al., 1978), but future dating is needed to reliably constrain the age control on the recovered sedimentary section during cruise P336.

**Redeposited Intervals**

*Turbidites.*

Although the facies are typically pelagic, there are a number of minor redeposited intervals (0.5 to max 1 cm thick sand layers) that contain considerable amounts of shell fragments (debris of bivalves, gastropods, serpulidae and benthic foraminifera) with either (i) volcanic material, indicating sediment transport from the north or (ii) terrestrial material (mainly feldspar and quartz), indicating a sediment source in the south (Crete Margin). An example is seen in interval GeoB10405-1, 21.5-22.5 cm (Fig. 47C) where a brownish gray bed shows a graded erosive base. Smear slide analyses revealed mainly siliciclastic components suggestive of redeposition along the Cretan Margin. From its stratigraphic position (i.e. 20 cm above Z-2 ash layer) this turbidite layer might be a valuable candidate to be related to the 1636 BP M>8 earthquake.

*Mass-movement deposits*

From a sedimentological point of view, clear evidences for mass-movement deposits only were identified in cores retrieved in study area A and C, whereas for study area D and E – where seismic data indicate major and relatively young landslides deposits and slope failure scars – clear evidences for mass movements deposits are missing. None of the mass movement events can be related unambiguously to the 365 AD earthquake and clustered seismic activity around that period (see Stiros, 2001).

*Study area A: Slide complex western basin*

The study area A was chosen as coring site based on multiple stacked wedges showing chaotic to transparent seismic facies in the 3.5 kHz seismic profiles, indicating young mass movement deposits (Fig. 48). However core recovery was very limited (max 75 cm). Nevertheless, clear evidences of mass-movements deposits (i.e., mud clasts, sand patches, and sedimentary folds) were identified both above and below the stratigraphic marker horizon Z-2 (Santoroni event) in core 6-1 and 7-1, respectively. Most probably, the limited core-penetration
depth does not allow to correlate these mass-movements to the deposits identified in the 3.5 kHz seismic profiles. Nevertheless the occurrence of stacked mass-movement deposits in the upper part of the sedimentary succession suggests an ongoing, rather catastrophic type of sedimentation in this area.

![Fig. 48. High-resolution 3.5 kHz seismic reflection profile across study area A showing chaotic to transparent facies and wedge-shaped geometries. Arrows indicate locations of cores and small vertical lines indicate recovered core length (<60 cm). For location see Figs. 23 and 27.](image)

**Study area C: Horseshoe structure**

Study area C comprises a bathymetric high with a distinct horseshoe-shaped geometry that was surveyed extensively during P336 (Fig. 49). Two coring transects crossing the structure in E-W and N-S direction revealed normally stratified sections on top and next to the bathymetric high lacking any evidences of landslide or mud-flow deposition (cores GeoB10419,-21,-23, and -24), but heavily disrupted and slumped sections on the relatively steep flanks (see seismic profiles above). The cores retrieved on the flanks (cores GeoB10416, -17 and -18) are characterized by tilted and folded beds, repetition of strata, syn-sedimentary folds and normal faults, mud clasts and sand patches (Fig. 47D and E), both above (cores -17 and -18) and below (core -16) the stratigraphic marker horizon Z-2 (Santoroni event). This suggests that the flanks of the bathymetric high are highly exposed to small scale submarine slumping and creeping.
Fig. 49. Compilation of results from study area C: Two perpendicular seismic profiles (top), the gravity cores on those profiles (middle), and a bathymetric chart for location (bottom). See text for discussion.
**Study area D: “Slide” Cretan Margin**

A major, relatively young landslide deposit was identified in the seismic section offshore Crete (see Ch. 6.4 above). 5 Gravity cores adjacent (core -26 upslope and core -57 downslope) and on the landslide deposit (cores GeoB10425, -32 and -33) were retrieved in order to date and to characterize the landslide deposit (Fig. 50).

However all cores show similar lithostratigraphic successions characterized by the “normal” succession of (from top to bottom) yellowisch brown sandy to silty mud, the Z-2 Santorini event layer, light (olive) gray to grayish sandy to silty mud and sapropel S1. This succession overlies a >4 m thick (not cored deeper) packet of relative structureless homogenous to only very slightly mottled light gray to light olive gray clayey silts that look very similar to Unit 4 recovered in the other study areas (e.g. study area C – see above) but mostly lack indications for stratigraphic succession such as sand or volcanic ash layers that could be correlated from core to core.

To tell from the 3.5.kHz seismic data, which clearly shows a rough surface and disturbed, chaotic internal signature that are not overlain significantly by post landslide parallel reflections (see Ch 6.3), the landslide should be rather young and the >4 m long gravity core should have reached the landslide deposits. However, from the sedimentological observations it only can be speculated whether

(i) the lower part of the succession corresponds to amalgamated muds of the landslide body that – in this case – would have occurred relatively short before the onset of Sapropel depositions ~10 ka B.P;

(ii) the sedimentary section represents a primary sedimentary deposits and, therefore, the landslide either is older and not reached with coring or, all cores were recovered from internally coherent slump, slide or out runner blocks. If the latter would be the true, the landslide can also be younger than S1 and Z-2.

Future investigations such as pore water chemistry or paleomagnetic analysis are need to test the hypothesis of having disturbed (pore water chemistry would not be in equilibrium) or distorted (there would be an anomaly in magnetic declination values) sediments in the cores.
Fig. 50. Compilation of results from study area D across the landslide body (for location see Fig. 23): Seismic profile (top), gravity core information (middle), and bathymetric chart for location (bottom). See text for discussion.
Study area E: Scarp structure

Study area E represents a ~75 m high scarp clearly visibly in both multibeam bathymetry and seismic reflection data. It is interpreted to represent a major head scar of a relative young slope failure event (see Ch. 6.1, 6.3 and 6.4 above). Lithological and stratigraphic description of 5 core along two coring transects crossing the structure in NE to SW direction (both transect projected onto one section in Fig. 51) revealed no significant differences and show similar sedimentary succession as discussed above at study area D. Hence, no final conclusions can be drawn on timing and mechanism of scarp formation.

The only evidence for sediment remobilization along the head scarp are identified in core GeoB10458 that was recovered immediately below the scarp. Here, the sediment above sapropel S1 is characterised by abundant clasts and carbonate concretions and shows an elevated sedimentation rate. However, no clear redeposition event could be identified. The sediment here is interpreted as talus deposits at the foot of the head wall suggesting continuous diffusion of the steep head scarp wall.

Carbonate aggregates and carbonate crusts

Well- to friably-cemented carbonate clasts and nodules occur in all cores mainly in the upper part of the sedimentary section. They are largely more abundant in cores recovered on or immediately below steep slopes (e.g. cores GeoB10416, -17 and -18 in study area C and core -58 in study area E). Generally, they range in diameter from 0.5 to 10 mm, have irregular, subangular shapes with rounded to spherical botryoidal surfaces and are light beige to light brown in color. Exceptionally, in core GeoB10416(-1), -18 and -58 distinct indurated carbonated clasts of up to 5 cm in diameter have been recovered. They have dark gray to brown indurated surfaces (Fig. 47F). This clasts can be interpreted as reworked carbonate crust clasts and suggest favorable condition for starved sedimentation and hardground formation on the horseshoe-shaped bathymetric high in study area C and along or on top of the headwall scar in study area E. This interpretation is assured by the occurrence of a well-preserved coral test recovered in core 18 (deep water coral Caryophyllia, probably C. calveri, Fig. 47G), as corals also need a firm substrate to grow on. Most probably, starved sedimentation is a consequence of moderate to strong currents, that might occur in the Cretan Sea, as already suggested by Chronis et al. (2000), but – potentially – hard ground formation and deep water corals association in study area C.
could also somehow be related to significantly elevated thermal gradient measured along the bathymetric high (see Ch. 6.1 above).

Fig. 51. Compilation of results from study area E: Two near-parallel seismic profiles (top), the gravity cores on those profiles (middle), and a bathymetric and track chart for location (bottom right). See text for discussion.
**Special features**

Exceptional sedimentary structures consisting of up to 30 cm long vertical cylindric tubes with diameters up to 3 cm have been identified in cores from study area D and E (Fig. 47H and I). They are filled with soupy, light (olive) gray, sandy to silty mud that often “flows out” during core opening – potentially indicating slightly over-pressured pore water conditions within these cylindrical channels. It remains unclear whether these structures are formed by bioturbation, or whether they represent fluid conduits and fluid escape structures somehow related to the landslide deposits identified in seismic cross sections in these two study areas (see Ch. 6.4 above).

**6.8. Physical properties**

(S. Stegmann, A. Kopf)

The database of physical properties of the CRESTS cores consists of the P-wave velocity, bulk density, magnetic susceptibility and fractional porosity, logged with the GEOTEK MSCL and the undrained shear strength $S_u$, measured with the fall cone penetrometer (Ch. 5.8.). The properties are described and briefly discussed for each study area (see Fig. 23) with cross-refering to the seismic data (Ch. 6.3) and sedimentological description (Ch. 6.7) above.

*Study area A: Slide complex western Heraklion Basin*

Sediments taken in study area A comprise of sandy to silty mud and are characterized by a density of 1.6 to 1.7 g/cm$^3$ and a fractional porosity of ca. 60 %. Undrained shear strength values ($S_u$) range between 4 and 12 kPa. Sandy layers correlate with an increase of the magnetic susceptibility up to 100 Si.

*Study area B: Eastern Heraklion Basin*

Here, the sediments in the upper 60 cm are very homogenous with a density of $\sim$ 1.8 g/cm$^3$, a very low constant magnetic susceptibility (20 Si) and a fractional porosity of 0.5 %. $S_u$ increases with a more or less linear trend with a significant step as a result of carbonate concretions.

*Study area C: Horseshoe Structure*

Generally, the thickness of the background sediment (sandy to silty mud) exceeds more than 2.5 m on the NNE flank of the horseshoe structure (GeoB10416, GeoB10417, GeoB10418). The
relative homogenous density of ~1.8 g/cm$^3$ shows variability in case of presence of carbonate concretions, pumices and mud clasts (?). These fragments cause an increase in $S_u$, ranging between ~10 and 30 kPa. The magnetic susceptibility of the background, matrix sediment is relative low (30 Si). Fractional porosity ranges between 50 and 60%. In the north-south-transect downslope from the top of the structure (GeoB10421, GeoB10424, GeoB10423) a high dynamic sedimentation is perceptible with an general increase of $S_u$ (20-40 kPa). Significant peaks of $S_u$ correlate again with the magnetic susceptibility in case of carbonate concretions and mud clusts in redeposition layers. Sapropel layers show an decrease in density (and an increase in fractional porosity, respectively).

**Study area D: Slide Cretan Margin**

Slide processes are reflected in the physical properties.

In the upslope, undisturbed material of core GeoB10426 consist on two distinct sedimentary packages. The upper section (0-1.8 m) are characterized by a mean density of 1.8 g/cm$^3$ and a porosity of 0.6%. $S_u$ increases linear with depth from 10 to 20 kPa. In the deeper section from 2-2.9 m a significant jump in density up to 2 g/cm$^3$, which comes along with a sudden decrease of porosity (mean 0.4 g/cm$^3$). $S_u$ is less constant. Magnetic susceptibility is very constant.

The failed deposits of the Cretan Margin (cores GeoB10425, GeoB10432, GeoB10433 and GeoB10457) can be differed: material near the scar is similar to the non-failed sediments with a high density of 2 g/cm$^3$ (low porosity of 0.5%) and a linear increase of $S_u$. In contrast, the farthest removed deposits (cores GeoB10432, GeoB10433 and GeoB10457) reveal a process of homogenisation as a result of the displacement: density and porosity ranges about 1.8 g/cm$^3$ and 0.6%, respective. $S_u$ is more or less constant, which exclude the condition of having been normaly consolidated.

**Study area E: Scarp Structure**

Physical properties of the relative young scarp structure (Ch. 6.7.) represent a very homogenous feature with an average density of 1.8 g/cm$^3$. Upslope (core GeoB10455) and downslope (core GeoB10454) sediments are characterized by a linear increase of $S_u$ from 20 to 40 kPa. Sediments immediately near the scarp (core GeoB10452) and within the channel-like failure structure (Ch. 6.7.) (cores GeoB10458 and GeoB10453) evince a less pronounced linear trend of $S_u$. 
Study area F: Kamilonisi Basin

In this location, only one core was taken. However, recovery was good and four units could be distinguished. The lithological units 1,2,3 (background sediment, sandy to silty mud) are less dense (1.6 g/cm³) than the silty mud with C₇₀ content (Unit 4) and show an inverse feature of the fractional porosity. Units 1, 2 and 3 show a significantly higher magnetic susceptibility (see Appendix 9.3).

7. References


8. Acknowledgements

We thank Master Michael Schneider for his relaxed, expert way to steer Poseidon through the Eastern Mediterranean waters. Thanks go also to the crew of R/V Poseidon for their friendly support and efficient technical assistance with the various devices used.

Our colleagues in Greece, namely Dimitris Sakellariou and Vasilios Lykousis from the Hellenic Centre for Marine Research, are acknowledged for their discussion of scientific targets and help with the Greek authorities for receiving a research permission.

Thanks go also to the German Ministry for Education and Research (BMBF) for providing the funds to realise CRESTS. Additional funding was provided by the German Science Foundation (to RCOM, Bremen), for which we are very grateful.

We want to thank our colleague Katrin Huhn for having put enormous effort into the CRESTS proposal and cruise preparation. This report is dedicated to her newborn son Ole Magnus.
9. Appendices

9.1 Station list

9.2 Lithologs and core photographs

9.3 MSCL data logs (electronic version only)

9.4 Press coverage
9.1 Station list
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Note: The table contains data on various stations with their respective dates, times, descriptions, and locations. The table is part of a cruise log with details on various activities such as station numbers, dates, times, descriptions, latitude, longitude, wind, and other relevant data points. The specific activities include measurements, sampling, and profiling, among other tasks. The data is structured to provide an overview of the operations conducted during the cruise.
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<td>12:22</td>
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**Cruise:** POS 336 Mappin

**Position:**

**Voyage:**

**Stations:** 298

**Speed:** 4.4 kn Wireline max.: 2382 m

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<th>Stat. No.</th>
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**Remarks:**

**Position:**

**Voyage:**

**Stations:** 298

**Speed:** 4.4 kn Wireline max.: 2382 m
### Station Log

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**Maping Distance:** 2365.6 km  
**Voyage:** 1564.5 km  
**Station:** 335,08 h  
**Windspeed:** 2.0 m/s  
**Waves:** 2.5 m  
**Time for Air sampling:** 2.5 h
9.2 Lithologs and core photographs
Core Log GeoB10404-2

Date: 30.4.06

depth (mbsf)

0
0.1
0.2
0.3

event layers

Bioturbation

Lithological Units

Coring disturbed

fall Penetrometer Test
Not measured
Core Log GeoB10406-1

Date: 3.5.06

Lithological Units

stacked mud-flow deposits

Fall cone penetration test

Undrained Shear Strength (kPa)

0 2 4 6 8

0.5

depth (mbsf)

event layers

Bioturbation

Core Log GeoB10406-1

Date: 3.5.06

Lithological Units

stacked mud-flow deposits

Fall cone penetration test

Undrained Shear Strength (kPa)

0 2 4 6 8

0.5

depth (mbsf)

event layers

Bioturbation

Core Log GeoB10406-1

Date: 3.5.06

Lithological Units

stacked mud-flow deposits

Fall cone penetration test

Undrained Shear Strength (kPa)

0 2 4 6 8

0.5

depth (mbsf)

event layers

Bioturbation

Core Log GeoB10406-1

Date: 3.5.06

Lithological Units

stacked mud-flow deposits

Fall cone penetration test

Undrained Shear Strength (kPa)

0 2 4 6 8

0.5

depth (mbsf)

event layers

Bioturbation

Core Log GeoB10406-1

Date: 3.5.06

Lithological Units

stacked mud-flow deposits

Fall cone penetration test

Undrained Shear Strength (kPa)

0 2 4 6 8

0.5

depth (mbsf)

event layers

Bioturbation

Core Log GeoB10406-1

Date: 3.5.06

Lithological Units

stacked mud-flow deposits

Fall cone penetration test

Undrained Shear Strength (kPa)

0 2 4 6 8

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event layers

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Core Log GeoB10406-1

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stacked mud-flow deposits

Fall cone penetration test

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Lithological Units

stacked mud-flow deposits

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Undrained Shear Strength (kPa)

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0.5

depth (mbsf)

event layers

Bioturbation

Core Log GeoB10406-1

Date: 3.5.06

Lithological Units

stacked mud-flow deposits

Fall cone penetration test

Undrained Shear Strength (kPa)
Core Log GeoB10410-1

Date: 4.5.06

Fall cone penetration test

Undrained Shear Strength (kPa)
Core Log GeoB10413-1

Date: 5.5.06

Lithological Units

Bioturbation

Fall cone penetration test

depth (mbsf)

Undrained Shear Strength (kPa)

0 5 10 15 20

1a

1b
event layers

Bioturbation repetition of unit 1

slumped remobilized?

(lithostratigraphy - i.e. volcanoclastic layer and sapropel is missing)

Lithological Units

1a

1b

0 20 40 60 80 100

Undrained Shear Strength (kPa)

217 kPa

165 kPa

Fall cone penetration test

Core Log GeoB10417-1

Date: 6.5.06
Core Log GeoB10432-1

Date: 11.5.06

Lithological Units

1

2

3

4

Fall cone penetration test

depth (mbsf)

0

0.5

1

1.5

0 10 20 30 40
Core Log GeoB10452-1

Date: 14.5.06

Lithological Units

Event layers

Bioturbation

Fall cone penetration test

Undrained Shear Strength (kPa)

Core log image with depth in meters below sea floor (mbsf) and undrained shear strength graph.
Core Log GeoB10457-1

Date: 16.5.06

Depth (mbsf)

Event layer

Lithological Units

Bioturbation

Fall cone penetration test

Undrained Shear Strength (kPa)

Core Log GeoB10457-1 Date: 16.5.06
Core Log GeoB10458-1

Date: 16.5.06

Depth (mbsf)

0

0.5

1

1.5

2

Depth vs. Undrained Shear Strength (kPa)

0 50 100 150 200

Fall cone penetration test

Event layers

Bioturbation

Lithological Units

1a

1b?

2

3

4
9.3 MSCL data logs (electronic version only)

9.4 Press coverage
Ποσειδών
Ο Ποσειδών
Στο Ποσειδών η άφθονη αναπαραγωγή

Ποσειδών

Η πλοηγή του Ποσειδών ξεκινάει στην Κύθη.

Ποσειδών

Ο Ποσειδών εξερευνά την Κρήτη.

Ποσειδών

Στο Ποσειδών η άφθονη αναπαραγωγή

Ποσειδών

Η πλοηγή του Ποσειδών ξεκινάει στην Κύθη.

Ποσειδών

Ο Ποσειδών εξερευνά την Κρήτη.
Στο Ηράκλειο το "Ποσειδών"  

- Το πρωτόκολλο της Βέρνης επικαλείται τη Τουρκία

Διεθνές πρόβλημα, η εργασία μεγάλων οικονομικό ζημιών και της διαχωριστικής σχέσης μεταξύ της Ελλάδας και της Τουρκίας. Η Αγκυρα και η Βέρνη έχουν δώσει ομολογίες της ανίκανης και της ανικανής διαμάχης. Η Τουρκία επικαλείται στον πρόπολο της ήττας της στο Πρωτάθλημα της Ευρωπαϊκής Κουπές του Ακροπολίδου του 1976 και του Τουρκία του 1997. Η Ελλάδα επικαλείται στον πρόπολο της ανίκανης και της ανικανής διαμάχης.

Ο Καπετάνιος του "Ποσειδών" κ. Σάντερ

Πει ότι "δεν έχει περιέλθει σε γνώση της ελληνικής πλευράς και τάτοιο".

"Το πλοίο βρίσκεται στην Κρήτη. Οι έρευνες εγκατέλειπε και γνωρίσει ότι στο προβλήμα διάστημα είπε ακόμα για το θέμα."

Η Τουρκία

Οι θέσεις της Αγκυρας γύρω από το ζήτημα ανάκυψαν με την έρευνα του ιταλικού πλοίου "Ποσειδών" στον Ακρόπολι. Η Ελλάδα διαμοιράζεται την ισχύ της και την αναποδοχή του ιταλικού πλοίου "Ποσειδών". Οι Τουρκοί διαμοιράζονται την ισχύ της και την αναποδοχή του ιταλικού πλοίου "Ποσειδών". Οι Ηνωμένες Πολιτείες διαμοιράζονται την ισχύ της και την αναποδοχή του ιταλικού πλοίου "Ποσειδών". Οι Ελληνικές Πολιτείες διαμοιράζονται την ισχύ της και την αναποδοχή του ιταλικού πλοίου "Ποσειδών".
Διπλωματικό θρίλερ

"Εδεσε" ο "Ποσειδώνας"

Ανεφοδιάζεται το διεθνές σκάφος

Στις 9 χιλιόστρωσε το πρώτο φάσμα, όπως ήταν προγραμματισμένο, το ερευνητικό σκάφος "Ποσειδώνας" στο λιμάνι του Ηράκλειο και έδεσε στην προβλήτα 4.

Από χάρη ξεκίνησαν οι εργα- λέες ανεφοδιασμού του σκάφους και παρα τον θά- ρυμα που είχε προκληθεί ο πλοίαρχος αλλά και το πλήρω- μα εξείδρευε σαν να μην συμβαί- νει τίποτα και σαν να μην τους έχει αισθαντάται αλλά αυτός ο θάρυμα. Η έκτα τουλάχιστον έδειξε να διαλύεται, εφόσον η θάρυμα έγινε αργότερα για τους επαγγελματίες να δουλέψουν εύκολα στο πλοι- τικό τους πολεμικό σκάφος του τουρ- κού ναυτικού.

Ο ερευνητικό σκάφος θα ξε- κινήσει και πολύ τις ημέρες το Σάββατο, εσωτερικά και θα ανανεο- ριστεί από το λιμάνι του Ηρά- κλείου το δια προς την Κύπρο. Μέχρι τότε είχαν ακούσει από παράσημα θάρυμα της ασφαλείας που έχει ξεκινήσει από τις πρώτες ημέρες της ερευνής της σκά- φους, θα έχει λήξει.

Χάκε στο πρώτο, πάντως, ο πλοίαρχος του "Ποσειδώνας" Μι- χαλέλλας, με δηλώσεις του εκείνη σαφές πως τόσο ο ίδιος όσο και το πλήρωμα του σκά- φους, δεν μπορούσαν σε τέτοιες διαδικασίες και αυτό που τους ενδιαφέρει είναι να ολοκληρώ- σουν την αποστολή που έχουν αναλάβει.

"Οκτώ ολοκληρώσης ερευ- νής και εντόπισης Σάββατο το πλοίαρχος του "Ποσειδώ- 

Από χάρη ξεκίνησαν οι διαδικασίες για την ανεφοδιασμό του πλοίου, ενώ σήμερα και σήμερα αναμένονται μέλη του πληρώ- 

το βάθος της σκάφους. Έχει δοθεί πλήρης αναλογία και εξελικτική για τη δεύτερη φάση των ερευ- 

νής της προσβολής. Ο πλοίαρχος το "Ποσει- 

Διπλωματικό θρίλερ

"Εδεσε" ο "Ποσειδώνας"

Ανεφοδιάζεται το διεθνές σκάφος

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"Αυτό το θέμα αναπό- λογο ασφαλείας των καραμελαντών της Ελλά- 

δις της Τουρκίας και της Γερμανίας, θα έχει αναλάβει την επικύρωση του ερευνητικού σκάφους, θα μόνο για την υλικά -νή το τάχθη στο λιμάνι του
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