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A high resolution seismic sequence analysis of the Malta Plateau

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Jan L. Spoelstra
Director

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A High Resolution Seismic Sequence Analysis of the Malta Plateau

John Osler and Oya Algan

Executive Summary:

A high resolution seismic study of the Malta Plateau has been conducted. This is an area in which several SACLANTCEN sea-trials SWAC1, SWAC2, BACCHUS98, and SCARAB98 have been conducted as well as the NATO exercise Dynamic Mix 96. An objective of the SCARAB (SCAttering and ReverberAtion for large Bandwidths) experiments is to isolate the physical mechanisms that cause bottom scatter and to relate them to mean and second order reverberation statistics. Of specific interest is the relationship between the physical properties and composition of the seabed and where energy is scattered: the seabed, acoustic basement, within sub-seabed layers or from boundaries between layers. Accordingly, this high resolution seismic study was conducted in order to characterize the regional extent of sub-seabed reflectors and to establish the depositional mechanisms which prevailed for Plio-Quaternary sedimentation.

Six seismic units (or depositional sequences), bounded by erosional unconformities, are present on the continental shelf, overlying an acoustic basement. Seismic sequence analysis is used to identify the depositional systems, associated sedimentation conditions, and relative sea level changes. The onlapping character of all the sequence boundaries reveals a major sea level rise throughout the Plio-Quaternary. On the basis of the geometry of the internal reflectors within several of the sequences, the erosional unconformities between the sequences may be attributed to periods of non-depositional (sediment bypassing the deposition surface) and/or minor erosional processes. These could occur during periods of regression (seaward migration of coastal deposits) or sea level stillstand. It is anticipated that the physical properties of the sediment in the immediate vicinity of the erosional unconformities differ from those in the adjacent sequences. For the sequences themselves, it is anticipated that the physical properties of the sediment are relatively homogeneous within a sequence and with respect to other sequences, with the exception of the uppermost sequence, Seismic Unit 1.

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A High Resolution Seismic Sequence Analysis of the Malta Plateau

John Osler and Oya Algan

Abstract:

A high resolution seismic study of the Malta Plateau was conducted to characterize the Quaternary sediment layers, mapping their regional extent and determining the environmental conditions during their deposition. Seismic stratigraphic analysis indicates that there are six seismic units (or depositional sequences) bounded by erosional unconformities. The basement surface, that is an erosional truncation in some places, indicates that a hiatus probably occurred during Messinian to Early Pliocene. The terminations of all the sequence boundaries onlap the acoustic basement in a landward direction, revealing an overall relative sea level rise. The termination of the internal strata (reflectors) in Units 2, 3 and 4 have an oblique parallel pattern and toplap at their upper surface, characteristic of periods of sea level stillstand and/or a decrease in the rate of sea level rise. It is anticipated that this depositional history would cause the physical properties of the sediment in the immediate vicinity of the erosional unconformities to differ from that in the adjacent sequences. Within a given sequence and with respect to the other sequences, it is anticipated that the physical properties of the sediment are relatively homogeneous, with the exception of the uppermost sequence, Seismic Unit 1.

Carbonate buildup structures are observed at the boundary between Units 2 and 3 in the northwest part of the study area and imply a very shallow water depositional condition during their formation. The uppermost layer, Unit, 1, is the most extensive geographically and gets thicker towards the coast of Sicily. The parallel configuration of its internal reflectors and the progradational character of the unit suggest that it is comprised of coastal sediments deposited during the Holocene highstand of sea level. In the shelf-slope transition, sequences are deformed by mass movements that might be attributable to tectonic activity in the region. Several basement outcrops were observed in the study area. Some have northwest-southeast trending lineations, as observed on Sicily, while others are isolated structures, possibly dikes or salt domes.

Keywords: Malta Plateau, sequence stratigraphy, sea level changes, Quaternary sediments, seismic reflection

Contents

1
Introduction

A high resolution seismic study of the continental shelf and shelf-slope transition in the Malta Channel, south of Sicily, was conducted in order to characterize the regional extent of sub-seabed reflectors and to establish the depositional mechanism for shelf sedimentation through the sea level changes during Pleistocene to present.

Seismic stratigraphic analysis is used as a powerful tool to identify the depositional systems, associated sedimentation conditions, and relative sea level changes (*e.g.* Vail, 1977; Haq *et al.*, 1987) (see Appendix C). The basement of the Malta Plateau is constituted by Messinian low-stand strata (Finetti, 1984). The Malta Plateau was exposed to sub-aerial erosional processes during the Messinian salinity crisis (~ 5 My) when the Mediterranean Sea was almost dried by blockage of the Strait of Gibraltar to the Atlantic water mass. Later, it became a depositional area of Plio-Quaternary sediments (Argnani, 1993; Max *et al.*, 1993a, b).

Study area

The area between Malta and Sicily, the Malta Channel (Figure 1), is the extension of Ionian Sea in the central Mediterranean. The shelf area in this region is narrow and has shelf breaks at various water depths between 80 and 190 m (Carter *et al.*, 1972). The Malta Plateau (Malta Rise) is situated between Malta and Sicily, confined by the 200m bathymetric contour (Figure 1), and is connected to the Adventure Bank in the west. Between Malta and Sicily, the plateau maintains almost constant depths (at around 100-200 m). The morphology of the sea floor in the study area is a result of regional structural elements of the tectonics, such as the Sicilian Channel rift zone and the Malta graben-horst and thrust which extends to the Apennines in the north. The water depth to the south of Sicily gradually increases from 10 m to 100 m towards the Malta Channel. Depth increases follow two geographical trends: from northeast to southwest to the south and west of Sicily and from northwest to southeast along the Malta Escarpment (Figure 1).

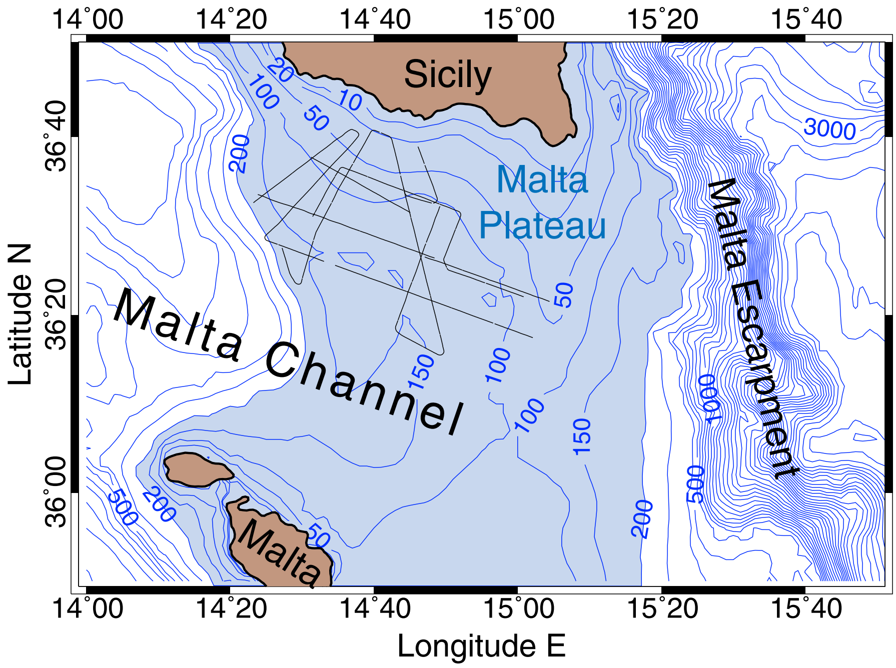

Figure 1: Generalized bathymetry of the Malta Channel and Escarpment. The Malta Plateau is shaded blue and the seismic tracks in this study are in black. Contours of DBDB-V bathymetry are in blue. The contour interval is 100 m for water depths in excess of 200 m and as indicated for water depths less than 200 m.

2
Geological Setting

The Malta Plateau is one of the geomorphological features of the Sicilian-Tunisian Platform (STP), an extremity of the North African passive continental margin in the south central Mediterranean Sea. The STP is a micro-plate that includes shallow water depositional environments such as the Malta and Tunisia plateaus, the Adventure and Medina banks, and also some structural elements, such as the Sicily Channel rift zone and the Maghrebian fold-thrust belt that extends from Africa to Sicily (Barberi *et al*., 1974; Catalano and D'Argenio, 1982; Argnani, 1990; Argnani, 1993). The study area is north of the Sicily Channel rift zone, which is dominated by a combined, pull-apart and strike slip system. The initiation of rifting in Late Miocene (~10 My) or Early Pliocene (~4 My) continued with high intensity until the Late Quaternary (~ 0.1 My) and then ceased before present time (Finetti, 1984). An extensional tectonic regime was active, supporting a rifting mechanism for the Sicily Channel during the Middle Pliocene (~3 My), whereas strong vertical tectonic movements dominated in Late Pleistocene (Catalano *et al*., 1993a). The northern portion of the STP is part of a Late Cenozoic orogenic belt that developed from the Apennines in Italy to the Maghrebides in North Africa (Catalano *et al*., 1993b). There are numerous northwest-southeast trending faults in southern Sicily, generally parallel to the Malta Escarpment (Gardiner *et al*., 1993).

The Malta Plateau is a submerged southward extension of the Hyblean Plateau in mainland Sicily (Grosso and Lentini, 1982). The Hyblean Plateau consists of Meso-Cenozoic carbonates and volcanics. This area has been subjected to continuous subsidence during Late Miocene-Early Pliocene when marls, evaporites, and pelagic chalks were deposited. The deposition of shallow water carbonates off the southeastern tip of Sicily indicates that the area was stable since Middle-Pliocene. Pleistocene sediments have been observed at approximately 120 meters above sea level (Gardiner *et al*., 1993). In southeastern Sicily, the hiatus and unconformity between the Lower Pliocene and Lower Pleistocene indicate the occurrence of widespread erosion after early Pliocene times (Gardiner *et al*., 1993).

The geologic basement of the continental shelf of Malta Plateau is constituted by Messinian low-stand strata (Finetti, 1984). The Malta Plateau was exposed to sub-aerial erosional processes during the Messinian salinity crisis (~ 5 My) when the Mediterranean Sea was almost dried with the blockage of the Strait of Gibraltar to the Atlantic water mass. The sea level was 250 to 380 m lower than its present level in Tyrrhenian Sea which is north of Sicily (Kastens *et al*., 1987). Later, it became a depositional area of Plio-Quaternary sediments (Gardiner *et al*., 1993; Argnani, 1993; Max *et al.*, 1993a, b). Gardiner *et al*. (1993) identified Lower and Upper Pliocene layers overlying the Messinian evaporites in the Malta Platform at water depths greater than 200 m. They also noted the prograding wedge of Pleistocene deposits and pointed out that the depositional center for Plio-Pleistocene sediments has migrated to the west-northwest with time. Max *et al.* (1993a, b) observed an 8 to 12 m thick sedimentary layer consisting of recent fine-grained sediments which overlies six different seismic units in the west central-Malta Plateau. They interpreted the upper six units as having been deposited during the Plio-Quaternary. To the southwest of Sicily, Di Stefano *et al.* (1993) identified six sequence boundaries and estimated the ages by the biostratigraphic composition of well logs correlated with the seismic data. The estimated ages of the sequence boundaries are 0.6 My, 1.2 My, 2.4 My, 2.6 My, 3.1 My and 3.8 My respectively and the estimated ages of the maximum flooding surfaces are 0.92 My, 1.85 My, 2.45 My, and 3.38 My respectively. As the location of the seismic reflection profiles in Di Stefano *et al.* (1993) do not overlap any of the profiles in this study and use a lower frequency source, it is not clear whether these are the same sequence boundaries identified in this study.

Sedimentation during the Late Pleistocene–Holocene was synchronous with a general rise in sea level during the last eustatic hemicycle characterized by an overall climatic warming and the melting of the continental ice sheets (*e.g.* Rudiman and McIntyre, 1981). On the basis of various investigations carried out in Mediterranean Sea (*e.g.* Hernandez-Molina *et al.*, 1994; Saito, 1991), the sedimentation of lowstand deposits took place between 20 ky and 18 ky during the time of maximum ice volume and an extensive portion of the continental margins were exposed to subaerial conditions. Erosional processes are observed on the continental shelf, extending to between 110 and 150 m water depth (Perissoratis and Mitropoulos, 1989). A later eustatic rise started between 18 ky and 14 ky, continuing until around 6 ky (Fairbridge, 1961; Chappel and Shackleton, 1986). This has favored sediment accumulation in the proximal parts of the shelf. The lowest Holocene sequences developed within this transgressive context caused the landward retreat of the coastline. Various authors have shown that this transgression was characterized by brief stillstands. The deposition of upper Holocene sequences occurred in a highstand context during the last 6 ky.

Surficial sediments in the region have different compositions depending upon the water depth (Tonarelli *et al.*, 1993). Carbonate sediments dominate in shallower areas with a water depth of less than approximately 75 m. In the deeper water of the Malta Plateau, terrigeneous sediments are mixed with pelagic and hemipelagic sediments. The source of the carbonate materials in the area is the African carbonate shelf environment (Tonarelli *et al.*, 1993), however sediments from the Malta Plateau have a more pelagic character similar to those of deep water Pantelleria Basin.

3
Survey Equipment and Data Acquisition

Equipment

The reflection seismic survey was conducted by RV *Alliance* in April 1998. The seismic source was an EG&G model 265 Uniboom which has a repeatable short pulse length and a broad bandwidth (approximately 600 to 6000 Hz). Its electromechanical assembly consists of an insulated round metal plate of radius 0.2 m and rubber diaphragm adjacent to a flat-wound electrical coil. A short duration high power electrical pulse discharges into the coil and the resultant magnetic field explosively repels the metal plate. The plate motion in the water generates a single broadband acoustic pressure pulse less than 1 ms in duration with a broadband source level of 207 dB re 1 μPa for an input of 300 J. The source was mounted on a catamaran with a source depth of about 0.2 m and tow speed of 4 to 5 knots. The pulse repetition rate was 1 pulse per second (or 1 pulse approximately every 2.5 m). Uniboom pulses are initiated by a trigger controlled from a GPS clock. The data acquisition is also keyed to GPS, thereby avoiding any possible errors in clock synchronization. The receiver array consisted of a single channel surface towed array of 10 hydrophones. The horizontal separation of the source and receiver was approximately 21 m, as they were towed just slightly astern and outside the wake of the vessel, on the port and starboard sides respectively. In the preparation of the isopach maps, a travel time correction, which is a function of water depth and a depth averaged sound speed, is applied to the reflector travel times to correct for the horizontal separation.

Data acquisition

The signal is passed through two gain stages. The first stage is a Stanford pre-amplifier that applies a 24 dB gain and high pass filter above 200 Hz to remove much of the mechanical noise due to the turbulent flow. The second gain stage is a Krohn-Hite bandpass filter from 500 to 8000 Hz, typically with 10 dB gain on the input signal and 20 dB gain on the output signal, although these were changed by up to ±6 dB depending on water depth. An analog copy of the reflection seismograms was printed on an EPC thermal paper chart recorder. Digital data, sampled at 12 kHz, were stored for backup purposes on 4 mm DAT tapes, and acquired as 2 byte integers in SEG-Y format on an HP Series 700i workstation. The gain setting of the second stage was adjusted such that the highest amplitude seabed reflector used the top 1 or 2 bits without clipping, thereby using as much of the 16 bits of dynamic range as possible. Accordingly, the amplitude scale is -16384 to 16384 (-2^{15} to 2^{15}) and clip settings used in displaying the data (Section 4) are in terms of this amplitude scale.

Survey Tracks

For characterizing regional seismic reflectors beneath the seafloor, seismic reflection profiles were obtained along several tracks: boom02, boom03, boom04, boom05, udbe1, ubdw3, and udbe4 as indicated in Figure 2. To facilitate the interactive data analysis (Section 4), the seismic reflection profiles were typically divided into segments of 3600 seismograms (1 hour of elapsed time) each with a 0.25 s time window, starting a variable time after the trigger. Seismic reflection profiles were also collected along a number of shorter tracks during acoustic bottom loss experiments. The profiles were used in consistency checks (Appendix B), but not in the preparation of isopach maps. Plots of all the seismic data, navigation, and oceanographic measurements are archived in Holland *et al*. (1999).

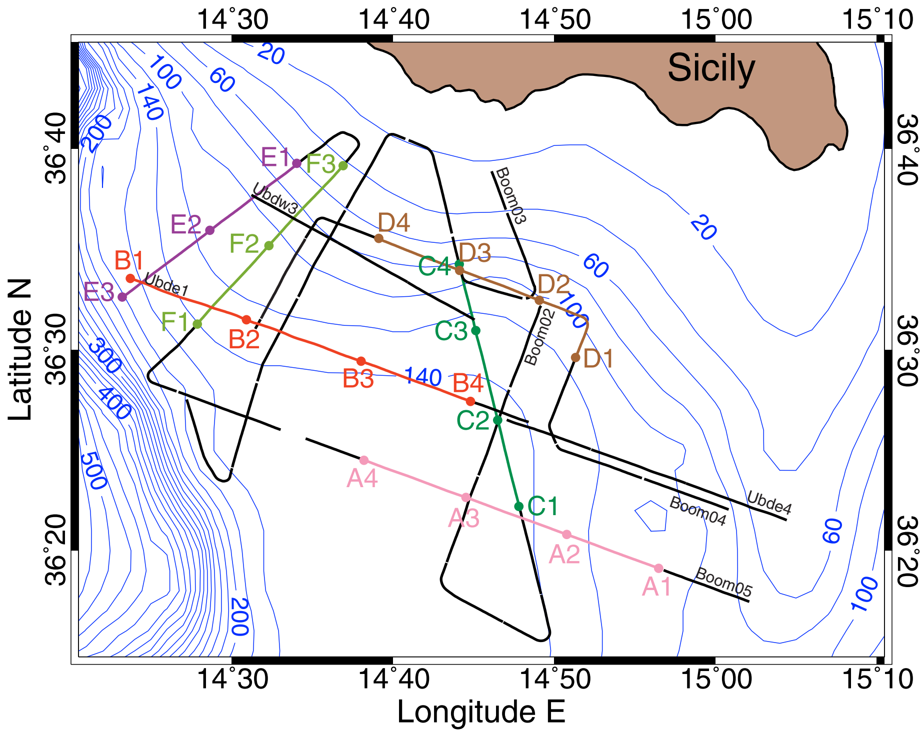

Figure 2:Seismic reflection tracks in the Malta Channel. Seismic profiles of lettered segments are displayed in Figure 4. Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

4
Data Processing

Identification of Reflectors and Their Characteristics

High resolution seismic reflection profiles collected from the study area were displayed using two "clip" settings to modify the amplitude scale of the data. Points with an amplitude beyond the maximum positive or negative values defined by the clip are assigned the corresponding value of the clip. To analyze the deeper structure, such as identification of basement and the first sedimentary cover immediately above it, a clip setting of ±300 was typically used. To examine the upper sedimentary layers and structures, a clip setting of ±900 was typically used.

To understand the regional extent of the various seismic units, major reflectors were identified on large-scale hardcopy images of the seismic reflection profiles. This analysis revealed that the principal trends in bathymetry, geological structures of the area, and sediment thickness were best examined using segments of the reflection profiles with geographic orientations as follows:

1. Northwest to southeast: boom04 (a, b, e, f, g), boom05 (a, b, c, d, e, f), ubde4 (a, b, c, d), ubsw2 (a, b, c, d, e), ubde1 (a, b, c, d), and ubdw3 (a, b, c, d)

2. Northeast to southwest: boom02 (a, b, c, d, e, f, g, h, i), boom03 (b, c, d, e, f, g, h, i), boom04 (c, d, h, i), and boom05 (g, h, i, j, k, l)

The boundaries between different seismic sequences (units) are based upon the identification of major unconformities. These generally produce strong reflections that are regional in extent. The correlation of units between different seismic lines was based on their lateral continuity away from intersection points and their specific internal configurations, such as parallel, sub-parallel bedding (see Appendix C, for definitions)

Digitizing the Travel Time of Seismic Reflectors

The Seismic Unix software package (SU), version 3.2 (Cohen and Stockwell, 1998), was used for processing and visualizing the seismic data. Picking of the travel time of different unit boundaries was accomplished by using a version of an SU module, SUXPICKER, which was modified for our requirements (Appendix A). Travel time picks were made for every 60th seismogram, a horizontal spacing of approximately 150 m. Seabed, major seismic reflectors, and acoustic basement (defined as the top of the first strata of consolidated material) were given unique identifiers (in ascending order from 1 to 7). Sub-units with relatively weak reflections, often showing onlaps and downlaps to the successive layers were assigned identifiers from 8 to 12. The sub-unit tracks within the main seismic units were observed clearly and therefore picked in profiles boom02, boom05 and ubde1. The rest of the seismic profiles do not show these reflectors, probably due to higher ambient noise levels and/or sea-state. The travel time picks for each segment are stored in an individual file which may be overlain on reflection profiles using a combination of SU and in-house software modules (see Appendix A for details).

Two measures are taken to control the quality of the travel time picks. Hardcopy images of the segments of a seismic reflection profile, with travel time picks overlain, are assembled to ensure the consistent identification of reflectors defining the boundaries between units. In addition, the travel time and reflector identifiers are checked at all points on intersecting tracks (see Appendix B).

Preparation of Isopach Maps

Contour plots of the thickness of sedimentary units (isopachs) have been prepared using the travel time picks. The difference in vertical incidence travel times between the reflectors bounding a unit, corrected for the horizontal source-receiver separation (Section 3), are gridded with a resolution of 0.005 degrees (555 m in latitude and approximately 447 m in longitude). The gridding algorithm (*trigrid* in IDL 5.2, Research Systems Incorporated, 1998) uses Delaunay triangulation of the geographic location of the travel time picks. For each contour plot, the locations that are used in the gridding are displayed in red. This is to assist in identifying areas of the contour map which are prone to error, typically due to interpolation across large distances or near boundaries.

5
Seismic Stratigraphic Analysis

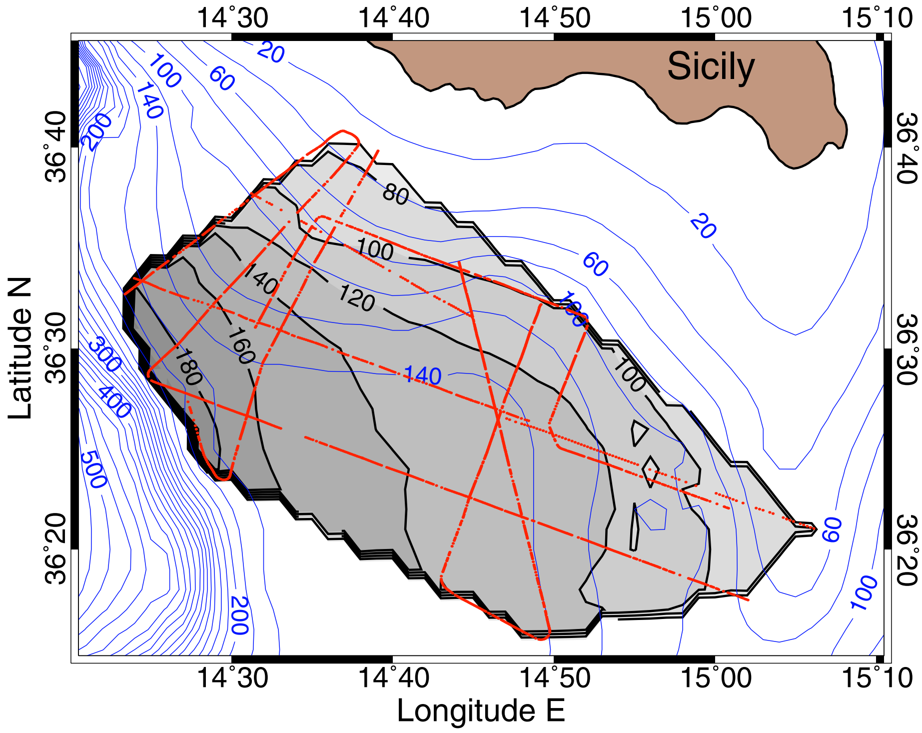

Figure 3: A comparison of bathymetry from the R/V Alliance echo sounder (black contours with gray shading) at positions along the seismic tracks (red) and DBDB-V (blue contours).

Bathymetry

A bathymetric map has been prepared using the single beam bathymetric sounder which operated during collection of the seismic reflection profiles (Figure 3). This data has been gridded to the same resolution (1 minute) as the Digital Bathymetric Data Base-Variable Resolution (DBDB-V) which is used to display the regional bathymetry. A comparison of the two bathymetry data sets reveals siginificant discrepancies, up to 40 m in the northwest corner of the survey area. Some general features of the bathymetry include: a gradual increase from 80 m to 200 m towards the southwest; the tendency for contours which are less than 100 m to parallel the coast of southern Sicily; and in the east, the 100 m contour approximately outlines the outcropping ridge (Figure 4 A1-A2).

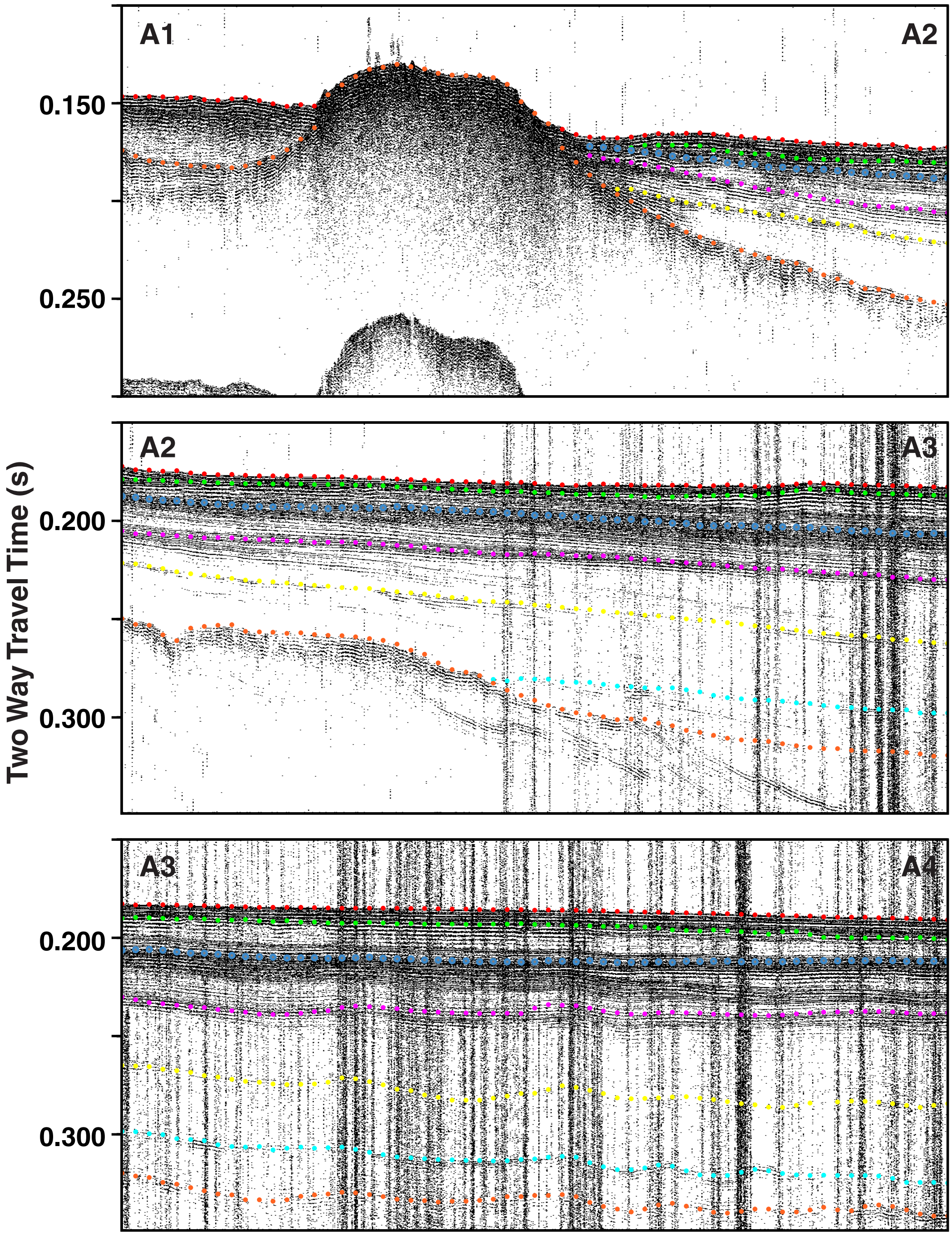

Figure 4 (A):Single channel seismic reflection profile segments from track boom05 (see figure 2 for location). Seismic Units 1, 2, 3, 4, 5, and 6 are bounded by the unconformities which are colour coded red (seabed), green, blue, magenta, yellow, cyan, and orange (acoustic basement) respectively. Note onlap of sequence boundaries to acoustic basement in A1-A2 and A2-A3. Clip set to 400.

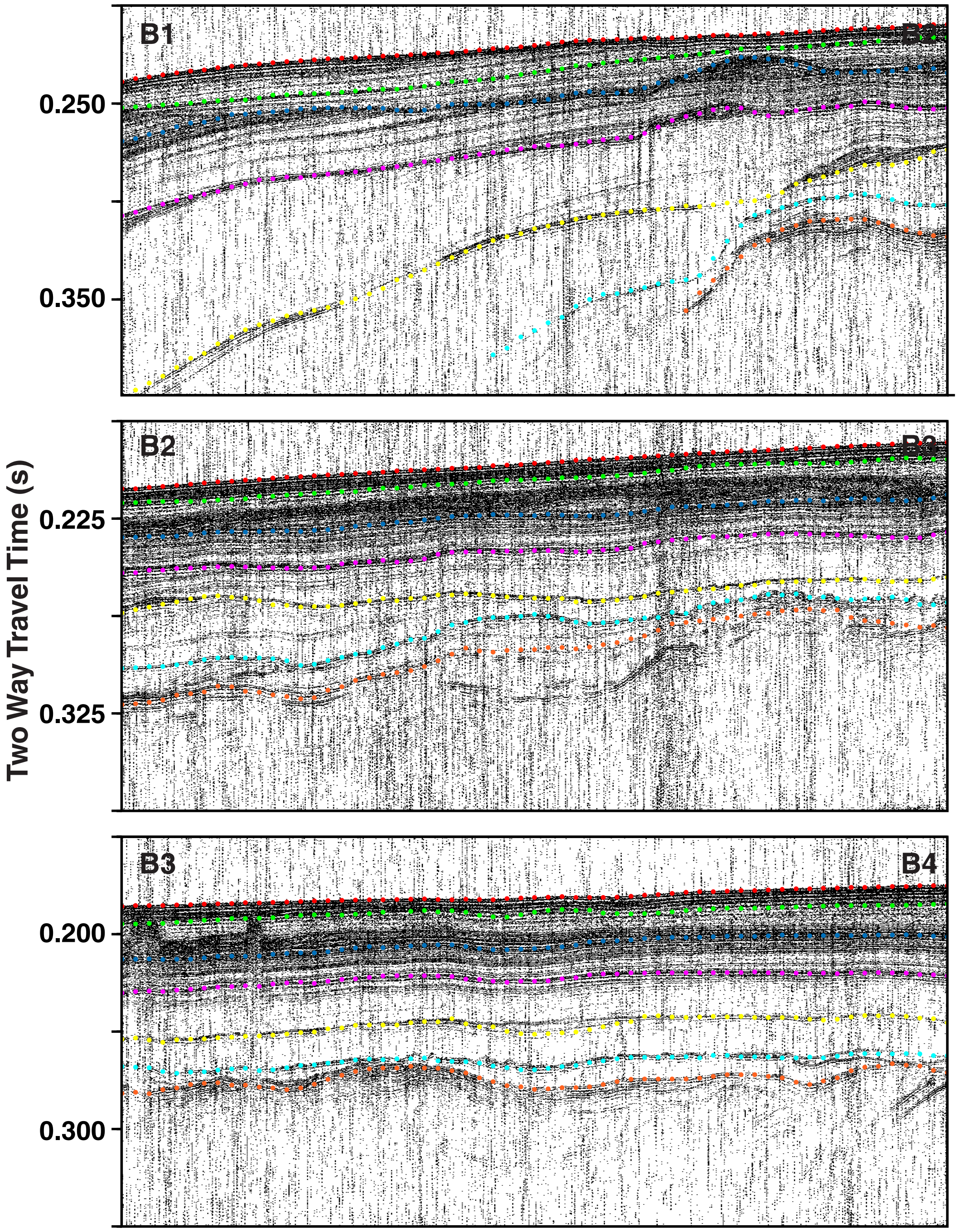

Figure 4 (B): Single channel seismic reflection profile segments from track Ubde1(see figure 2 for location). Seismic Units 1, 2, 3, 4, 5, and 6 are bounded by the unconformities which are colour coded red (seabed), green, blue, magenta, yellow, cyan, and orange (acoustic basement) respectively. Note carbonate buildup in B1-B2. Clip set to 600.

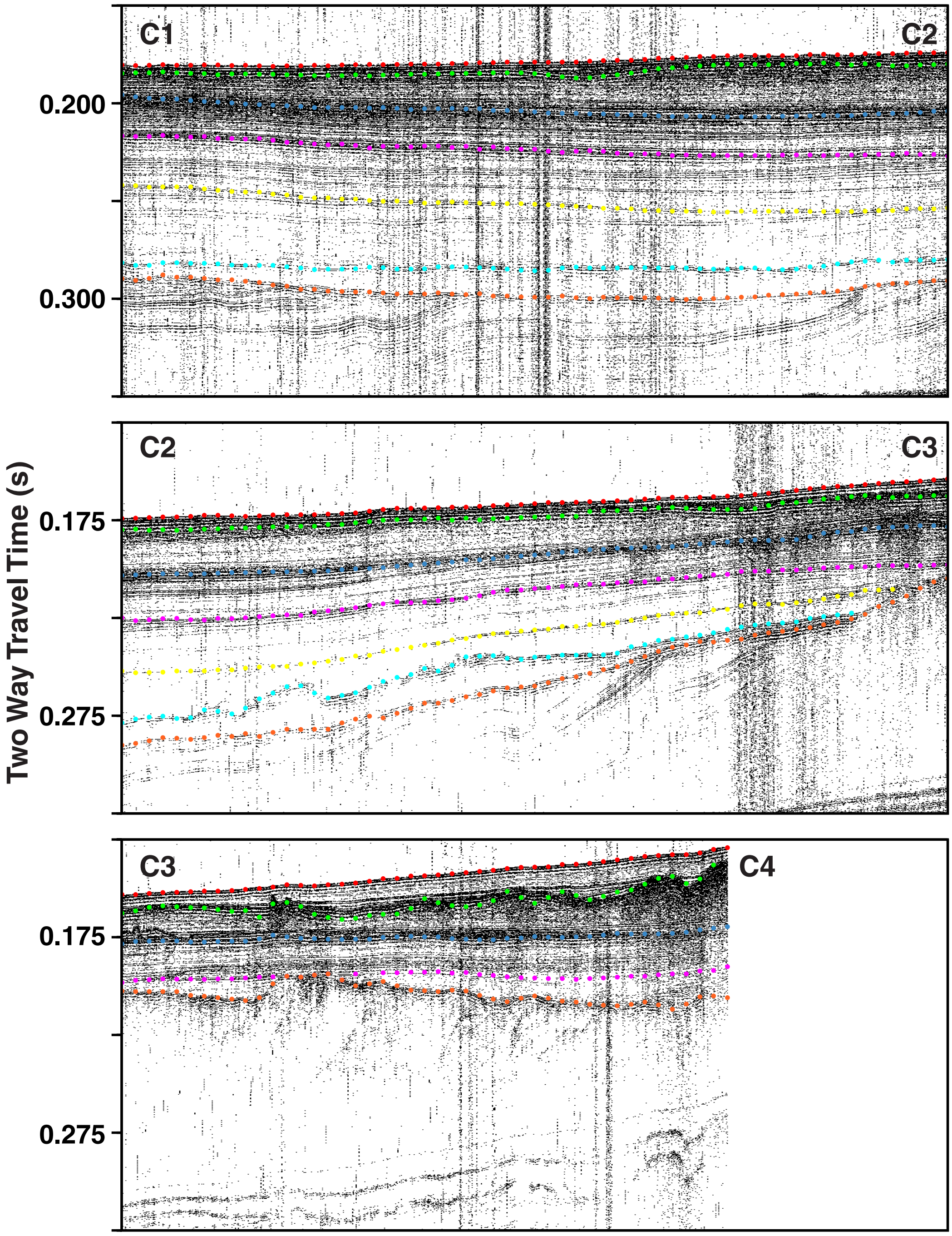

Figure 4 (C): Single channel seismic reflection profile segments from track boom02 (see figure 2 for location). Seismic Units 1, 2, 3, 4, 5, and 6 are bounded by the unconformities which are colour coded red (seabed), green, blue, magenta, yellow, cyan, and orange (acoustic basement) respectively. Clips are set to 600, 900, and 1200 for C1-C2, C2-C3, C3-C4 respectively.

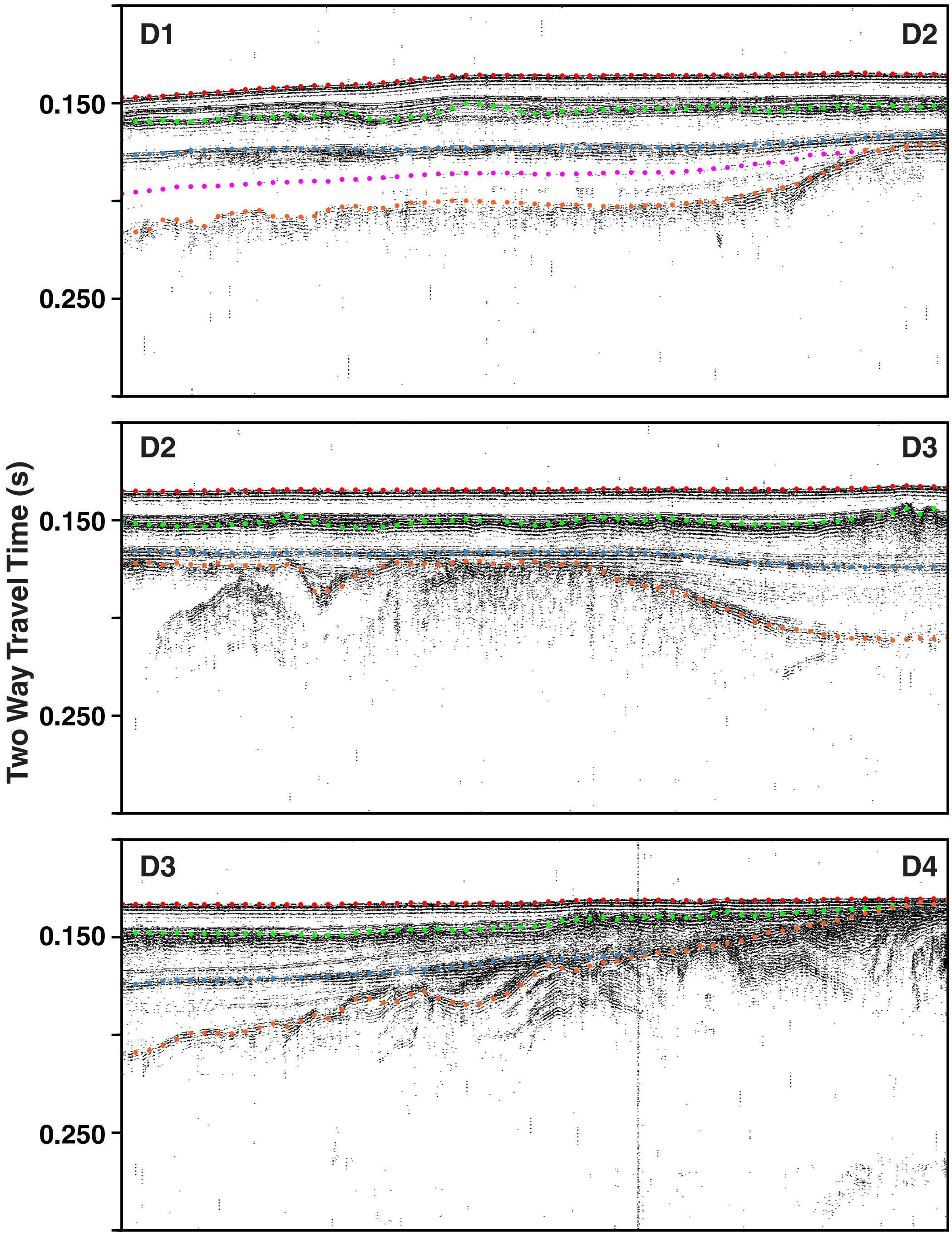

Figure 4 (D): Single channel seismic reflection profile segments from track boom04 (see figure 2 for location). Seismic Units 1, 2, 3, and 4 are bounded by the unconformities which are colour coded red (seabed), green, blue, magenta, and orange (acoustic basement) respectively. Note onlap of sequence boundaries to acoustic basement in D1-D2 and D3-D4. Clip set to 400.

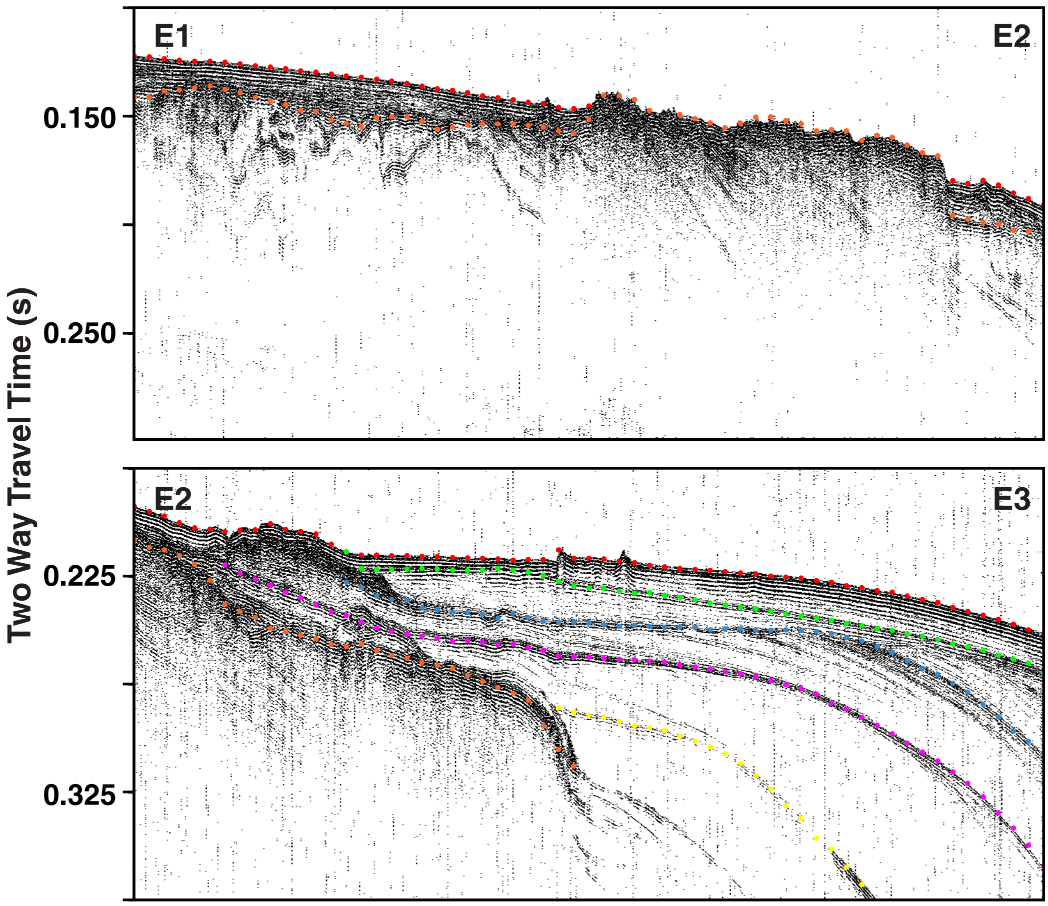

Figure 4 (E): Single channel seismic reflection profile segments from track boom05 (see figure 2 for location). Seismic Units 1, 2, 3, 4, and 5, are bounded by the unconformities which are colour coded red (seabed), green, blue, magenta, yellow, and orange (acoustic basement) respectively. Note toplaps of internal strata in Units 3, 4, and 5, and mass movements seaward of the basement outcrop (E2-E3). Clips set to 800 and 400 for E1-E2 and E2-E3 respectively.

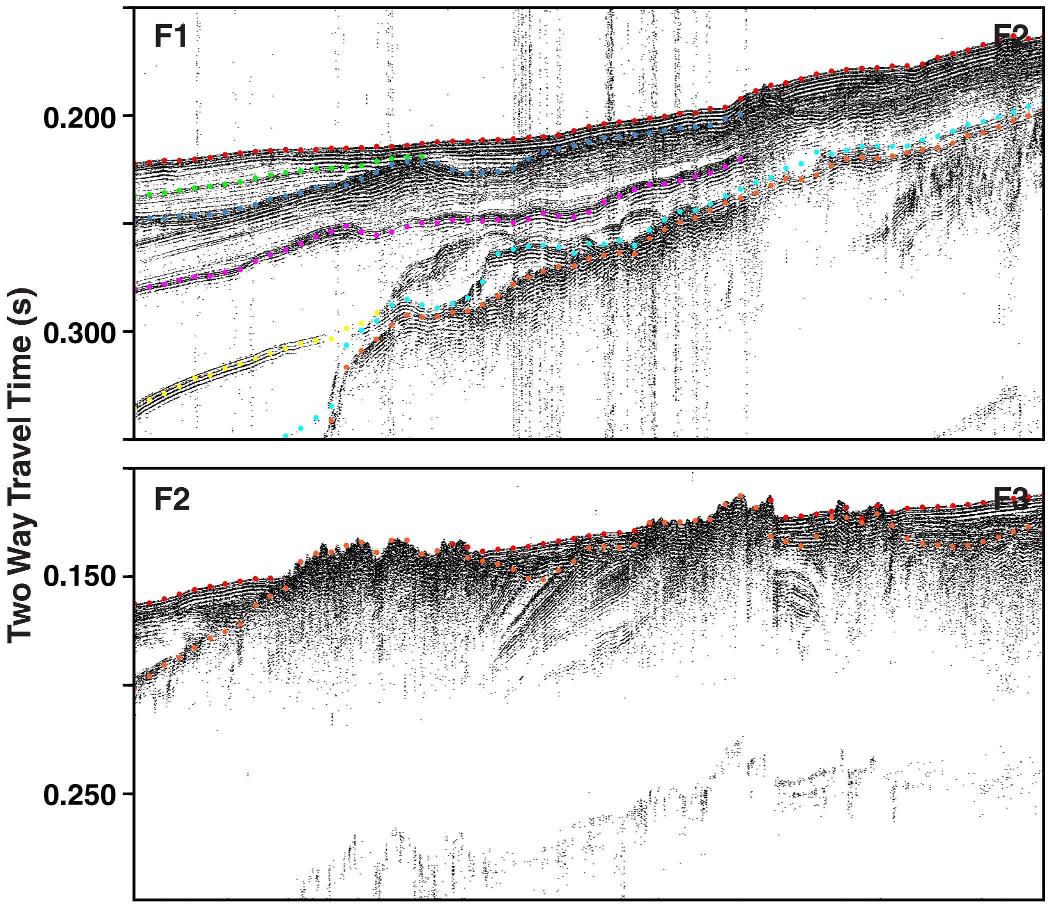

Figure 4 (F): Single channel seismic reflection profile segments from track boom05 (see figure 2 for location). Seismic Units 1, 2, 3, 4, 5, and 6 are bounded by the unconformities which are colour coded red (seabed), green, blue, magenta, yellow, cyan, and orange (acoustic basement) respectively. Note deformation of units in F1-F2 due to mass movements and minor faults in acoustic basement in F2-F3. Clips set to 400 and 800 for F1-F2 and F2-F3 respectively.

Acoustic Basement

The acoustic basement beneath the sedimentary layers is constituted by two different geological formations. One of the formations is easily recognized by the absence of its internal reflections (Figure 4 A1-A2). The other formation exhibits folded layers and has an erosional truncation at its top (Figure 4 C1-C4). In previous studies (Jongsma *et al*., 1984; Max *et al*., 1993a, b), this basement is identified as Miocene aged limestones and dolomites. The internally featureless unit might be related to the Meso-Cenozoic volcanics of Hyblean Plateau (Grasso, 1993) or thick limestones or dolomites (Max *et al*., 1993a, b). There are minor faults observed in the basement, however no manifestation of these faults was observed in the overlying sediments.

Basement morphology is variable in the study area (Figure 5). It outcrops the sea floor in the northwestern (Figure 4 E1-E2) and eastern parts (Figure 4 A1-A2) of the study area where the water depth is less than 100 m. In the central part of the study area, there appear to be drainage channels (Figure 5) which have incised the basement. The basement subject to this erosion is a folded sedimentary formation (Figure 4 C1-C4). A map of sedimentary thickness between the basement and the seabed is shown in Figure 6. The thickness of the sedimentary cover exceeds 160 ms[1] (approximately 132 m). It is thinnest in areas where the basement rises to and is exposed at the sea floor. The maximum thickness is found to the southwest and is greater than the depth of penetration of the boomer sound source. Overall, the thickening trend is parallel to the bathymetry.

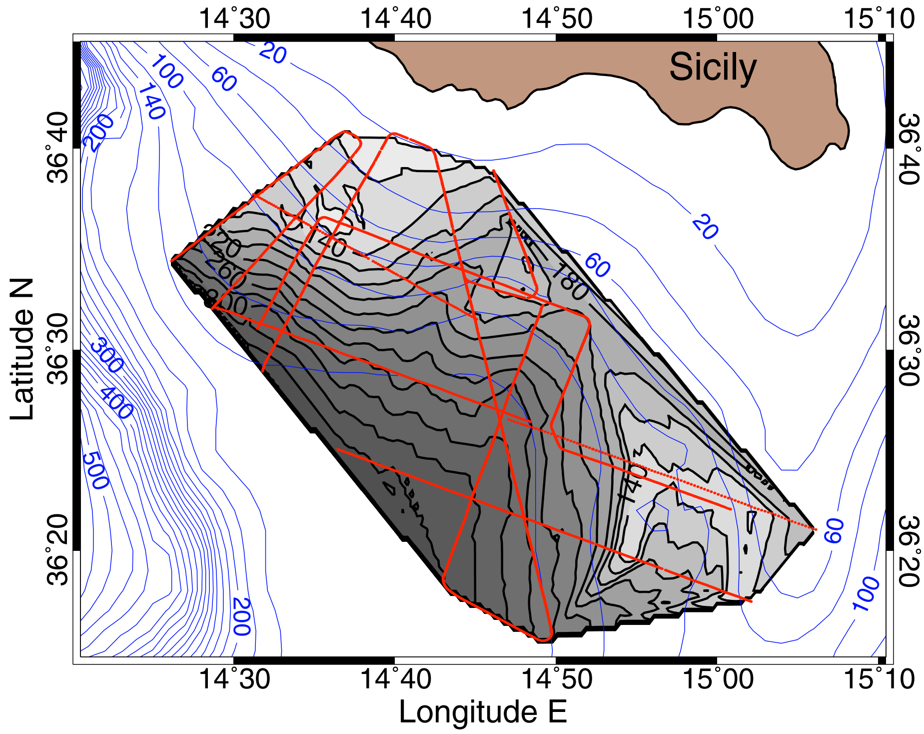

Figure 5:Depth to acoustic basement in two way travel time (black contours in milliseconds with gray shading). Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

Sedimentary Units

Seismic stratigraphic analysis was undertaken following the standard method of Vail *et al.* (1977). Depositional sequences were distinguished by their conformable reflectors

[1]Travel-times are always specified as "two way travel-times", that is the entire time of flight from the source to a given reflector and back to the receiver, corrected for the horizontal separation between the source and receiver.

which are bounded by unconformities at their upper and lower surfaces (Mitchum *et al.*, 1977). Reflection terminations at sequence boundaries and reflection configurations within the sequences were then examined. Consistent with Max *et al.* (1993a, b), six major depositional sequences (seismic units) are observed in the seismic reflection data from the continental shelf of the Malta Plateau. These sequences are separated from one another by unconformities (Figure 4 A, B, C, D and E) and vary in thickness and regional extent.

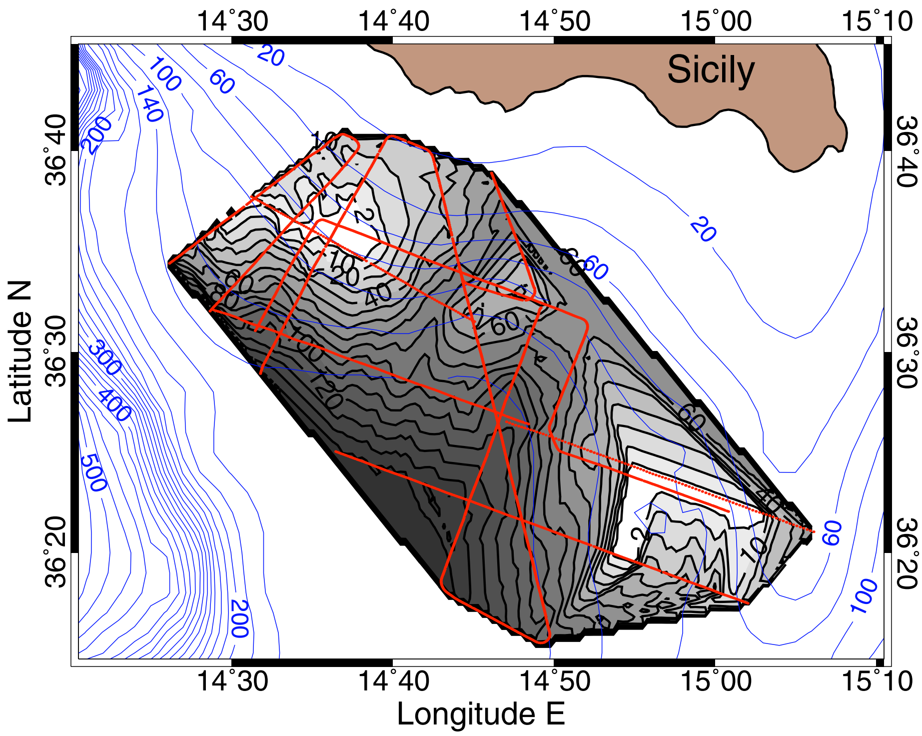

Figure 6: The total combined thickness of seismic Units 1 through 6 in two way travel time (black contours in milliseconds with gray shading). Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

Seismic Unit 1

This unit is more spatially extensive than the other seismic units. Typically, it has a concordant attitude on the basal surface (Figure 4 A, B, C, and D), but the boundary with Unit 2 can be rough and wavy in some locations. It has an erosional character in the shallower depths in the northern part of the study area (Figure 4E). It is comprised of closely spaced parallel internal laminations and has a thickness of up to 40 ms (approximately 33 m) in the study area (Figure 7). The isopach map of this unit indicates thickening occurs both landward, where the water depth is less than 100 m, and seaward as the water depth increases beyond 150 m. Its acoustic facies is strong parallel strata. In the northern part where the water depth is shallower than 100 m, a sub-unit can be identified. This might be a coastal deposit onlapping the upper surface of Unit 1. The lower boundary of Unit 1 appears to have a minor erosional surface or it could also be a transgressive surface. Its progradational character and onlap termination corresponds to the highstand shelf sediments of Holocene. Analysis of gravity cores by Max *et al.* (1993a, b) in the southeastern portion of our study area, revealed that Unit 1 consists of shallow water calcareous muds with shells, shell fragments and coarse terrigenic material. It is likely that the composition of Unit 1 is different in the north of the study area with a larger component of finer grained terrigenic material as it is almost acoustically transparent (Figure 4 D1-D2, D2-D3).

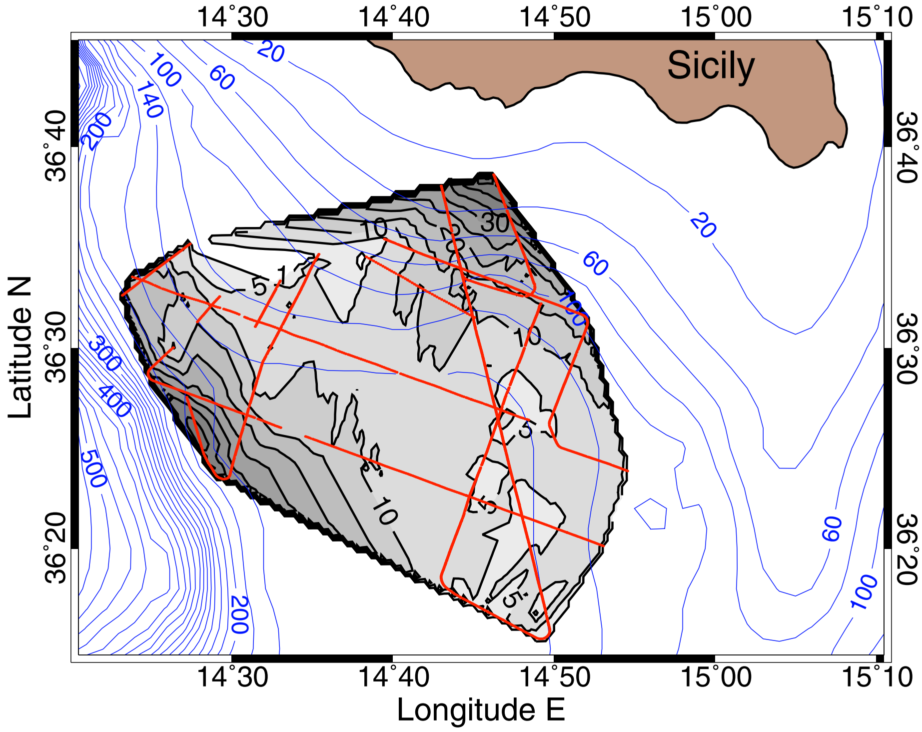

Figure 7:Isopach map of seismic Unit 1 in two way travel time (black contours in milliseconds with gray shading). Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

Seismic Unit 2

This unit displays an internal setting that largely parallels the sea floor. It is observed within most of the study area. Within the unit, the upper part has low reflectivity while the lower part has strong well-defined reflectors. It is separated by unconformities from overlying and underlying units (Figure 4 A, B, C, D and E). In the northwest, where the shelf-slope transition is apparent, it is characterized by an oblique parallel internal configuration, toplapping at the upper boundary, and carbonate buildup structures (Figure

4 B). This is indicative of a shallow water environment and suggests a minor period of sea-level fall. Sediment thickness differs considerably from Unit 1 (Figure 8). It has a typical thickness of 10 to 20 ms (8 to 16 m), but can vary from 2 to 40 ms, thinner where there are basement outcrops, and thicker in the west where a depositional center is observed below the shelf break.

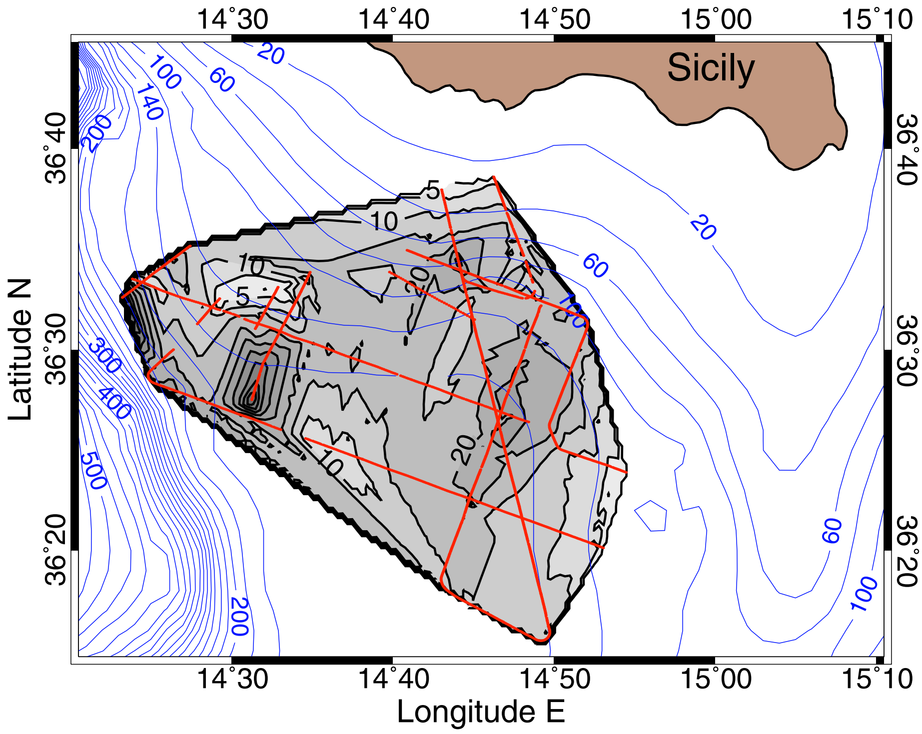

Figure 8:Isopach map of seismic Unit 2 in two way travel time (black contours in milliseconds with gray shading). Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

Seismic Unit 3

The upper boundary of this unit is an unconformity with toplaps of oblique parallel strata in the northwest of the study area (Figure 4 E). The basal conformity displays downlap terminations that have a parallel internal configuration. In the rest of the study area, this unit has internal reflections with parallel and sub-parallel laminations The thickness of the unit is typically 15 to 25 ms (12 to 20 m) (Figure 9), but can vary between 5 and 35 ms (about 3 to 29 m). The thickening of this unit mainly occurs in water depths greater than 130 m (Figure 9). Onlap terminations of the unit boundary lie on the acoustic basement where it rises to sea floor. Toplap terminations of internal strata on the upper boundary are indicative of a sea-level stillstand (Figure 4 E2-E3).

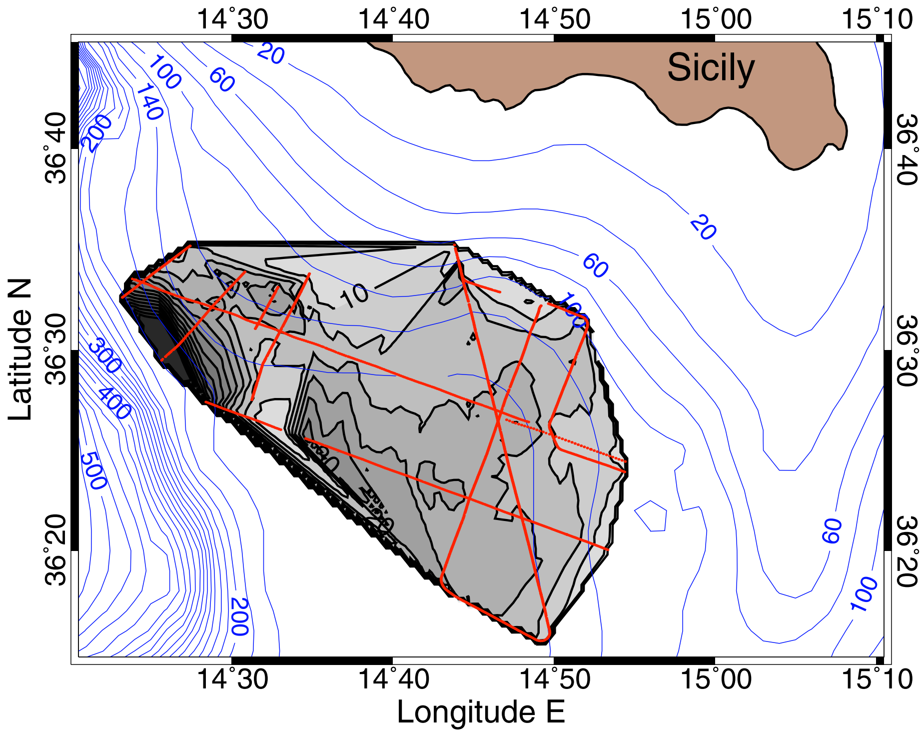

Figure 9:Isopach map of seismic Unit 3 in two way travel time (black contours in milliseconds with gray shading). Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

Seismic Unit 4

Similar to Unit 3, this unit shows apparent toplaps to the upper boundary in the northwest of the study area, and onlaps on acoustic basement in the other parts (Figures 4 A, C, D and E). The lower boundary is concordant to Unit 5. It has moderately laminated and wavy internal reflectors. Each internal reflector laps out in a landward direction at the top of the unit, with the successive terminations lying progressively seaward. The thickness of the unit (Figure 10) ranges from 5 to 40 ms. It is restricted to the deeper part of the sedimentary basin (Figure 5). The unit continues offshore with concordant boundaries, thickening to the southwest, with isopachs which are similar in shape to the bathymetry contours.

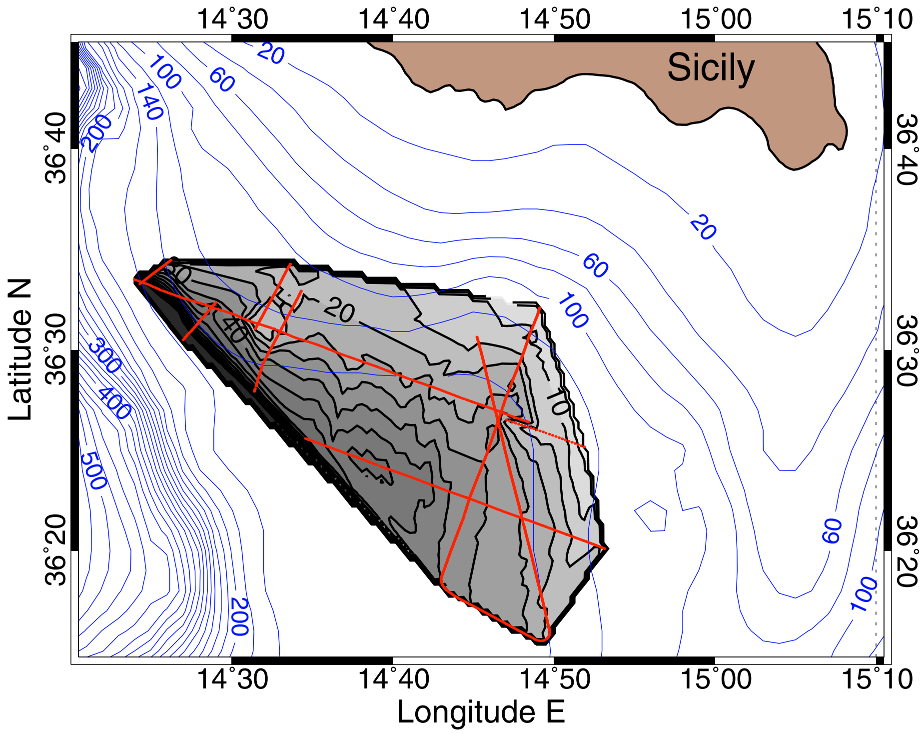

Figure 10:Isopach map of seismic Unit 4 in two way travel time (black contours in milliseconds with gray shading). Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

Seismic Unit 5

This unit is concordant with its top and bottom boundaries, onlapping only to the acoustic basement (Figure 4 A, C, D). The basal erosional surface is undulated in the northeastern part of the study area. Its internal reflectors consist of weak laminations of wavy and sub-parallel bedding. As with unit 4, the spatial distribution of this unit is generally controlled by basement morphology. Its thickness increases towards the south and southwest with a maximum thickness of approximately 40 ms at a water depth of about 140-160 m (Figure 11). This deposit continues offshore with concordant boundaries, however its full lateral extent could not be followed to the west of the study area because of the limited depth of penetration of the sound source with increasing water depth and thickness of some of the overlying units. From the data available, it appears that the depositional center has shifted to the southeast relative to that of the overlying Unit 4.

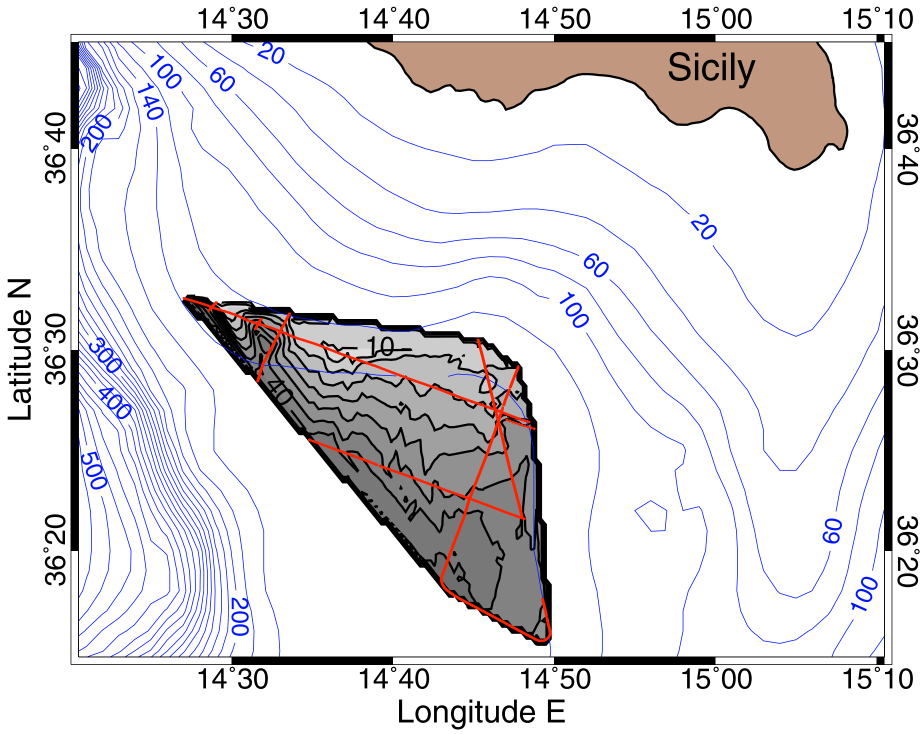

Figure 11:Isopach map of seismic Unit 5 in two way travel time (black contours in milliseconds with gray shading). Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

Seismic Unit 6

This is the lowest unit of Plio-Quaternary sequence, and onlaps against the acoustic basement over which it is deposited (Figure 4 A, B, C). Unit 6 has the smallest spatial distribution in the study area. It is not observed in the northern part where the water depth is less than 120 m. As with units 4 and 5, its distribution is a function of the basement morphology (Figure 5). Its internal reflectors are weak, but they are parallel and sub parallel. Its maximum thickness is approximately 30 ms (Figure 12).

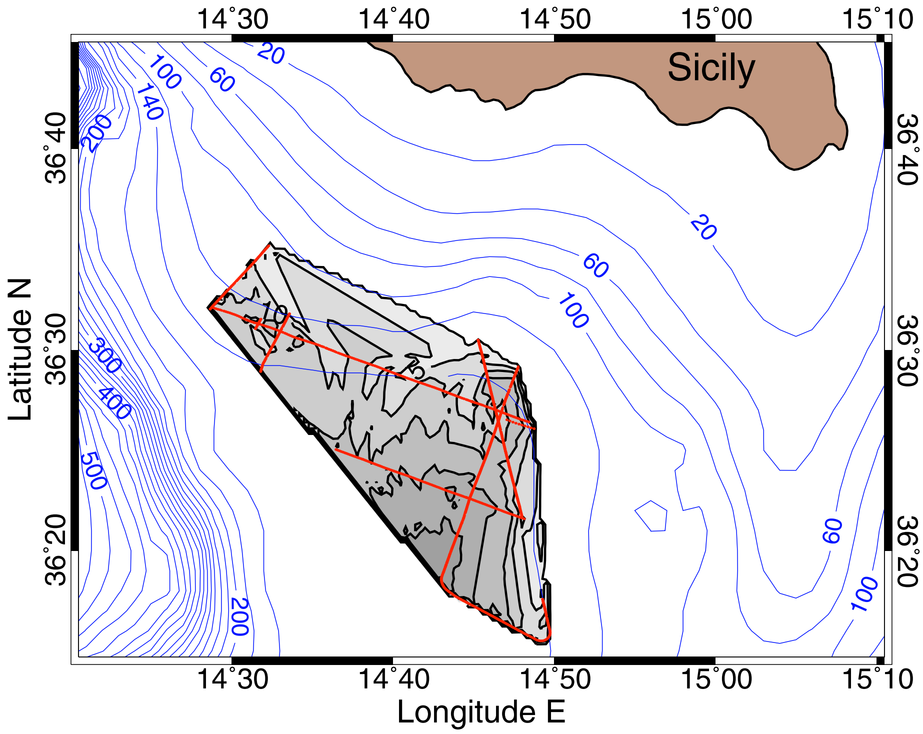

Figure 12:Isopach map of seismic Unit 6 in two way travel time (black contours in milliseconds with gray shading). Contours (in 20 m intervals) of DBDB-V bathymetry are in blue.

6
Discussion

A seismic sequence analysis of the high resolution seismic reflection data (Section 5) revealed that six seismic units (or depositional sequences) are present on the continental shelf and transition to continental slope. A depositional history for the Malta Plateau may be developed based on an examination of the terminations of the sequence boundaries and of the terminations of internal reflectors within each sequence. In turn, the physical properties and acoustic reflectivity of the sediments may be speculated using the depositional history.

Depositional History and Relative Sea Level

Within the study area, the upper and lower boundary terminations of the seismic sequences are observed at two locations: in the northwest where water depth is about 160-170 m (Figure 4 E2-E3); and in the southeast near the basement outcrops (Figure 4 A1-A3). The terminations of all the sequence boundaries onlap the acoustic basement in a landward direction, indicative of a relative overall sea level rise throughout the Plio-Quaternary depositional history (Figure 13). A relative fall of sea level would be manifest as a downward shift of onlaps overlying an unconformity surface (Appendix C) (Vail *et al*., 1977) and this has not been observed.

The termination of the internal strata (reflectors) in Units 2 and 3 (and to a lesser extent Unit 4) have a distinguishable oblique parallel pattern and toplap at the upper boundary of the sequence (Figure 4, A2-A4, B1-B3, C1-C3, E2-E3). Some lower boundary terminations of the internal reflectors in these Units are also observed, though not as clearly. The toplap terminations of the internal reflectors are characteristic of erosional unconformities. A cumulative relative rise of sea level that occurs over several million years is commonly characterized by shorter pulses of sea level rise alternating with intervals of stillstands (Vail *et al*., 1977). During a stillstand of sea level or when sea level rise is slow, each strata laps out in a landward direction at the top of the unit with successive terminations lying progressively seaward.

The unconformities between the sequences may be attributed to periods of non-depositional or minor erosional processes (Vail *et al*., 1977; Sangree and Widmier, 1977). In a non-deposition environment, the sediment flux bypasses the depositional surface (Appendix C). In the case of erosion, it might be due to subaerial exposure or to a more energetic shallow water environment. These could occur during periods of regression (seaward migration of coastal deposits) and/or stillstand of sea level (Figure 13). The gently divergent wedge shaped form of Units 4, 5, and 6 and the parallel and sub-parallel configuration of the internal reflectors in most units is characterisitic of sediments deposited in a shelf environment with a uniform rate of deposition on a uniformly subsiding or stable basin plain (Mitchum *et al*., 1977; Sangree and Widmier, 1977). The onlapping in Unit 1 differs from that of the lower sequences in terms of its parallel configuration of reflectors and progradational character. Further, it is more extensive geographically and gets thicker towards the coast of Sicily, suggestive that it is comprised of coastal sediments. This unit can be attributed to the highstand of sea level during the Holocene. Carbonate buildup structures are observed at the boundaries between Units 2 to 3 and 3 to 4 (Figure 4 B1-B2) in the northwest part of the study area. These biogenic structures are evidence of a very shallow water depositional condition.

It is possible to suggest a time scale for the sequence boundaries, even though no isotope dating of sediment samples is available. The erosional truncation of the basement surface indicates that a hiatus probably occurred during Messinian to Early Pliocene. For Units 5 and 6, the time scale is based on the depth at which the sequence boundaries onlap the basement, with the assumption that tectonic effects may be ignored. The onlap terminations of Units 5 and 6 on the acoustic basement are seen in the depth[2] intervals from 150 to 175 m and 195 to 220 m, respectively. It is widely accepted that sea level fluctuated from 100 or 150 m below present sea level to a few meters above during the Middle-Late Pleistocene (150 to 20 ky) (Chappell and Shackleton, 1986). If Units 5 and 6 were shallower than 150 m relative to present sea level, there should be evidence of sub-aerial erosion, such as gullies. As none is observed, their deposition was probably before 150 ky (during the Pliocene-Pleistocene). The upper unconformity boundaries of Units 4, 3 and 2 may be related to successive lowstands-stillstands that ended at 130 ky, 18 ky, and 6 ky and were followed by sea level rises (Chappel and Shackelton, 1986; Fairbridge, 1961).

Sediment Sound Speed

A hypothetical sound speed structure for the six seismic units identified in the study area on the Malta Plateau is presented in Figure 13. Unit 1, comprised of fine grained coastal deposits, is likely to have the lowest absolute sound speed due to its high porosity and the highest sound speed gradient as the porosity decreases rapidly as a function of depth. The sound speed of the remaining units may vary with their composition, but an overall gradient in the sound speed is expected as the overburden pressure increases as a function of depth leading to de-watering and consolidation. In the vicinity of the sequence boundaries, the sound speed should increase due to several factors. As discussed, the sequence boundaries are erosional unconformities created by minor erosion or non-deposition. Due to the higher energy depositional environment, the grain size of the sediment in the vicinity of the erosional unconformity is probably coarser than that which forms the bulk of the units. In addition, carbonate build up structures are observed at some sequence boundaries and there is the possibility of chemical alteration/cementation, especially if there was sub-aerial exposure.

[2] Depth (in metres) to the reflectors in question is calculated using the travel time in the water at a depth averaged sound speed of 1512 m/s and the travel time in the sediment at a sound speed of 1650 m/s.

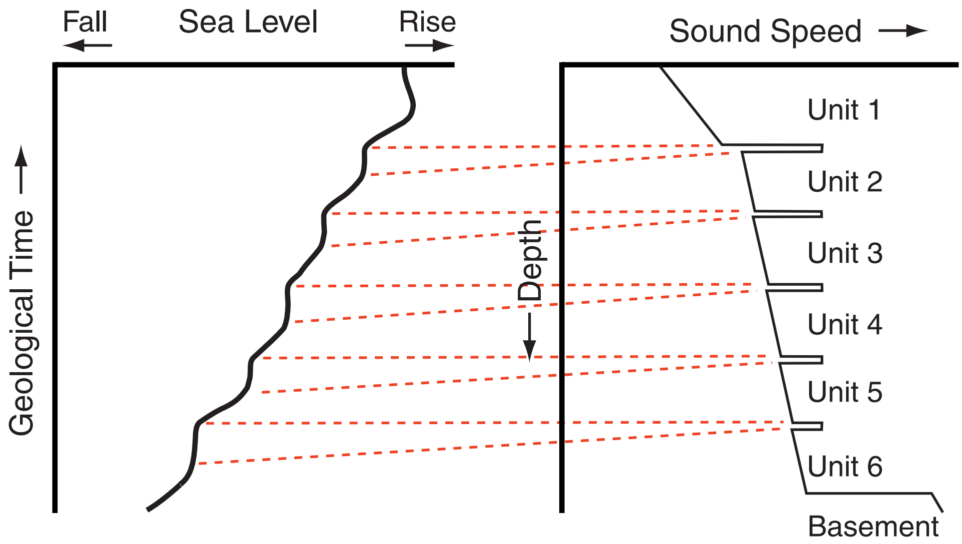

Figure 13: A schematic representation of sea level changes in the Malta Channel and a hypothetical sound speed structure for the six seismic units based on a seismic sequence analysis. There is an overall increase of sea level throughout the depositional history, punctuated by periods of sea level stillstand in which the erosional unconformities are formed.

Mass Movements and Tectonic Activity

The depositional sequences tend to be laterally continuous from their onlap of the acoustic basement heading offshore. There is an exception, however, in the northwest of the study area where the sequences are deformed by mass movements (Figure 4 F1-F2 and E2-E3). Some sediment is slumped seaward of the basement outcrop and minor faults are observed in the basement. The mass movements may be attributable to tectonic activity along the fold-thrust belt or rift zone in the region, though rifting and associated fault activities have supposedly ceased from Late Quaternary to present (Finetti, 1984). None of the minor faults in the basement extend into the overlying sedimentary layers, supporting the view that the region has not been tectonically active in this period.

7
Conclusion

The Plio-Quaternary geological history of the continental shelf of the Malta Plateau results from a series of depositional and erosional episodes. In the study area, the acoustic basement and its truncated erosional surface represent the beginning of one of these episodes. The erosion of the basement occurred during a major sea level fall during Messinian or the latest global sea level fall during the Pre-Late Pliocene and Pre-Pleistocene (~2 to 0.45 My). In either case, it must have been exposed to subaerial erosion. The six seismic units in the study area are mainly controlled by the high-frequency sea level changes during Pleistocene. Units 5 and 6 are likely transgressive sequences, onlapping to the basement. Unit 6 rests directly on the basement, which is an erosional surface in much of the study area. Unit 5 has concordant internal reflectors and is concordant with Unit 6. The presence of the landward onlapping sequence boundaries of Units 2, 3, and 4 is indicative of a continually rising sea level. The erosional unconformities between these units with toplapping internal reflectors are indicative of stillstands or lowstands of sea level. Unit 1 is comprised of coastal sediments deposited in the latest rise of sea level during Holocene. Compressional wave sound speed is likely to increase in the immediate vicinity of the sequence boundaries as the processes which create the erosional unconformity lead to local increases in grain size and degree of consolidation of the sediment.

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Appendix A

Programs:

segy2su converts the data stored in SEG-Y format (Barry *et al*., 1975) into SU format (Cohen and Stockwell, 1998).

sugethw reads the trace header fields in SU format files, retrieving information for each seismogram.

suswell is applied to the data to remove the travel time variations which are induced by vertical motion of the surface towed boomer sound source in the wave field. It automatically determines the arrival time of the seabed for each seismogram and then applies a low pass filter, 0.1 Hz, to these arrival times as a function of the elapsed time along the survey track. For a boomer towed at the typical speed of 5 knots, this effectively removes any bathymetric variation, real or apparent, less than 25 m. This an SU program which has been written at SACLANTCEN.

suxpick_cont is applied to SU format files to add the water depth and geographical position of the boomer from the IMS navigation files to the trace headers for each seismogram. This is an SU program that has been written at SACLANTCEN.

suxpicker allows the travel times of up to 16 reflectors to be digitized with an interactive display of the data. The travel time picks are stored in an ascii file which may be read directly into the program used to prepare sediment thickness charts. This is a version of the program that has been modified at SACLANTCEN to suit our purposes.

suxwigb prepares binary postcript plots of the seismic reflection profiles.

mk_graph_inp_v3.f is a FORTRAN program which converts the data in the pick files into binary format, determines the number of points per reflector and relates the reflector identifier to the color scheme, creating input files for *psgraph* and *xgraph.* This is a program written at SACLANTCEN.

xgraph and *psgraph* may be used to produce plots of reflector travel times as a function of ping number on X-windows or in postcript format respectively.

psmerge merges postcript plot of the picked travel times with postcript plots of the reflection data. It will also combine multiple postscript plots onto one page.

isopach.pro is an IDL (Research Systems Incorporated, 1998) program which combines the pick files from the different segments to create isopach maps. It grids and then contours the geographical distribution of sediment thickness between any pair of reflectors. This is a program written at SACLANTCEN.

Unix Shells:

jopick is a shell for running the program *suxpicker.*

jopltpic is a shell for running the programs *xgraph*, *psgraph*, *mk_graph_inp_v3, suxwigb,* and *psmerge.*

jopngtim is a shell for running the program *sugethw.*

Appendix B

To ensure that the regional extent of reflectors is correct, it is imperative that the identification of reflectors be checked for consistency at all intersection points of the survey tracks. This has been accomplished by plotting the navigation of all survey tracks in the vicinity of an intersection point to determine the time and "ping number" of the respective seismograms at the point of intersection (Table 1). (*jopngtim*, Appendix A, may be used for obtaining this information). Then, plots of the appropriate segments of the seismic reflection profiles, with color-coded travel time picks overlain, may be checked for consistency at these locations. (*jopltpic*, Appendix A, may be used for the preparation of the plots).

Table 1: Interception points controlled in the study area.

Interception Point	Seismic Lines	Time	Date	Longitude	Latitude	Ping Number
1	Boom04-e Boom03-h	0:37:51 0:33:13	16/04/98 12/04/98	14,80902	36,54405	389 169
2	Boom04-e Boom03-g	1:29:31 23:49:29	16/04/98 11/04/98	14,73698	36,56595	3521 1178
3	Boom04-g Boom03-d	3:00:56 21:19:51	16/04/98 11/04/98	14,60986	36,60493	1772 3055
4	Ubde1-b Boom03-c	8:17:36 20:05:41	11/04/98 11/04/98	14,55009	36,51544	1055 2172
5	Ubde1-b Boom04-i	8:06:01 4:34:51	11/04/98 16/04/98	14,52706	36,52176	359 192
6	Ubde1-a Ubsw2-d	7:48:16 15:36:46	11/04/98 11/04/98	14,49177	36,53224	2904 3217
7	Ubde4-a Boom04-c	8:30:11 22:36:41	19/04/98 1504/98	14,83172	36,42926	1073 327
8	Ubdw3-c Boom03-d	16:13:06 21:09:56	18/04/98 1104/98	14,60129	36,59285	209 2447
9	Ubdw3-c Boom04-g	16:27:36 3:23:16	18/04/98 16/04/98	14,58287	36,60091	644 3124
10	Boom02-g Boom02-b	2:16:56 20:39:11	11/04/98 10/04/98	14,77551	36,44093	3589 1352
11	Boom02-h Ubde1-d	2:24:01 10:13:36	11/04/98 11/04/98	14,77281	36,44943	393 804
12	Boom02-h Ubsw2-a	2:24:26 12:30:56	11/04/98 11/04/98	14,77265	36,44994	419 2877
13	Boom02-b Ubsw2-a	20:33:01 12:26:51	10/04/98 11/04/98	14,77864	36,44822	977 2632
14	Boom02-i Ubdw3-a	3:25:11 14:09:31	11/04/98 18/04/98	14,74932	36,5261	461 106
15	Boom02-i Boom04-e	3:56:51 1:29:36	11/04/98 16/04/98	14,73687	36,56609	2381 3526

Interception Point	Seismic Lines	Time	Date	Longitude	Latitude	Ping Number
	Boom03-g	23:49:29	11/04/98			1178
16	Boom02-f	1:09:11	11/04/98	14,80033	36,36036	3129
	Boom05-c	17:56:26	17/04/98			1638
17	Boom02-c	21:33:36	10/04/98	14,74573	36,37642	1000
	Boom05-c	18:27:26	17/04/98			3498
18	Boom05-h	22:27:56	17/04/98	14,47933	36,5353	747
	Ubde1-a	7:42:16	11/04/98			2540
19	Boom05-h	22:28:21	17/04/98	14,47984	36,53574	772
	Ubsw2-e	15:48:21	11/04/98			304
20	Boom05-l	3:05:16	18/04/98	14,40746	36,55609	2969
	Ubde1-a	7:06:21	11/04/98			385
21	Blsw2	13:11:31	01/01/04	14,54755	36,5114	841
	Boom03-c	20:02:16	11/04/98			1966
22	Boom03-c	20:02:16	11/04/98	14,54754	36,51143	1966
	Bldw2	15:53:11	16/04/98			483
23	Boom02-g	2:13:16	11/04/98	14,77688	36,43659	3368
	Blsn1	20:53:26	13/04/98			224
	Blds1	16:57:06	13/04/98			502
	Bldn1	14:55:01	13/04/98			962
	Blen1	19:04:06	13/04/98			219
24	Boom02-b	20:35:46	10/04/98	14,77727	36,44495	1144
	Bldw1	16:03:56	13/04/98			449
	Blsw1	21:54:36	13/04/98			439
	Blde1	17:41:06	13/04/98			186
25	Boom02-h	2:21:11	11/04/98	14,77388	36,44602	221
	Bldw1	16:06:11	13/04/98			516
	Blsw1	21:56:36	13/04/98			499
	Blde1	17:41:46	13/04/98			206
26	Ubsw2-a	12:24:36	11/04/98	14,78192	36,44728	2497
	Blds1	16:49:56	13/04/98			287
	Blsn1	21:01:16	13/04/98			459
	Blen1	19:12:51	13/04/98			1507
	Bldn1	15:04:06	13/04/98			389
27	Blsn1	20:58:56	13/04/98	14,78046	36,44407	389
	Blsw1	21:52:41	13/04/98			381
	Blde1	17:45:36	13/04/98			322
	Bldw1	16:01:51	13/04/98			386
	Blew1	20:05:26	13/04/98			452
28	Bldw3	10:06:46	21/04/98	15,03402	36,37249	416
	Bldn3	9:16:26	21/04/98			798
29	Blde4	14:15:06	20/04/98	14,82757	36,53832	349
	Boom04-d	0:24:31	16/04/98			3223
30	Bldw4	13:41:06	20/04/98	14,82283	36,53772	604
	Blde4	14:12:41	20/04/98			276
	Bldn4	12:32:01	20/04/98			931
31	Bldn4	12:31:51	20/04/98	14,82272	36,53993	926
	Boom04-d	0:27:56	16/04/98			3430

Appendix C

C1. Seismic Stratigraphic Analysis - Sequence Stratigraphy

Seismic stratigraphic analysis (or sequence stratigraphy) is a relatively new method in sedimentology and has been widely used for studies of both large-scale and small-scale depositional systems. It provides a dynamic view of stratigraphy and hence, the relations between relative sea level changes and sedimentation. A sequence stratigraphy analysis develops a chronostratigraphic framework of cyclic, genetically related strata. This short summary follows Vail (1977) and Vail *et al*. (1991) and is intended to provide a general view of the principles and common definitions of seismic stratigraphy.

Seismic stratigraphic analysis is based on the identification of units (sequences) that are bounded by stratal discontinuity surfaces or their correlative conformities, on seismic profiles. These surfaces are created by erosion or non-deposition on the shelf and an associated increase in both supply and grain size of the sediment deposited in the basin. The basic units of sequence stratigraphy are: depositional sequences (time scales of 0.5 to 5 My); system tracts (time scales of 0.2 to 1.0 My); and periodic parasequences or simple sequences (time scales of 0.01 to 0.5 My). All of these are considered to be glacioeustatic cycles with a smaller magnitude of sea level change and higher frequency than tectonically induced transgressive-regressive facies cycles.

Depositional sequences:

A depositional sequence is a stratigraphic unit composed of a succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities. It is chronostratigraphically significant because it was deposited during a given interval of geologic time limited by the ages of the sequence boundaries. Two types of chronostratigraphic surfaces are related to sequences: unconformities and their correlative conformities forming sequence boundaries and stratal (bedding) surfaces.

A sequence represents a genetic unit that was deposited during a single episodic event. A depositional sequence is generally 10 to 100 meters thick, although the range may be from 1000 m to few millimeters. To define and correlate a depositional sequence accurately, the sequence boundaries must be defined and traced. Usually the boundaries are defined at unconformities based on discordant relations of strata to unconformities.

Boundaries of depositional sequences

Unconformity: A surface of erosion or non-deposition that represents a significant hiatus, separating younger strata from older.

Conformity: A surface with no evidence of erosion or non-deposition that separates younger strata from older rocks.

Relations of strata to sequence boundaries

Baselap is a lapout (lateral termination of strata at their depositional pinchout) at the lower boundary of a depositional sequence. Two main types of baselap can be recognized (see Figure A1): *onlap* is a horizontal stratum that laps out against an inclined surface (the progressive landward onlap of the coastal deposits in a given stratigraphic unit is called *coastal cnlap)*; *downlap* is an inclined stratum that terminates downdip against a horizontal or inclined surface.

Toplap is a lapout at the upper boundary of a depositional surface. It is evidence of a non-depositional hiatus, resulting from a depositional base level (such as sea level) being too low to permit the strata to extend farther updip. During the development of toplap, sedimentary bypassing, and possibly minor erosion, occur above base level while prograding strata are deposited below base level. It is mostly related to shallow marine deposits, such as deltaic complexes.

Erosional Truncation is the lateral termination of a stratum by erosion. It occurs at the upper boundary of a depositional sequence.

C2. System Tracts

A system tract is a set of linked contemporaneous depositional systems. In other words, each depositional sequence is composed of systems tracts. Depositional systems within each systems tract are limited by changes in sedimentary facies. There are 4 systems tracts: lowstand, transgressive (retrograding highstand), highstand (prograding highstand), and shelf-margin.

Lowstand

At the base of the lowstand system tract is a Type 1-sequence boundary that is characterized by subaerial erosion with valley incision on the shelf, and turbidite fan complexes and a lowstand prograding complex in the basin. Lowstand depositional system sediments are largely composed of shallowing-upward lowstand deltas or shorelines that prograde into deep basin and onlap landward with pinchout in the vicinity of the offlap break of the preceding highstand.

Transgressive

The physical boundary between lowstand and transgressive systems tract is defined by the first flooding surface. The top lowstand surface marks the change from lowstand progradation to retrogradation. Transgressive sytem tracts consist of sequences that thicken landward until they thin by onlap at their base. The boundary between the marine and nonmarine sediments is commonly a set of retrograding ravinement surfaces (transgressive surfaces or erosion).

Highstand

The physical boundary between the transgressive and highstand systems tract is called the maximum flooding surface. It is a submarine condensed section characterized by downlap above and apparent truncation below.

Shelf-margin

The boundary between the highstand and shelf-margin system tract is a Type 2 sequence boundary which is characterized by subaerial exposure of shelf, minor erosion and a shelf-margin prograding complex that pinches out by onlap landward of the offlap break of the previous highstand. The top of the shelf-margin systems tract is called the top shelf-margin surface.

More than one type of systems tract will be present in any one sequence. For example, a Type 1 sequence has a Type 1-sequence boundary at its base and is composed of a lowstand, a transgressive and a highstand systems tract. A Type 2 sequence has a Type 2-sequence boundary at its base and is composed of a shelf-margin, a transgressive and a highstand systems tract.

Parasequences or Simple Sequences

These sequences correspond to the stratigraphic units deposited within fourth- and fifth-order cycles. They are best developed within the transgressive and early highstand systems tracts. A para-sequence is a chronostratigraphic unit composed of a largely conformable succession of genetically related beds or bed sets bounded by flooding surfaces. A simple sequence has the stratal and lithologic characteristic of a sequence, but its duration is that of a parasequence. Simple sequence and parasequence boundaries do not coincide, but they represent a similar cyclicity.

C2. Seismic Stratigraphy and Global Changes of Sea Level

Sequential ordering of beds is a result from the combination of regional to global casual factors that modify local environmental processes. The causal factors are tectonic, climatic and eustatic changes that are expressed as cyclic variations or short-term events (single and multiple). Tectonic and eustatic processes combine to cause relative changes of sea level.

Relative Rise of Sea Level

Either sea level itself, or the land surface (sea bed) or both in combination may rise or fall during a relative change. A relative change of sea level is defined as an apparent rise or fall of sea with respect to the underlying initial depositional surface (Figure A2). During a sea level rise, if the sediment supply is sufficient, coastal deposits progressively onlap the underlying initial surface of deposition. If the relative sea level rise is more rapid than the rate of deposition, then the onlap of marine deposits (*marine onlap)* occurs. During a relative rise of sea level, both transgression and regression can occur depending on the changing rate of terrigeneous supply (Figure A2). A relative rise of sea level is indicated by coastal onlap.

Relative Stillstand of Sea Level

Stillstand is a constant position of sea level with respect to the underlying initial surface and is indicated by coastal toplap. During a relative stillstand of sea level, if the sediment supply is sufficient, deposition in the coastal environment is prevented above the base level and the strata are prevented from onlapping the initial depositional surface. Each unit of strata laps out in a landward direction at the top of the unit, but the succesive terminations lie progressively seaward (Figure A3). A cumulative relative sea level that occurs over several million years commonly is characterized by shorter pulses of sea-level rise alternating with intervals of stillstand.

Relative Fall of Sea Level

A fall of sea level with respect to the underlying initial surface of deposition is indicated by a downward shift of coastal onlap (Figure A4). That is, a shift down-slope and seaward from the highest position of coastal onlap in a given marine sequence to the lowest position of coastal onlap in the overlying sequence.

A Cycle of Relative Change of Sea Level

A cycle of relative change of sea level is defined as an interval of time during which a relative rise and fall of sea level take place. It typically consists of a gradual relative rise, a period of stillstand and a relatively rapid fall of sea level.

If a sufficient sediment supply is available, one or more depositional sequences are deposited during one cycle of relative rise and fall of sea level. If a cycle contains a continuous relative rise until a stillstand of sea level, only one sequence is likely to be deposited during that time. The abrupt fall at the end of the cycle tends to produce an unconformity that will separate the sequence from the overlying one of the next cycle. If a cycle contains two or more paracycles, at least two sequences are likely to be deposited during the cycle. The boundary between the sequences would be marked most commonly by downlap of the underlying sequence, although toplap of the underlying sequence may be present.

After a rapid rise of sea level, a surface of non-deposition may be developed before the progradational deposits of the stillstand are laid down. The surface should be marked by downlap of the overlying progradational deposits.

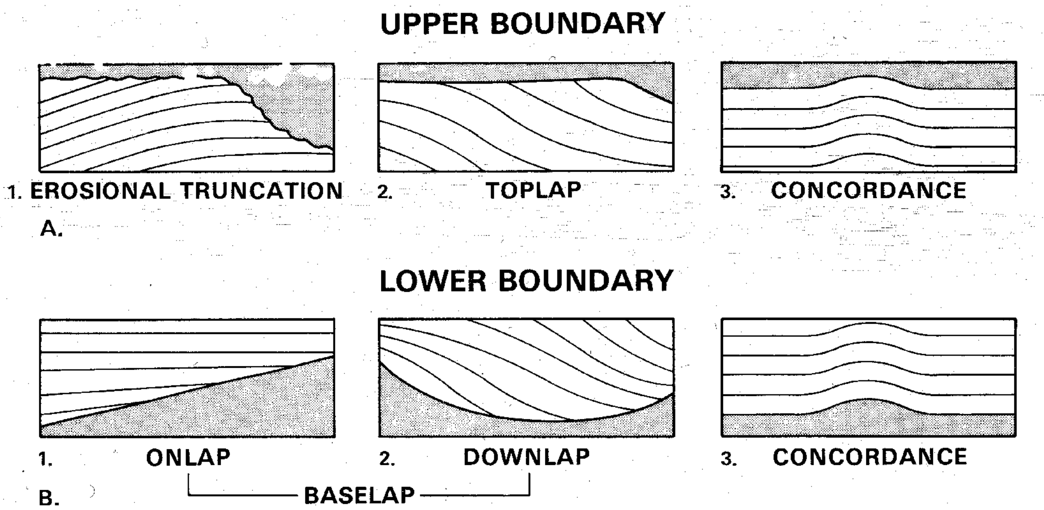

Figure A1: Relations of strata to boudaries of depositional sequences. A. upper boudary of a sequence. B. Lower boundary of a sequence (from Mitchum et al., 1977).

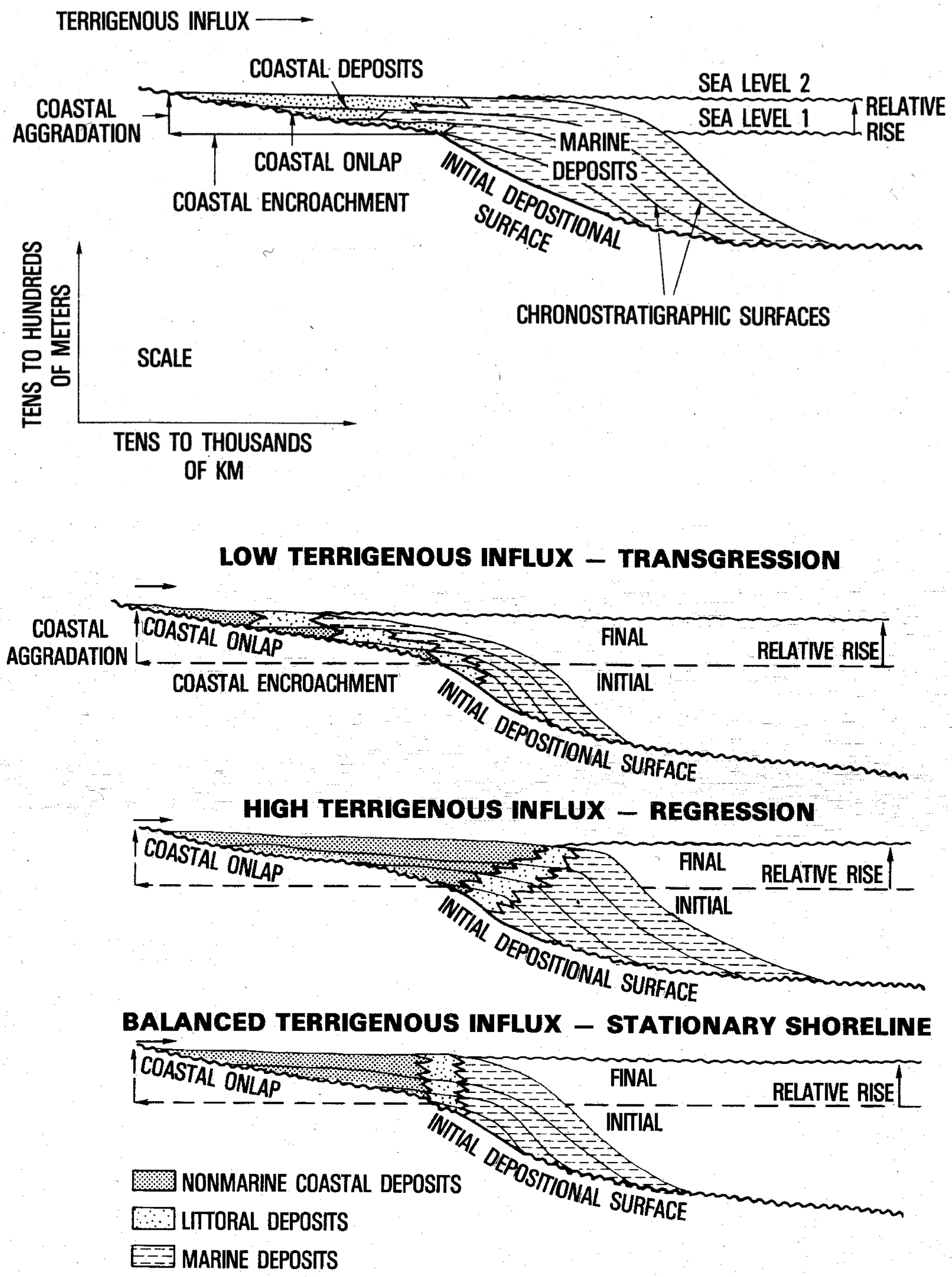

Figure A2: A relative rise of sea level (above). Transgression, regression and coastal onlap during relative rise of sea level (below) (from Vail et al., 1977).

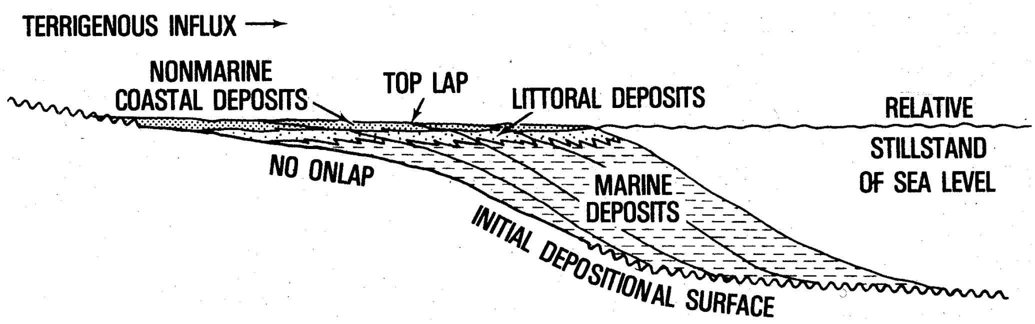

Figure A3: Relative stillstand of sea level (from Vail et al., 1977).

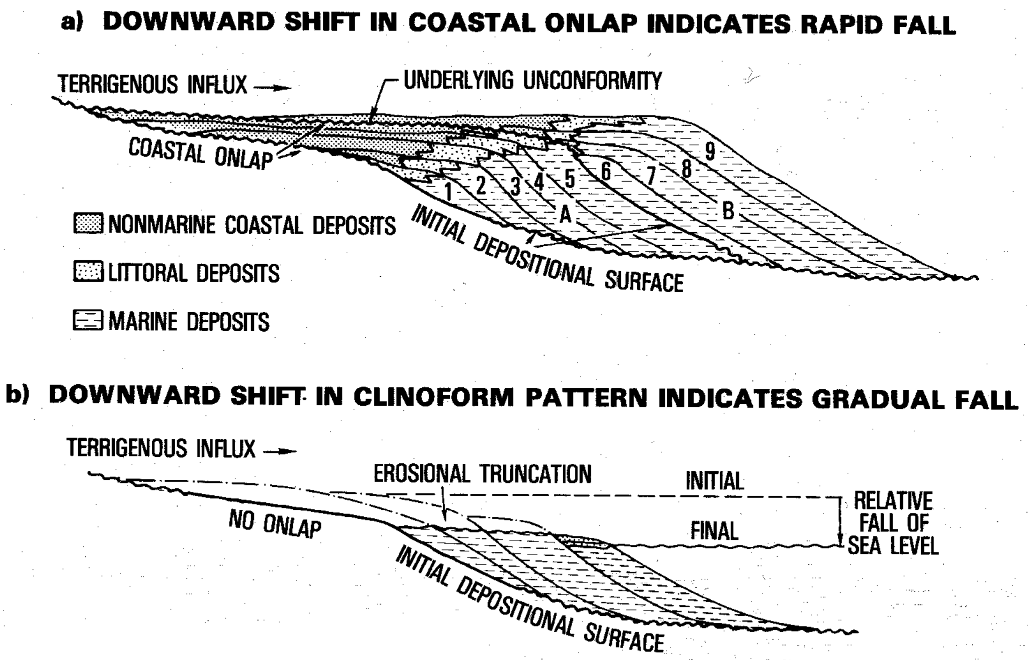

Figure A4: A relative fall of sea level: (a) rapid and (b) gradual (from Vail et al., 1977).

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