

**DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL
AND APPLIED SCIENCE**

**MIOCENE TO RECENT STRATIGRAPHY,
STRUCTURAL ARCHITECTURE AND TECTONIC
EVOLUTION OF THE FLORENCE RISE,
EASTERN MEDITERRANEAN SEA**

**by
Pınar GÜNEŞ ÖZER**

October, 2009

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ARCHITECTURE AND TECTONIC EVOLUTION OF THE
FLORENCE RISE, EASTERN MEDITERRANEAN SEA**

**A Thesis Submitted to the Graduate School of Natural and Applied Science of
Dokuz Eylül University In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Institute of Marine Sciences and Technology,
Marine Geology and Geophysics Program**

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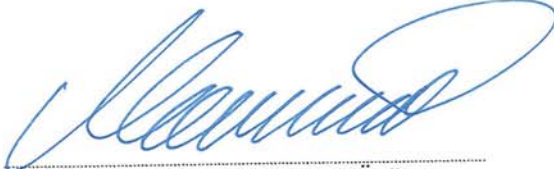
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Prof.Dr.Günay ÇİFÇİ

Supervisor



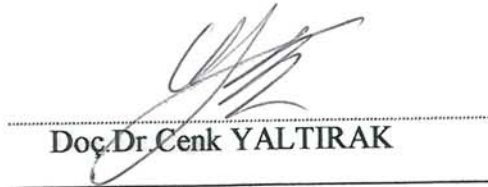
Prof.Dr.Mustafa ERGÜN

(Jury Member)



Prof.Dr.Doğan YAŞAR

(Jury Member)



Doç.Dr.Cenk YALTIRAK

(Jury Member)



Doç.Dr.Derman DONDURUR

(Jury Member)

Prof.Dr. Cahit HELVACI
Director
Graduate School of Natural and Applied Sciences

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MIOCENE TO RECENT STRATIGRAPHY, STRUCTURAL ARCHITECTURE AND TECTONIC EVOLUTION OF THE FLORENCE RISE, EASTERN MEDITERRANEAN SEA

ABSTRACT

New multi-channel seismic data were acquired by Dokuz Eylül University and Memorial University of Newfoundland (MUN) over the Florence Rise, eastern Mediterranean Sea, during the summer of 2007. The Miocene-Recent structural architecture, tectonic and sedimentary evolution of the Florence Rise south of Turkey in the eastern Mediterranean Sea is delineated using detailed interpretation of ~700 km of high-resolution multi-channel seismic reflection profiles. Three seismic stratigraphic units are identified. Unit 1 is Pliocene-Quaternary in age and is characterized by a strongly reflective acoustic package which shows considerable lateral continuity and three subunit which 1a,1b,1c identified in Unit 1. Unit 2 is generally characterized by a low reflectivity package with weak and often discontinuous reflections: it represents the Messinian evaporite succession and two subunit which 2a, 2b are identified in Unit 2. Unit 3 underlies the Messinian evaporites of Unit 2, and constitutes the acoustic basement in the study area. In its uppermost portion, it is characterized by lower frequency rhythmic reflections, showing good lateral continuity.

Analysis of structural and stratigraphic architectures reveals that the Florence Rise can be divided into four structural domains: a) Domain 1- In the north, the salt cored fold belt, with predominantly (but not ubiquitously) south-verging thrusts, extends into the Antalya Basin b) Domain 2- is composed of a broad corrugated seafloor high, in which the corrugations are mirrored at the pre-Pliocene-Quaternary 'M' reflector. Narrow (1 km-wide) zones of discontinuity in this area may be interpreted as basin inversion structures bounded by high-angle faults. c) Domain 3- To the south of the broad core of Florence Rise, lies a 15-20 km bathymetric high zone of complexly faulted slivers with Pliocene-Quaternary growth strata wedges and the

folded faulted and shear zone in core of the Florence Rise, d) Domain 4- the strike slip belt.

Detailed interpretation and mapping of the seismic reflection profiles showed that the structural and stratigraphic architecture core of the Florence Rise is in Domain 3 characterized by 4-5 northwest-southeast trending anticline-syncline pairs. The anticlines are invariably cored by northwest-southeast trending thrusts, thus representing ramp anticlines with the synclines between thrust culminations representing piggy-back basins. Temporal and spatial relationship of these large-scale structures and the stratigraphy and growth stratal architecture of Units 1-3 successions clearly document a two-phase history for the Miocene to Recent kinematic evolution of the Florence Rise. The first phase of deformation occurred in the Miocene and affected the Florence Rise. It involves the northwest-trending, southwest-directed fold-thrust structures in Unit 3. The second phase of deformation occurred in the central portion of the Florence Rise, the fold-thrust belt displayed a protracted activity from the early Pliocene to Recent with intervals of accelerated growth during the middle Pliocene-Quaternary.

Key Words: Florence Rise, Eastern Mediterranean

DOĞU AKDENİZ FLORANSA YÜKSELİMİ'NİN MİYOSEN'DEN GÜNCELE STRATİGRAFİSİ, YAPISAL MİMARİSİ VE TEKTONİK EVRİMİ

ÖZ

Dokuz Eylül Üniversitesi ve Newfoundland Memorial Üniversitesi (MUN) tarafından 2007 yılının yazında, Doğu Akdeniz'deki Floransa Yükselimi hakkında yeni çok kanallı sismik veriler elde edilmiştir. Türkiye'nin güneyinde, Doğu Akdeniz'de yer alan Floransa Yükselimi'nin Miyosen döneminden bugüne kadarki yapısal mimarisi, tektonik ve evrimi, yaklaşık 700 km boyunca yüksek çözünürlüklü, çok kanallı sismik yansıma profillerinin detaylı şekilde yorumlanması sonucunda sunulmuştur. Üç sismik stratigrafik birim tespit edilmiştir. Birinci birim Pliyosen-Kuvaterner içerisinde 1a, 1b ve 1c olarak adlandırılan, önemli ölçüde doğrusal devamlılık gösteren üç alt birimden oluşan, güçlü refleksiyon veren akustik bir paket ile karakterize edilmektedir. İkinci birim genellikle zayıf ve çoğunlukla sürekli olmayan yansımalarla sahip bir akustik paketi ile karakterize edilmektedir: Messiniyen evaporit çökelimini temsil etmektedir, ve ikinci birim içinde 2a ve 2b olarak iki alt birim tespit edilmiştir. Üçüncü birim, ikinci birimin Messiniyen evaporitlerinin altındadır ve çalışma alanının akustik tabanını teşkil etmektedir. En üst kısmında, iyi doğrusal devamlılık gösteren, daha düşük frekanslı ritmik yansımalar ile karakterize edilmektedir.

Yapısal ve stratigrafik yorumlar, Floransa Tümseği'nin dört yapısal alana bölünebileceğini ortaya koymaktadır: a) birinci alan – kuzeyde, hakim olan güneye uzanan bindirmelere sahip tuz özlü bükülme kuşağı, Antalya havzasına doğru uzanmaktadır; b) ikinci alan – kıvrımlı deniz tabanı yapıları gösteren Pliyosen öncesi – Kuvaterner yapıları“M” reflektöründe tuz tektoniğinden kaynaklanan ve nedeni henüz açıklamamış ters dönmüş yapılardan oluşmaktadır. Bu alanda dar (1 kilometre genişliğinde) kesinti zonları, yüksek açılı faylarla sınırlanmış basen inversiyon yapıları olarak yorumlanabilir; c) Üçüncü alan – Floransa Yükselimi'nin güneyinde, Pliyosen-Kuvaterner içerisinde büyüme yapıları (grow strata wedges) olan, 15-20 kilometrelik batimetrik bir yükselim, karmaşık faylanmaya sahip bant

zonu ve Floransa Tmseęi'nin merkezinde kıvrımlanmış faylı kayma zonu yer almaktadır; d) drdnc alan – yanal atımlı kuşak olarak tanımlanan bu alan birinci alan ile benzer morfolojik zellikler gstermekte ve yanal atımlı faylar ile sınırlı deęişken kıvrımlı deniz tabanı yapısı sunmaktadır.

nc alan ierisinde Floransa Ykselimi'ne ait sismik refleksiyon profillerinin ayrıntılı yapısal ve stratigrafik yorumlanması ve haritalanması, Floransa Ykselimi'nin merkezinin kuzeybatı-gneydoęu uzanımlı antiklinal-senklinal ift ile karakterize edildięini gstermektedir. Antiklinaller senklinaller kuzey-batı, gney-doęu uzanımlı kuzey-doęu, gney-batı ynl bindirme faylarının ekirdeęini oluřmaktadır; bylece bu bindirme fayları ramp antiklinalleri ve pigy back basenler ile temsil edilmektedir. Bu byk lekli yapıların stratigrafisi ve byme yapılarının tectonic mimarileri, Floransa Tmseęi'nin Miyosen'den Gncel'e iki ařamalı bir kinematik evrimden getięini aık řekilde ortaya koymaktadır. Birinci deformasyon ařaması Miyosen dneminde gerekleşmiř ve Floransa Tmseęi'ni etkilemiřtir ve bu etki Birim 3 ierisinde kuzeye eęilimli, gneybatı ynl kıvrımlı-bindirme yapıları olarak grlmektedir. İkinci deformasyon ařaması Floransa Ykselimi'nin ekirdek blmnde, kıvrımlı-bindirme kuřaęı erken Pliyosenden bugne kadar gelen ve orta Pliyosen-Kuvaterner dnemde hızlanan byme aralıkları gsteren, bir aktivite gstermektedir.

Anahtar kelimeler: Florans Rise , Doęu Akdeniz

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CHAPTER ONE

INTRODUCTION

1.1. Tectonic Framework of the East Mediterranean

The Mediterranean Sea and its surrounding land mass (Fig. 1.1) have long been recognized as an excellent “natural laboratory” for the study of fundamental plate tectonic processes, including rifting, passive margin development, contraction and associated subduction, ophiolite emplacement and orogenesis, and as such it is one of the most extensively studied regions of the World (e.g., Hsü et al., 1975; Dixon and Robertson, 1984; Kastens et al., 1990; Emeis et al., 1996; Robertson, 1998; McClusky et al., 2000).

The present-day tectonic framework of the east Mediterranean is controlled by the latest phase of this protracted diachronous collision between the African and Eurasian plates, and the displacements of the smaller Arabian and Aegean-Anatolian Microplate (A.E. Aksu et al., 2005) (Fig. 1.1). The final collision of the Arabian Microplate with the Eurasian Plate in the Late Miocene along the Bitlis-Zagros fold-thrust belt initiated the west-directed tectonic escape of the Aegean-Anatolian Microplate along two intra-continental transform faults: the North Anatolian and East Anatolian Transform Faults (Şengör et al., 1985; Dewey et al., 1986). The North Anatolian Fault zone moves dextrally, while the East Anatolian Transform Fault shows a complementary sinistral motion (Fig. 1.1). To the west, the Aegean-Anatolian Microplate is colliding with the Apulia-Adriatic platform (Underhill, 1989), which forced the microplate to progressively rotate toward the free face along the Hellenic Arc (Taymaz et al., 1991; Mann, 1997). Thus the westward displacement of the Aegean-Anatolian Microplate and its counterclockwise rotation is driven by both the north-northwest pushing of the Arabian Microplate as well as the pulling of the subducting African Plate beneath the Hellenic Arc (Reilinger et al., 1997; McClusky et al., 2000). Plate Tectonic studies based on global seafloor spreading and earthquake slip vectors show that the African Plate is presently moving in a north-northeast direction relative to the Eurasian Plate at a rate of 10 mm/yr, whereas

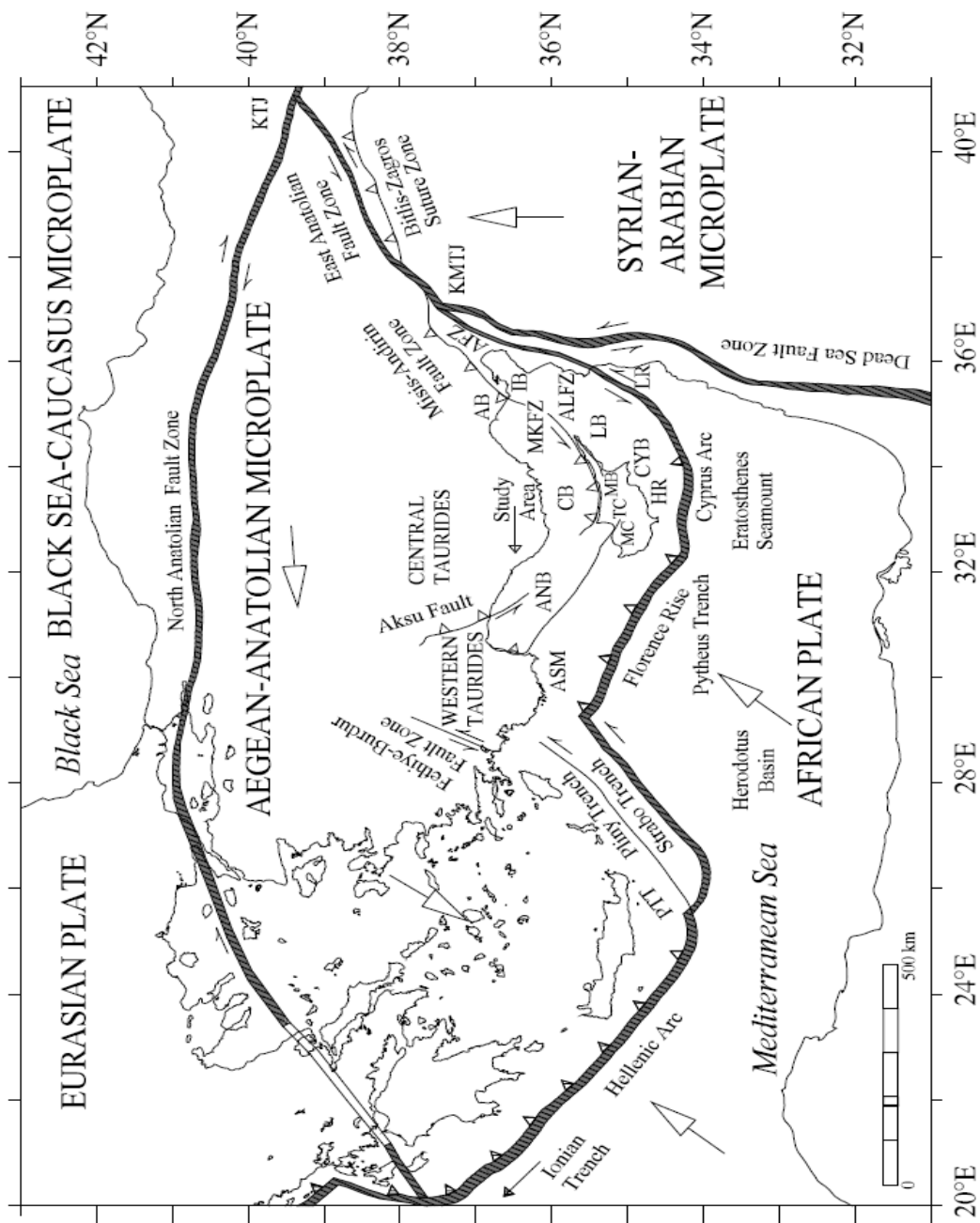


Figure 1.1 Simplified tectonic map of the eastern Mediterranean Sea (modified from Aksu et al., 1992). PTT – Ptolemy Trench, KTJ – Karlova Triple Junction, MB- Misaoria Basin, MC- Mamonina Complex, TC- Troodos Complex, LB- Latakia Basin, MKFZ- Misis-Kyrenia Fault Zone, IB- Iskenderun Basin, AFZ- Anaximander Seamounts, ANB- Antalya Basin. Large arrows show plate motion relative to fixed Eurasian Plate. Subduction zones are shown by double lines with filled triangles positioned on the overriding plate. Major thrust faults are shown by single lines with hatched triangles on the hanging wall. The strike-slip faults are displayed by half arrows showing the directions of relative displacement.

the Arabian Microplate is moving in a north-northwest direction at a rate of $\sim 18\text{-}25$ mm/year (Jestin et al., 1994; McClusky et al., 2000,2003). The differential motion between the African Plate and Arabian Plate is accommodated by the sinistral, transpressional Dead Sea Transform Fault. The boundry between the African Plate and Aegan-Anatolian Microplate is delineated by the Hellenic Arc and the Pliny-Strabo Trenches in the west and the Florence Rise, Cyprus Arc and the Tartsus Ridge in the east (Fig. 1.1). The western and central segments of the two arcs are nearly perpendicular to the relative motion of the African and Anatolian Plate, forming the subduction sutures, whereas the Pliny and Strabo Trenches and Tartus Ridge are sub-parallel to the slip vector, with a predominantly sinistral transform motion.

1.2 Previous Work

The eastern Mediterranean region is a one of the greatest geological puzzles. Despite extensive local and regional studies, significant controversies stil exist about the Late Miocene-Recent kinematic evolotion of the region, particulary the timing and style of deformation, and the temporal and spatial distribution of strain, as well as the nature and thickness of the crust across the floor of the eastern Mediterranean Sea. The Exact position of the boundry between the African Plate and Aegean-Anatolian Microplate remains controversial. Vidal et al. (2000) suggested that the eastern segment of the Anatolian-African plate boundary is situated between Cyprus and Eratosthenes Seamounts, running along the junction of the Hecateus Ridge and Levantine Basin. Vidal et al. (2000) suggested that further to the east the plate boundry is not a sharp discontinuity, but it is delineated by two northeast-trending lineaments: the Latakia and Larnaka Ridges in the South and norht, respectively (Figs. 1.1 and 1.2). Others have suggested that the eastern portion of the Anatolian-African plate boundry is delineated by a single zone, represented by the east-west trending bathymetric escarpment east of the Hecateus Ridge which links the arcuate Latakia Ridge its northeast trending continuation, the Tartus Ridge (Fig. 1.2; Kempler and Garfunkel, 1994; Ben-Avraham et al., 1995; Robertson, 1998). In a recent study, Mascle et al. (2000) showed the presence of a belt of $N145^{\circ}E$ trending, crustal-scale right-lateral transtensional faults offshore Egypt that bound thick-

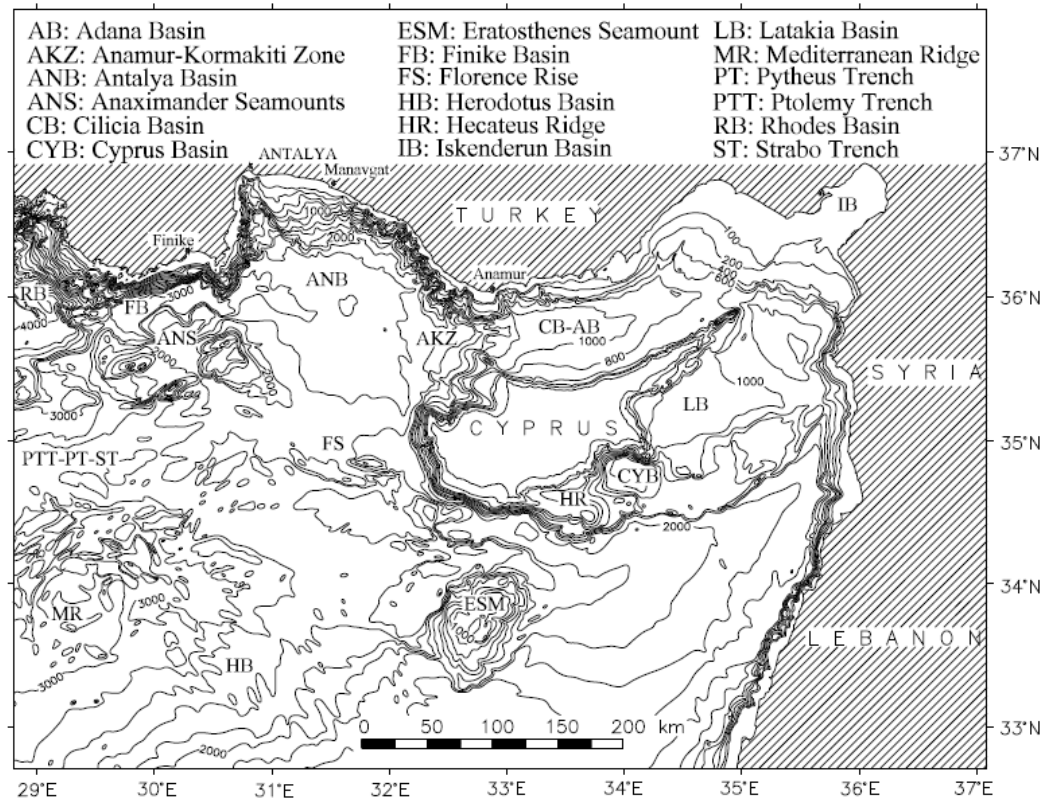


Figure 1.2 Bathymetric chart of the eastern Mediterranean (modified from Aksu et al, 1992).

sediment-filled graben, and extend southward to obliquely transect the eastern Nile deep-sea fan. They speculated the presence of north trending relays that connect this fault system with the trending relays that connect this fault system with the Gulf of Suez rift zone. Mascle et al. (2000) suggested that this fault zone probably defines the western boundary of a newly delineated Sinai-Levantine Microplate which represents the northeastern segment of the African craton disconnected from the African Plate as a consequence of the collision between the Eratosthenes Seamount and Island of Cyprus. They showed that this microplate moves independently from the surrounding African Plate, and the Arabian and Anatolian-Aegean Microplates along the Dead Sea Transform Fault to the east, the Cyprus Arc is also controversial. Roberthson (1998) placed this boundary along the Florence Rise and linked it with the Cyprus Arc. However, Papazachos and Papaioannou (1999) documented the presence of a major north-northeast striking right-lateral transform fault with a thrust component offshore western Cyprus, and suggested that this fault defines a relay between the Florence Rise and Cyprus Arc.

Large convergent Margins, such as the eastern Mediterranean region consist of chains of arcs (e.g. Hellenic and Cyprus Arcs and Florence Rise; Fig. 1.1). Many studies have concentrated on the development of the arcs themselves rather than on the links between the them (e.g., Kenyon et al., 1982; Ben-Avraham et al., 1995; Bohnhoff et al., 2001; Laigle et al., 2002; Ten Veen and Kleinspehn, 2003). However, the link sor corners between the arcs are of fundamental importance to the evolution of these systems because they are the focus of changes in plate kinematics and stress field, thus providing likely sites for the development of triple junction, changes in polarity of subduction and possibly ophiolite obductions. Excessive strain at these locations may result in extreme topographic features some of which may be complementary, such as deep depressions (e.g. Rhodes and Finike Basins), tilted blocks and structural highs (e.g. Anaximander Mountains). At the final stages of ocean closure, the corners become embayments preserved in outline during continental collision. Recent Studies on the Anaximander Mountains and the Rhodes Basin situated around the junction between the Hellenic Arc and the Florence Rise reveal complicated structural framework (Woodside et al., 2002; Zitter et al., 2003).

For Example Woodside et al. (2002) suggested that the Anatolian and African Plates along the Florence Rise are more or less sutured, and that a ~15 km-wide arc parallel dextral wrench zone and its associated positive flower structures are the predominant structural elements of the central and western Florence Rise. They further noted that there is no evidence for typical subduction along the arcuate trend of the Florence Rise. However, the well defined Benioff zone delineated across the Florence Rise by Papazachos and Papaioannou (1999) suggests that the subduction of the African Plate beneath the Aegean-Anatolian Microplate must have slowed-down or stopped only recently. Zitter et al. (2003) showed that eastern Anaximander Mountains have affinity with the Florence Rise, where the Tectonic framework is characterized by an anastomosing network of faults, pop-up, and positive flower structures.

1.3 Plate Boundaries in the Eastern Mediterranean

The current plate interaction and boundaries in the Eastern Mediterranean control the tectonic framework and the structural systems seen in the area.

The interaction between the Aegean-Anatolian plates involves mainly convergence, leading up to the ultimate collision of continental part of the two plates. The boundary between the plates can be found on the sea floor of the East Mediterranean sea along two arcs, the Hellenic Arc and the Cyprus Arc (Fig. 1.1). The Cyprus Arc will be of greater focus in this section, due to its relationship with the Florence Rise, however the structure of both arcs will be addressed.

1.3.1 The Hellenic Arc

The Hellenic arc forms the western convergent boundary between the African and Aegean-Anatolian plates. The convergence of Africa and Europe began between 120 and 83 Ma (Rosenbaum et al., 2002). The convergence rate has varied through time, with at least two periods of rapid convergence (120-67 Ma and 52.4-19.2 Ma) followed by relatively slow convergence from the early Miocene to present time

(Rosenbaum et al., 2002). The evolution of the Hellenic arc occurred quite late in this period and is thought to have begun with the initiation of subduction of the African plate beneath the Aegean-Anatolian in the late Miocene. The relative motion at that time was north-south at the front of the arc and oblique along the western branch. By Pliocene time, subduction was locked to the south inducing left lateral motion along the south margin and subduction along the western arc (Mascle et al., 1986). The Hellenic arc has many of the features characteristic of subduction zones, such as sedimentary and volcanic arcs, as well as seismic activity both at the surface and at depth. There is also an associated broad ridge, called the Mediterranean ridge, that extends along the entire arc, from the southwest coast of Greece to the northwest corner of Cyprus. The ridge is about 1300 km long. 150 to 300 km wide and contains about 10 to 12 km sediment that has been deformed in a compressional setting. Along the present day Hellenic arc system, the mode of convergence changes from normal subduction and compressive regimes in the west to strike-slip and collisional regimes in the east. The Hellenic arc is separated into main branches: the western Ionian branch and the eastern Levantine Branch (Peters et al., 1985).

The Ionian Branch is northwest-southeast trending feature located at the base of the continental slope along the west coast of Peloponnesus. It is made up a series of discontinuous depressions, with a maximum depth of 5000 m, separated by ridges (Peters et al., 1985). Earthquake data suggest that both active subduction and right lateral transverse motion, mainly along the Cephalonia transform fault, occurs along this branch of the arc (Sachpazi et al., 2000; Papazachos et al., 2000).

The Levantine Branch of the Hellenic Arc extends from just south of the island of Crete, northeastwards towards the island of Rhodes in the Eastern Mediterranean sea. In general, this branch consists of a system of subparallel narrow troughs that lose their distinctive trench morphology, become deeper, and merge to the northeast along the arc. South and east of Crete, the Hellenic margin is characterized by two trenches, namely the Pliny Trench to the north and Strabo trench to the south, separated by a wide and sedimented plateau (Mascle et al., 1986). The Pliny trench has a depth of up to 4000 m and is characterized by step wall that dip up to 13

degrees toward the trench floor (Peters et al., 1995). It is made up of small, relatively sedimented depression that generally form an en echelon arrangement (Masclé et al., 1986). The trench opens to the east into a wide, sedimented, graben like feature. South of the Pliny trench lies the shallower.

1.3.2 The Cyprus Arc

In its easternmost segment the Cyprus Arc is defined by the southwest-northeast-trending Nahr el Kebir graben of southwestern Syria. This structure can be readily traced to the southwest where it connects with the northeast-trending Tartus Ridge (Ben Avraham et al. 1995), which in turn links with the similar trending Latakia Ridge, and further connects with the east-west trending Cyprus Arc situated between the Eratosthenes Seamount and Cyprus. Further to the west, the Cyprus Arc is delineated by the southeast-northwest-trending Florence Rise, north of the Pytheus Trench, a prominent deep which consists of a series of small elongate basins (Hsü et al., 1978). The Florence Rise is a large accretionary wedge developed as the result of prolonged northeast subduction of the African Plate beneath the Aegean-Anatolian Microplate (Woodside, 1977). Eratosthenes Seamount is a bathymetric high situated on the edge of the African Plate, south of Cyprus. Drilling results clearly indicate that the seamount consists of Cretaceous-Miocene carbonate successions (Robertson, 1998), which overly an intermediate-thickness attenuated continental crust (Makris et al., 1983). Eratosthenes Seamount is presently colliding with Cyprus, thus constricting the subduction along this segment of the Cyprus Arc (Robertson, 1998). The now-sutured Hecateus Ridge north of the Cyprus Arc and the Mamonia and Troodos Complexes of Cyprus suggest that the process of microplate accretion has been a common process in the evolution of the Island of Cyprus. Along the Florence Rise portion of the Cyprus Arc, subduction is more obvious, marked by moderate seismic activity, whereas in the east there is little or no evidence for subduction and seismicity does not clearly delineate the plate boundary (Woodside, 1976, 1977; Nur and Ben Avraham, 1978; Ben Avraham et al., 1978; Şengör, 1979; Dewey and Şengör, 1979; Rotstein and Kafka, 1982; Kempler and Ben Avraham, 1987; Ambraseys and Adams, 1993; Oral et al., 1995; Vidal et al., 2000).

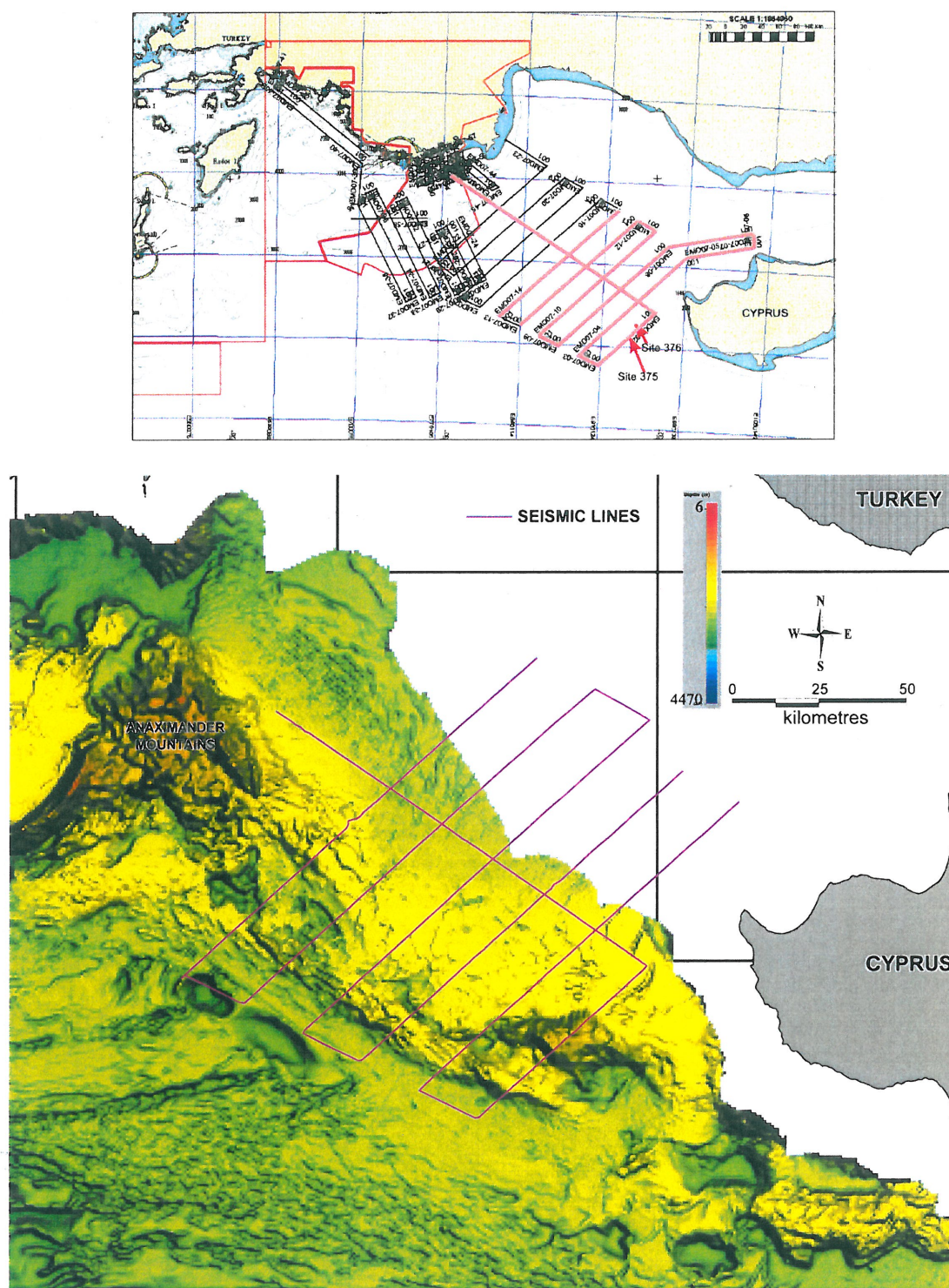


Figure 1.3 is showing the study area on multibeam map and the holes were located near the top (Site 375) and on the northern flank (Site 376) of a raised portion of the eastern Florence Rise (Shipboard Scientific Party, 1978), henceforth referred to in this thesis the 'DSDP Sites'.

1.4 Geological Background of the Florence Rise

The Florence Rise was not apparently significant enough to warrant a name prior to surveys carried out in the 1970s using the Research Vessel *Florence* By Institut FrancLais du Petrole (IFP) (e.g. Sanco et al., 1973). It was named after the IFP survey ship and described as a ‘wide asymmetric arc that may correspond to the southwardoverthrust structures known in Cyprus (Biju-Duval et al., 1974). The pre-Messinian topography of the Florence Rise, like that of the modern feature, was inferred to be more marked in the east than in the west because a broader area exists in the eastern Florence Rise where the Messinian evaporites are either missing or very thin, as at Deep Sea Drilling Project (DSDP) Site 375 (Sage and Letouzet, 1990; Woodside et al., 2002).

On published seismic reflection data, the pre- Messinian seismic horizons appear clearly effected by northerly dipping thrusts, and the resulting stacked napped may be responsible for the elevation and overall morphology of the rise according to Sage and Letouzed (1990). It is possible that these nappes were emplaced at about the same time (i.e. Langhian to Tortonian) as the nappe emplacement over the external zone of the Hellenic and Taurides (e.g Le Pichon and Angelier, 1979). The Lycian nappes of the Taurides (Gutnic et al., 1979) may have extended through the western Anaximander Mountains, just northwest of the Folrence Rise; however, the Antalya Basin, which is known to extend south from Turkey through the eastern Anaximender Mountains (according to results of sampling during the ANAXIPROBE Survey (Woodside et al., 1997)), may be seen to be more directly related to the Florence Rise and was emplaced mainly during pre-early Miocene times (Morcoux et al., 1989).

The Glomar Challenger drilled two holes on the Florense Rise during Leg 42 of the DSDP in 1975 (Hsü et al., 1978). The holes were located near the top (Site 375) and on the northern flank (Site 376) of a raised portion of the eastern Florence Rise (Fig.1.3) (Shipboard Scientific Party, 1978), henceforth referred and to in this thesis the ‘DSDP Sites’. The Messinian evaporites at Site 375 comprises gypsum and gren

dolomitic marlstone that only represent the uppermost, shallow part of the Mediterranean Evaporite Formation. The Messinian evaporites at Site 376 includes also anhydrite and halite (see Chapter 3). At this site the pre-Messinian sequence was probably deposited in a basin with water depths greater than 1000 m (Shipboard Scientific Party, 1978).

The very close correlation between pre-Messinian Neogene sediments drilled at Site 375 and the Kythrea Group of northern Cyprus indicates a common depositional basin (Baroz et al., 1978). Similarities in both the structure and sedimentology of the Florence Rise and Kyrenia Range had previously been inferred by Giermann (1966, 1969), who suggested that the Florence Rise and Kyrenia Range were two parts of a once continuous arc that was offset by major fault running northwest-southeast west of Cyprus and separating Eratosthenes Seamount from Cyprus. The fault resulted from differential movement between the Arabian block and the African Plate which caused a wedge-shaped accommodation zone to form around the Cyprus area, and resulting in sinistral offset of the Florence Rise from the Kyrenia Range (Giermann, 1969).

The morphological boundary of the Florence Rise (Domain II-III) is between the Antalya Basin to the north (Domain I), the northeastern Herodotus Basin (Domain IV) to the south, the Anaxagoras Mountain part of the Anaximander Mountains to the northwest (northwest of the Domain III) (Figs. 1.1, 4.1). Seismic lines were run roughly perpendicular to the rise between these boundaries in this study. The Antalya Basin will be of greater focus in this section, due to its relationship with the Florence Rise, however the structure of other boundaries will be addressed.

1.4.1 Antalya Basin

The Antalya Basin is a predominantly marine depocenter, situated in a forearc setting between the Florence Rise and Cyprus Arc (i.e., the boundary at the level of crystalline basement between the African Plate and the Aegean-Anatolian microplate) in the south and Taurus Mountains of southern Turkey in the north (Fig. 1.1). In

the east, it is connected to the connected to the Outer Cilicia Basin by bathymetric rise referred to as the Anamur-Kormakiti (Anastasakis and Kelling, 1991). In the west, the Antalya Basin bounded by the Beydağları Mountains and their submarine extensions, the Anaximander Mountains, which define a pronounced bathymetric feature immediately south of the Lycian Nappes and the Antalya Complex of southwestern Turkey (Figs. 1.1, 1.2)

The Antalya Basin is characterized by thick sediments dipping towards the north-northeast. The dip and thickness of the sedimentary units increase in the same direction , attesting to continuing northward tilting of the basin (Woodside, 1977; Sage and Letouzey, 1990). This is also well substantiated by the nature of Messinian evaporites, as observed in seismic data. The Messinian evaporites thin towards the Florence Rise and pinch out along the north side of the structural core ridge underlying it. Evaporitic diapirism is locally present and associated with shallow depressions of the sea floor where slightly elevated backscatter occurs in the multibeam imagery (Woodside et al., 2002). There does not appear to be any significant deformation in the sediments other than that caused by depressions over the diapirs. The current deformational activity along the Florence Rise is therefore low to non-existent on the Antalya Basin side; on the other hand it is shown in the following that the most deformational activity characterizes the area just south of the Florence Rise.

1.4.2 Anaximander Mountains

The Anaximander Mountains are enigmatic Morpho-tectonic highs, situated at the complicated junction between the Hellenic and Cyprus Arcs (Fig. 1.1). They are bounded by the Hellenic and Cyprus Arcs (Fig. 1.1). They are bounded to the west by the deep Rhodes Basin, to the east by the outer portion of the Antalya Basin and to the south by the Mediterranean Ridge. The Anaximander Mountains are separated from the Turkish continental margin by the Finike Basin, a broadly E-W trending 5-10 km wide, and 3000 m-deep depression.

The Anaximander Mountains emerge as three prominent morpho-tectonic elements: the Anaximander Mountain (sensu stricto) in the west, the Anaxagoras Mountain in the east and the Anaximenes Mountain in the middle. The Florence Rise are bounded to the Northwestern by Anaxagoras Mountain which eastern part of the Anaximander Mountains. The Anaximander Mountain is a large, Broadly E-W trending and N dipping asymmetric structure (Fig. 1.4) (Aksu et al., 2009). The southern flank of the structure is bounded by a very steep S-dipping escarpment, where the seafloor is sharply offset by 700-900 m. The northern slope of the mountain gently dips northward, and the structure merges with the Finike Basin at the foothills of the southwestern Turkish continental slope. The Anaximenes Mountain is a step-sided broadly arcuate structure which is concave to the northwest. It has a NE-WSW toward its southwestern end (Fig. 1.4) (Aksu et al., 2009). The northern flank of the structure is demonstrably steeper than its southern flank. The crest of the Anaximenes Mountain is elevated ~400 m above the 20-30 km wide flat-bottomed valley between the Anaximander and Anaximenes Mountains, referred to as the Sırrı Erinç Plateau, and ~500-700 m above the northern flank of the Mediterranean Ridge to the south (Aksu et al., 2009) (Figs 1.4, 4.1).

The Anaxagoras Mountain is a NW-SE trending broad high that is morphologically connected to the Florence Rise. The Northwestern margin of the Anaxagoras Mountain is bounded by an arcuate NW dipping escarpment, where the seafloor is elevated ~700 m above the Sırrı Erinç Plateau to the northwest. The northeastern margin of the Anaxagoras Mountain displays two to three small escarpments, progressively leading into the outer Antalya Basin. Toward the southwest, the Anaxagoras Mountain is linked to the Anaximenes Mountain, and together they form a NW-facing concave structure (Aksu et al., 2009).

1.5. Objectives

The multi-channel seismic data used in this study were acquired in 2007 and a systematic processing sequence has been applied to prepare the data for interpretation. Consequently, several structural and isochron maps are produced to

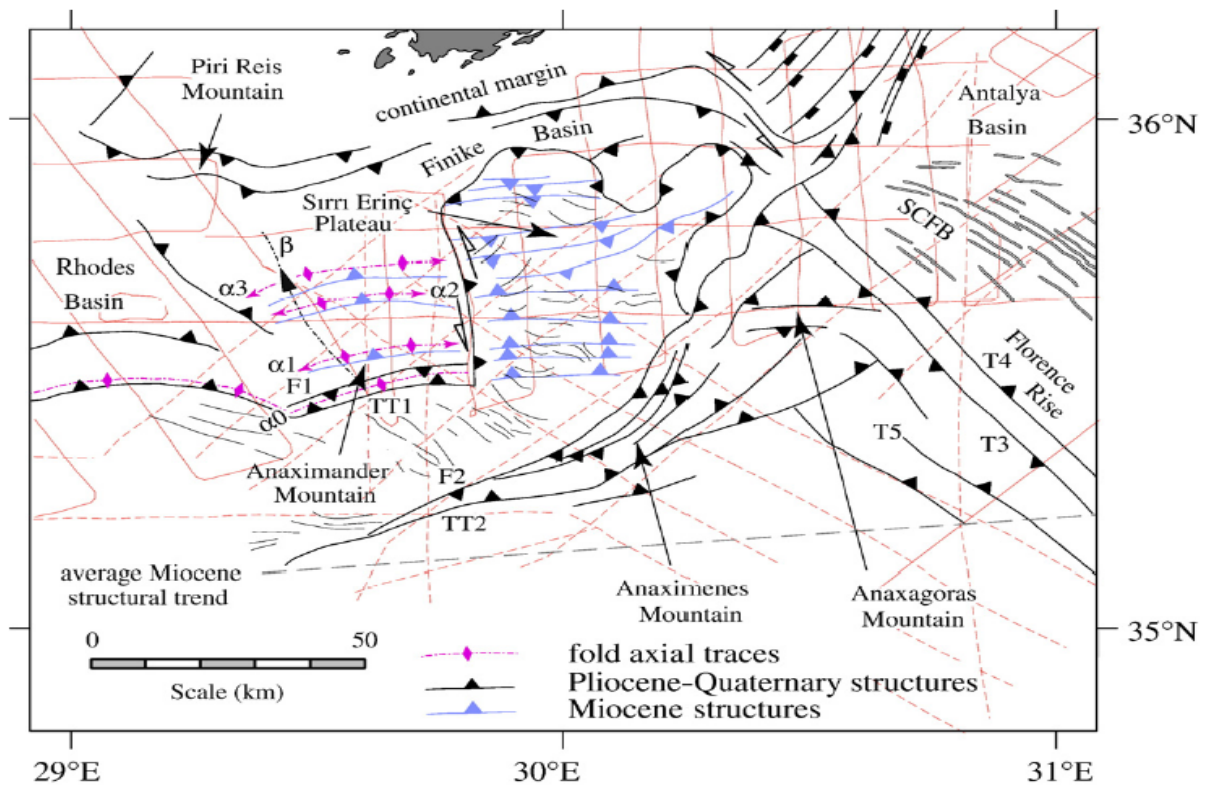


Figure 1.4 Miocene and Pliocene-Quaternary tectonic map of the Anaximander Mountains and environs, formed by Aksu et al, (2009).

delineate the regional distribution and variation of the geological structures and the stratigraphic sequences within the study area.

The geophysical objectives of this thesis are :

- 1) to determine the appropriate parameters for the processing of the multi-channel seismic data in Florence Rise,
- 2) to evaluate the effects and success of each individual processing step,
- 3) to process the data to the final image so as to make the profiles look as similar to the real subsurface geology as possible.

The geological objectives of this thesis are:

- 1) to construct a detailed tectonic architecture for the eastern Florence Rise and to provide correlations between the offshore features in the study area,
- 2) to produce detailed maps of tectonic structures and to delineate their role in the Miocene to Recent deformation observed within the study area,
- 3) to produce detailed isopach maps of Pliocene-Quaternary correlations with result of the DSDP Sites 375-376,
- 4) to interpret the role of the Florence Rise within the Miocene to Recent kinematic evolution of the eastern Mediterranean.

1.6. Global Positioning System Constraints on Continental Deformation in the Eastern Mediterranean

The Global Positioning System (GPS) observations a precise measurement of continental motion and deformation. These, in turn, contribute to the understanding of the rheological models of the continental lithosphere and the forces causing the active deformation (Reilinger et al., 1997). The analysis of the movement vectors shown in Figure 1.5, suggests that the Syrian-Arabian Microplate is moving north-northwest at a rate of about 25 mm/year, the African Plate is moving northward at a rate of about 10 mm/year and the Aegean-Anatolian Microplate is rotating counterclockwise with an internal deformation of <2 mm/year, relative to Eurasian Plate (DeMets et al., 1990, 1994). The movement of African Plate relative to the

Arabian-Syrian Microplate is accommodated along the sinistral slip of the Dead Sea Fault. The rotation of the Aegean-Anatolian Microplate is accommodated along the dextral North Anatolian Fault and its extension into the Aegean Sea (i.e. the North Aegean Trough) in the north, and along the sinistral East Anatolian Fault in the east.

Continental blocks tend to escape from collisional zones to prevent the subduction of continental material and to reduce the topographic elevation (McKenzie, 1970; Şengör, 1979; Jackson and McKenzie, 1988; Jackson, 1992). The westward movement of the Aegean-Anatolian Microplate is a prime example of a tectonic escape, in this case resulting from the collision of the Syrian-Arabian Microplate with the Eurasian Plate along the Bitlis-Zagros Suture zone, in eastern Turkey.

Jackson and McKenzie (1984) measured the earthquake slip vectors along the North Anatolian Fault and obtained an Euler vector with a rotation pole of 14.6° N, 34° E and rate of 0.64° /my for the Anatolian segment of the Aegean-Anatolian Microplate and Eurasian Plate. Accordingly, they suggest that the western Aegean segment of the microplate is separated from the eastern Anatolian segment of the microplate by a north-south oriented extension zone and added that the intensity of earthquakes in western Turkey compared with the non-seismic character of the central Turkey provides support for this two-microplate hypothesis. Taymaz et al. (1991) obtained a similar Euler vector, only with a change in the rotation rate (0.78° /my). However, Reilinger et al. (1997), derived two Euler vectors: one using only ten GPS stations located in the central portion of the Anatolian segment of the microplate and the other using all the stations south of North Anatolian Fault zone and west of East Anatolian Fault zone, which indicate rotation poles and rates of $29.2 \pm 0.8^{\circ}$ N, $32.9 \pm 0.4^{\circ}$ E, $1.3 \pm 0.1^{\circ}$ /my and $31 \pm 0.8^{\circ}$ N, $32.2 \pm 0.4^{\circ}$ E, $1.7 \pm 0.2^{\circ}$ /my, respectively. These two Euler vectors imply a statistically negligible difference and point a pole position situated near the Sinai Peninsula. Based on the similarity of these Euler vectors, Oral et al. (1995), and Reilinger et al. (1997) suggested that the rotation of the Aegean-Anatolian Microplate may be better characterized by a single plate model. In this model, the Aegean-Anatolian Microplate displays little

deformation in the east and a notably increasing deformation toward the Hellenic Arc, resulting in north-south extension in the southeastern Aegean region.

The Euler poles of Reilinger et al. (1997) display a 14° shift to the north from those calculated by Jackson and McKenzie (1984) and Taymaz et al. (1991). This shift in the pole position denotes a smaller radius of curvature for the rotation of Aegean-Anatolian Microplate relative to Eurasian Plate. Based on the examination of the curvature of the North Anatolian Fault, Westaway (1994) suggested that a rotation curvature for the Aegean-Anatolian Microplate must exist along the trace of this fault to accommodate the observed geometry. The rotation curvature obtained by Reilinger et al. (1997) overlaps the trace of the North Anatolian Fault along the eastern-central portion but deviates toward south from the western portion. Using the earthquake focal mechanisms and the geological maps, Barka and Kadinsky-Cade (1988), Barka et al. (1997) noted a change from a strike-slip and extensional character to a more complex system of restraining and releasing bends along the North Anatolian Fault, towards the west. This change in the character of North Anatolian Fault may explain the deviation of the fault from the rotation pole estimated by Reilinger et al. (1997).

Systematic analysis of the GPS velocity field based on a fixed Eurasian Plate shows a counterclockwise rotation of the Aegean-Anatolian Microplate with an increase in the horizontal velocities towards west-southwest (Fig. 1.5). The high velocities observed in the southwestern part of the microplate is interpreted to occur as a result of the southward retreat of subduction of the African Plate along the Hellenic Arc (McClusky, 2000).

The evaluation of the GPS data generally supports McKenzie (1970)'s earlier ideas on the deformation field in the eastern Mediterranean. The counterclockwise rotation of the Aegean-Anatolian Microplate relative to Eurasia suggested by the GPS measurements provides a better understanding of the geological architecture in Florence Rise, and is further discussed later.

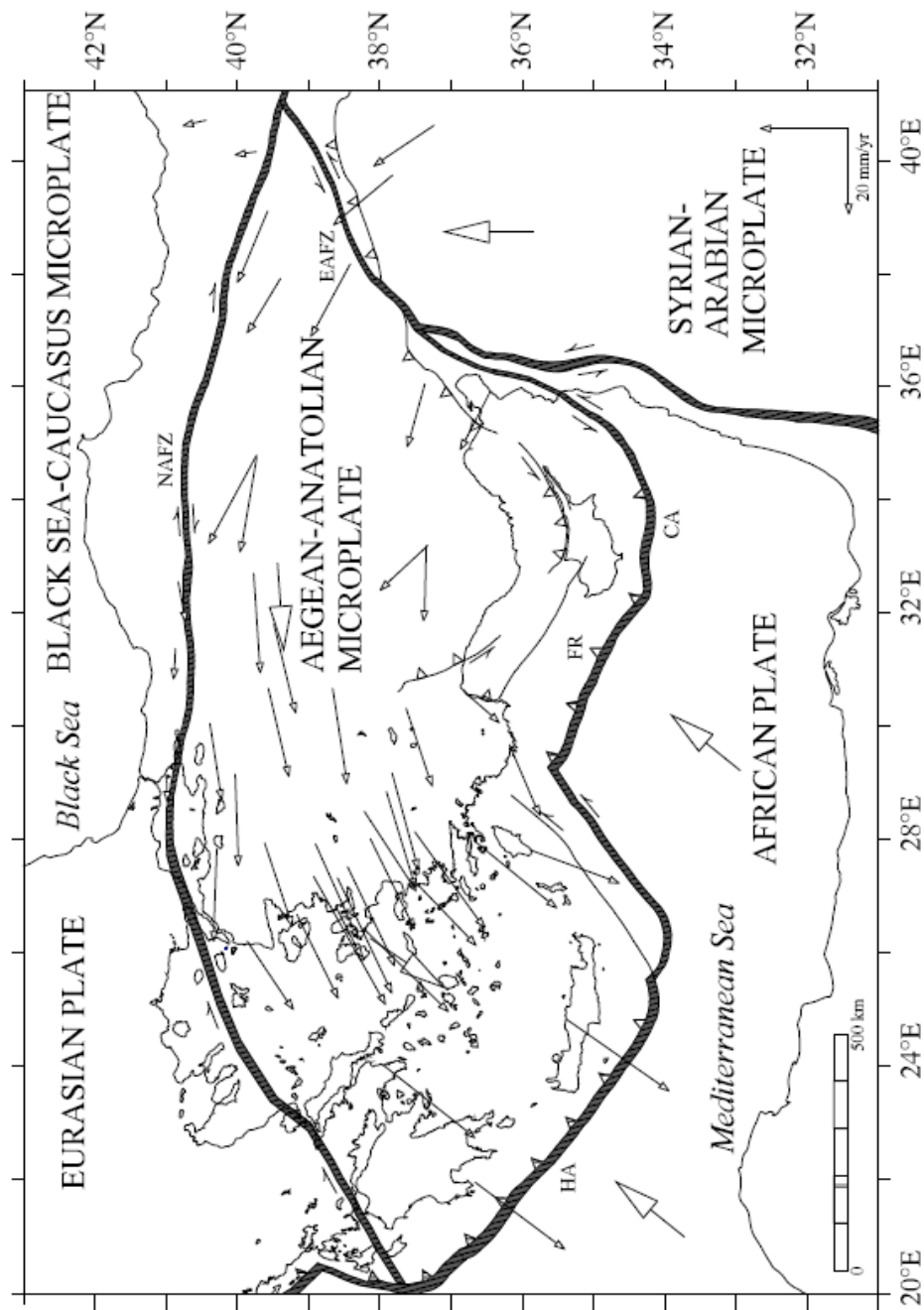


Figure 1.5 Global Positioning System (GPS) horizontal velocities measured relative to Eurasian in the period 1988-1994 (modified from Reilinger et al. (1997) and Robbins et al. (1995) NAFZ- North Anatolian Fault Zone, EAFZ – East Anatolian Fault Zone, HA, Hellenic Arc, FR- Florence Rise, CA- Cyprus Arc. Large arrows show plate motion relative to fixed Eurasian Plate. Subduction zones are shown by double lines with filled triangles positioned on the overriding plate. Major thrust faults are shown by single lines with hatched triangles on the hanging wall. Strike-slip faults are displayed by half arrows showing the directions of relative displacement.

1.7. Seismicity

The Alpine-Himalayan belt is a prominent zone of active seismicity where earthquakes are generated along the boundaries between the larger Eurasian, African and Indo-Australian Plates and several smaller Syrian-Arabian and Aegean-Anatolian Microplates. The boundary between the African and Eurasian Plates in the easternmost Mediterranean, including the Aegean Sea is fairly complex, and this region is considered as the most active portion of this zone of seismicity. The seismicity map shown in Figure 1.3 constitutes the data from the Kandilli Observatory, Earthquake Research Institute-KOERI, and International Bathymetric Chart of the Mediterranean- Seismicity-IBCM-S.

A number of large historical and recent earthquakes provide valuable information on the character of the recent tectonic activity in the eastern Mediterranean region (Barazangi and Dorman, 1969; Ambraseys, 1970; McKenzie, 1970, 1972; Nowroozi, 1971; Comninakis and Papazachos, 1972; Papazachos, 1973; Büyükaşıkoglu, 1980; Rotstein and Kafka, 1982). The seismicity in eastern Mediterranean Sea generally increases from east to west (Fig. 1.6). The focal depth distribution of earthquakes with magnitudes greater than 4 reveal that the hypocenters >50 km are mainly concentrated in the region of the Hellenic Arc, the Florence Rise, the Anaximander Seamounts including the Finike Basin, the Adana-Iskenderun Basins, the southern regions of Cyprus and along the volcanic arc in central Anatolia. Earthquakes with epicenters <50 km are concentrated along the North Anatolian Fault, the East Anatolian Fault and in the onshore extension of the Antalya Bay, the Isparta Angle. Three recent major earthquakes have occurred along the western flank of the Isparta Angle in 1914 ($M=7$), 1971 ($M=6.2$) and 1957 ($M=7$), whereas the eastern flank does not appear to be seismically active. In central Anatolia both historical and recent earthquakes suggest a lower seismic activity compared to western Anatolia (Ambraseys, 1970;1988; Ambraseys and Finkel, 1987; Barka et al., 1997). The most important earthquakes in this area are the 1938 Kırşehir earthquake with a magnitude of 6.8 (Parejas and Pamir, 1939; Ketin, 1969; Barka et al., 1997) and the three historical earthquakes that occurred in 1668, 1717 and 1835 (Ambraseys and Finkel,

1987; Öztin and Bayülke, 1990). Western Turkey is characterized by high seismic activity, with several large earthquakes delineating the master faults of the east-west trending graben systems, such as the 1899 Büyük Menderes, 1928 Torbalı, 1955 Balat, 1969 Simav, 1970 Gediz and 1995 Dinar earthquakes. Little or no seismic activity is observed in the southern part of central Anatolia (including the Mut Basin)

The boundary between the African Plate and the Aegean-Anatolian Microplates can be seismically traced from the Ionian Sea in the west across the Hellenic Arc, Florence Rise-Cyprus Arc into the Bitlis-Zagros Suture zone in the east (Figs. 1.1, 1.6). The Hellenic Arc subduction zone, including the Ptolemy, Pliny and Strabo Trenches along its western margin is seismically very well defined by a narrow, north-concave belt of shallow, intermediate and deep earthquakes, with a prominent Benioff zone. The Florence Rise and Cyprus Arc can also be traced seismically as another north-concave belt, but with a notably lower seismicity. The absence of unequivocal oceanic crust in the Levantine Basin (McKenzie, 1972) and the lower earthquake activity strongly suggest that the continental fringes of the African Plate are beginning to collide with the Aegean-Anatolian Microplate, and that the small continental fragment, the Eratosthenes Seamounts is choking the subduction zone (Robertson, 1998). Rotstein and Kafka (1982) used the recent earthquake data to suggest that a continuous zone of seismicity east of the Anaximander Seamounts defines the northern boundary of the African Plate. Seismic reflection data clearly document the presence of a prominent northeast-trending ridge (i.e. Tartus Ridge, Ben Avraham et al., 1995) which defines the northern boundary of the African Plate with the Syrian-Arabian Microplate in the east and the Aegean-Anatolian Microplate in the north. The Tartus Ridge links the Cyprus Arc with the Dead Sea Fault and the East Anatolian Fault on a triple junction near the town of Kahramanmaraş (Figs. 1.1, 1.6 ; Ben Avraham et al., 1995; Vidal et al., 2000). In southeastern Turkey, the plate boundary is characterized by two southwest-northeast oriented, internally parallel zones of seismicity. The southern zone lies along the Bitlis-Zagros Suture zone, while the northern lesser zone correlates with the present-day trace of the East Anatolian Fault.

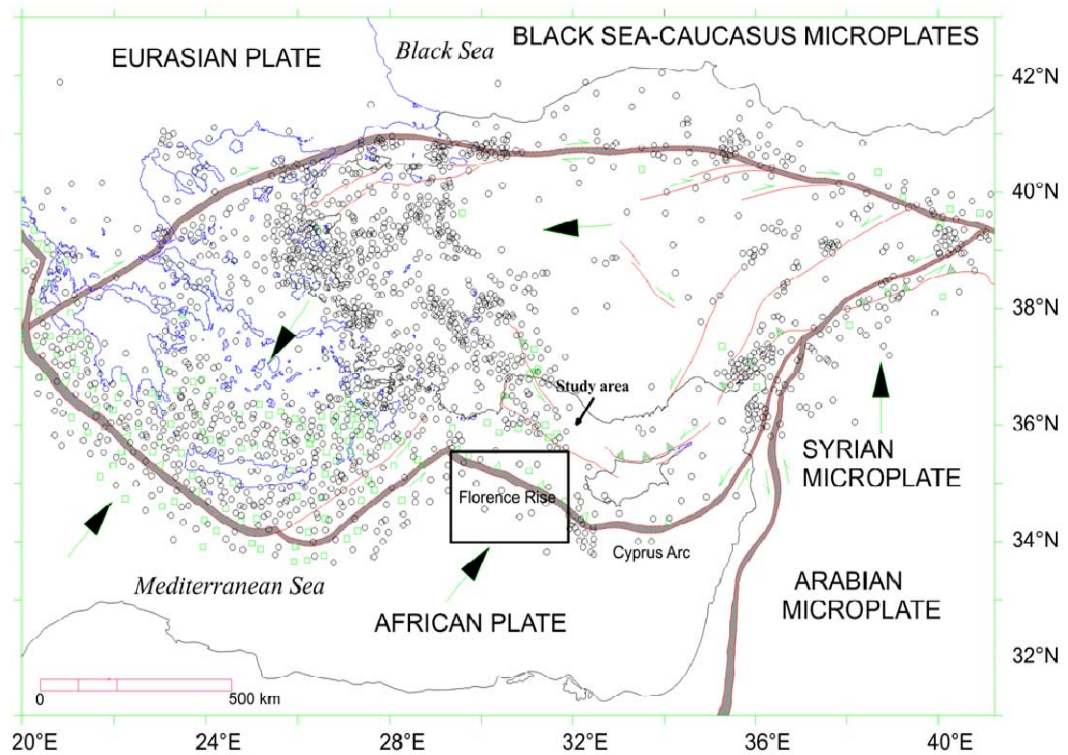


Figure 1.6. Seismicity map of the eastern Mediterranean showing the distribution of earthquake epicenters with magnitudes >4 , compiled using data from Kandilli Observatory Earthquake Research Institute, and International Bathymetric Chart of the Mediterranean-Seismicity-IBCM-S. Focal depths <50 km and >50 km are represented by filled circles and open squares, respectively. Large arrows show plate motion relative to fixed Eurasian Plate. Subduction zones are shown by double lines with filled triangles positioned on the overriding plate. Major thrust faults are shown by single lines with hatched triangles on the hanging wall. Strike-slip faults are displayed by half arrows showing the directions of

The analysis of seismicity in the eastern Mediterranean provides a better understanding of the past and recent tectonic processes that control the movement of the African and Eurasian Plates and the reorganization of the smaller microplates (i.e. Aegean-Anatolian and Syrian-Arabian Microplates). The focal depth distribution of the earthquakes together with the associated fault plane solutions contributes greatly to the interpretation of the complex geological structures in the area.

Fault plane solutions obtained from the earthquake data, which consist of the azimuth angles of the stations with respect to the epicenter and the initial direction of the P waves recorded at those stations, shows evidence of a complex deformation in the eastern Mediterranean (Fig. 1.7). The major fault activity obtained from the fault plane solutions of earthquakes in the Iskenderun and Adana Basins reveals a predominantly strike-slip character. A similar strike-slip character is also recognized along the North Anatolian Fault and East Anatolian Fault zones. In the western portion of the North Anatolian Fault, the strike-slip character is accompanied by a distinct normal slip component. In western Turkey normal fault activity occurs along several well defined graben systems. The Florence Rise and the Antalya Basin and the area to the south of Cyprus is characterized by both reverse and normal faulting with a strike-slip component. The fault plane solutions from the Harvard Seismology Centroid-Moment Tensor (CMT) database (from 1976 to 2002) shown on Figure 1.7 are of the earthquakes with magnitudes equal and greater than 4.

The regional and focal depth distribution of earthquakes in relation to the plate boundaries is very important in delineating the role of Florence Rise within the tectonic processes that control the eastern Mediterranean. The information provided by the fault plane solutions helps to note the character of the fault activity in the study area, providing a tool to compare with what is shown by the seismic data.

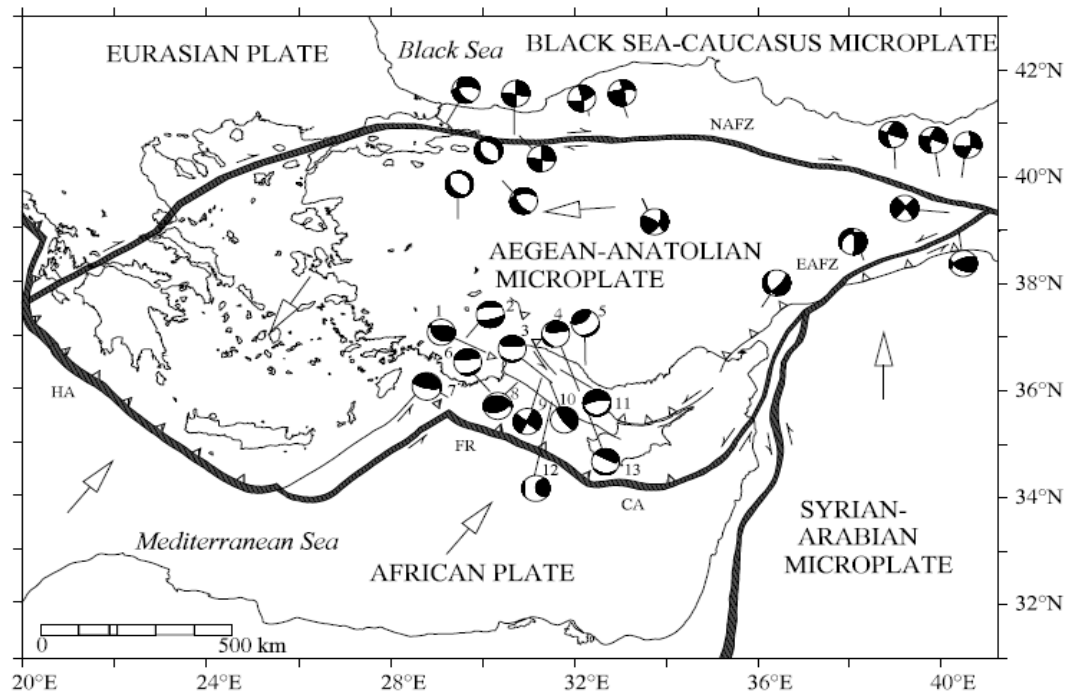


Figure 1.7. Fault plane solutions (lower hemisphere projection) for major earthquakes in the eastern Mediterranean region (compiled from Jackson et al., 1984 and Harvard CMT Catalog). The dark quadrants represent compressional stresses. The numbers posted on the map refer to the earthquakes that occurred within the Antalya Bay area and the date and focal depth of these earthquakes are given in Table 1.1. NAFZ- North Anatolian Fault Zone, EAFZ- East Anatolian Fault Zone, PT- Pliny Trench, ST- Strabo Trench, FR- Florence Rise, CA- Cyprus Arc, KTJ- Karl ova Triple Junction, MKFZ- Misis-Kyrenia Fault Zone, AFZ- Amanos Fault Zone, ALFZ- Amanos-Larnaka Fault Zone, KMTJ- Kahramanmaras Triple Junction, The active subduction zones are marked by double lines with arrow heads positioned on the overriding plate. The major thrust faults are shown by single lines with arrow heads on the hanging wall. The strike-slip faults are displayed by half arrows showing the directions of relative displacement.

CHAPTER TWO

DATA ACQUISITION

2.1. The Seismic Reflection Method

The seismic reflection method involves measuring the two-way-traveltime of the seismic waves from the source to the receivers. Figure 2.1 shows the reflection geometry of a seismic wave path in the case of a dipping reflector in a homogeneous and isotropic medium. Here, h stands for the shortest source-reflector distance, x is the lateral source-receiver distance and v is the average velocity of medium.

The traveltime function, which corresponds to a tilted hyperbola, is constrained by the physical properties of the subsurface media (in terms of the propagation velocity of the seismic waves), the depth and dip of the reflector as well as the source-receiver distance.

2.2. The Acquisition Parameters and the Geometry of the Survey

In 2007 approximately ~2500 km of multi-channel seismic reflection profiles were collected from the Florence Rise and Anaximander Mountains in eastern Mediterranean Sea. These profiles were obtained using the Institute of Marine Sciences and Technology, Dokuz Eylül University and the Memorial University of Newfoundland multi-channel seismic acquisition system on the R/V *Koca Piri Reis* of the Institute of Marine Sciences and Technology, Dokuz Eylül University, Izmir, Turkey (Fig. 2.2). During acquisition, the common-mid-point shooting technique (Fig. 2.3) was used, allowing redundant sampling of a given reflector, where the multiplicity of subsurface coverage is given by:

$$\text{Fold} = 1/2 [\text{Number of channels (Hydrophone Group Interval / Shot Interval)}].$$

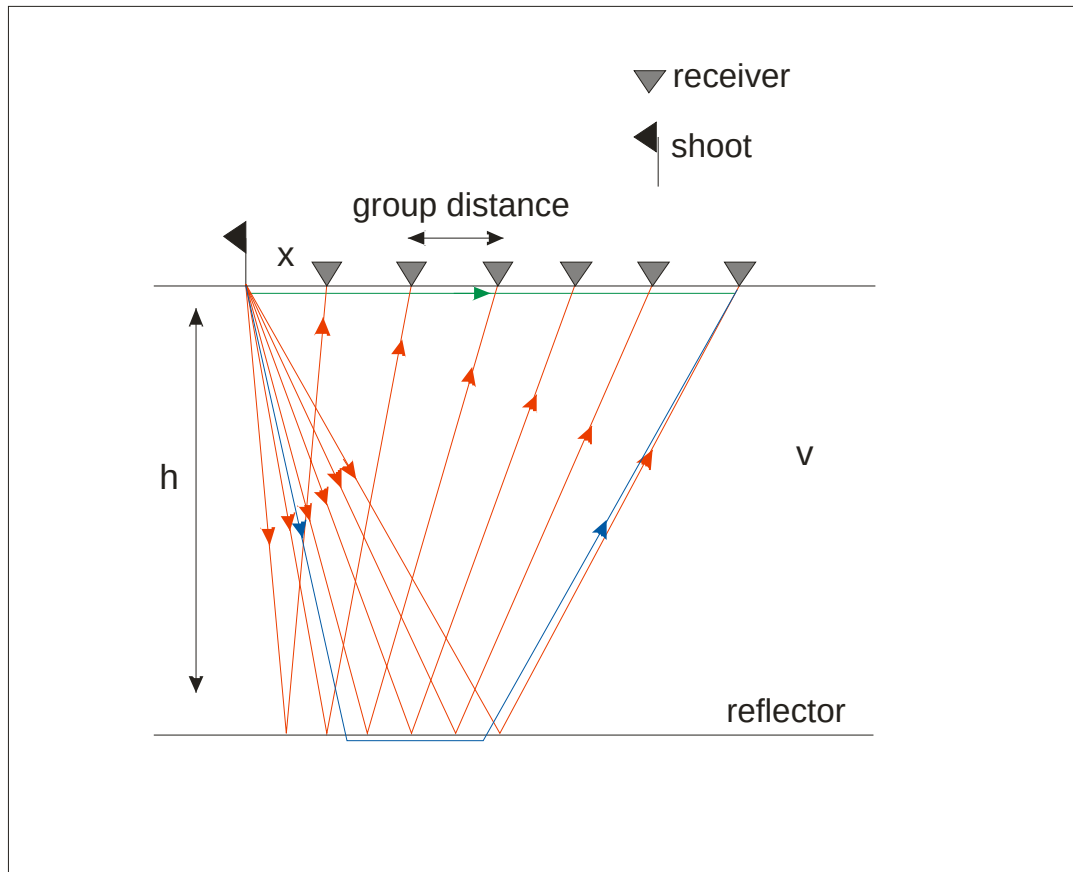


Figure 2.1 Showing the reflection geometry of a seismic wave path.

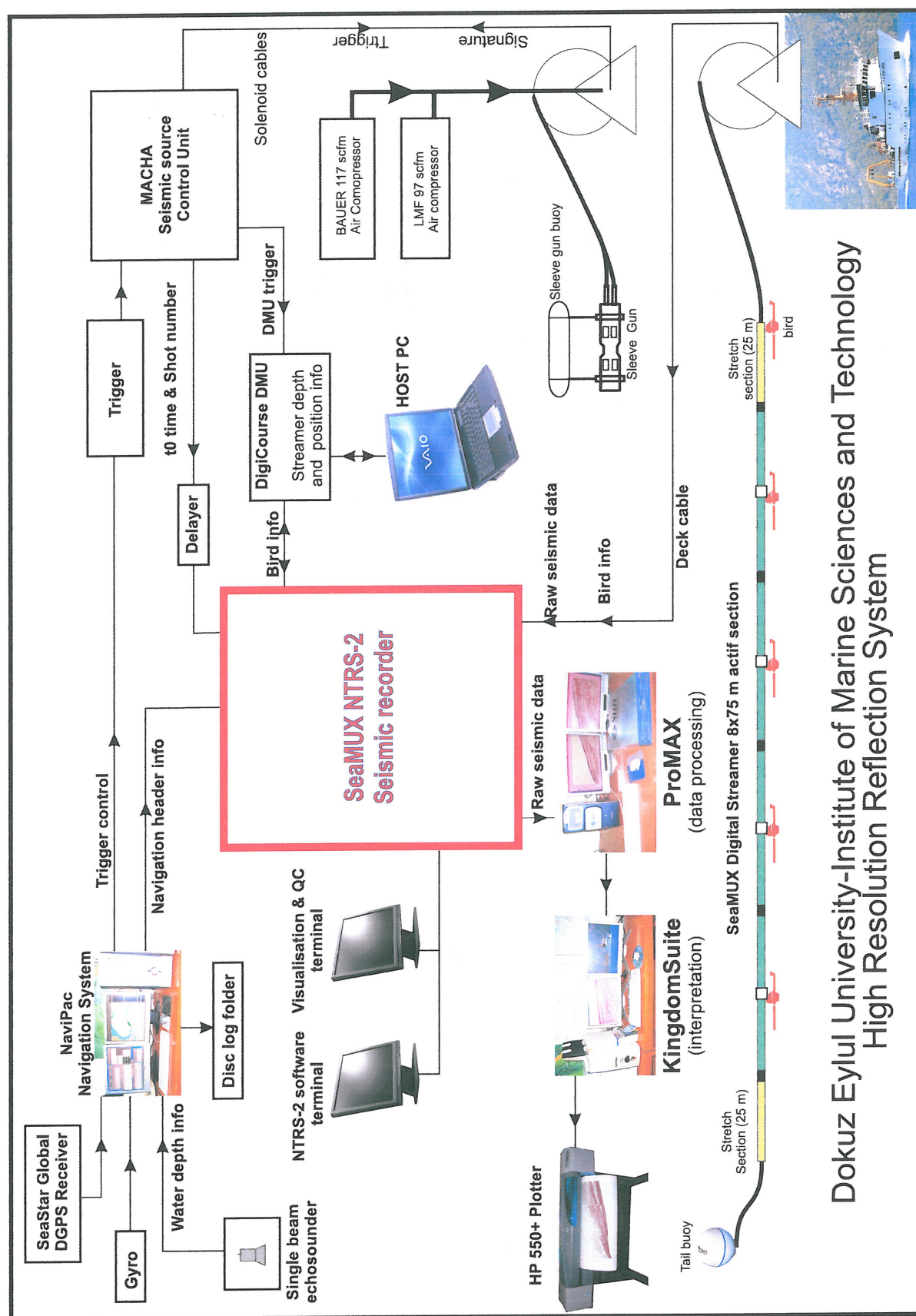


Figure 2.2 Showing the Dokuz Eylul University of Marine Sciences and Tecnology High Resolution Reflection System.

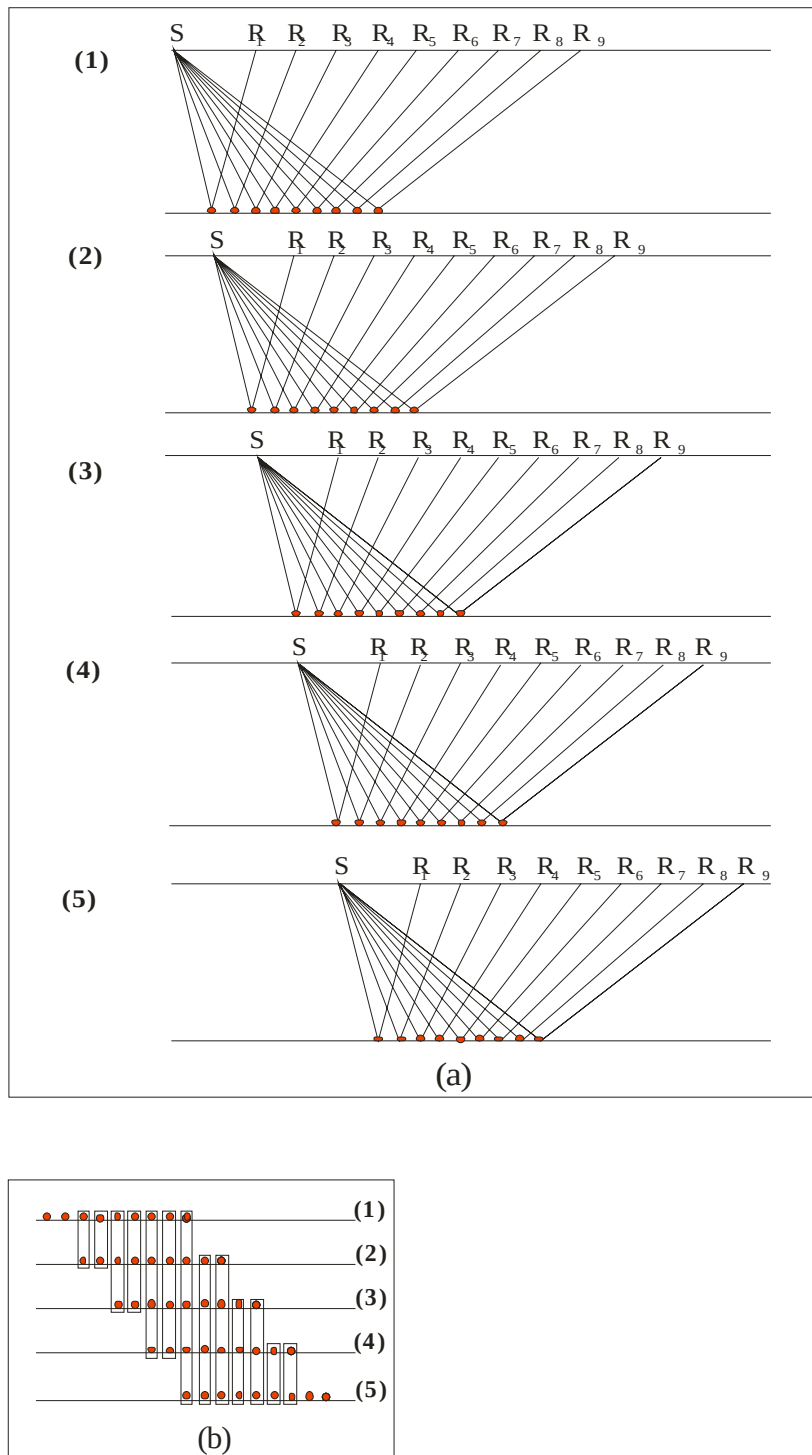


Figure 2.3 (a) Common-mid-point(CMP) seismic acquisition configuration;
(b) resultant multiple subsurface coverage.

The source consisted of a Halliburton sleeve gun array, employing gun sizes of 40, 20 and 10 cubic inches. The total volume was typically 200 cubic inches (3278 cm³). The design bandwidth 24 of the full 200 cubic inch source is approximately flat over 30-180 Hz. During the 2007 survey, shots were fired every 25 m, and reflections were detected using a Hydrosience Technologies Inc. multi-channel streamer (450m long 72 channel x 6.25m) (Fig. 2.2). The resultant 9-fold data were recorded digitally on NTRS-2 seismic recorder for four seconds below the sediment-water interface.

Approximately 700km of the data set collected from the Florence Rise was used in this study. These multi-channel data were processed by the author at the Institute of Marine Science and Technology, Dokuz Eylül University, Turkey, as well as the Memorial University of Newfoundland. Data were processed using the ProMAX software with automatic gain control, velocity analysis, normal move-out correction, stack, filter (typically 50-200 Hz bandpass), migration .

Most of the profiles were collected in a northeast-southwest direction which is perpendicular to the general trend (strike) of the geological structures in the area. An additional line was shot extending in a west-northwest – east-southeast direction, parallel to the general trend of geological structures and crosscutting all other lines. Four tie-lines were shot extending in a west northwest-east southeast direction across the rise and intersecting the rest of the profiles. The resultant coverage constitutes a grid with line separation of around 15 km (see Appendix). The details of the shooting geometry for the data are shown in Figure 2.4.

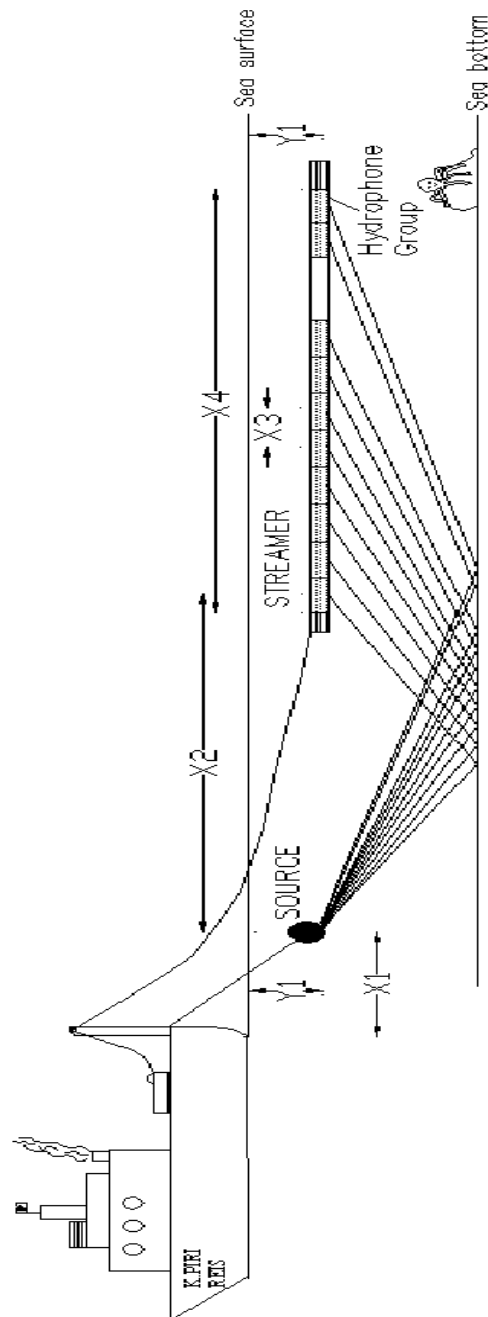


Figure 2.4 showing the details of the shooting geometry for the data.

Stern to source (X_1) : 30m

Source to center of first hydrophone (X_2) : 70m

Hydrophone group interval (X_3) : 6.25m

Active streamer length (X_4) : 450m

Source and streamer depth (Y_1) : 3m

CHAPTER THREE

MARINE SEISMIC DATA PROCESSING

3.1 Data Processing

The data processing to be completed for this thesis involved bringing raw seismic data from shot records to fully interpretable seismic images. The Landmark based computer program, ProMAX, was used to complete this task. The processing flow involved a complete scheme determined through analysis of the data and changes somewhat from line to line.

3.1.1 Data Processing Scheme

The general processing flow used is shown in Figure 3.1. Further discussion of certain steps are discussed in the following section.

- (1) Demultiplex Data. The data were recorded on optical discs in SEG-Y format. To be usable by the Promax processing package, the data had to be read from the disc and converted to the appropriate format. The converted SEG-Y data was then written to and stored on disc.
- (2) Analysis of Data Quality. The data was analyzed to locate noisy traces, other noise problems and static shifts created by changes in recording delays.
- (3) Definition of Trace Headers. Field file identification numbers and channels number are defined.
- (4) Trace editing. Involves killing or cropping bad traces
- (5) Static Correction. Static time shifting to bring all data to the same datum.
- (6) Filtering. Band Pass filter are applied to eliminate low and high frequency noise. In some cases, F-K filtering and muting is used to eliminate aliased signals.
- (7) Geometry application. Geometry applied to assign source-receiver offsets and common depth points (CDP's) to the data.

- (8) Velocity analysis. Involves generating semblance spectra and constant velocity stacks to pick appropriate stacking velocity.
- (9) Normal Moveout Correction. Correction applied to convert data to zero offset.
- (10) Stack. Summing all traces for the same common depth point to increase the signal to noise ratio.
- (11) Migration. Kirchhoff time migration algorithm applied to restore dipping reflectors to their true subsurface positions.
- (12) Filtering. In some cases, time variant filtering is used to eliminate noise generated through migrating the data.
- (13) Trace Mixing. Adjacent traces are averaged to make the reflections appear more continuous.
- (14) Muting. Data is muted immediately above the sea bed.

3.1.2 Trace Editing

All of the lines processed required some trace editing due to noise problem in select traces. Spurious noise spikes, likely created by random noise, are a problem along certain traces. They are usually random, sometimes affecting an entire trace, sometimes just affecting a short time period along a trace. If the entire trace is affected, the trace is zeroed using the trace kill command (Fig. 3.2). In some cases, the same channel had noise problems across numerous shots suggesting a problem with the channel during acquisition. These noise dominated channels generally do not have usable reflection data recorded even if the noise is eliminated by frequency filtering. Therefore, it is warranted to kill the noisy trace across all affected shots (Fig. 3.3).

3.1.3 Static Correction

Each of the lines processed for this thesis require some degree of static correction. Some of the adjustments were recorded as time delays in the recording log and are easily applied to the affected shots.

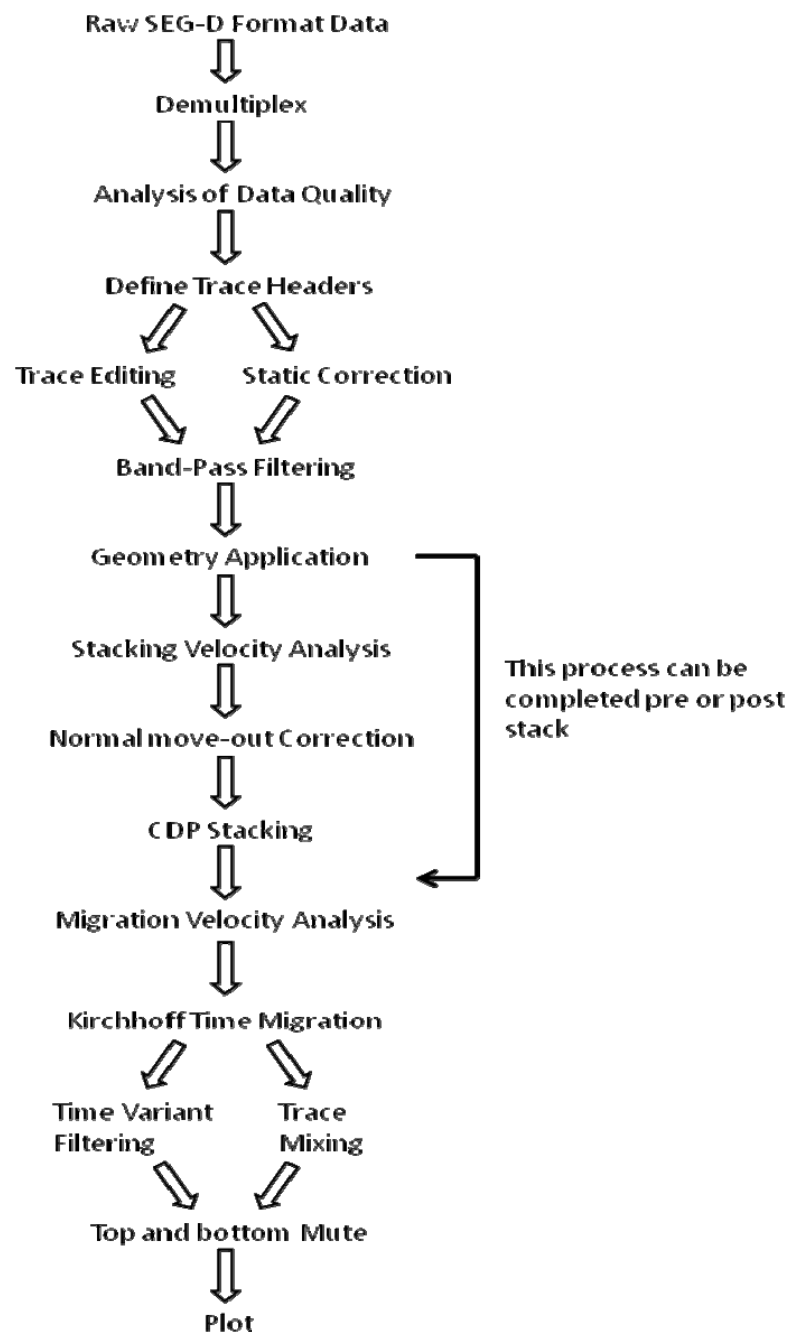


Figure 3.1 Schematic Processing Flow applied to each of seismic lines processed for this thesis.

The  symbols indicates that the below processes may not have been applied to all lines processed, their application depended on need and data quality.

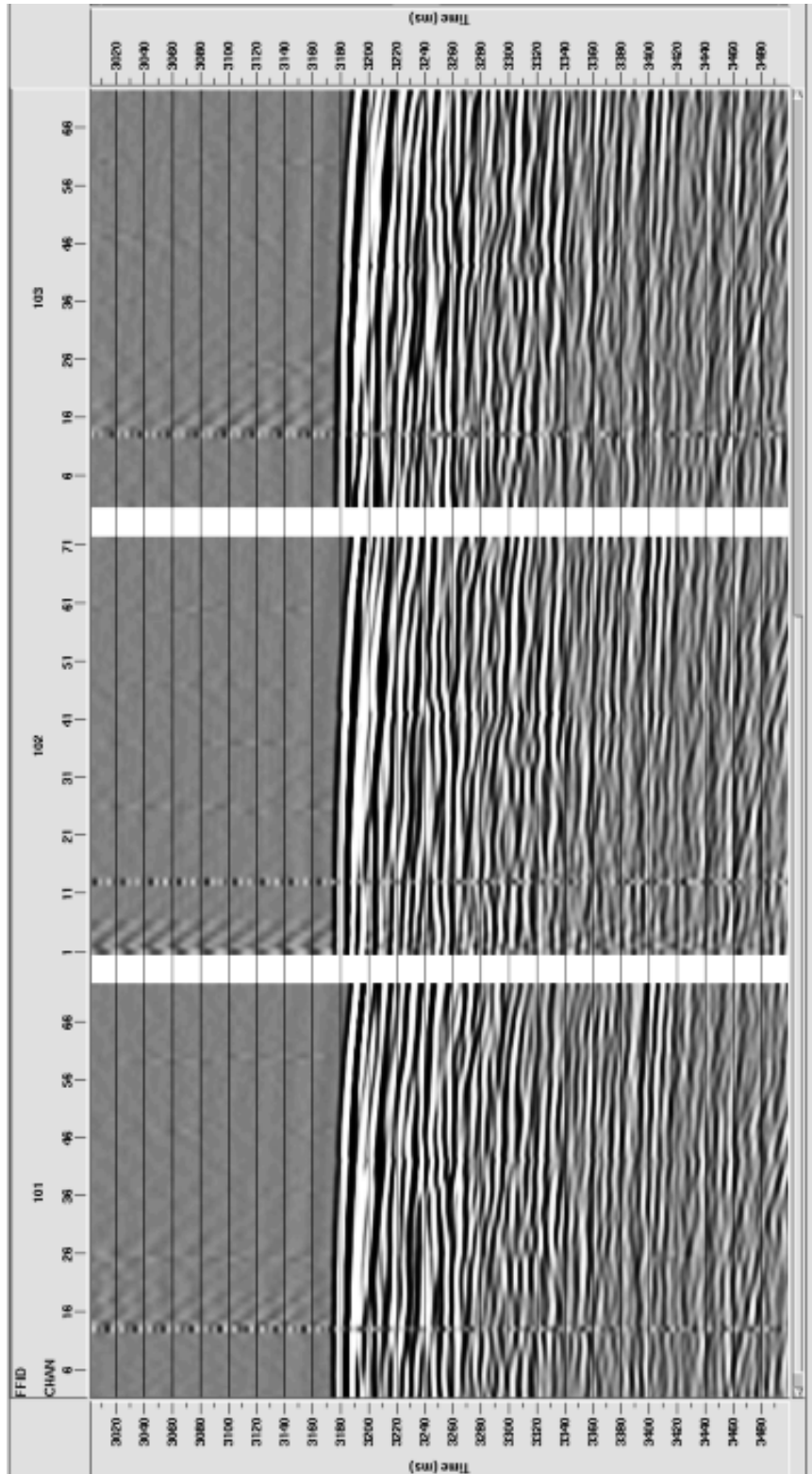


Figure 3.2. Showing before the Trace Kill command on Line 14.

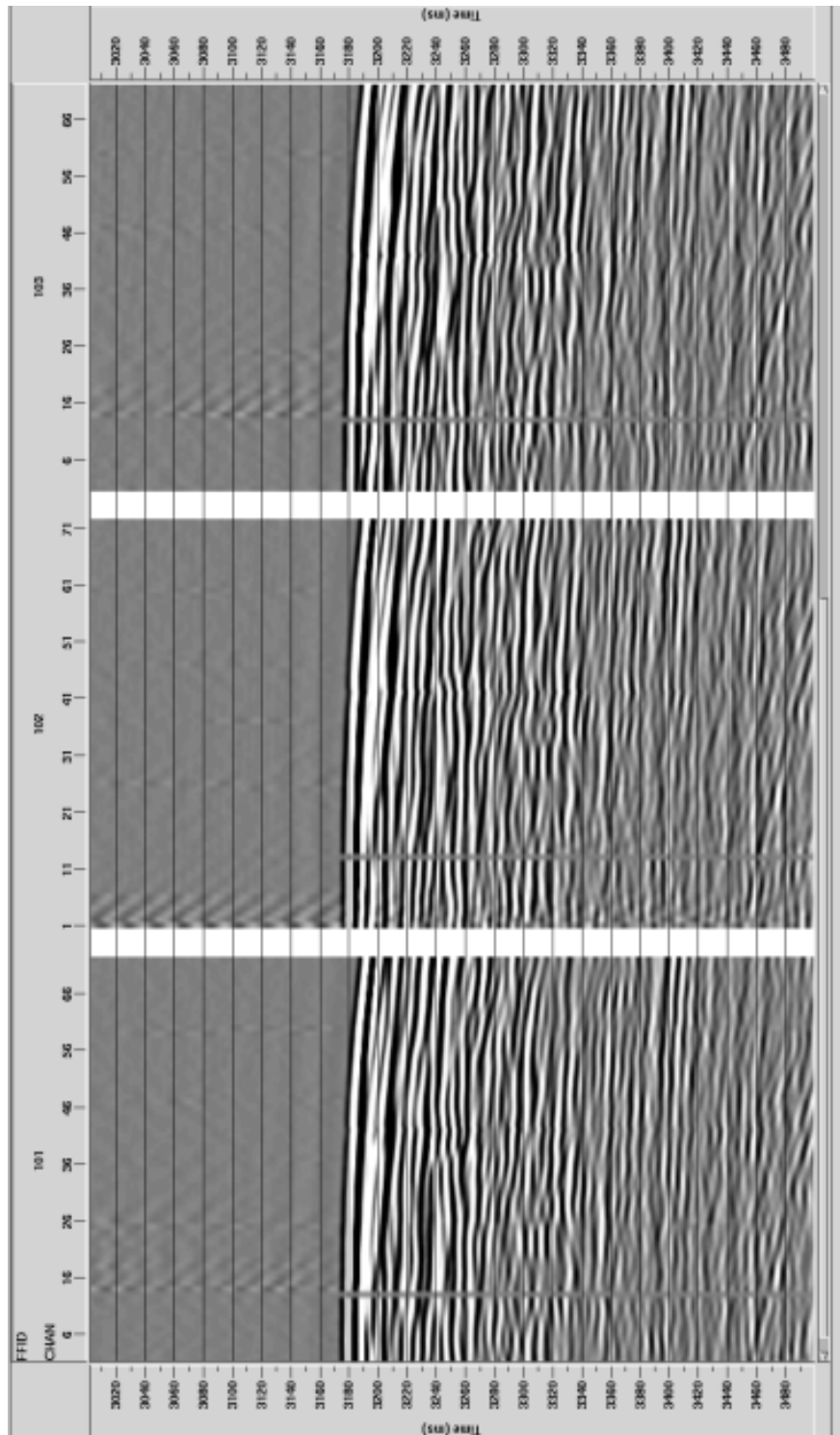


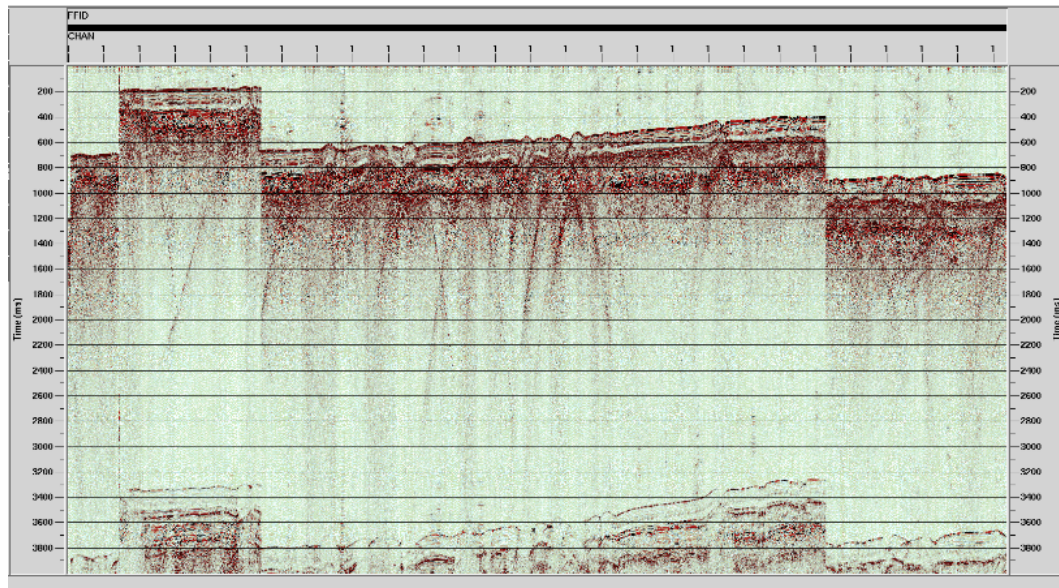
Figure 3.3. Showing on Line 14 with channel 13 effectively zeroed using the Trace Kill command.

Other required static corrections are more random and not documented in the recording logs. These corrections are needed due to jumps in the starting time of random shots caused by problems with the recording and shot pulse generator device. The amount required for these corrections 30ms and have to be determined and applied individually for each shot (Figs. 3.4a, 3.4b).

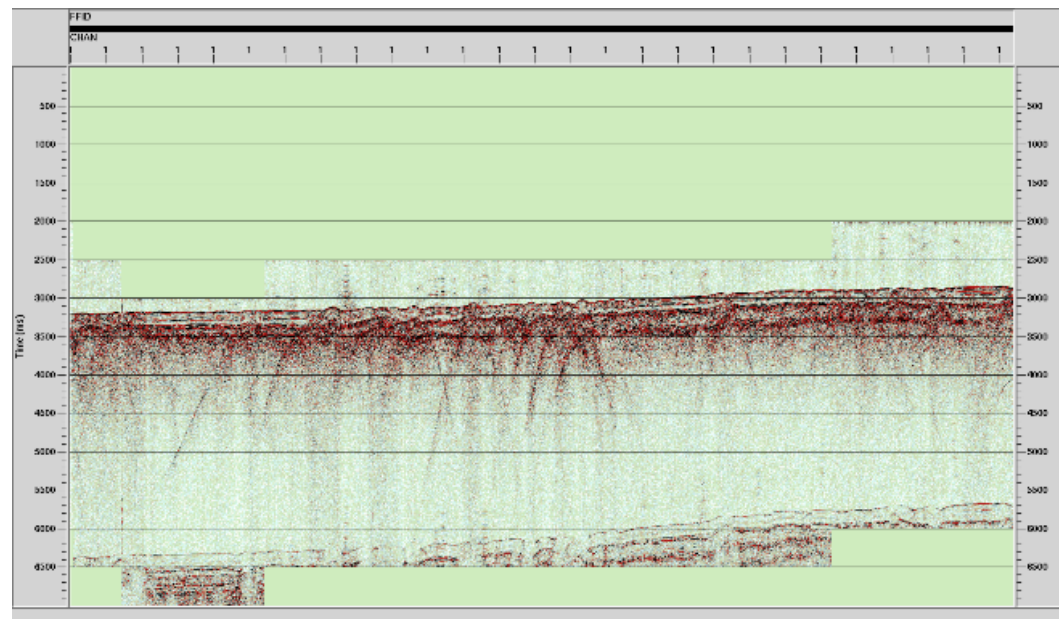
3.1.4 Amplitude Recover

During wave propagation from a point source, the amplitude of the wave decays in proportion to the radius of the wavefront, an attenuation mechanism known as spherical divergence. The velocity, which generally increases with depth, amplifies this effect. The pore fluids in the media, through which the waves are propagating, consume part of the wavefield energy, which also is recognized as amplitude losses in the deeper portions of the seismic section. Thus, the more porous the medium and the longer the raypath, the more the attenuation. It has to be noted that high frequency waves are absorbed more than the low frequency waves.

The penetration achieved on the Florence Rise seismic data has not been high enough to recognize a decay in the amplitudes below the seabed due to absorption or even spherical divergence (relatively common in deep water). A gain recovery technique, known as the Automatic Gain Control (AGC) with a sliding time window, was applied to the data for display purposes. The scale factor used in the gain function was calculated by picking the amplitude of the middle sample in each sliding window and taking the inverse of it. The width of the window was selected as 500 ms because a broad sampling interval has been sufficient to give the desired result - overall even signal level but retaining local high amplitudes of stronger reflections.



(a)



(b)

Figure 3.4. Showing the recording time delays: (a) before (b) after the correction on Line 14.

3.1.5 Field Geometry and CMP Sorting

Accurate introduction of the shooting geometry to the dataset is crucial in terms of reliable results in the subsequent processes, such as velocity analysis. The positions of the source and receivers were defined by carefully determining several parameters, including the minimum and maximum offset, the shot and receiver intervals, and the sailing azimuth. Missed shots or misfired shots were treated to match the data with the observer's log. After the geometry information was incorporated with the data, the originally acquired shot and receiver coordinates were transformed to midpoint and offset coordinates by assigning each trace to the midpoint between the associated shot and receiver locations, a process known as common-mid-point (CMP) sorting. Consequently, traces corresponding to the same midpoint were assembled to form a CMP gather, where the number of traces represent multiple coverage (i.e. the fold of the data). It is worth noting that a common-depth-point (CDP) is equal to a CMP in the case of a horizontal reflector. However, it is common to use the term CDP to refer to a CMP even in the presence of dipping reflectors, which is the case in the ProMAX processing software.

3.1.6 Band-Pass Filtering

Pre-stack band pass filtering was applied to all profiles to eliminate low and high frequency noise. The filter type and filter parameters were picked through analysis of the raw data and using amplitude and frequency spectra. The chosen filter was an Ormsby band-pass with a sufficiently great frequency bandwidth as to not limit the temporal resolution. The low cut filter parameters were set at 50 and 60 Hz with the high cut parameters set at 200 and 250 Hz: a minimum of two octaves is preserved (Fig. 3.5).

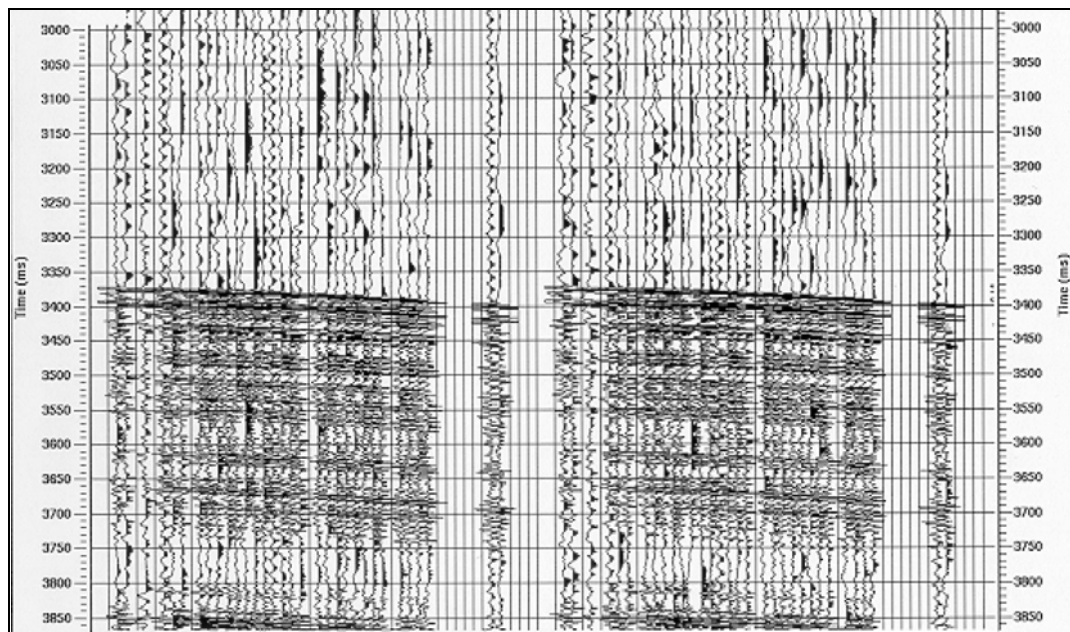


Figure 3.5a. Before the application of Ormsby Bandpass Filter.

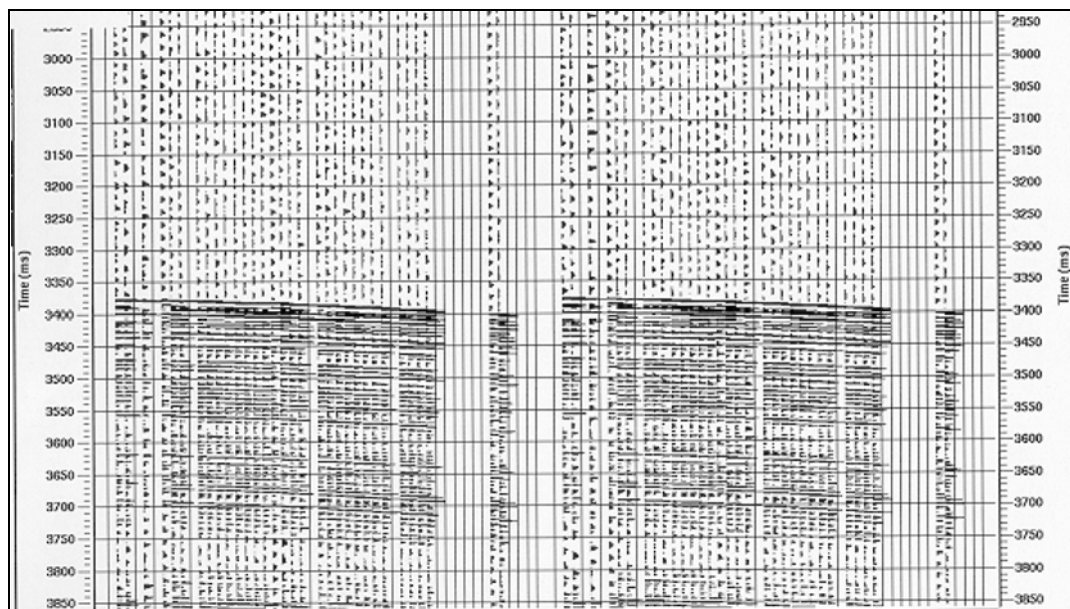


Figure 3.5b. After the application of Ormsby Bandpass Filter.

3.1.7 Velocity Analysis, Normal Moveout Correction

The quality of seismic imaging highly depends on the accuracy of the velocities used during processing. Velocity analysis is performed based on the variation of normal moveout (NMO) with travel time with the assumption of hyperbolic reflection t - x trajectories. It is usually applied to CDP gathers because of the reasonable hyperbolic alignment they display. The estimated velocities are then used to eliminate the time delay associated with the finite distance between the source and the receiver in the CDP gather, a process known as the NMO correction.

The velocities that can be derived from seismic data are the root-mean-square (rms) velocities, which are related to the interval velocities in the Dix equation (Dix, 1981). NMO velocity, stacking velocity and rms velocities are considered equal in the case of a short spread length relative to the reflector depth. Velocity generally tends to increase with depth due to increasing confining pressure and increasing sediment density associated with dewatering and lithification. In addition, sediment type and porosity also affect the velocity. The less porous the medium, the higher the velocity (i.e. the velocity is higher in limestone than shale).

In order to increase the signal-to-noise ratio a supergather with a set of adjacent CDPs that sample a full range of offsets is formed prior to the application of the velocity analysis. The range of velocities to be used in the analysis is limited by the minimum and maximum expected velocities. The maximum stacking velocity must be defined to include the high velocities associated with steeply dipping events and off-plane reflections. The distance interval for velocity analysis must be small enough to sample the lateral changes in the subsurface. Assignment of velocity functions to CDPs between the velocity pick locations are achieved by bilinear interpolation. The number of CDPs to in the gather, semblance, and velocity function stack panels, aims to maximize the signal-to-noise ratio and to provide a viable vertical and horizontal resolution of the semblance peaks.

The velocity spectrum is determined by the measurement of coherency among the traces in a NMO-corrected CDP gather, using a range of constant velocities. The semblance method of measuring the coherency is performed by using the cross-correlation of traces in a CDP gather.

The gather panel is achieved by forming a common-offset-stacked gather of a number of CDPs and observing the effect of NMO correction using a specified range of velocities. If the velocities used in the removal of normal moveout are greater (or smaller) than the primary stacking velocities then hyperbolae corresponding to events appear undercorrected (or overcorrected) (Figs. 3.6a, 3.6b)

Finally, the velocities, which are able to flatten the hyperbolae on the gather are picked as the stacking velocities. Note that multiple reflections are more distinguishable on the common offset gather compared to a stack. On the semblance panel, particularly at the portions where decay in the resolution occurs, this property of gather panel is very useful in separating the peaks associated with the primary reflections from that of the multiple reflections.

3.1.8 Stacking

Common midpoint stacking is based on summing the traces in a NMO-corrected CMP gather, in which each primary reflection should occur at the same time on each trace. The traces in a CMP gather corresponding to various offsets are summed at each time sample to give a single trace (equivalent to zero offset) on the stacked section

Stacking is one of the most efficient steps in data processing in terms of improving the data quality. It not only compresses the dataset but also attenuates both random and coherent noise. The primary reflections tend to have less NMO than the multiple reflections. For a primary and a multiple reflection which arrive

at the receiver at zero offset and the same time, the NMO of the primary reflection is less than the multiple because a greater portion of the travel path of a multiple reflection is confined to the shallow part of the subsurface. Hence, its propagation velocity is lower compared to the primary reflection, which penetrates into the deeper, higher velocity media. As a result of NMO correction using the velocities estimated via velocity analysis, the hyperbolae corresponding to the primary reflections are flat in time while the multiple reflections remain undercorrected. During CMP stacking, the aligned primary reflections will add up constructively, yielding high amplitudes, while the undercorrected multiple reflections will not show amplitudes that stand out on the stacked section. The random noise, because of its uncorrelable character from trace to trace, will also be attenuated by the stacking process (i.e., the signal-to-noise ratio being enhanced by $n^{1/2}$, where n is the stacking fold).

A near trace gather and a stack section of a range of shots are displayed in Figure 3.7. Note that, on the stack section reflectors stand out more distinctly and an improvement in the signal-to-noise ratio is recognized.

3.1.9 Migration

On a stacked seismic image, dipping reflectors appear at slightly incorrect locations with respect to the location of the sources and receivers, and diffraction hyperbolas occur where there are discontinuities along the reflectors. Migration is the processing technique used for moving these reflectors to their true subsurface locations and collapsing the diffraction hyperbolae. As a result migration produces a seismic record with a reasonable spatial resolution that accurately illustrates the geological setting of the subsurface (Figs. 3.8 and 3.9). A dipping reflector, when migrated, moves in the updip direction and appears steeper and shorter.

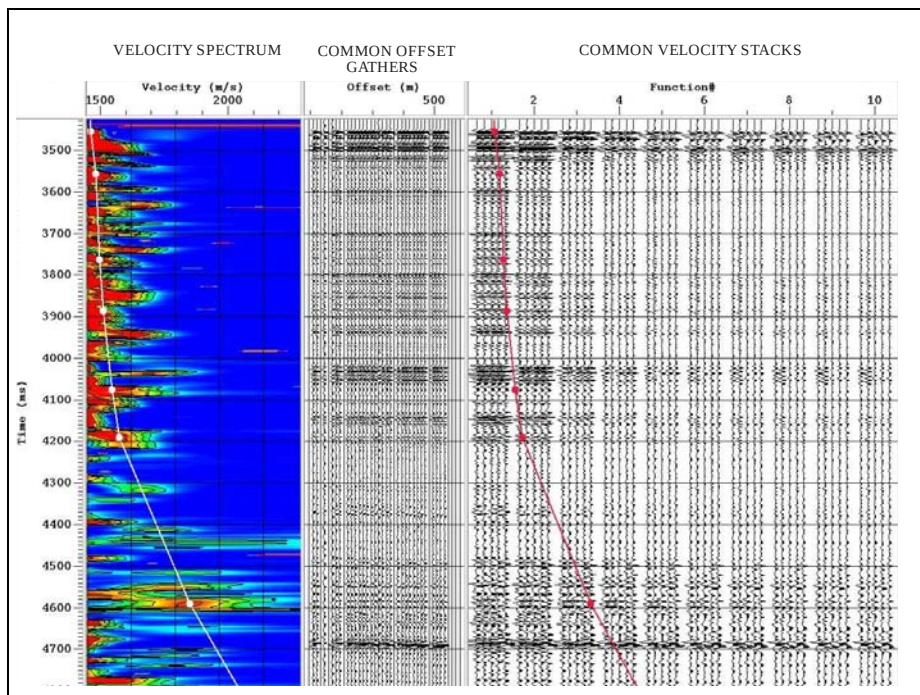


Figure 3.6a. Velocity analysis display showing the methods used to derive stacking velocities (e.g velocity spectrum, common offset gathers and common velocity stacked)

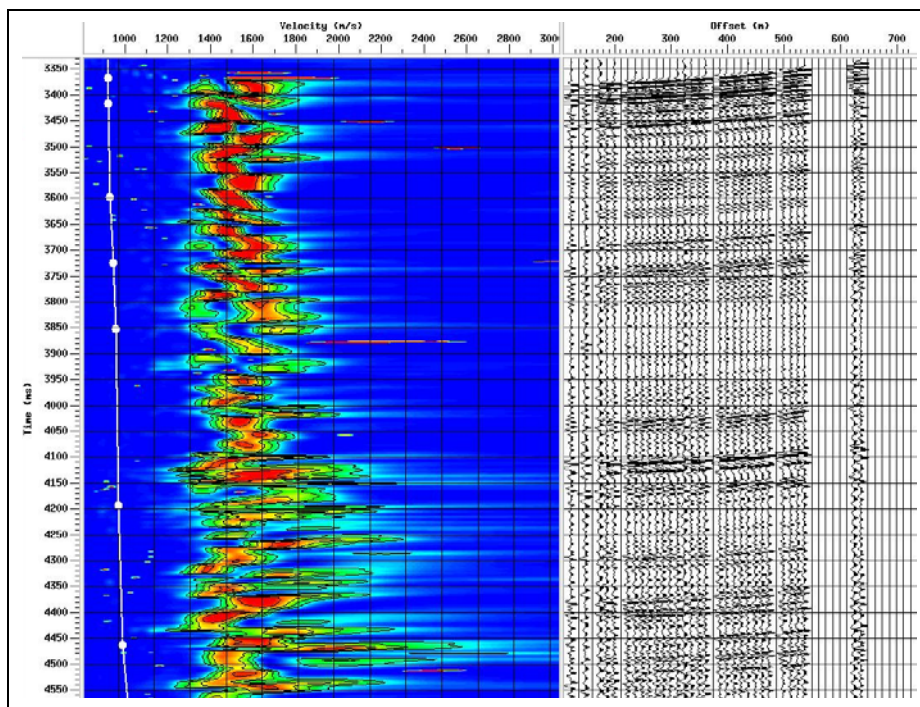


Figure 3.6b. White line corresponds to the velocities. Note that the events on the gather panel appear over corrected when velocities smaller than the primary stacking velocities are picked.

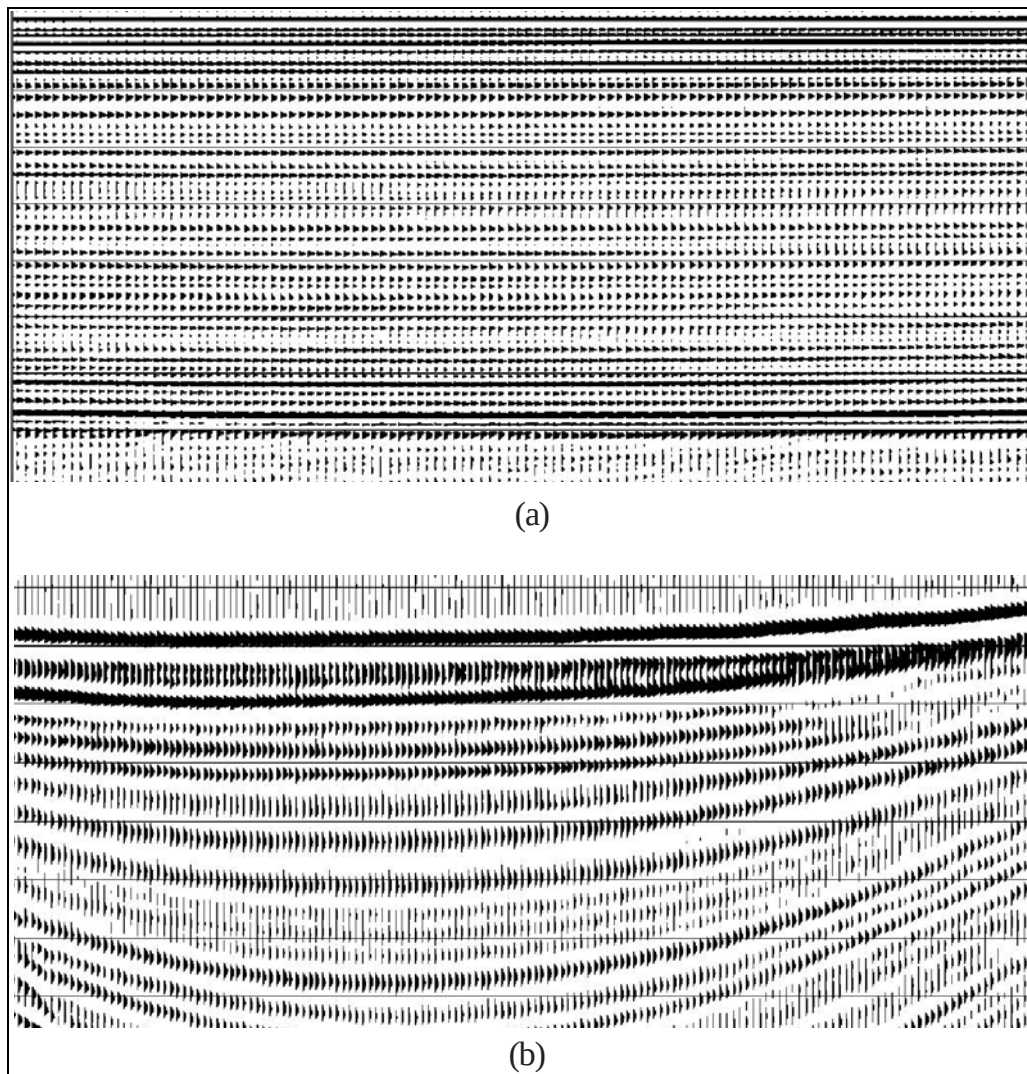


Figure 3.7. (a) near trace gather and (b) a stacked section.

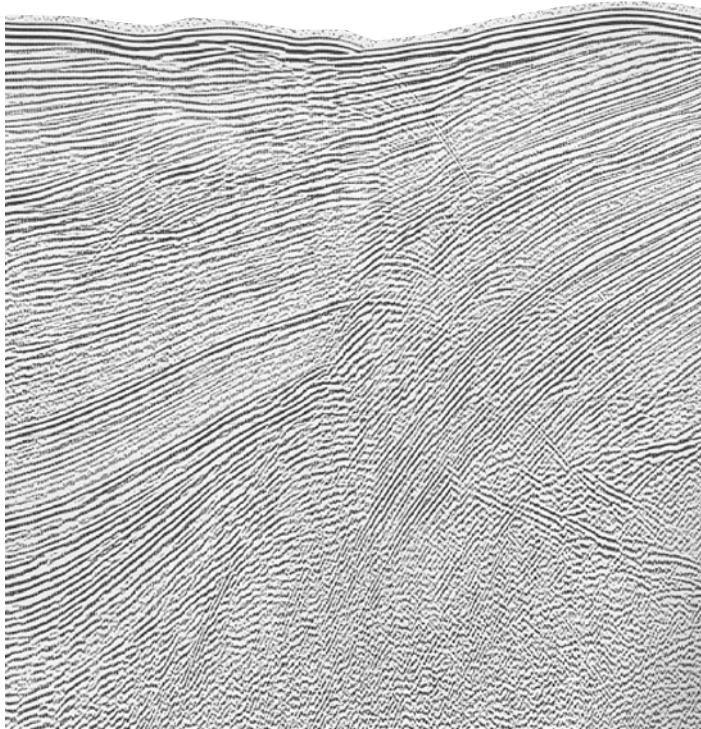


Figure 3.8 Stacked Seismic reflection profile.

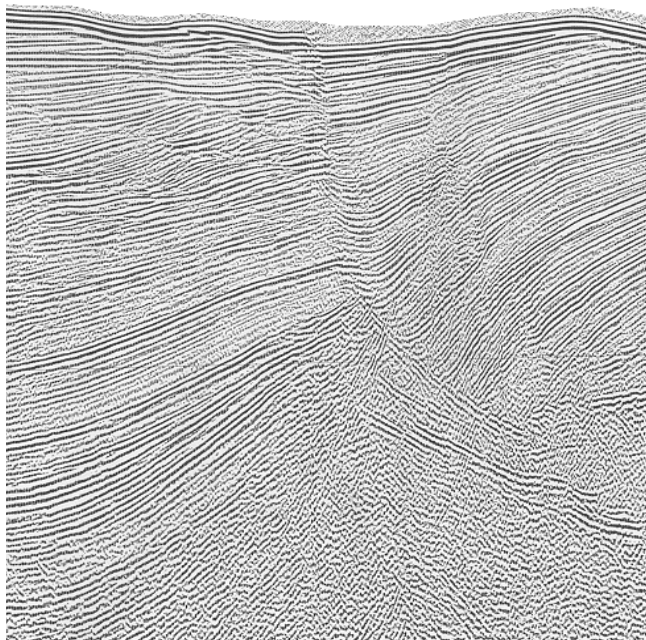


Figure 3.9. After application of Kichhoff Time Migration.

Synclines are represented by bowties on the stacked sections if their curvature is greater than that of incident wave fronts. Migration restores these bowties to synclines by moving the flanks in an updip direction (Figs. 3.10, 3.11). When migrated, anticlines become smaller while synclines broaden. The size of the migrated structures is constrained by the velocities used for migration (i.e. the higher the velocities, the more the migration, and hence, the more pronounced the updip displacement). In addition the lateral and vertical displacements of reflectors that occur during migration have to be taken into consideration when determining the profile length and recording time. If either of them is too short, then, the true or pseudo locations of the reflectors may not be represented on the seismic section due to limited imaging space.

The Kirchhoff migration algorithm applies amplitude and phase corrections, compensating for several attenuation mechanisms including the spherical divergence, to enable equal contribution to summation along the hyperbolic trajectory from events appearing at various travel times. The technique has the advantage of: (1) migrating events with steep dips up to 90° , (2) handling moderate lateral velocity variations, (3) remaining efficient when velocity varies vertically.

During the migration of the Florence Rise profiles, the Kirchhoff time migration was performed. When the stacking (or rms) velocities obtained through velocity analysis were used in migration, they resulted in overmigrated hyperbolas particularly at deeper portion of the section. The appropriate migration velocities, which were successful in collapsing the hyperbolas, were determined by performing a number of tests. It was not possible to suggest a regular percentage to be subtracted from the stacking velocities to achieve the required migration velocities. Instead, migration velocities were assigned based on their ability to attenuate the diffraction hyperbolas, at each sample point on the selected CDPs.

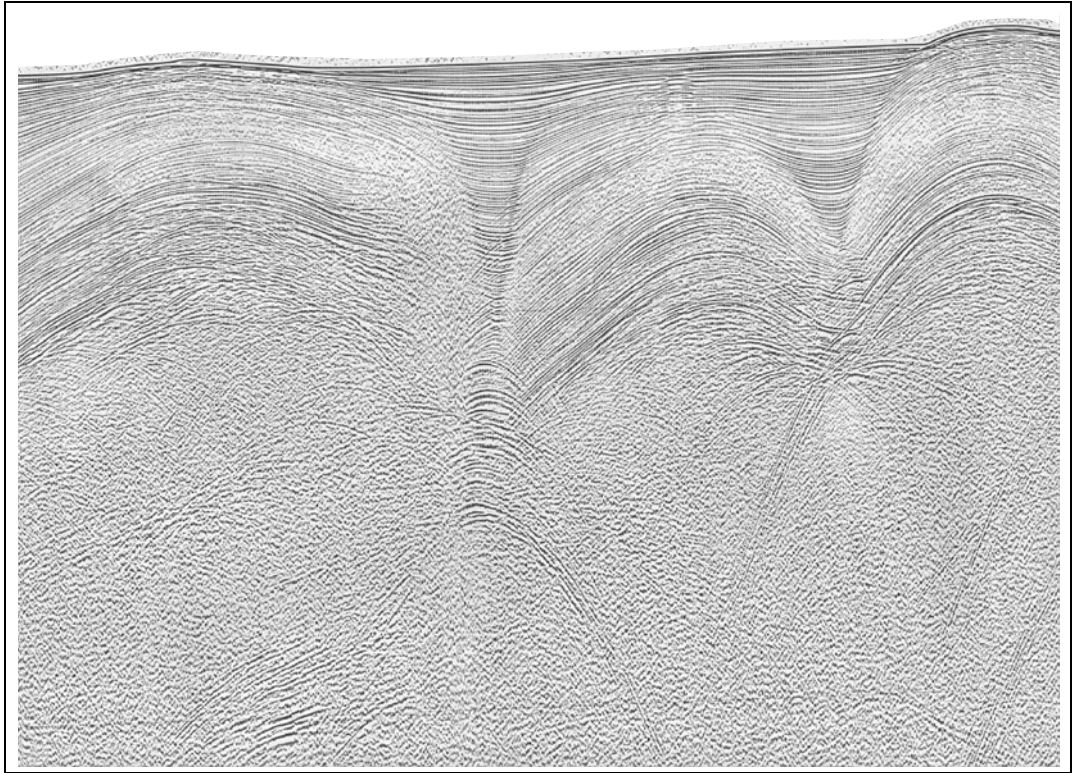


Figure 3.10 Stacked reflection profile.

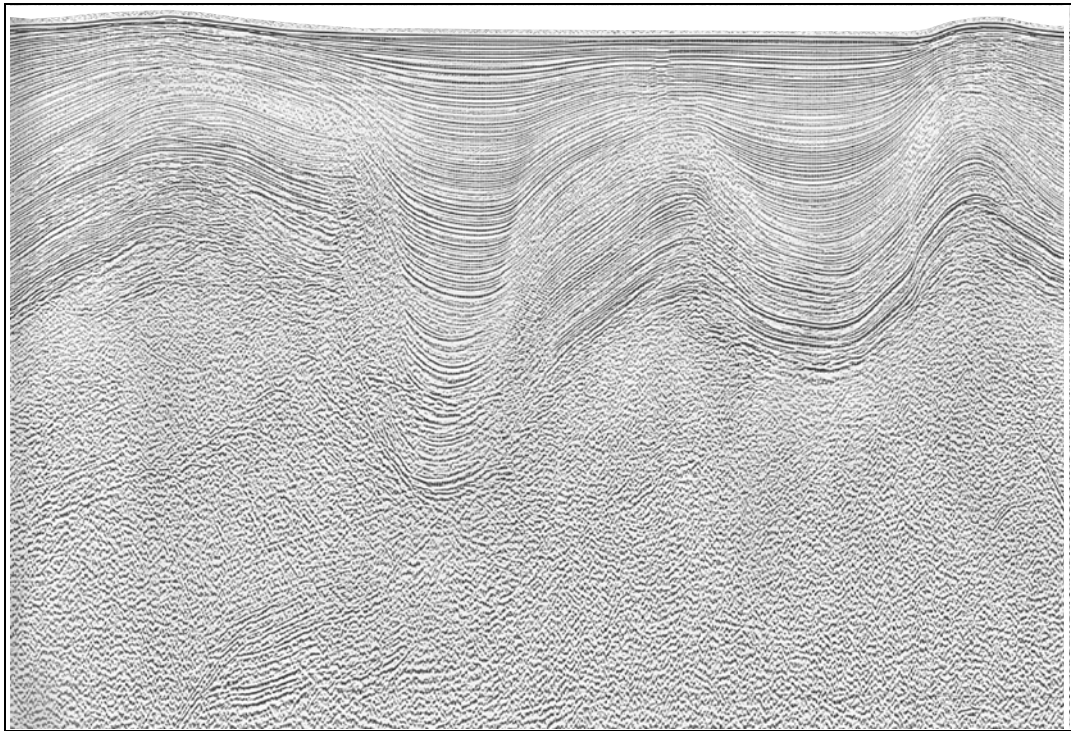
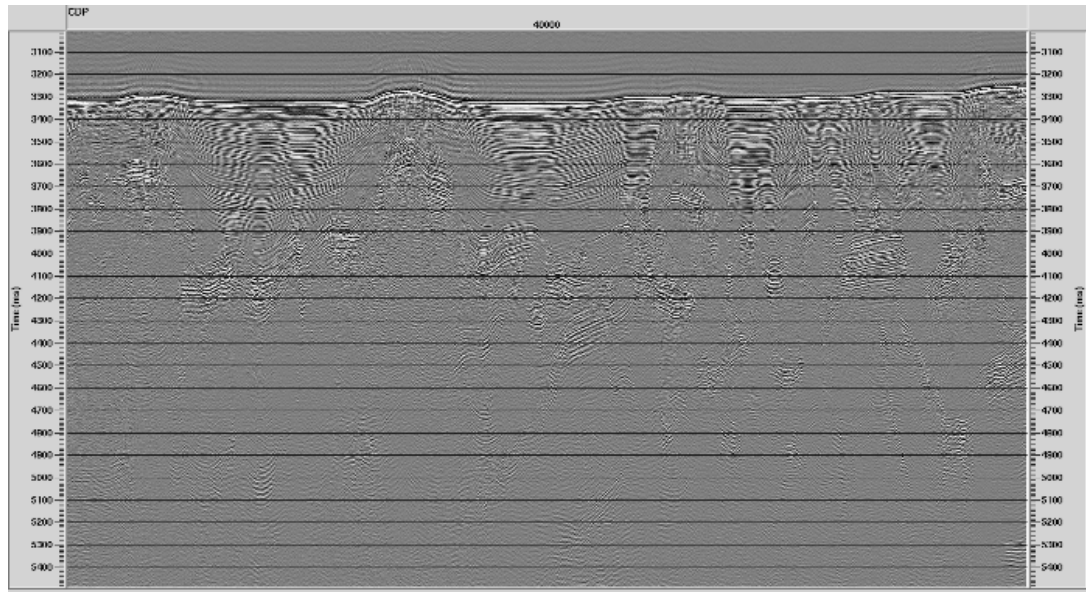
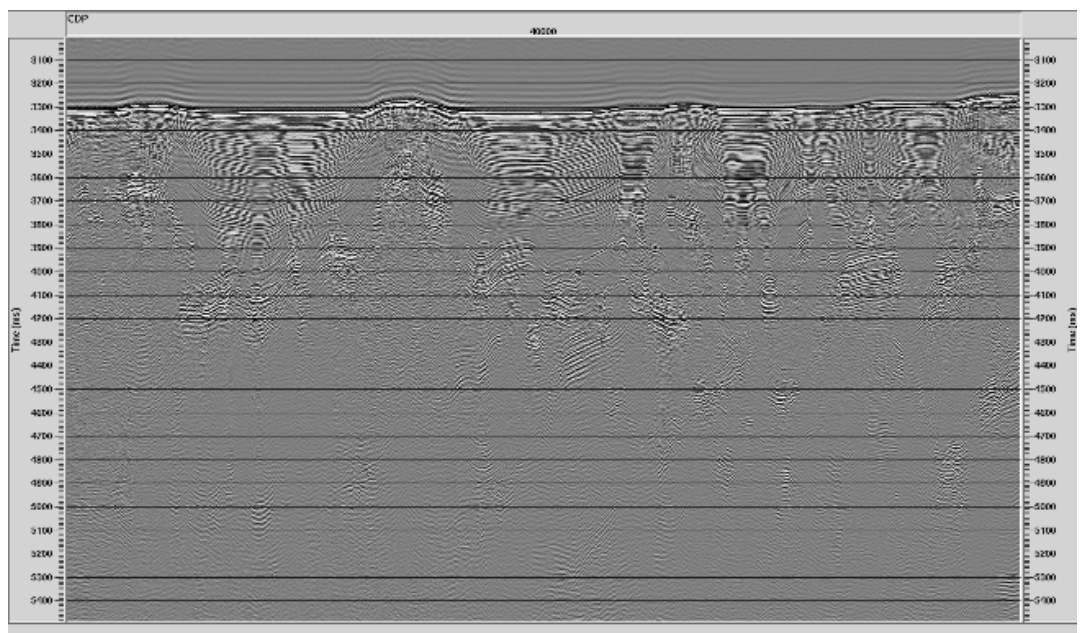


Figure 3.11 Seismic reflection profile shown in Figure 3.10 after the application of Kirchhoff Time Migration. Bowties are restored to synclines. Also note that the anticlines appear smaller While the synclines are broader.



(a)



(b)

Figure 3.12 (a) Showing before the application of Trace Mixing and (b) after the application of Trace Mixing.

3.1.10 Trace Mixing and Decimation for Plotting

Trace Mixing involves averaging adjacent traces and is done for two reasons in this data-set. The first reason is to make the reflections appear more continuous by enhancing low dip events. The second reason is plotting purposes. For the lines processed for this thesis, trace mixing is done with three adjacent CDPs. It is then possible to plot only every second trace after trace mixing (Fig.3.12a and 3.12b).

3.2 Summary of Data Processing

The processing flows for each of the lines processed for this thesis were similar, with minimal changes based on the amount of noise in the sections, the degree of spatial aliasing, and the number of static corrections required. There were also small variances in the filter parameters, and stacking and migration velocities. Overall, the processing resulted in quality seismic images despite the modest source volume and CDP stacking fold. Reflections are generally imaged 3-4 seconds two-way time below seabed, even when water depth is more than 1 km.

CHAPTER FOUR

STRATIGRAPHY

4.1 General Lithostratigraphy and Chronology of DSDP 375 and 376

Two deep boreholes were drilled on the Florence Rise by the Deep Sea Drilling Project (Sites 375 and 376; Fig. 4.1). The sediments encountered in these boreholes (Shipboard Scientific Party, 1978) are described here in detail to form the basis for correlations between the lithostratigraphic units and the seismic reflection profiles used in this study. Site 375 had a total drill depth of 821.5 m with spot coring. A predominantly pre-evaporite succession was recovered at this site. Site 376 was offset ~13 km to the north and was cored continuously into the Messinian evaporate succession. Eleven lithologic units have been distinguished: four units in the Pliocene-Quaternary pelagic succession, two in the late Miocene evaporite and post evaporite successions, a flysch-type unit in the Tortonian, and four units in the pre-Tortonian to Early-Middle Miocene sediments (Shipboard Scientific Party, 1978; Table 4.1). These units are described below.

4.1.1 Unit I: *nannofossil marl with interlayered sapropel and tephra*

Unit I is of Quaternary age and consists of soft nannofossil marls with minor, thin interbeds of sapropelic marl and volcanic ash (Table 4.1). Nannofossil marls consist chiefly of clay minerals and nannofossils. Unit I is a hemipelagic sequence, which was deposited in an environment which fluctuated between a stagnant and highly reducing environment (sapropel layers), and a slightly oxidized environment (light brown layers). The absence of burrowing and the predominant drab grey color of the marlstones suggest that slightly reducing conditions prevailed during the deposition of this unit.

Table 4.1 Summary chronology of the DSDP Leg 42, Sites 375 and 376 (data from Shipboard Scientific Party, 1978). Lithostratigraphic units at these sites are described in text.

Unit	Lithology	Cores		Subbottom depth (m)		Thickness (m)		Age
		Site 375	Site 376	375	376	375	376	
I	Grey to brown nannofossil marls with interlayered tephra and sapropels	-	1 to 5.1; 5-2-0-75 cm; 6-1 to 6-3-86 cm.	-	0-38.4		38,4	Quaternary
II	Grey nannofossil marls with a few sapropelic marl interlayers	-	5-2-75-150 cm; 5-3 to 5-5-43 cm	-	38.4-42.6		4,2	Late Pliocene
III	Brown to orange nannofossil marl with minor sapropelic marl interlayers	1-1-48-58 cm	5-5-43-150; 6-3-86-150 cm; 6-4-0-100 cm; 7-1-2832 cm.		42.6-48.1		5,5	Early to late Pliocene
IV	Slumped marls of Miocene and early Pliocene age		6-4-100-141 cm.	-	48.1-48.5	137,5	0,4	Early Pliocene
V	Marlstones with interbedded graded sandstones and siltstones subdivided into 4 subunits	1-1-58-60 cm	7-1-32-150 cm;		55-140.5		92,0	Late Miocene, Messinian
VI	Evaporites a - Gypsum and green dolomitic marlstone	1-1-60 cm	16 through 20	137.5-185 Corrected	140.5-188	47,5	47,5	Late Miocene, Messinian
	b - Anyhdrite and halite	through 4-1	21 through 23		188-216.5 (T. D.)		28,5	
VII	Marlstones with interbedded graded sandstones and siltstones	4 through 7		185-600		415,0		Late Miocene, Tortonian
VIII	Variagated marlstones to foram nanno limestones	8		600-641		41,0		Middle Miocene, Serravallian
IX	Dark coloured nannofossil marlstones	9		641-675		34,0		Middle Miocene, Serravallian
X	Reddish-brown nannofossil marlstones with interbedded light grey foraminiferal limestones	10		675-760		85,0		Middle Miocene, Langhian
XI	Dark green-grey limestones and marlstones	11		760-821 (T. D.)		61,5		Early Miocene, Burdigalian

4.1.2 Unit II: *gray nannofossil marls*

Unit II consists of nannofossil and foram-nannofossil marls with generally dull colors and a soft, but firm texture (Table 4.1). It is Late Pliocene in age. The upper part of the unit contains scattered small pyrite nodules. Burrows appear to be absent, except for slight burrowing at the base of the unit. The depositional setting of Unit II appears to have been similar to that for Unit I: generally reducing bottom conditions with periodic and short lived intervals of strong stagnation and a few episodes when the bottom waters were oxidized.

4.1.3 Unit III: *Brown to Orange Nannofossil Marls*

Unit III is characterized of nannofossil marls with bright colours (such as light brown, pale yellowish-brown, yellowish-gray, moderate brown and very pale orange) indicative of oxidizing conditions (Table 4.1). It is Early to Late Pliocene in age. The unit is well bedded and contains numerous thin layers which are moderately burrowed and apparently enriched in iron oxides, giving them a darker brown color than the surrounding sediment.

4.1.4 Unit IV: *slumped marls*

Unit IV consists of light to medium gray marls of Early Pliocene to Late Miocene in age (Table 4.1). It comprises of two chaotically deformed subunits: (i) a subunit consisting of medium gray nannofossil marls mixed with a light brown marls, with a sharp and undeformed upper contact with Unit III and (ii) a subunit consisting of light brown to pale yellowish-brown nannofossil marls. Lithologically this marl is identical to the brownish, oxidized marls of Unit III above. Unit IV is interpreted as a slump succession.

4.1.5 Unit V: nannofossil dolomitic marlstone with interbedded graded sandstones and siltstones

Unit V contains dolomitic marlstones and the turbiditic sandstones and siltstones (Table 4.1). Unit V is composed of four subunits which invariably contain the *Cyprideis pannonica* fauna, thus is interpreted as late Miocene-Messinian in age (Shipboard Scientific Party, 1978). Subunits Va, Vb Vc and Vd are all predominantly hemipelagic successions with relatively sparse turbidites.

Subunit Va

The main lithology in this subunit is a slightly silty nannofossil dolomitic marlstone, with minor amounts of interbedded siltstones and sandstones, including sapropelic layers.

Subunit Vb

This subunit consists of interbedded silty nannofossil dolomitic marlstones, siltstones and sandstones. It differs from Subunit Va in having a higher percentage of interbedded clastics and in containing no sapropelic layers.

Subunit Vc

This Subunit contains thinly bedded inter-layered laminated siltstones and marlstones of probably turbiditic origin.

Subunit Vd

This subunit is characterized by abundant dentrital gypsum, and distinctly greenish sandstones and siltstones.

4.1.6 Unit VI: Mediterranean evaporate

Unit VI contains gypsum, green dolomitic marlstone, anhydrite and halite which are identified as Messinian in age (Table 4.1). It is composed of two subunits.

Subunit VIa: gypsum and green dolomitic marlstones

This subunit underlies Unit V and contains olive grey to light grey gypsum. The unit includes crudely layered and recrystallized gypsum, coarse selenitic gypsum crystals, coarsely crystalline recrystallized gypsum with roughly equant and traced anhydrite and elongate selenitic “swallow-tail” gypsum crystals, set in a matrix of gypsiferous greenish-white marlstone.

Subunit VIb: anhydrite and halite

This subunit contains from top to base: (i) numerous small pieces of clear, coarsely crystalline halite with thin wavy interlayers of finely crystalline gypsum; (ii) larger fragments of white nodular anhydrite with large and small enter-oolitic folds and occasional chicken-wire structure with considerable amounts of gypsum; (iii) a fragment of banded anhydrite, in which thin dark brown, organic-rich laminae separate up to 1 cm thick bands of nodular anhydrite with occasional chicken-wire structure and (iv) banded halite with 2 to 4 cm thick layers of clear coarsely crystalline halite separated by 0.5 cm thick, brown, fine-grained gypsum layers containing rare anhydrite.

4.1.7 Unit VII: marlstones with interbedded graded siltstones and sandstones

This unit consists of a predominantly dark colored, partly dolomitic marlstone sequence (Table 4.1). It is upper Miocene (Tortonian) in age. Typically, the sequence shows a distinct cyclicity, with each cycle consisting of three subunits. Subunit A is a fine-grained terrigenous arenite and siltite with a sharp lower boundary. It grades upwards into a subunit B, which is composed of structureless, occasionally finely-laminated, dolomitic nannofossil marlstone with rare sand and volcanic glass. Subunit B is in turn, overlain by subunit C, which consists of

marlstones with sparse burrowing. The Marlstones of Member C are of essentially the same composition, their main difference from member B being the occurrence of layers rich in planktonic foraminifera.

4.1.8 Unit VIII: variegated nannofossil marlstones to foram-nanno limestones

Unit VIII consists of variegated mudstones, nannofossil marlstones and foram-nanno limestones, which exhibit a cyclic centimeter- to decimeter-scale alternations of dark mudstones and marlstones and light-colored foram-nanno limestones (Table 4.1). The dark layers are characterized by a sharp lower boundary. They gradually pass upwards into the light colored more calcareous and foraminifer-rich marlstone and limestones. The unit is Serravallian in age. Unit VIII represents an episode of slower deposition of distal turbidites and hemipelagic marls in a slightly more oxidizing environment between the dark marlstones of Unit IX (see below) and the dark greenish turbiditic facies of Unit VIII.

4.1.9 Unit IX: Dark Colored Nannofossil Marlstones

The Unit consists of dark colored mudstones and nannofossil marlstones interlayered with lighter colored, more calcareous nannofossil marlstones (Table 4.1). The age of the Unit IX recovered is Serravallian. The main difference between Unit IX and the underlying Unit X and overlying Unit VIII is mainly the change of colors, which range from medium dark gray to grayish-brown. The sequence shows a cyclic development, similar to the ones in Unit VIII and X, with darker-coloured argillaceous lithologies grading into lighter-coloured calcareous lithologies. The darker units show sharp lower boundaries and faint parallel lamination and occasionally graded and cross laminated layers of fine sand and silt are present at the base. The light colored lithologies contain only traces of terrigenous silt.

4.1.10 Unit X: reddish-brown and greenish-gray nannofossil marlstones with interbedded light gray foraminiferal limestones

Unit X is composed of reddish-brown dolomite-bearing nannofossil marlstones with interbedded grayish-blue green to greenish-gray nannofossil marlstones and hard, well cemented, very light coloured gray to bluish-white foraminiferal limestones (Table 4.1). The age of Unit X is Langhian.

In Unit X various kinds of cycles can be observed. Cycles similar to the ones described in Units VIII and XI consist of grayish-blue-green to greenish-gray and dark greenish-gray marlstone with sharp lower boundaries. Another type of cycle is composed of very light gray and bluish-white to pale blue, hard cemented foraminiferal limestones with sharp lower boundaries which grade into gray or red marlstones.

4.1.11. Unit XI: dark green-gray limestones and marlstones

Unit XI is composed of hard grayish-olive limestones and green marlstones (Table 4.1). It is Langhian in age. Recovery of samples from this unit is very poor. The limestones include planktonic foraminifera filled with a ferroan calcite cement and greenish-gray foraminifera-rich nannofossil-limestone, which are interbedded with greenish-black marlstones.

4.2 Correlation of Seismic Reflection Profiles With DSDP Site 375 and 376

DSDP Sites 375 and 376 are located on the Florence Rise (Shipboard Scientific Party, 1978; Fig. 4.1, Table 4.1), a marked feature in the bathymetry (Fig. 1.3) which runs from Cyprus to the Anaximander Mountains and separates the Antalya Basin from the Levantine Basin. Previous studies showed that the Florence Rise corresponds to a late Tertiary uplift bounded to the south by numerous reversed faults (Zitter et al., 2005). Seismic reflection profile EMED07-02 (Fig. 4.1) runs across the Florence Rise, close to the DSDP Sites 375 and 376. Both sites can be projected to seismic profile EMED07-02 which shows that the thick Messinian

salt layer pinches out toward both the northern and southern sectors of the structure, bringing the pre-evaporitic layers close to the sea floor, below a relatively thin cover of Pliocene-Quaternary sediment (Fig. 4.1).

In order to correlate the sedimentary successions drilled in the DSDP wells and the seismic reflection profiles the thicknesses encountered in the wells had to be converted to depth in milliseconds. The following interval velocities of $1700\text{--}1800\text{ ms}^{-1}$, $3500\text{--}5000\text{ ms}^{-1}$ and $2500\text{--}3000\text{ ms}^{-1}$ are used to convert the thicknesses of the Pliocene-Quaternary, Messinian evaporate succession and the pre-Messinian upper Miocene successions, respectively.

Drilling at Sites 375 and 376 showed that the Pliocene-Quaternary succession is approximately 137.5 meters thick (Shipboard Scientific Party, 1978; Table 4.1). Calculations using the above interval velocities suggest that the thickness of the Pliocene-Quaternary succession in line EMED07-02 is approximately 160 m. At the DSDP site 375 and 376 the Messinian evaporites are ~48 m and 68 m thick, respectively. Similar calculations suggest that there must be ~19-39 ms thick Messinian strata imaged in seismic profile EMED07-02. Underlying the Messinian evaporites an ~485 m succession of Tortonian and Serravalian marls and turbidites were drilled at Site 375 (Shipboard Scientific Party, 1978; Table 4.1). Calculations using the above interval velocities suggest that there must be an approximately 415 m-thick pre-Messinian strata must be present in seismic profile EMED07-02.

4.3 Seismic stratigraphy of the Florence Rise

Three seismic stratigraphic units are identified in the study area: these are labeled as Units 1-3 (Figs. 4.2, 4.3). A seismic reflection profile (i.e., Fig. 1.3) runs across the DSDP Sites 375 and 376, allowing direct correlations to be made with sediments drilled over the Florence Rise (Shipboard Scientific Party, 1978; Figs. 4.2, 4.4, 4.6). The ages of these seismic units are established through correlations with the lithological units described in section 4.1 (Table 4.1).

4.3.1 Unit 1: *Pliocene-Quaternary*

Unit 1 is characterized by a regularly reflective sediment package that consists of acoustically strong reflectors. These reflectors show excellent lateral continuity throughout the study area (Figs. 4.2, 4.3). The base of this unit is marked by a major angular unconformity. On the basis of its acoustic character and stratigraphic position at the base of the upper unit, this unconformity is correlated with the M-reflector, which is representing the ultimate desiccation of the Mediterranean basin during the Messinian (Ryan et al., 1966; Hsü et al., 1978). On the basis of its internal seismic character and stratigraphic architecture Unit 1 is divided into three subunits (Subunits 1a-1c; Figs. 4.2, 4.3). The upper Subunit 1a is characterized by parallel and continuous reflectors giving it a highly stratified appearance in seismic section (Figs. 4.2, 4.3). It is also mapped as a prominent subunit in the Cyprus Basin (Hall et al., 2005) and the Antalya Basin (Işler et al., 2005). A prominent transparent zone with occasional weak and discontinuous parallel reflections occurs near the base of subunit 1a. In many places, the base of Subunit 1a is a mild but conspicuous erosional unconformity (Fig. 4.6).

Table 4.2 summarized the inferred ages of the Pliocene-Quaternary Subunits in the study area. These ages are derived from the seismic reflection profiles using the assumption that (i) in the deepest portion of the basins, the Pliocene-Quaternary succession includes no discernible hiatus, (ii) the base of the Pliocene-

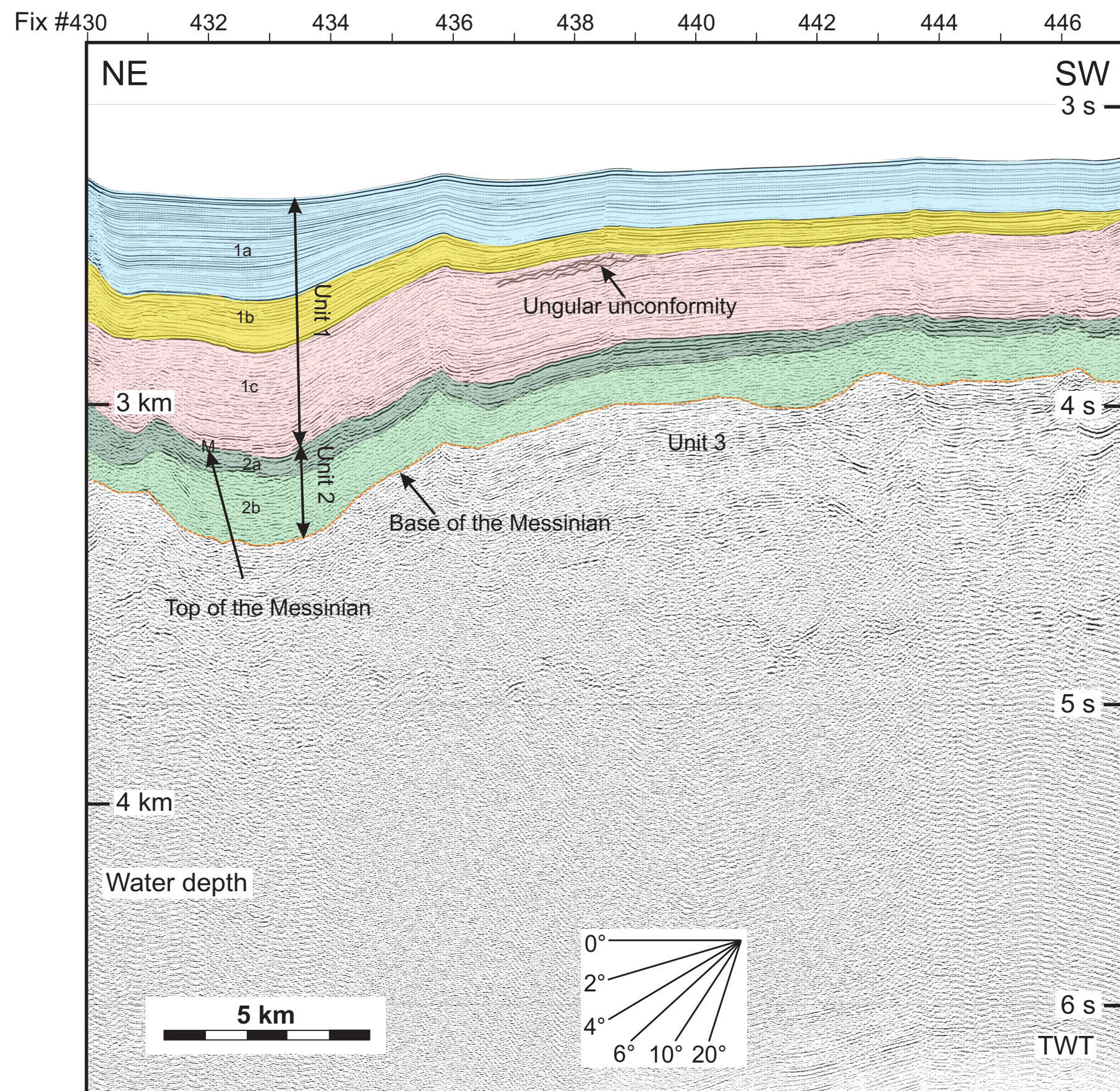
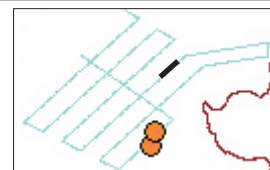


Figure 4.2 Seismic reflection profile (FIX 430-447).



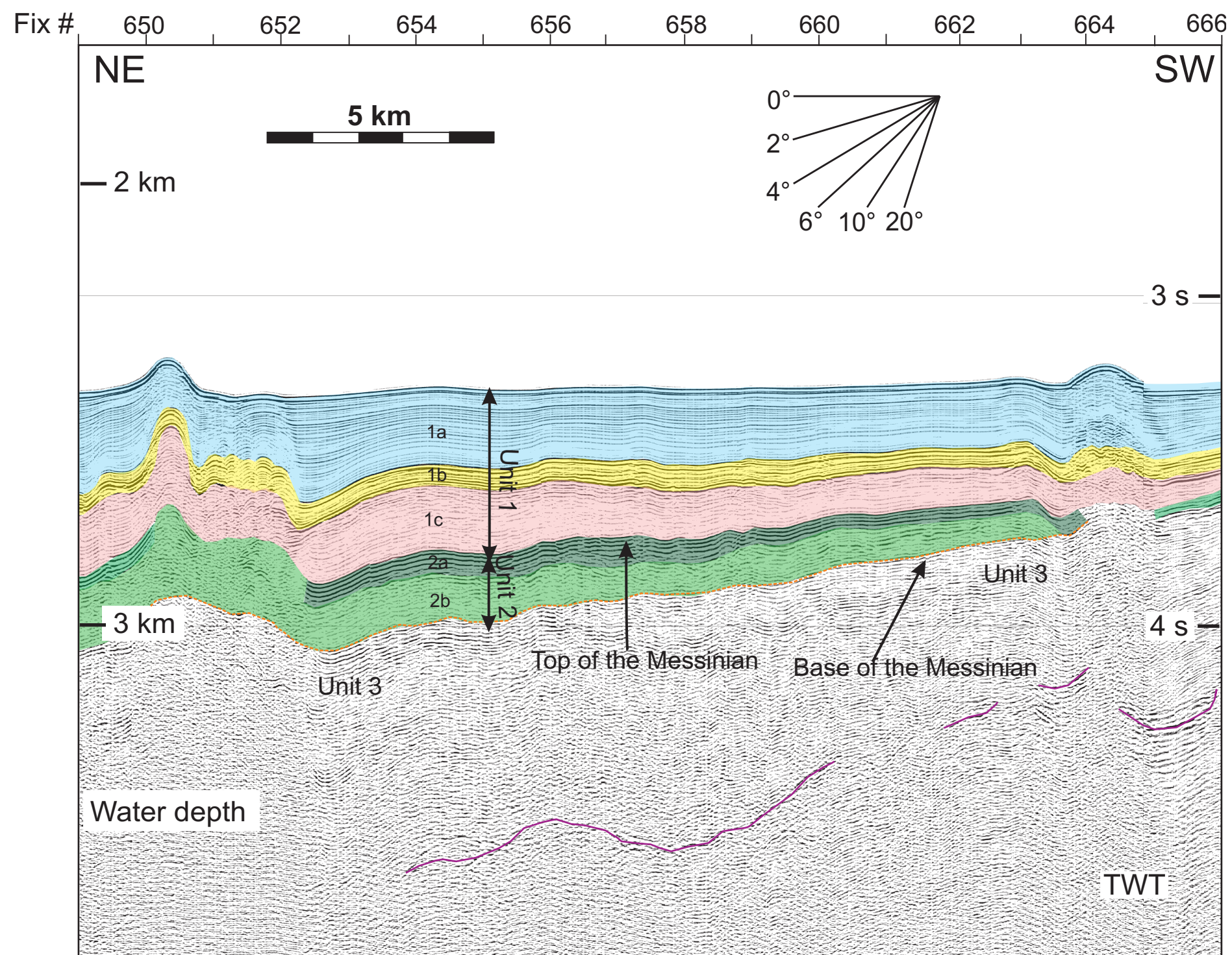
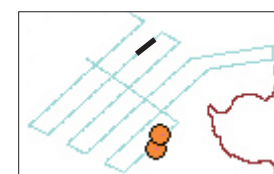


Figure 4.3 Seismic reflection profile (FIX 649-666).



Quaternary Subunit 1c is delineated by the M-reflector, and that this reflector represents the uppermost Miocene at ~5 Ma, (iii) the top of Subunit 1a at the seafloor represents the contemporary deposition at 0 Ma, and (iv) the sedimentation rate during the Pliocene-Quaternary was nearly constant. Provided that these assumptions are correct, a back-of-the-envelope calculation can be made by linear interpolation along lines drawn orthogonal to the reflectors in selected seismic profiles from deep basins that contain a complete Pliocene-Quaternary succession (e.g., Fig. 4.8). The results of this exercise show that Subunits 1a, 1b and 1c represent deposition from approximately 0-2 Ma, 2-3 Ma and 3-5 Ma, respectively (Table 4.2).

Subunit 1a is correlated with the Quaternary to Late Pliocene Units I and II of the DSDP Sites 375 and 376 (Fig. 4.5; Shipboard Scientific Party, 1978). Subunit 1a is further tentatively correlated with the shallow marine and terrestrial units of the Mesaoria Basin on Cyprus, namely the Apolos and Karraristra formations (Fig. 4.5; Cleintuar et al., 1977; McCallum and Robertson, 1990; Robertson, 1998; Hall et al., 2005; Calon et al., 2005), as well as the Pleistocene Antalya Tufa and Belkiş conglomerate of the onland Aksu, Köprü, Manavgat and Darıören Basins of the Antalya region of southwestern Turkey (Fig.4.5; Akay and Uysal, 1985; Akay et al., 1985; Karabıyıkoglu et al., 2000).

Subunit 1b has a generally stratified acoustic character, and shows a series of continuous parallel reflections with good lateral continuity (Figs. 4.2, 4.3). It is correlated with the Early-Late Pliocene Unit III of the DSDP Sites 375 and 376 (Fig. 4.5; Shipboard Scientific Party, 1978). Subunit 1a is tentatively correlated with the middle-upper Pliocene marls of the Athalassa Formation of the Mesaoria Basin on the Island of Cyprus (Fig. 4.5; Cleintuar et al., 1977; McCallum and Robertson, 1990; Robertson, 1998; Calon et al., 2005; Hall et al., 2005). The subunit can be further correlated with the Alakilise Formation in the Aksu, Köprü, Manavgat and Darıören Basins of the Antalya region (Akay and Uysal, 1985; Akay et al., 1985; Karabıyıkoglu et al., 2000).

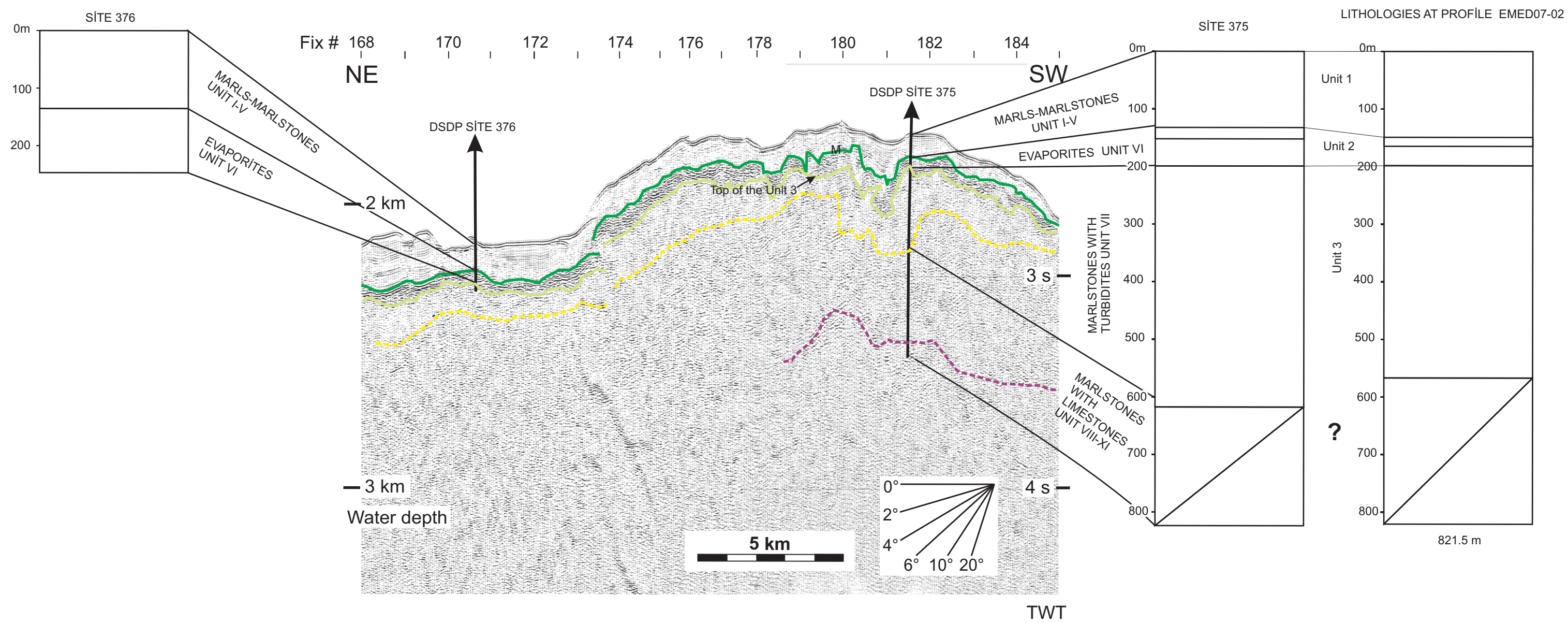
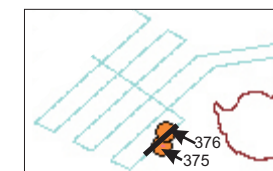


Figure 4.4 Correlation between the DSDP Sites and seismic reflection profile (FIX 168-184).



A strong and conspicuous reflector separates seismic stratigraphic Subunits 1b and 1c (Figs. 4.2, 4.3). The lower Subunit 1c is characterized by moderate to strong reflectors which exhibit considerable lateral continuity throughout the study area (Figs. 4.2, 4.3). This subunit directly overlies the M-reflector. Subunit 1c is correlated with the Early Pliocene age slumped marl successions of lithostratigraphic Unit IV of the DSDP Sites 375 and 376 (Figs. 4.4, 4.5; Shipboard Scientific Party, 1978). Subunit 1c is tentatively correlated with the Nikosia and Mirtou formations of the Mesaoria Basin and Kyrenia Mountains respectively (Fig. 4.5; Cleintuar et al., 1977; McCallum and Robertson, 1990; Robertson, 1998; Calon et al., 2004). Subunit 1c can also be correlated with the Yenimahalle Formation in the Aksu, Köprü, Manavgat and Darıören Basins of the Antalya region (Fig. 4.5; Akay and Uysal, 1985; Akay et al., 1985; Karabıyıkoglu et al., 2000).

4.3.2 Unit 2: Late Miocene (Messinian)

Unit 2 corelated with an evaporate layer that was widely deposited throughout the Eastern Mediterranean Sea during Messinian time. This unit is generally characterized by a low reflectivity package with weak and often discontinuous reflections (Figs. 4.2, 4.3), although in the Florence Rise and environs the succession has a stratified appearance delineated by discrete continuous reflectors with a corrugated geometry (Figs 4.2, 4.3). It is readily distinguished by its strongly reflective top (M-reflector) and occasionally by its less reflective and more discontinuous base. The reflector has been called the M-reflector by Ryan et al. (1973), and is known to be a Mediteranean-wide unconformity separating rocks of the Miocene and Pliocene epochs. DSDP Sites 375 and 376 over the crest and flank of the Florence Rise *sensu stricto* show that Unit 2 is correlated with the Messinian evaporites (Figs. 4.5; Hsü et al., 1973, 1978; Shipboard Scientific Party, 1978).

Based on the drillhole data from DSDP Sites 375 and 376 (Figs. 4.4, 4.5; Shipboard Scientific Party, 1978) Unit 2 is correlated with the marlstones and interbedded graded sandstones and siltstones of Unit V, and the anhydrite, halite,

		SEISMIC UNITS	ANTALYA ¹ BASIN	DSDP ² 375-376	ADANA ³ CILICIA BASIN	MESAORIA ⁴ BASIN	KYRENIA ⁵ MOUNTAINS
QUATERNARY		Unit 1	Antalya Tufa	I-II	Kuranşa	Apalos Karraristra Athalassa	Athalassa
PLIOCENE			Alakilise	III	Handere	Nikosia	Mirtou
			Yenimahalle	VI			
MIOCENE	MESSINIAN	Unit 2	Taşlık <i>Gebiz</i>	V-VI	Adana Gr.	Kalavassos	Lapatza
	TORTONIAN	Unit 3	<i>Karpuzçay</i>	VII	<i>Kuzgun</i>	<i>Koronia</i>	
	SERRAVALLIAN			VIII-IX	<i>Güvenç</i>	<i>Pakhna</i>	<i>Kythrea Group</i>
	LANGHIAN			X	<i>Cingöz</i>		
	BURDIGALIAN				<i>Karaisalı</i>		
	AQUITANIAN				<i>Gildirli</i>	<i>Terra</i>	
					<i>Aksu</i>		
	OLIGOCENE						
	EOCENE				Karsanti	Lefkara	Lapithos Group
	PRE-EOCENE BASEMENT		Antalya Complex		Aladağ Complex	Troodos Complex	Exotic Elements

Figure 4.5 Regional Stratigraphic correlation chart.

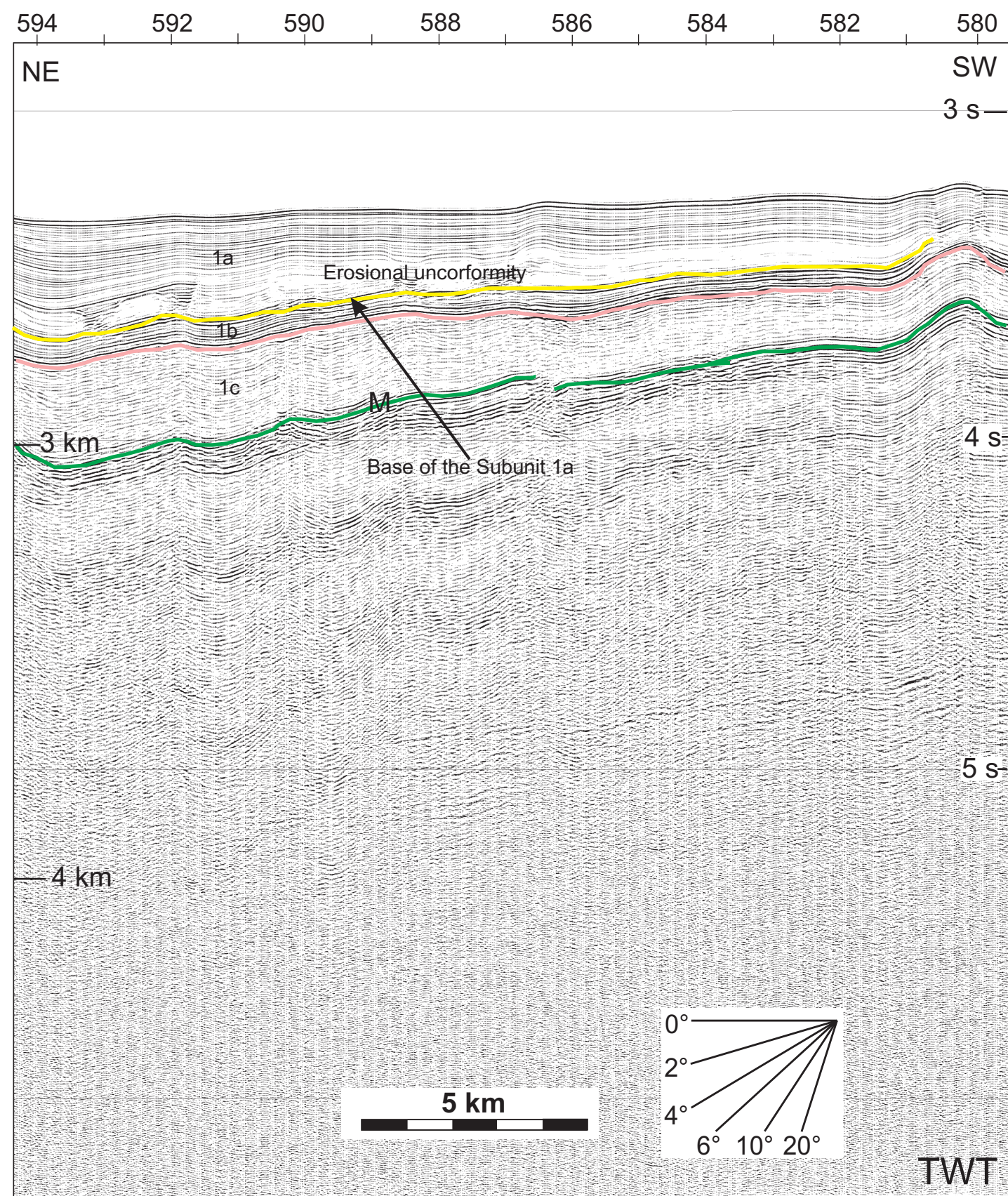
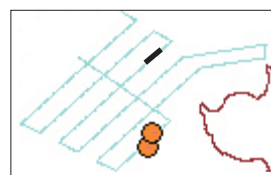


Figure 4.6 Seismic reflection profile (FIX 580-594).



gypsum and green dolomitic marlstones of Unit VI. Unit 2 is also correlated with other Messinian bedded pebblestone, sandstone, gypsiferous and fossiliferous limestone successions, including the Taşlık, Eskiköy and Gebiz formations, found in onland Aksu and Manavgat Basins (Figs. 4.5; Akay et al., 1985; Karabıyıkoglu et al., 2000), as well as the similar evaporate lithologies of the Kalavassos and Lapatza formations of the Mesaoria Basin and Kyrenia Mountains, respectively (Fig. 4.4).

In the DSDP boreholes, there is a gradational transition from Miocene lithostratigraphic Units V to VI. This boundary cannot be delineated in the seismic reflection profiles, therefore Units V and VI are lumped together in seismic stratigraphic Unit 2.

Two packages are recognized within Unit 2: subunit 2a, subunit 2b (Fig. 4.8). Subunit 2a, where present, immediately underlies the M-reflector. It has a strong seismic expression with continuous and parallel reflectors. Subunit 2a shows progressive onlap against the older structural highs. Subunit 2b comprises the seismically weak and transparent sequence, which either underlies subunit 2a, or shows an intercalating relationship with subunit 2a (Fig. 4.8). Where subunit 2a is absent, subunit 2b immediately underlies the M-reflector.

4.3.3 Unit 3: Miocene (pre-Messinian)

Unit 3 underlies the Messinian evaporites of Unit 2, and constitutes the acoustic basement in the study area. In its uppermost portion, it is characterized by lower frequency rhythmic reflections, showing good lateral continuity (Figs. 4.2, 4.3). Data from DSDP Sites 375 and 376 show that over the Florence Rise *sensu stricto*, the uppermost segment of Unit 3 can be readily correlated with Unit VII (Figs. 4.4, 4.5; Shipboard Scientific Party, 1978). These successions are mainly upper Miocene (Tortonian) in age and represent a typical flysch-like cyclic development with the turbidite succession gradually fining upwards into homogeneous marlstones (Shipboard Scientific Party, 1978). The uppermost segment of Unit 3 is tentatively correlated with the Karpuzçay and Geceleme

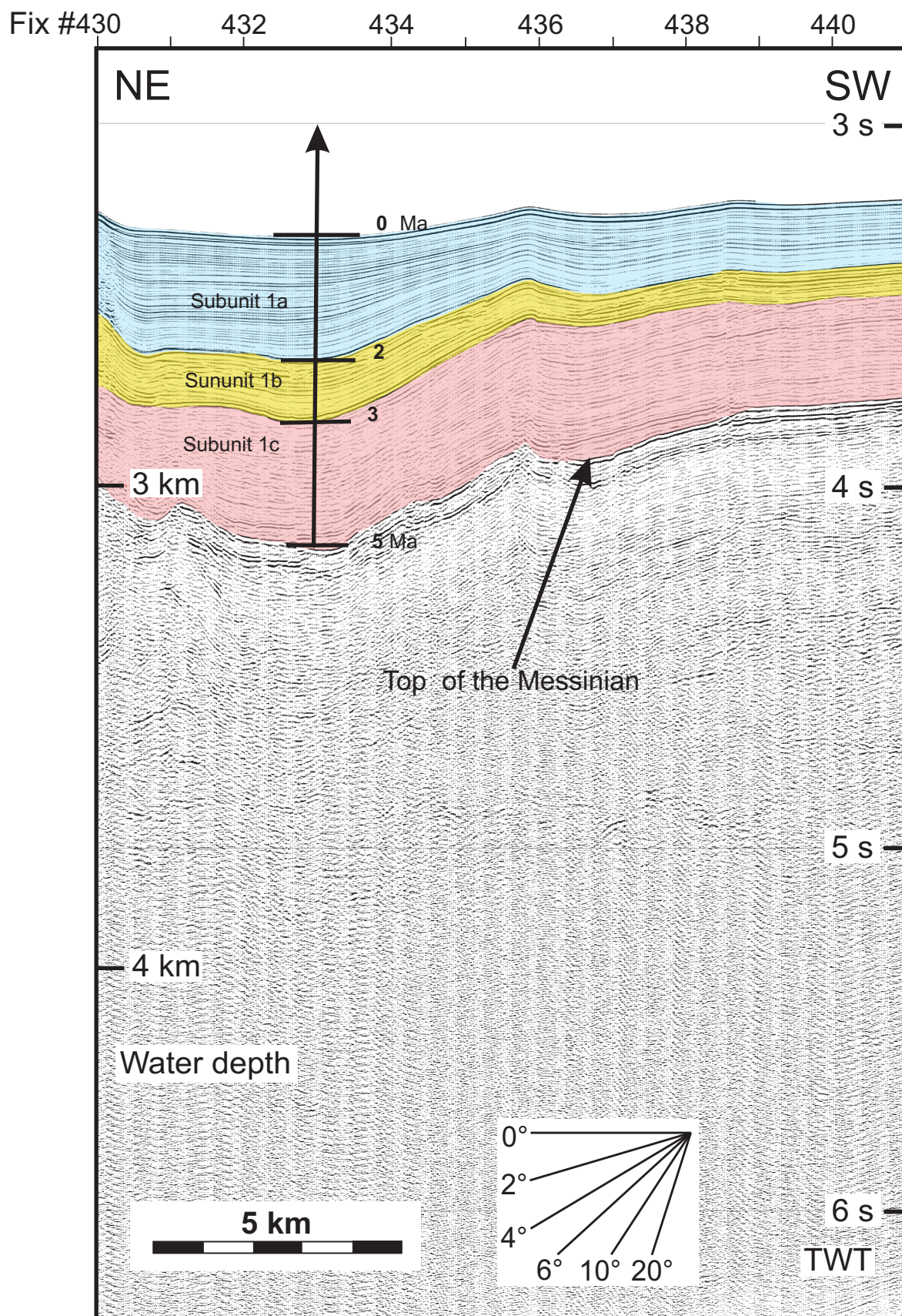
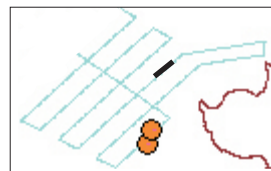


Figure 4.7 Seismic reflection profile (FIX 430-441).



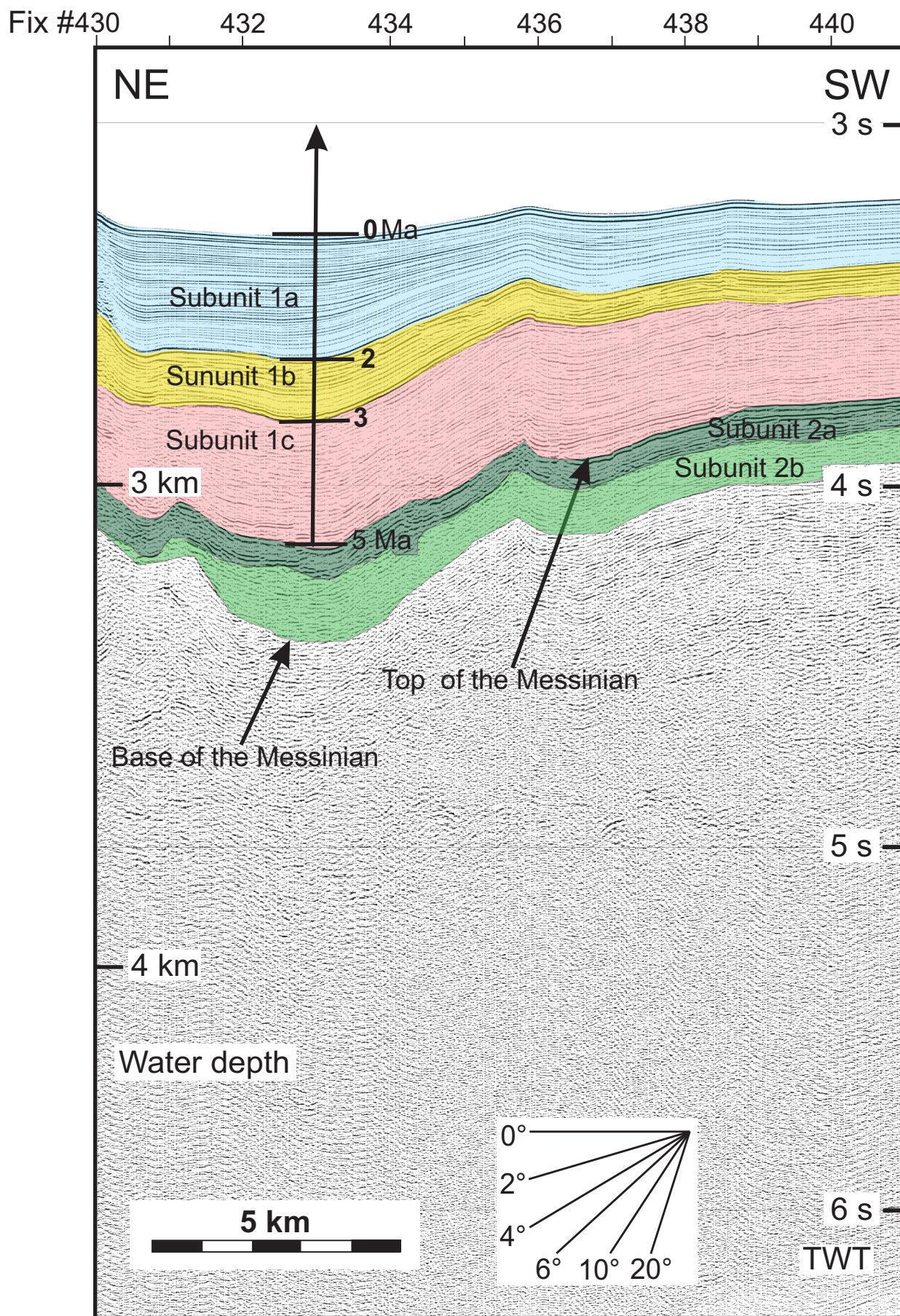
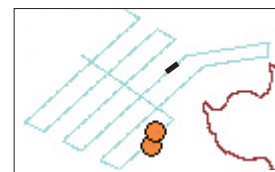


Figure 4.8 Seismic reflection profile (FIX 430-441).



formations of the onland Aksu and Manavgat Basins (Fig. 4.5; Akay et al., 1985; Karabıyıkoglu et al., 2000). The uppermost segment of Unit 3 is further correlated with the predominantly turbidite succession (marls and marly chalks) of the Kythrea Group of the Kyrenia Range and its lateral equivalent the Pakhna Formation of the Mesaoria Basin (Fig. 4.5; Robertson, 1998).

The lower portion of Unit 3 may include a diverse collection of regional lithostratigraphic units ranging from the lower Mesozoic to upper Oligocene. However, the source volume of the multichannel seismic survey was not large enough to image these successions.

An isochron map of the study area derived from Unit 1 thickness measured vertically at the each fix number location is displayed in Figure 4.9. This map was hand-contoured and digitized for presentation.

Table 4.2 Seismic units/subunits identified in the Florence Rise area and their inferred ages based on linear interpolations of vertical stratigraphic thickness as explained in the text.

	Seismic stratigraphic Units and Subunit	Inferred Ages (Ma)
Unit 1	Subunit 1a (Upper Pliocene-Quaternary)	~2.0-0
	Subunit 1b (Middle Pliocene-Quaternary)	~2.0-3.0
	Subunit 1c (Upper Pliocene-Quaternary)	~3.0-5.0
	Unit 2	>5.0

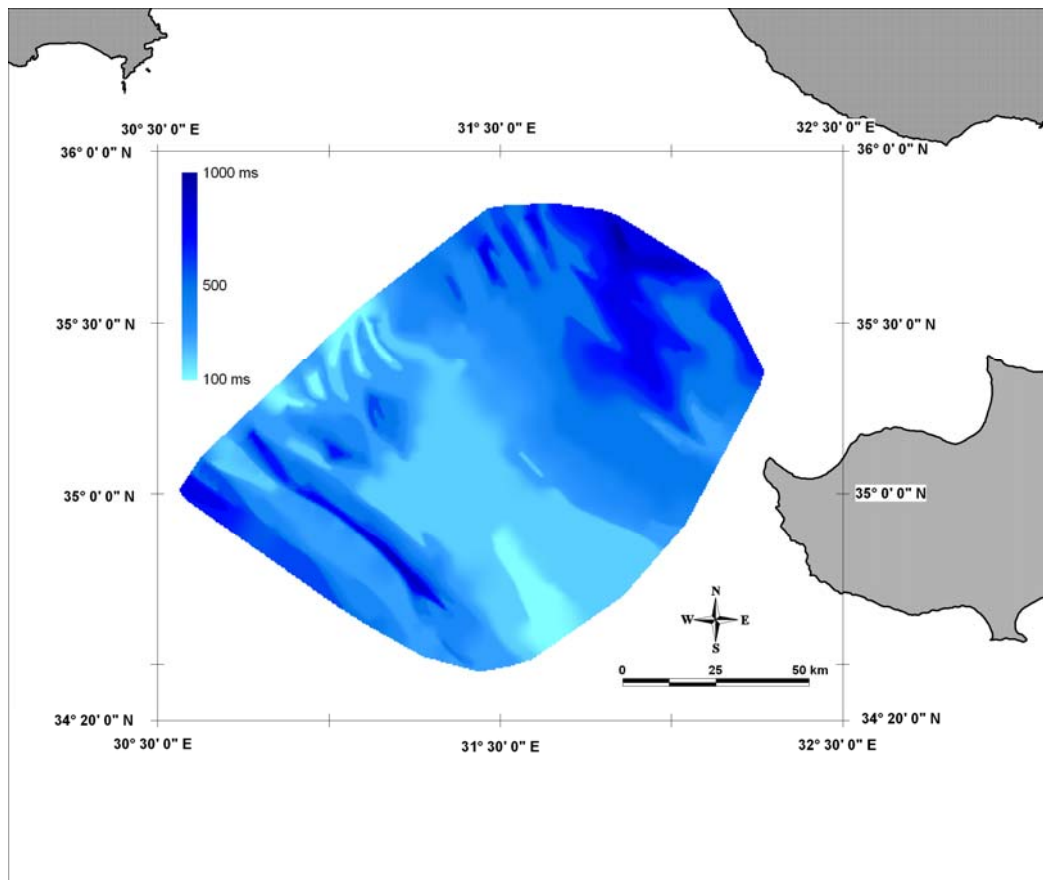


Figure 4.8 Showing the distribution of the Pliocene-Quaternary sediments thickness

CHAPTER FIVE

MORPHO-TECTONIC ARCHITECTURE OF THE FLORENCE RISE

The morphotectonic framework of the Florence Rise and environs is characterized by four distinct seafloor morphologies, which are also reflected in the morphology of the subsurface geology, exemplified by the M-reflector. On the basis the morphology of the seafloor and tectonic architecture of the underlying successions, the study area is divided into four major broadly internally parallel morpho-tectonic domains (Fig. 5.1). Domain 1 occupies the northern and northeastern portion of the study area, and extends northward into the Antalya Basin. Domain 2 defines a northwest-southeast trending belt south of Domain 1. In the east, the domain abuts the western fringes of Domain 3, whereas in the west it defines the northern slopes of the Anaxagoras Mountains. Domain 3 is another northwest-southeast trending narrow belt which is situated southwest of Domain 2. On its eastern portion, this domain includes an east-west trending tear-drop shaped ridge, known as the Florence Rise. Domain 3 extends toward the west into the Anaximender Mountains (Fig. 5.1). Domain 4 defines the southernmost regions of the study area and extends southward into the Mediterranean Ridge. In the following text, the morphology and subsequently the internal architecture of these four morpho-tectonic domains are described in detail.

5.1 Morphology of the domains

5.1.1 Domain 1

This domain is characterized by a corrugated seafloor morphology, broadly delineated by numerous E-W trending quasi linear deep troughs and their intervening ridges (Fig. 5.1). It occupies the northern portion of the study area and extends into the southern portion of the Antalya Basin. There is no multibeam data in the northernmost portion of this domain in southern Antalya Basin. Therefore, except for the existing bathymetric maps, detailed morphology

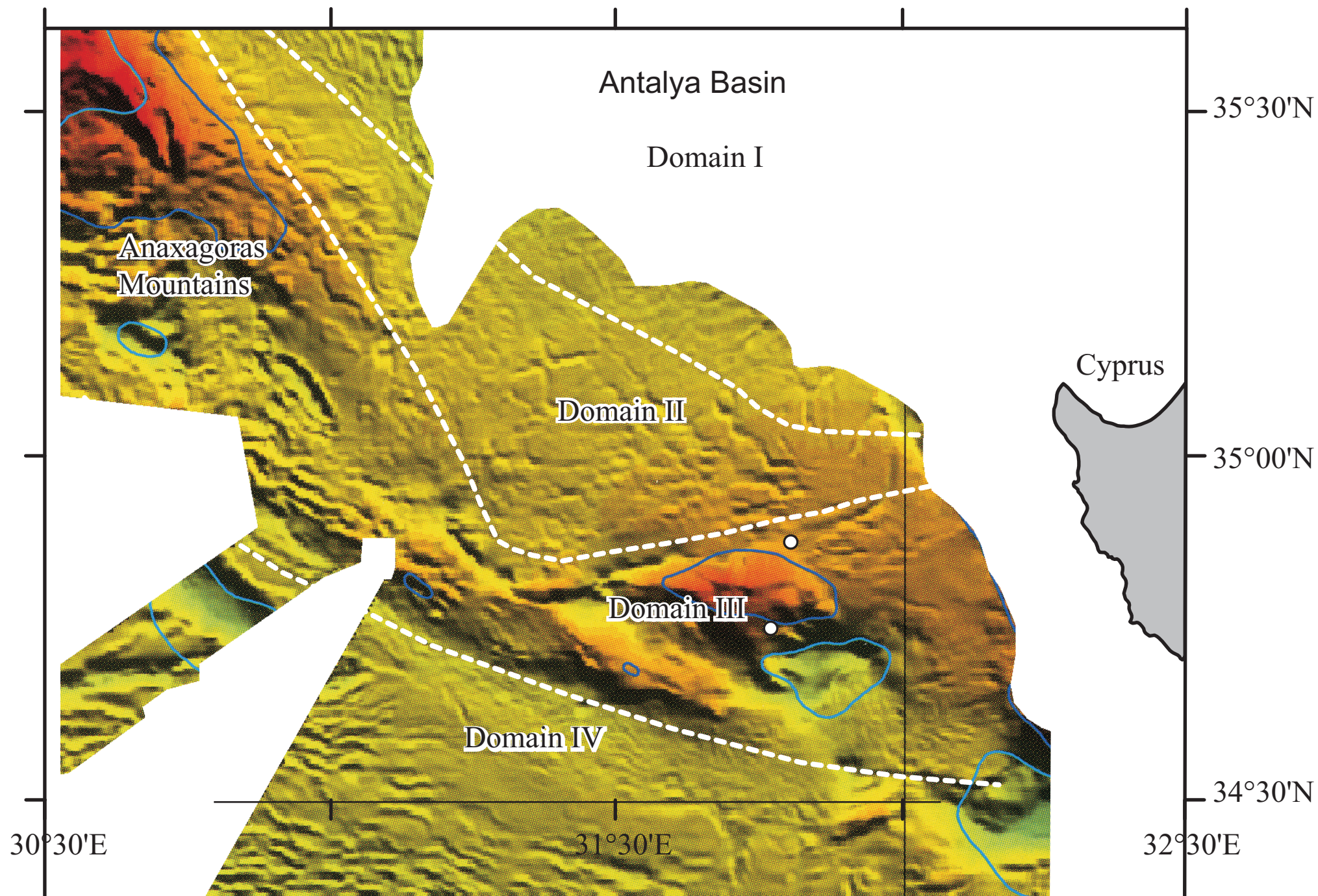


Figure 5.1 Multibeam bathymetry of the Florence Rise and environs (from Loubrieu et al., 2000), showing the physiographic domains discussed in text.

of the seafloor in this area is not known. In the southwestern portion of the Antalya Basin, northeast of the Anaxagoras Mountain, there is multibeam data, which show a seafloor characterized by tight corrugations with wave lengths ranging from ~3000-6000 m, and amplitudes ranging from ~50-100 m. Although this area is outside the scope of this thesis, the corrugated seafloor in this region strongly suggests that a similar morphology may extend toward the southeast into Domain 1 in the study area.

5.1.2 Domain 2

Domain 2 is a roughly triangular-shaped region of the seafloor, which clearly tapers both toward the west into the northern slopes of the Anaxagoras Mountain and toward the east into the northern fringes of the Florence Rise (i.e., Domain 3, see below; Fig. 5.1). It is delineated by quasi linear troughs that either show a predominantly northwest-southeast trend or east-west trend. The regions between these troughs are characterized by more-or-less flat seafloor with little elevation difference. The northwest-southeast and east-west trending structures often coalesce, creating a lazy-S like overall seafloor character.

5.1.3 Domain 3

Domain 3 is a prominent region of the study area, dominated in the east by the prominent tear-drop shaped, broadly east-west trending ridge, known as the Florence Rise (*sensu stricto*). The Deep Sea Drilling Project wells are drilled over the crest (Site 375) and over the northern slope (Site 376) of the Florence Rise (Fig. 4.3). Domain 3 is located immediately southwest of Domain 2 (Fig. 5.1). It is bounded to the south by Domain 4. Toward the west, Domain 3 gradually assumes a northwesterly trend and merges with the eastern fringes of the Anaxagoras Mountain, whereas toward the east, the domain takes a mainly east-west trend and passes south of the Island of Cyprus (Fig. 1.1). Morphologically the domain defines a broad, arcuate and narrow WNW-ESE trending high (Fig. 5.1). In detail, the high emerges as a number of internally parallel ridges and their

intervening troughs, which are clearly above the overall elevation of the seafloor to the north (Domain 2) and the south (Domain 4).

5.1.4 Domain 4

Domain 4 occupies the region south of Domain 3, and extends southward into the Mediterranean Ridge (Fig. 5.1). It is characterized by a variably corrugated seafloor morphology, broadly similar to that observed in Domain 1.

5.2 Structural architecture of the domains

5.2.1 Domain 1

Seismic reflection profiles in this domain show that the corrugated seafloor morphology observed in limited multibeam data is the expression of deeper and larger structures, which delineate a number of internally parallel, broadly northwest-southeast-trending folds, consisting of anticlines (referred to as ridges) and their intervening synclines (referred to as Pliocene-Quaternary basins; Figs. 5.3, 5.4). At the level of the M-reflector, the folds display 50-450 ms elevation difference between adjacent crests and troughs. The ridges define broadly arcuate northwest-southeast-trending, generally non-cylindrical anticlines delineated by the morphology of the M-reflector, as well as the internal architecture of the Messinian evaporites of Unit 2 (when present) and the underlying late Miocene (mainly Tortonian) succession of Unit 3. The crestal hinge lines of these anticlines are labeled in the figures and maps as E₀, E₁, E₂ etc. and trough hinge lines of the intervening basins are similarly labeled as X₁, X₂, X₃ etc. (e.g., Figs. 5.2, 5.3). These basins and ridges collectively form broadly curvilinear map traces (Fig. 4.2).

In Domain 1, the internal architecture of the Miocene successions of Units 2 and 3 and the middle to upper portions of the Pliocene-Quaternary succession of Unit 1 is characterized by five to seven northwest-southeast-trending fold structures, which exhibit broadly symmetrical as well as north- and south-tilted

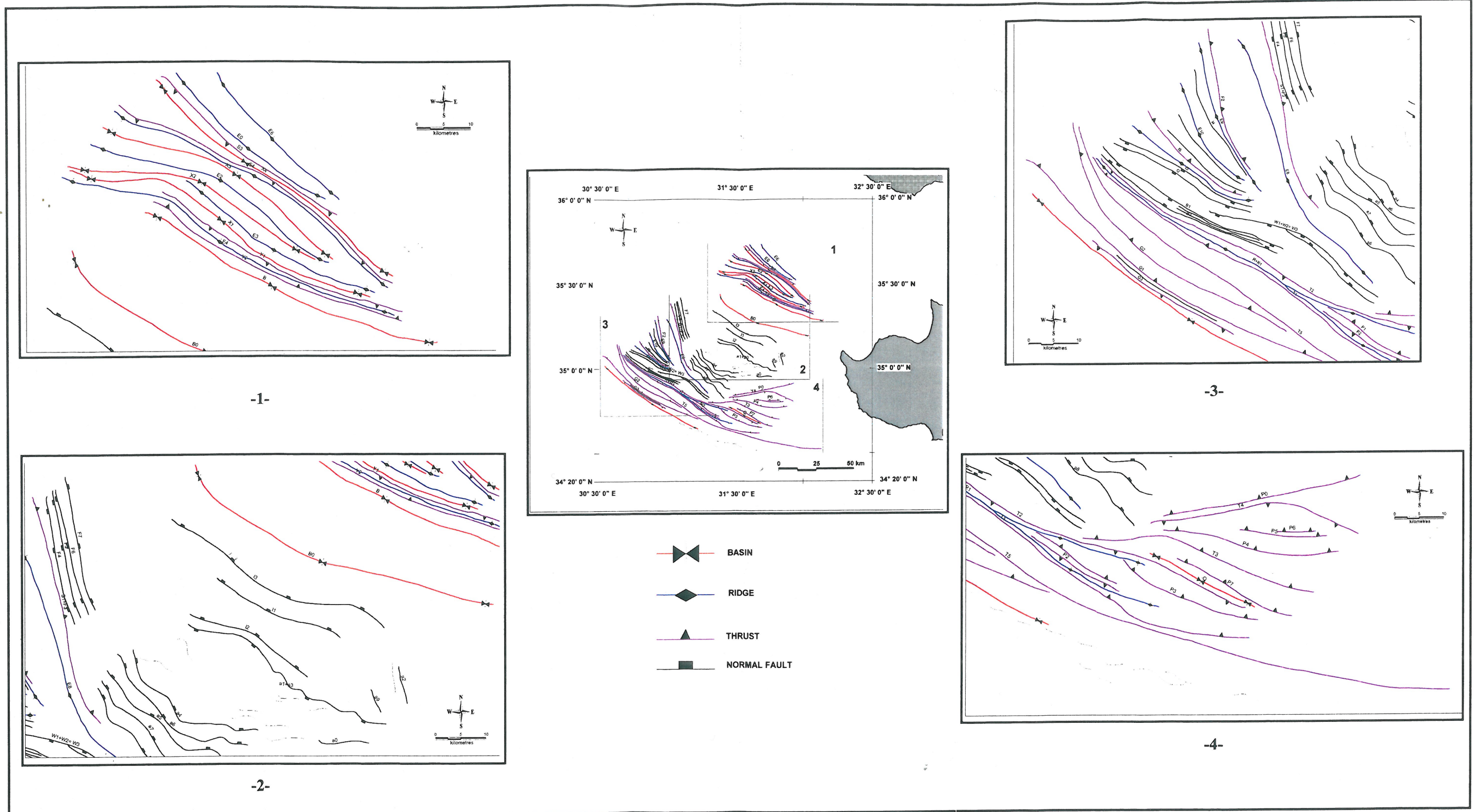


Figure 5.2 Map of the study area showing the structures identified and mapped in the seismic reflection profiles (General map together with the legend in the middle and detailed maps numbered from 1 to 4 at sides of the figure).

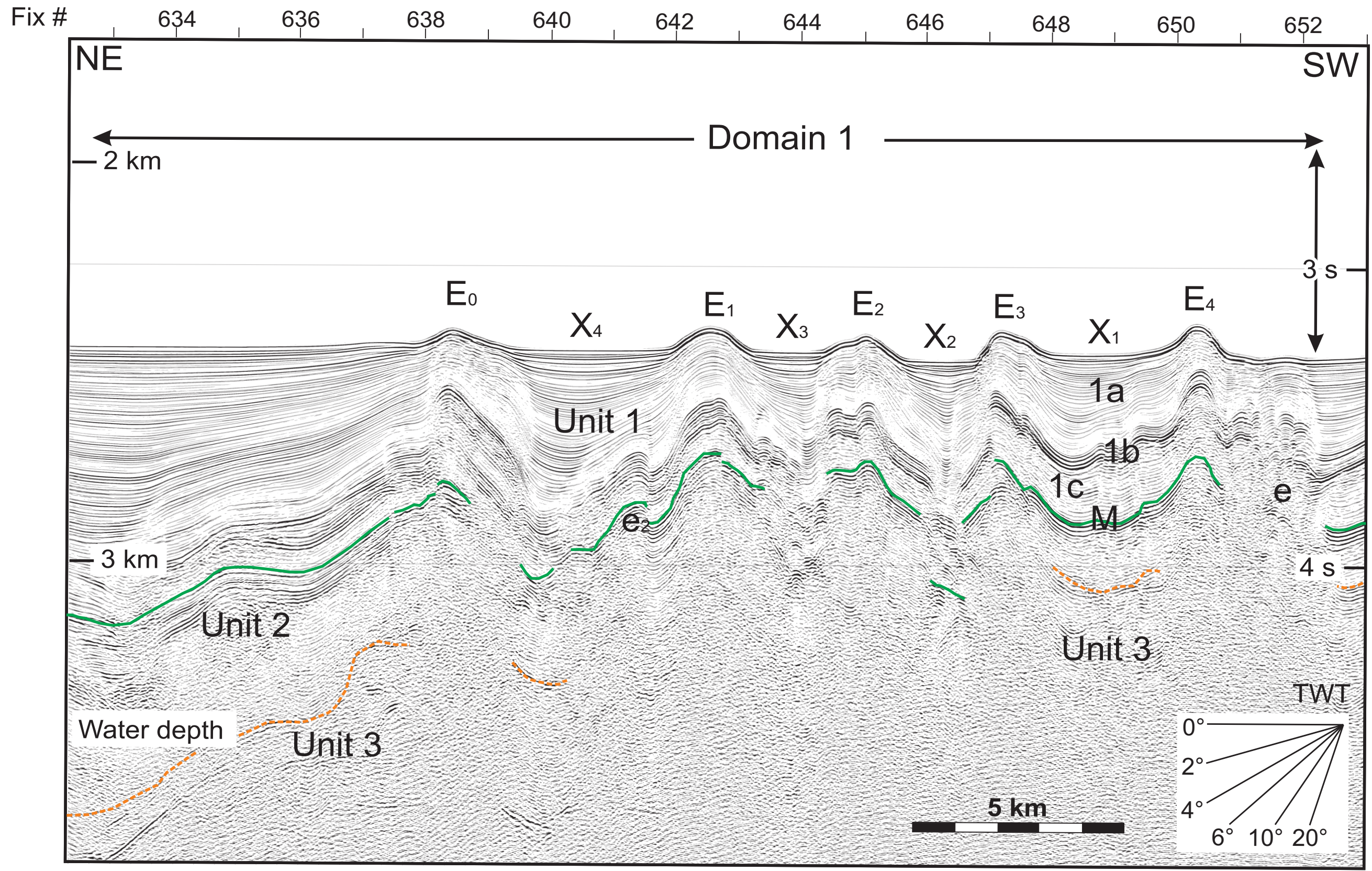
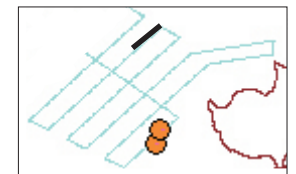


Figure 5.3 Seismic reflection profile (FIX 632-653).



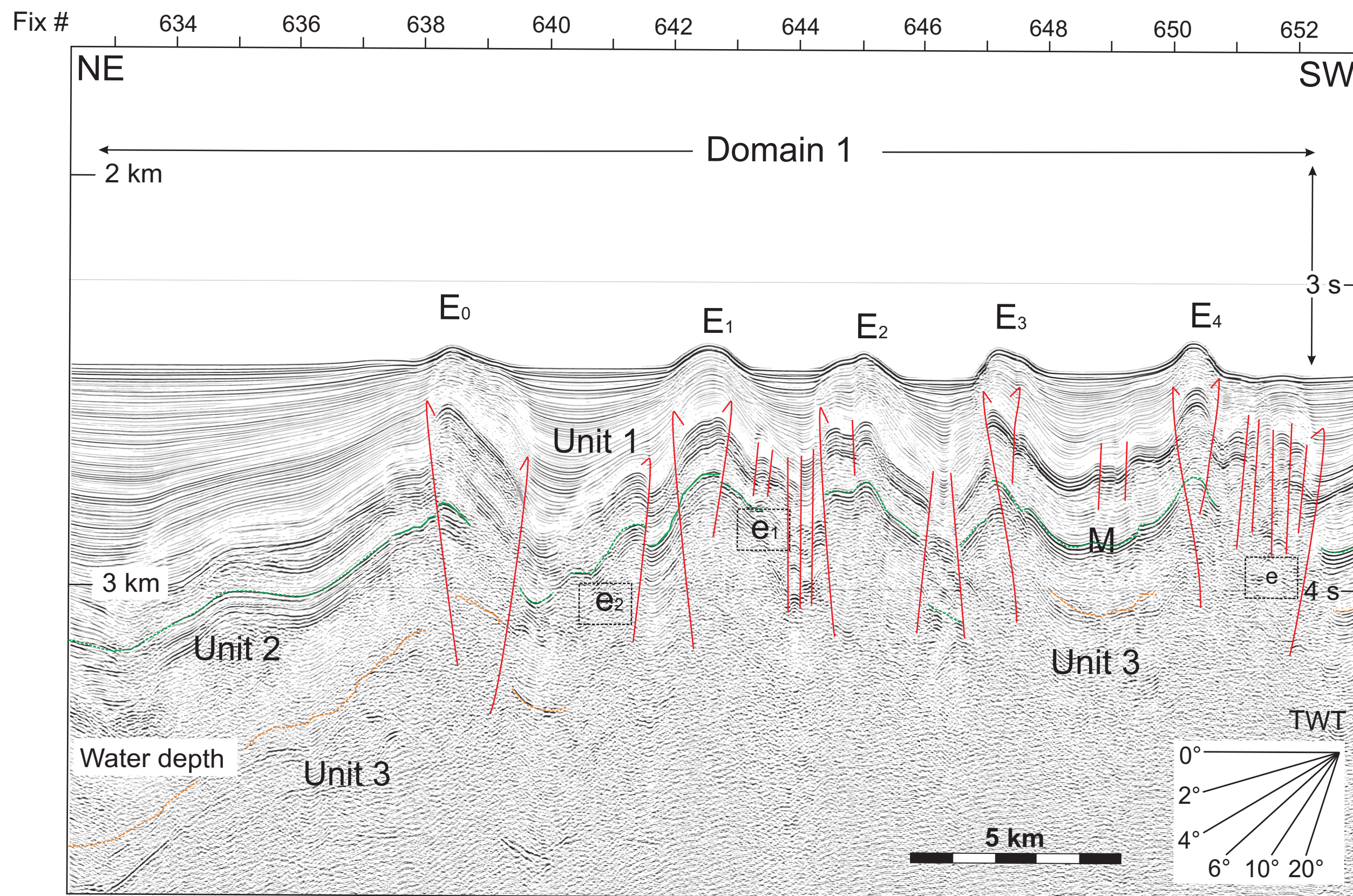
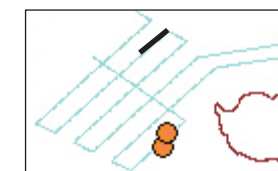


Figure 5.4 Seismic reflection profile (FIX 632-653).



asymmetrical cross-sectional geometries (Figs. 5.3, 5.5). For example, ridges E₁, E₂ and E₃ are clearly symmetrical structures (e.g., Figs. 5.3). However, ridges E₄ and E₆ in Figure 5.5 and ridges E₀ and E₆ in Figure 5.3 are clearly asymmetrical, and display long, gently northeast-dipping backlimbs, and shorter, but steeply southwest-dipping forelimbs. Similarly, Ridges E₂ and E₄ and E₇ in Figure 4.5 and ridge E₈ in Figure 5.3 are equally clearly asymmetrical, but display longer, gently southwest-dipping backlimbs, and shorter, and steeply northeast-dipping forelimbs.

Detailed examination of the seismic reflection profiles show that the core of the ridges are situated within Units 3 and 2, which is best illustrated in the morphology of the M-reflector (Figs. 5.3, 5.5). However, the external geometry of these ridges is still preserved in the lower to upper Pliocene-Quaternary succession with the reflectors showing dramatic thinning and occasionally draping over the M-reflector.

The overall internal architecture of Domain 1 suggests that the ridges are associated with a family of narrowly-spaced, thrust faults with markedly curved north- and south-verging trajectories. The thrusts of each fault pair are rooted deep in Unit 3 with tip points lying between the upper portion of Unit 3 and the lower to middle portion of Unit 1 (Figs. 5.6, 5.7). They display sub-vertical trajectories in the vicinity of the roots, but as traced up-section, they curve away from each other along progressively gentler trajectories (Figs. 5.6, 5.7). In many instances, the M-reflector is broken and show reverse-sense stratigraphic separations. The doubly-verging character of the thrust pairs and the north- and south-tilted asymmetrical cross-sectional geometry of the ridges bounded by these thrusts suggest that these thrust pairs represent positive flower structures (Figs. 5.2, 5.6, 5.7). Similar structures are described by Işler et al. (2005) in the Antalya Basin, as well as Hall et al. (2005) in the Cyprus Basin. Such structures are generally associated with transpressional deformation (e.g. Harding and Lowell, et al., 1983).

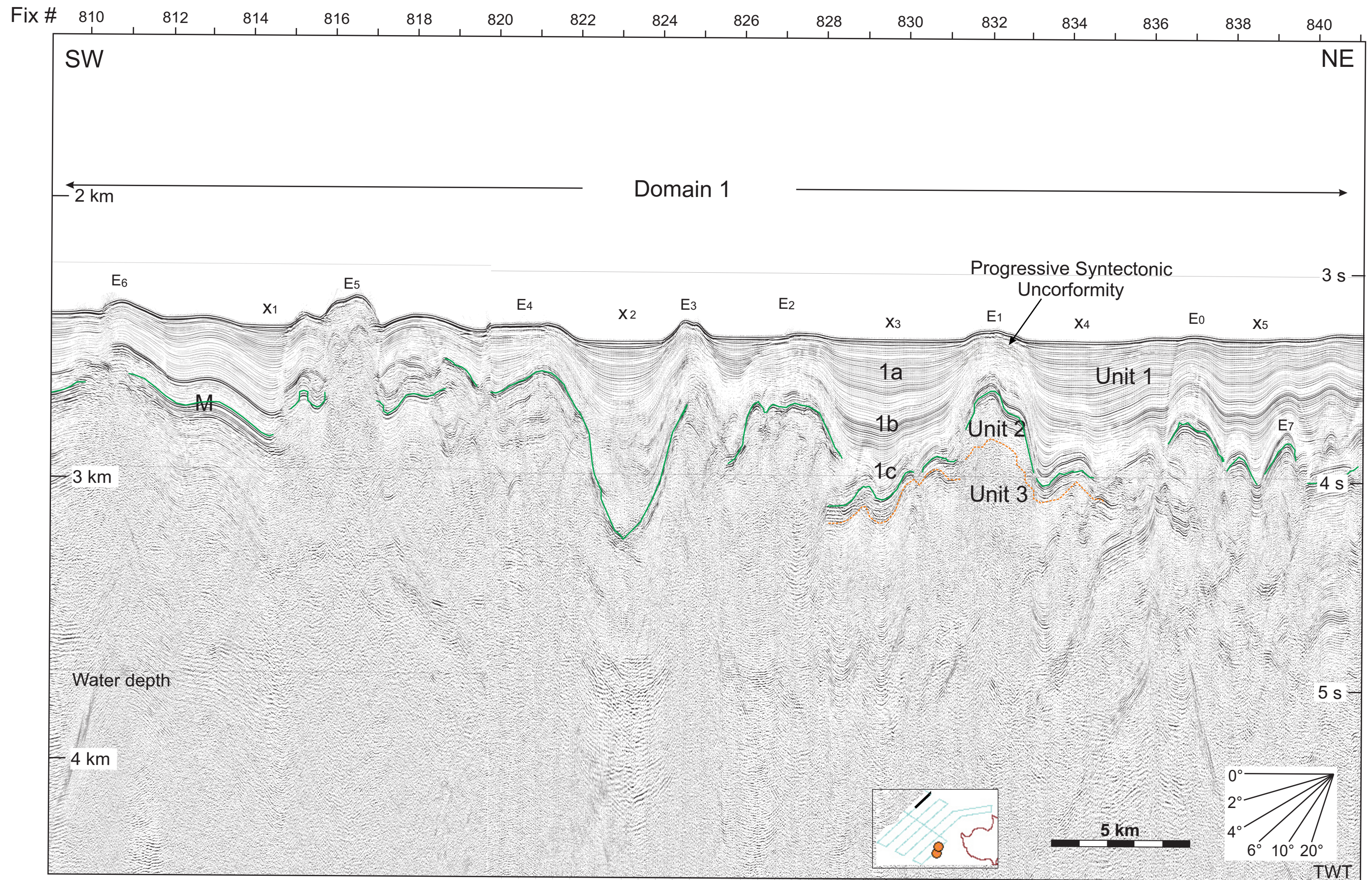


Figure 5.5 Seismic reflection profile (FIX 810-841).

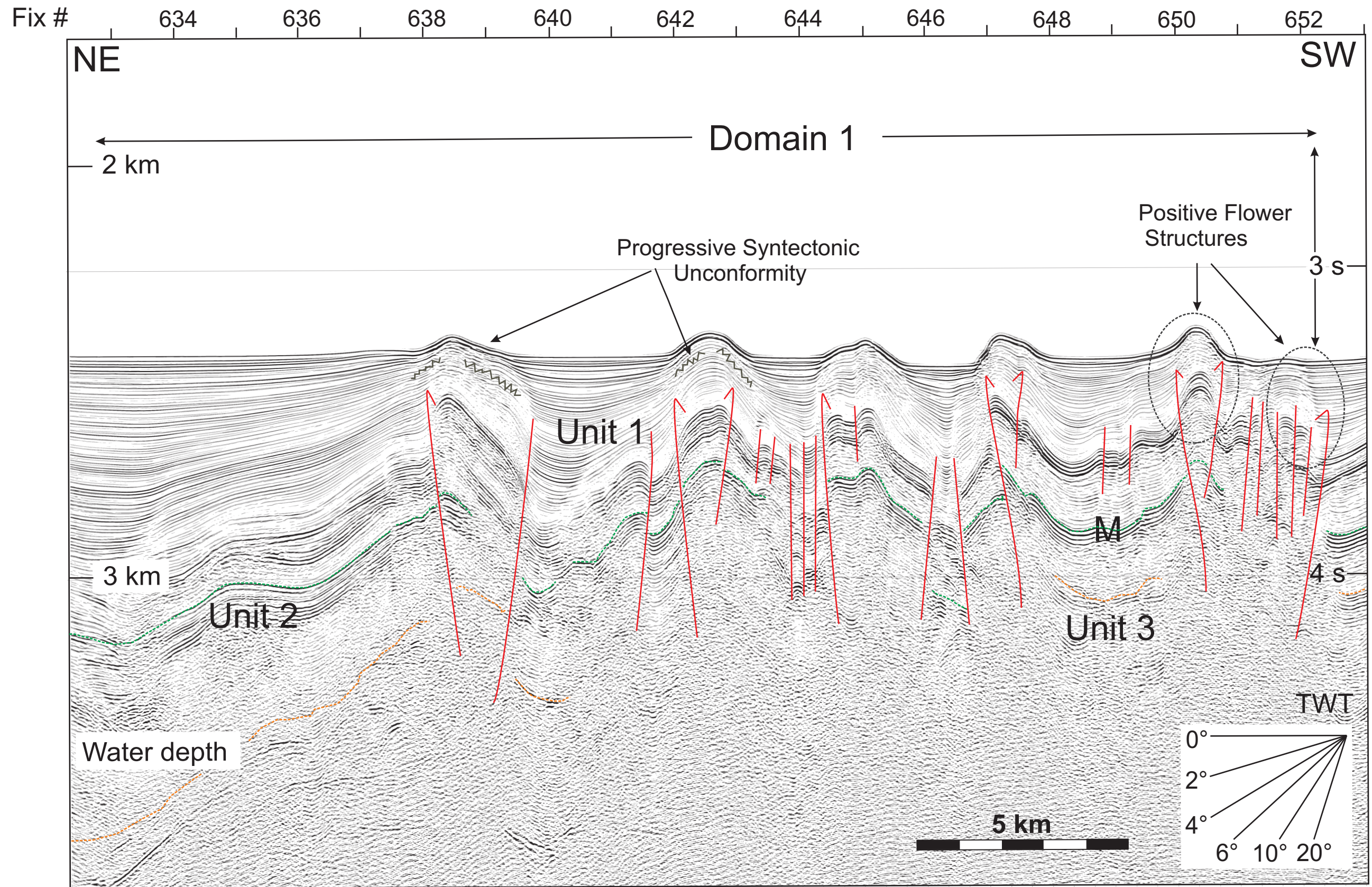
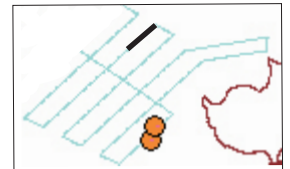


Figure 5.6a Seismic reflection profile (FIX 632-653).



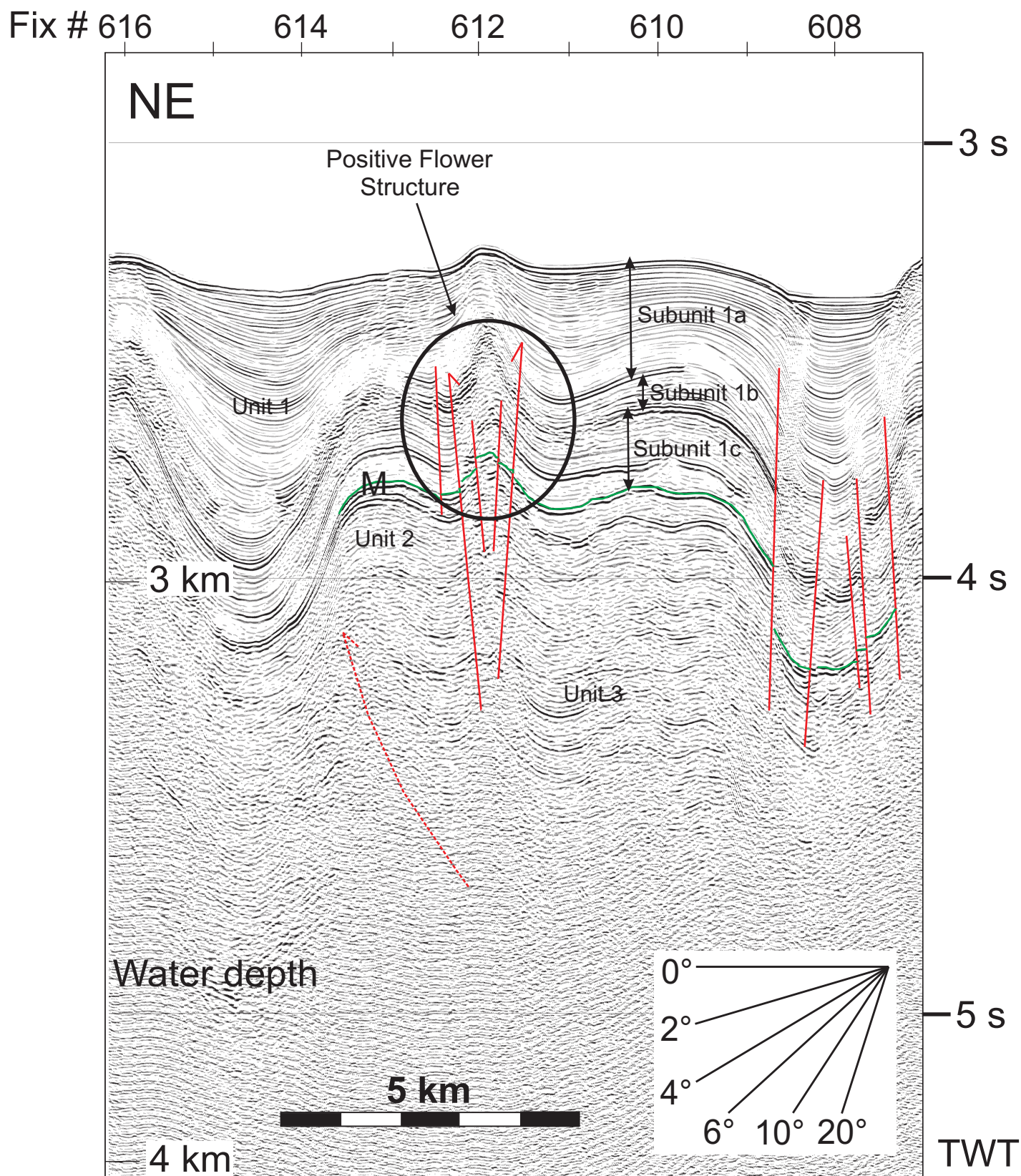
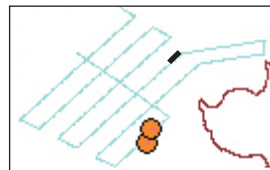


Figure 5.6b Seismic reflection profile (FIX 607-616).



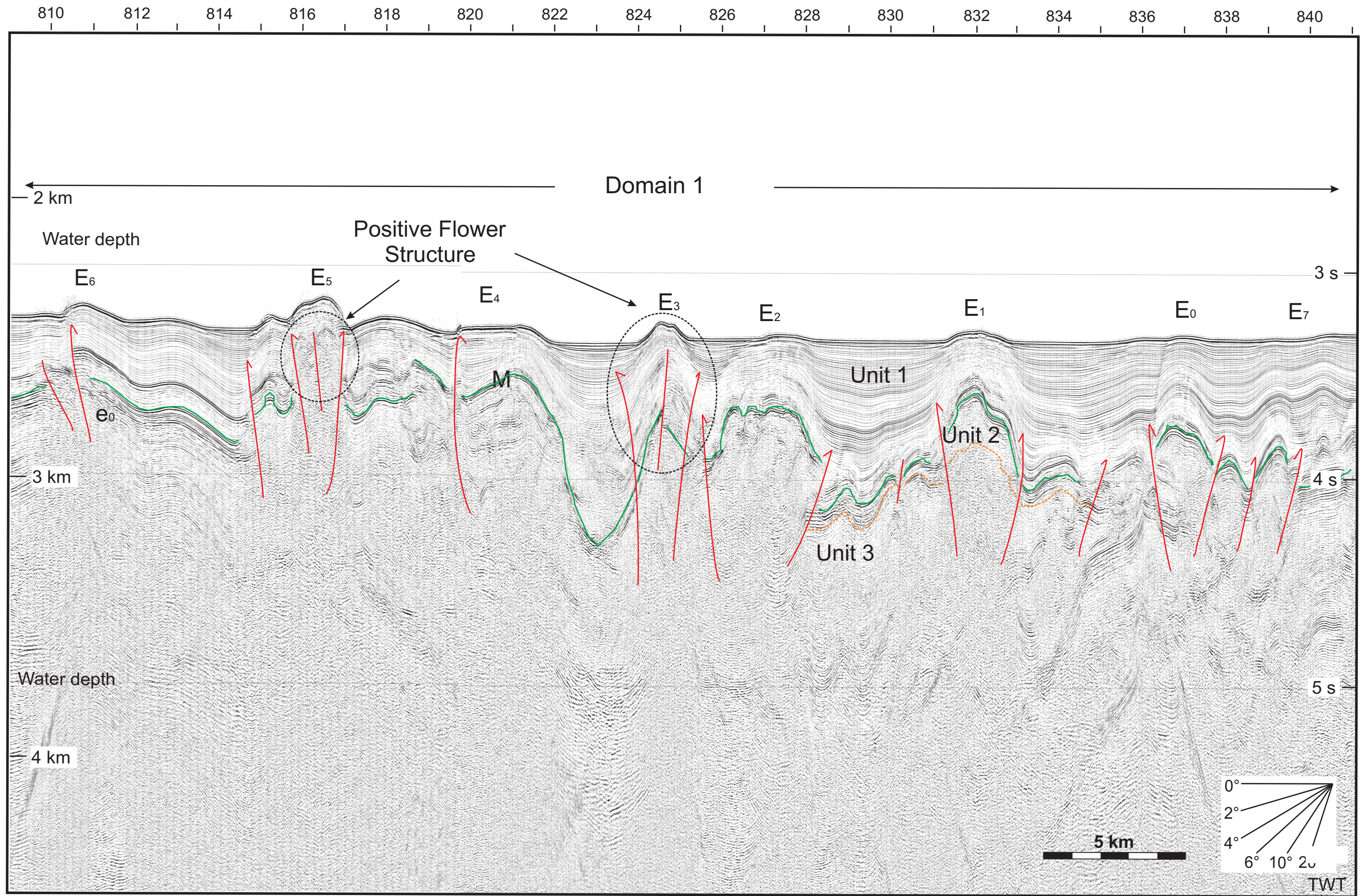
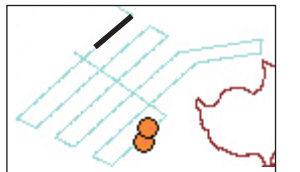


Figure 5.7 Seismic reflection profile (FIX 810-841).



The geometry of the intervening basins X_1 to X_5 are affected by the morphology and structures associated with the ridges. Some basins are clearly symmetrical depocentre, (e.g., X_2 in Fig. 5.3, 5.5, 5.6, 5.7). Yet, basins X_1 and X_3 (Fig. 5.5, 5.7) and basins X_4 and X_5 (Fig. 5.3, 5.6) are asymmetrical structures. Here the thrusts bounding the adjacent ridges are plowing into these basins (Figs. 5.6, 5.7). The internal architecture of the basins are best observed in the stratigraphy of the Pliocene-Quaternary strata of Unit 1. For example, the reflector packages within the middle to upper portion of the Pliocene-Quaternary succession show north- and south-directed thinning, which is accomplished either by interstratal onlap such as observed along the northeastern flank of ridge E_1 and the southwestern flanks of E_1 , E_2 and E_3 in the central-western portion of the study area (Fig. 5.6) or by progressive onlap against the older folded strata overlying the Miocene ridges such as seen along the northeastern flanks E_1 and E_2 in the westernmost portion of the study area (Fig. 5.7). This stratigraphic architecture represents growth strata wedges and suggests that the activity of thrust faults of the flower structures is contemporaneous with the deposition of the early, middle and in some places upper portion of the Pliocene-Quaternary successions (Figs. 5.6, 5.7, 5.8). In each growth strata wedge, the thinning toward the crestal regions of the ridges is accomplished by progressive southwest-directed or northeast-directed onlap and convergence of reflectors, which often leads to offlap reflection terminations. Some seismic profiles show mild erosion in the upper segments of the converging strata, such as seen along the southwestern flanks of ridges E_2 and E_3 (Fig. 5.9). These unconformities can be readily traced into the trailing piggyback basins where they become conformable horizons within the sequence (Figs. 5.6, 5.9). The thickness of section lost to onlap and erosion ranges from 50-100 ms. This stratigraphic architecture is characteristic of progressive syntectonic unconformities developed in active foreland basins (Riba 1976).

Often, the sea floor above the crestal area of the ridges truncates the underlying reflectors of the Quaternary succession and occasionally displays small scale inflections, which together suggests that the thrust faults of Domain 1 continue to be active in the present-day (Figs. 5.6, 5.7, 5.8).

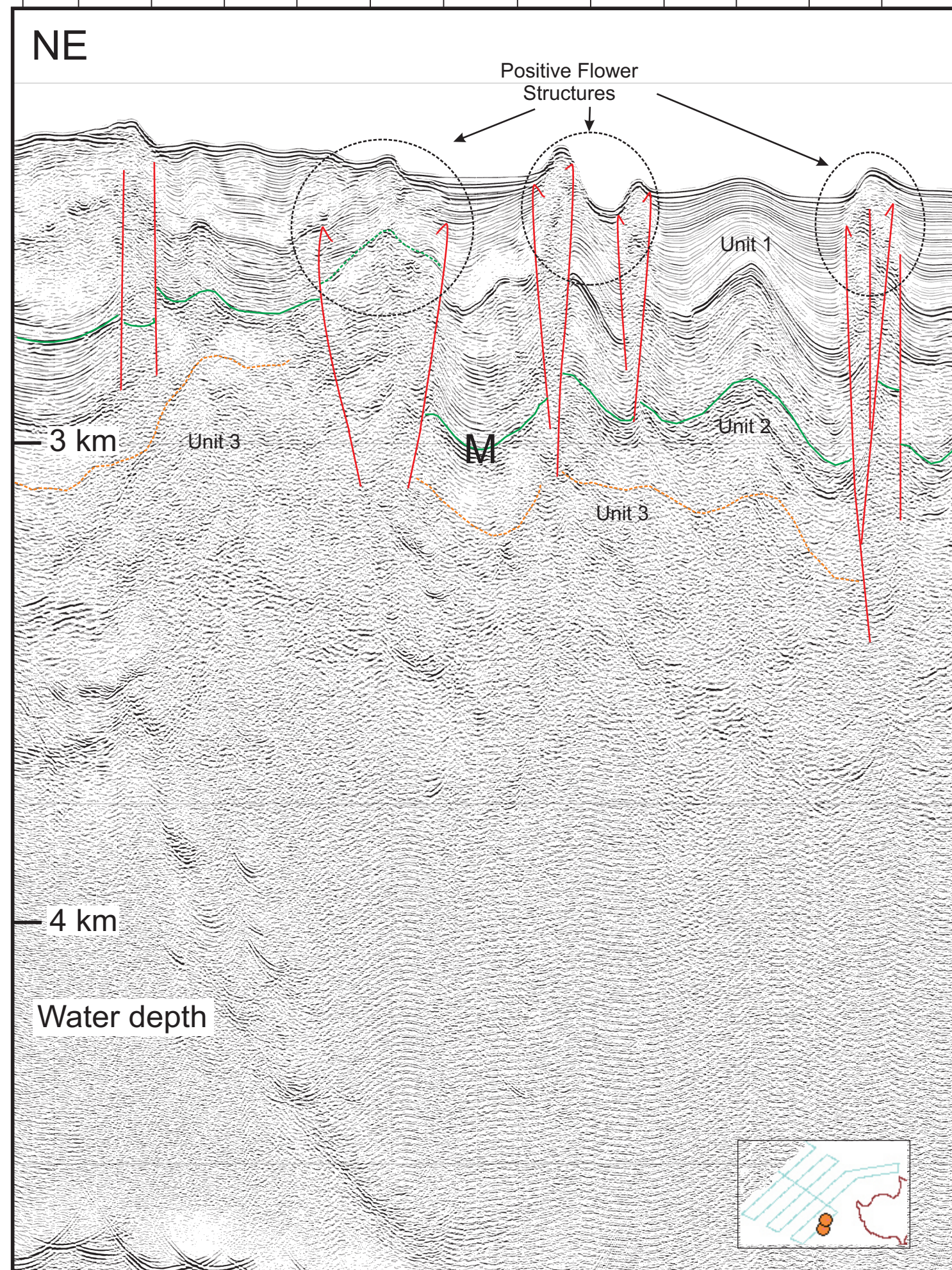


Figure 5.8 Seismic reflection profile (FIX 418-431).

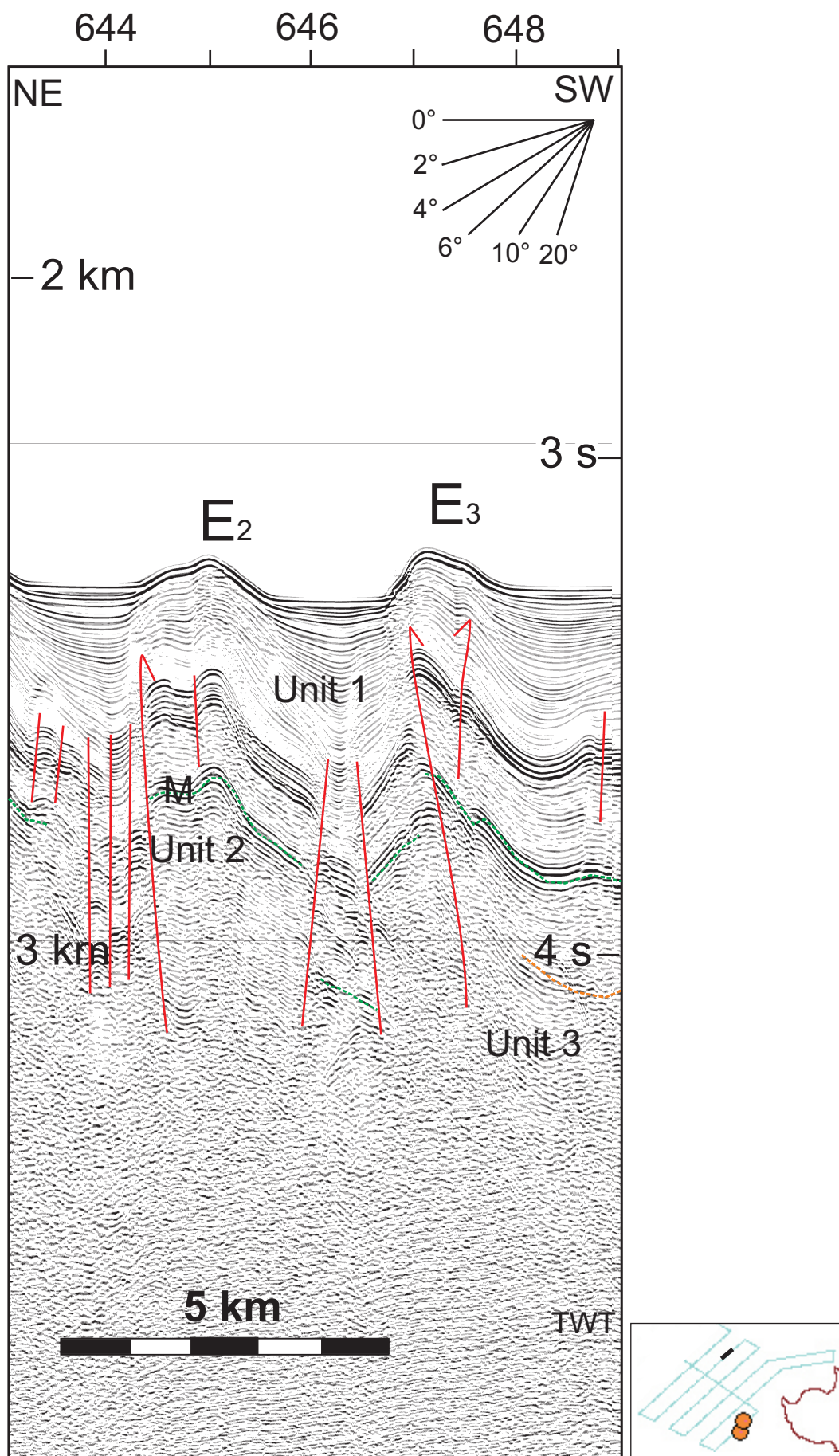


Figure 5.9 Seismic reflection profile (FIX 643-649).

Due to the poor resolution in the deeper portions of the seismic reflection profiles as well as the limited record length, the internal architecture of the core of the positive flower structures could only be imaged in a small number of profiles within the existing seismic grid (Figs. 5.6, 5.7, 5.8). However, the relief created by the doubly-verging thrust faults is prominent throughout the study area and is diagnostic of flower structures (e.g. Harding and Lowell, 1979; Harding, 1985) which enabled a tentative assignment of the domain boundaries.

5.2.2 Domain 2

Seismic reflection profiles document that the quasi linear troughs that show northwest-southeast or east-west trends are the surface reflection of deeper-seated structures. This domain is characterized by numerous prominent high angle faults (Figs. 5.10, 5.11). A similar domain with nearly identical morphology and structural architecture defining a narrow belt is also described from the Outer Latakia Basin, extending from the Kocasu-Hatay/Asi graben in the northeast toward the Larnaka region of southeastern Cyprus (Hall et al., 2005; Calon et al., 2005). Domain 2 is characterized by complex stratigraphic and structural architecture expressed primarily in the Pliocene-Quaternary succession (Figs. 5.10, 5.11).

The domain has an average width of ~15-20 km and in the multibeam map shows a fine-scale corrugated seafloor morphology (Figs. 5.1, 5.12). Detailed examination of the multibeam map and correlation of the structures with the seismic reflection profiles show that the internal architecture of this region is characterized by prominent high-angle faults (Figs. 5.10, 5.11). These faults clearly cut the M-reflector and extend to depths in seismic reflection profiles. The faults invariably cut nearly the entire Pliocene-Quaternary succession, with tip points at or very close to the seafloor. Because of the high exaggeration of the seismic profiles, coupled with the high fault angles, it is difficult to determine the sense of motion at these faults. When the upper portion of the seismic profiles is ignored and only the M-reflector is taken into account, a normal-sense separation can be envisaged with the hanging wall occurring at the basin side of the faults

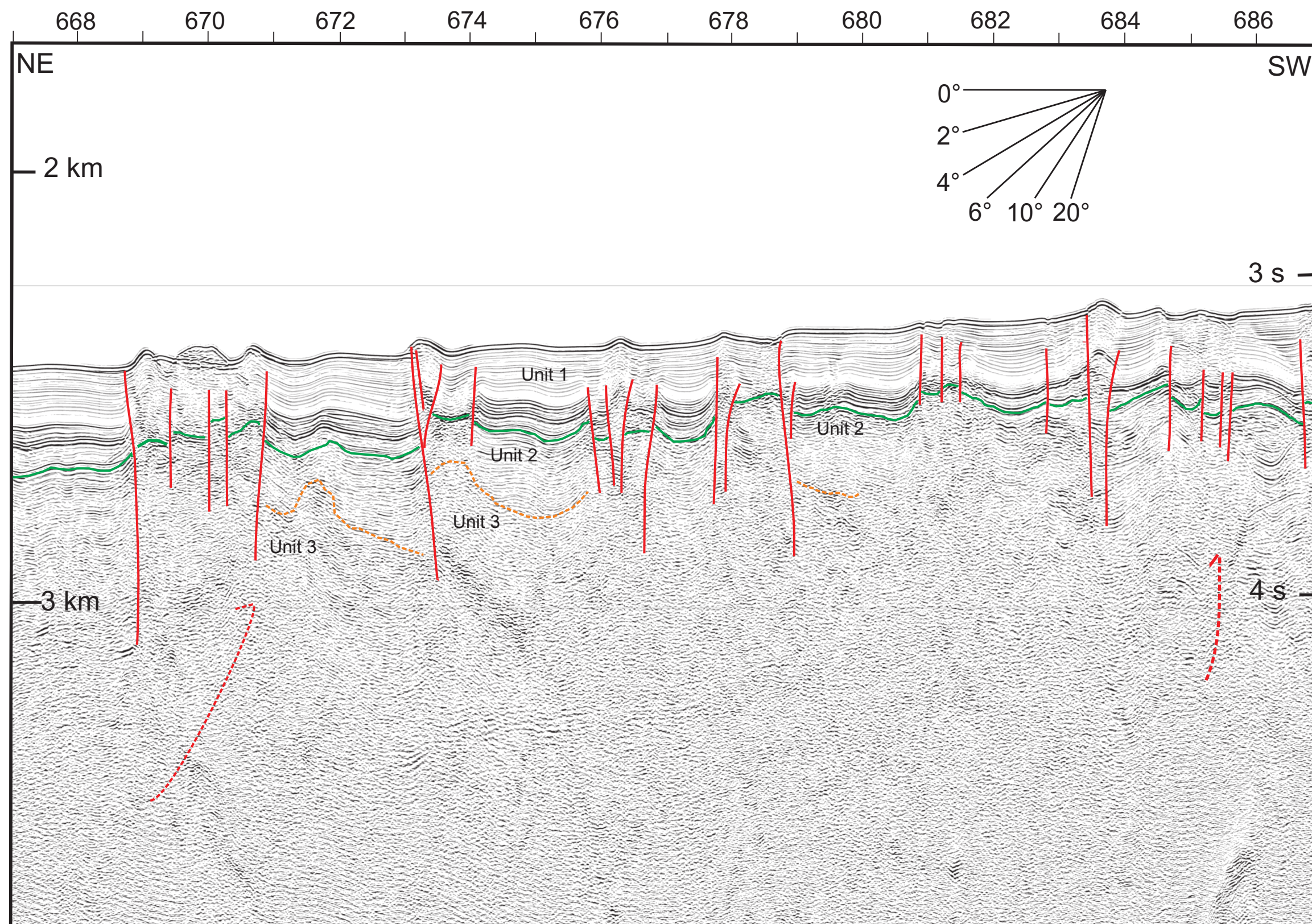
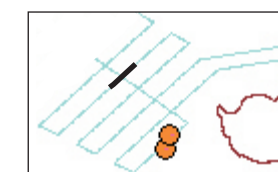


Figure 5.10 Seismic reflection profile (FIX 667-687).



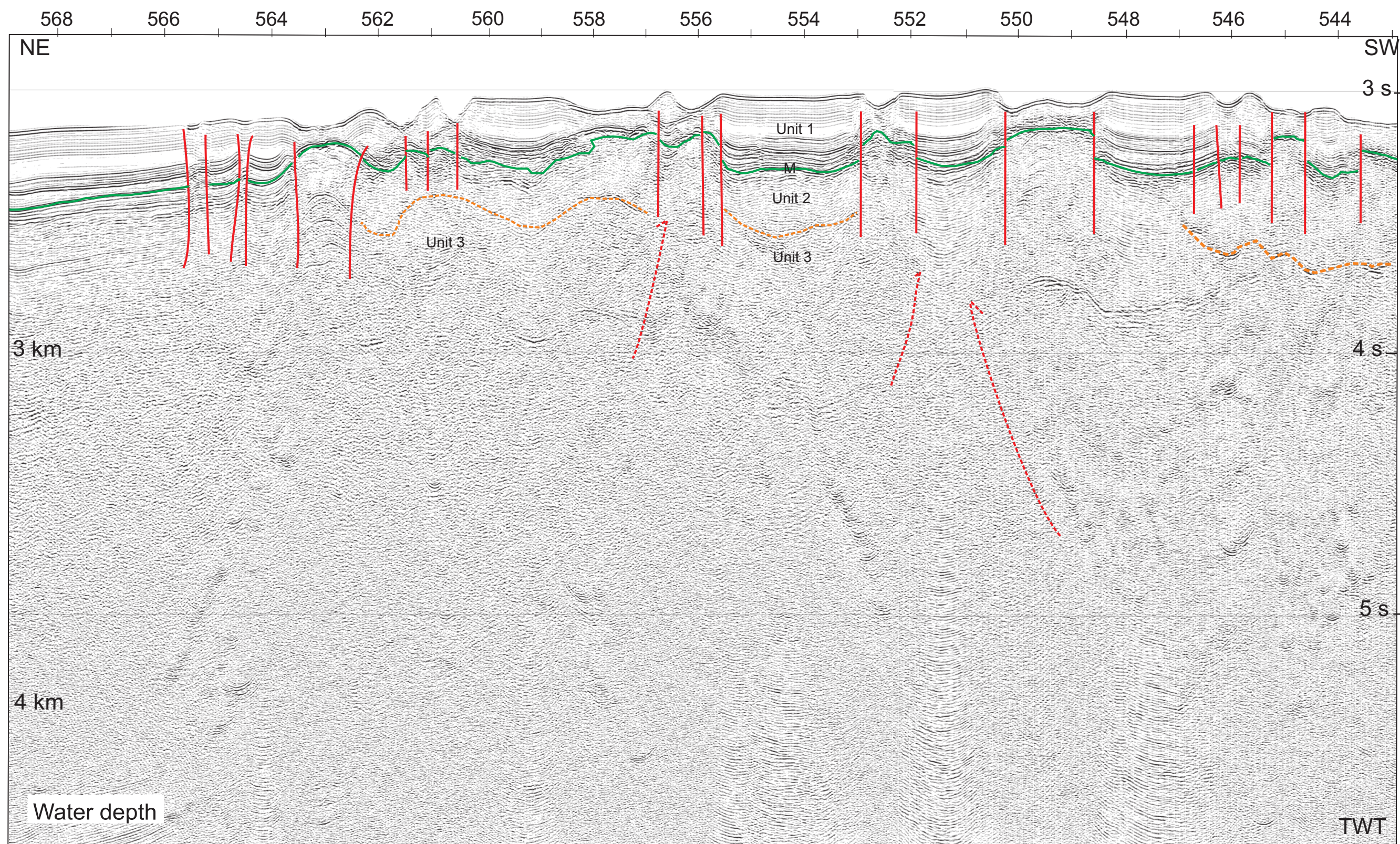
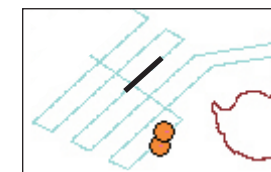


Figure 5.11 Seismic reflection profile (FIX 567-545).



(Figs. 5.13, 5.14). Yet, when the M-reflector is ignored and only the uppermost portion of the seismic profiles is taken into account, the sense of fault movement reverses, and one can make the argument that the foot wall of the faults occur at the basin sides of the faults. This dichotomy is also visible in the internal architecture of the Pliocene-Quaternary succession as explained herein: (i) the lower and middle subunits 1c and 1b display a concave reflection configuration where reflectors bend upward toward the edges of small basins created within the fault blocks, (ii) but, in several profiles the upper subunit displays a convex reflection configuration, with reflectors bending downward along the margins of the small basins and (iii) the mild unconformity that marks the base of the upper subunit 1a separates these two divergent reflection configurations (Figs. 5.13, 5.14).

Individual fault blocks within the domain have a width of ~500 m ->3000 m. Between adjacent fault blocks there is considerable change of thickness of the Pliocene-Quaternary succession, controlled by the topography of both the seafloor and the M-reflector (Figs. 5.10, 5.11). Within the fault blocks, the observed geometric pattern is such that the M-reflector forms prominent troughs and ridges, where troughs developed at the M-reflector occur immediately beneath elevated seafloor topographies, whereas ridges coincide exactly with seafloor depressions (Figs. 5.10, 5.11, 5.13, 5.14). Thus, the Pliocene-Quaternary succession is considerably thicker beneath the seafloor ridges than that observed beneath the adjacent seafloor depressions.

The three subunits of the Pliocene-Quaternary succession are clearly visible within this domain (Figs. 5.13, 5.14). The lower subunit is on average 90-213 ms thick. It shows mild to moderate onlap over the M-reflector, as well as some erosional down-cutting of the lower unit over the limbs of the troughs. A prominent angular unconformity is visible in the middle of the Pliocene-Quaternary succession and appears as a disconformity within the central segments of the troughs, but clearly truncates the two older Pliocene sequences on the limbs. The growth strata immediately below the unconformity are correlated with the middle Pliocene-Quaternary subunit 1b in the southern Antalya Basin (i.e.,

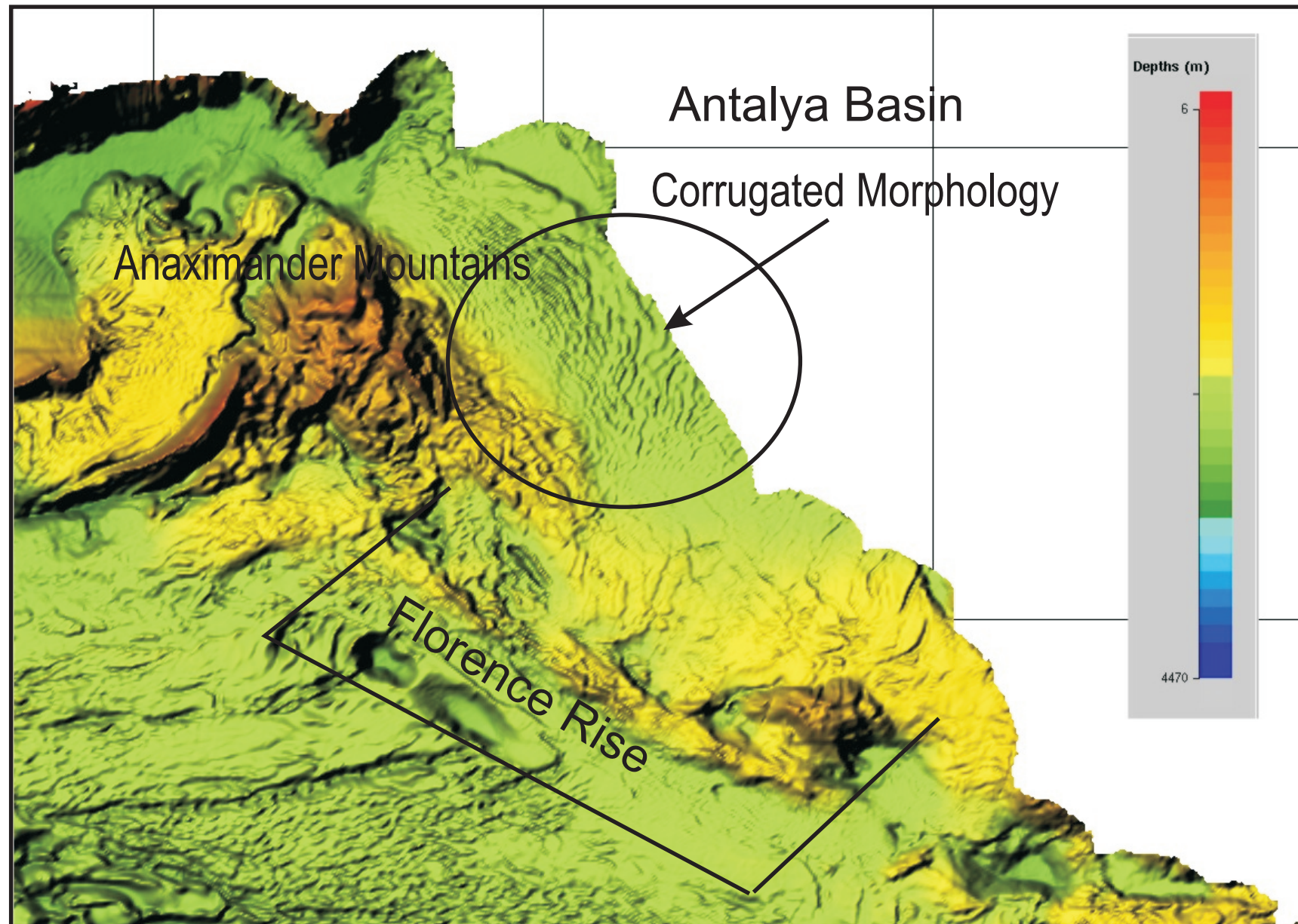


Figure 5.12 Showing the Corrugated Morphology of the seafloor in Domain 2 (from IFREMER, 2008).

Domain 1) where it reaches a thickness of ~100 ms. A 200-85 ms thick upper subunit 1a conformably overlies the unconformity and shows little thickness variation across the fault blocks. This morphology is very similar to that described in a similar domain in the Outer Latakia Basin (e.g., Calon et al., 2005).

The northwest-southeast and east-west trending high-angle fault zone records a complicated history of uplift and subsidence during the Pliocene-Quaternary, similar to that described in the Outer Latakia Basin (e.g., Hall et al., 2005; Calon et al., 2005). The structures below the unconformity in the middle of the Pliocene-Quaternary succession are attributed to folding and thrusting in the Pliocene, associated with the convergence between the African and Eurasian Plates. The middle Pliocene-Quaternary unconformity records a phase of uplift (but not emergence) of the entire region and the associated removal of the growth strata from the crests of the fold/thrust structures. The development of a prominent unconformity in the Florence Rise and environs, as well as in the eastern segment of the Cyprus Arc (Calon et al., 2005; Hall et al., 2005) suggest that this was a regional event. Here it is speculated that the docking of the Eratosthenes at the southern margin of the Island of Cyprus is the event responsible for the development of the middle Pliocene-Quaternary unconformity.

The phase of uplift and erosion that led to the development of the middle Pliocene-Quaternary unconformity is followed by a phase of subsidence, which continued for the duration of the deposition of the uppermost Pliocene-Quaternary subunit. The architecture of this fault zone suggests that the high-angle faulting overprinted the earlier fold/thrust structures and probably represents a strike-slip system with variable, but minor dip-slip movements.

5.2.3 Domain 3

Structures within Domain 3 consist of a series of at least four major northwest-trending, southwest-verging open and mildly asymmetric anticline-syncline pairs. These anticlines are represented by four prominent ridges E₉, E₁₀, E₁₁ and E₁₂, with the synclines represented by the basins X₆, X₇ and X₈ (Figs. 5.2, 5.16).

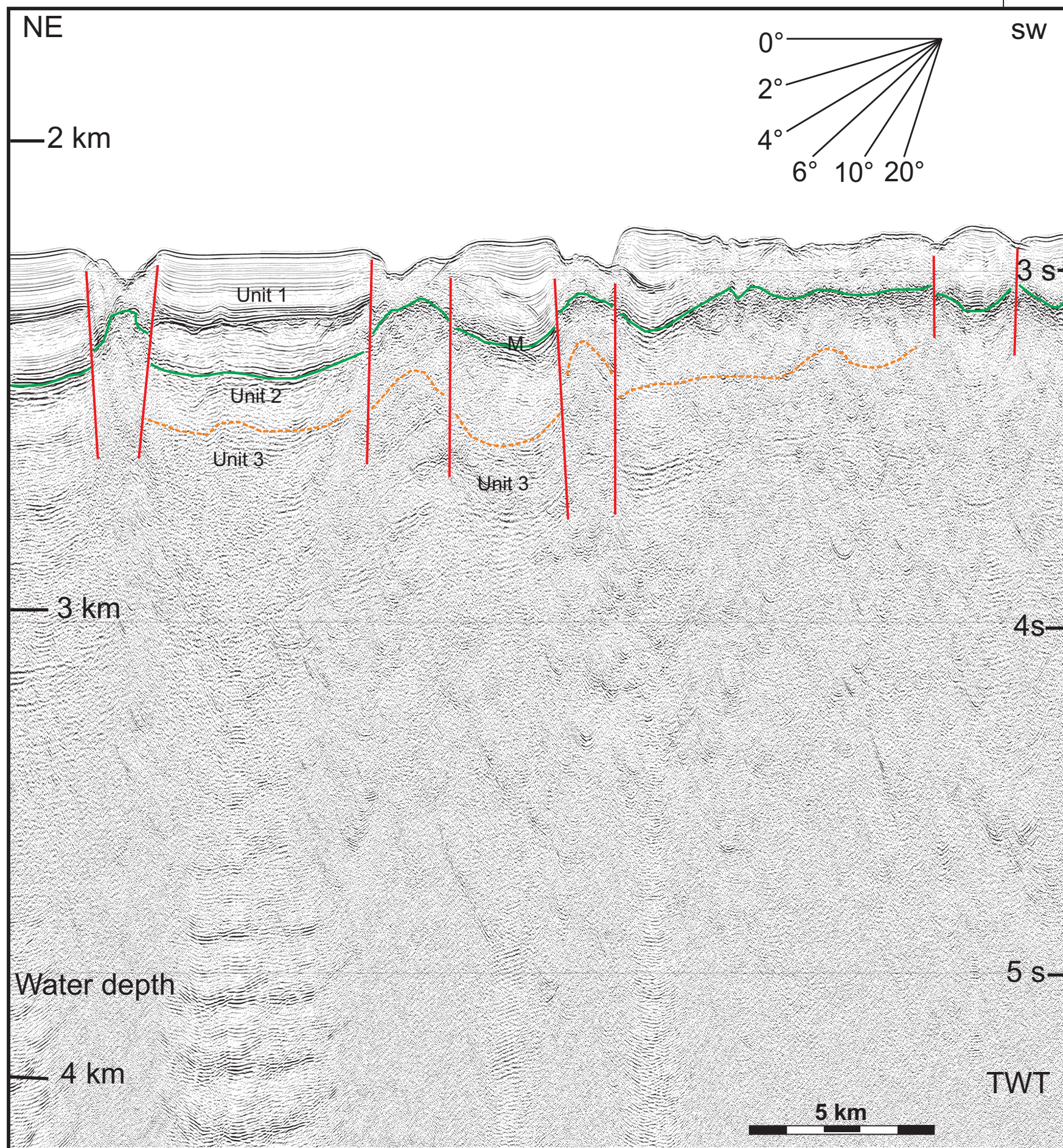
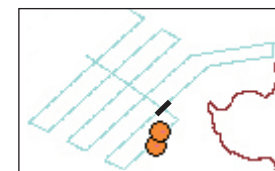


Figure 5.13 Seismic reflection profile (FIX 253-266).



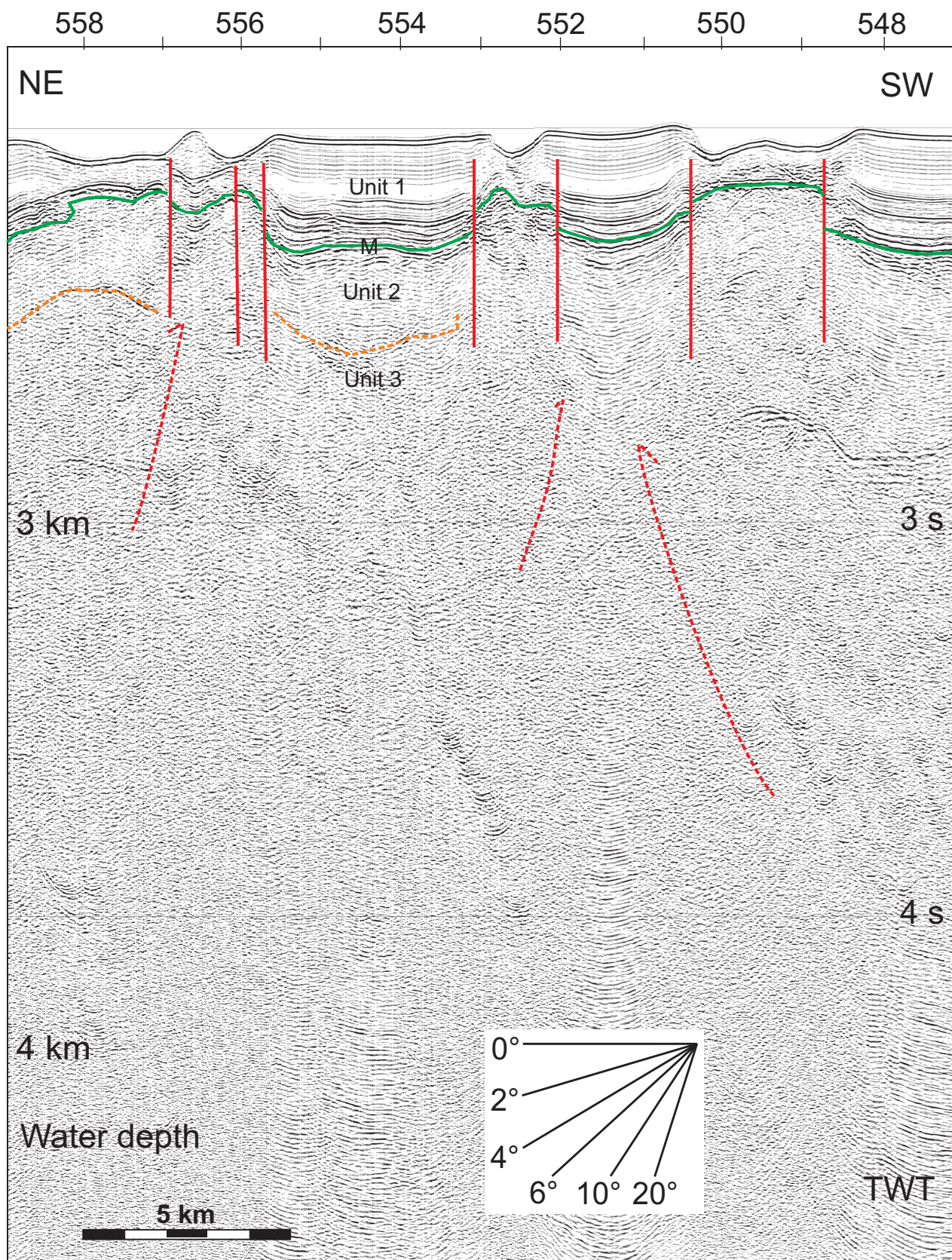


Figure 5.14 Seismic reflection profile (FIX 547-559).



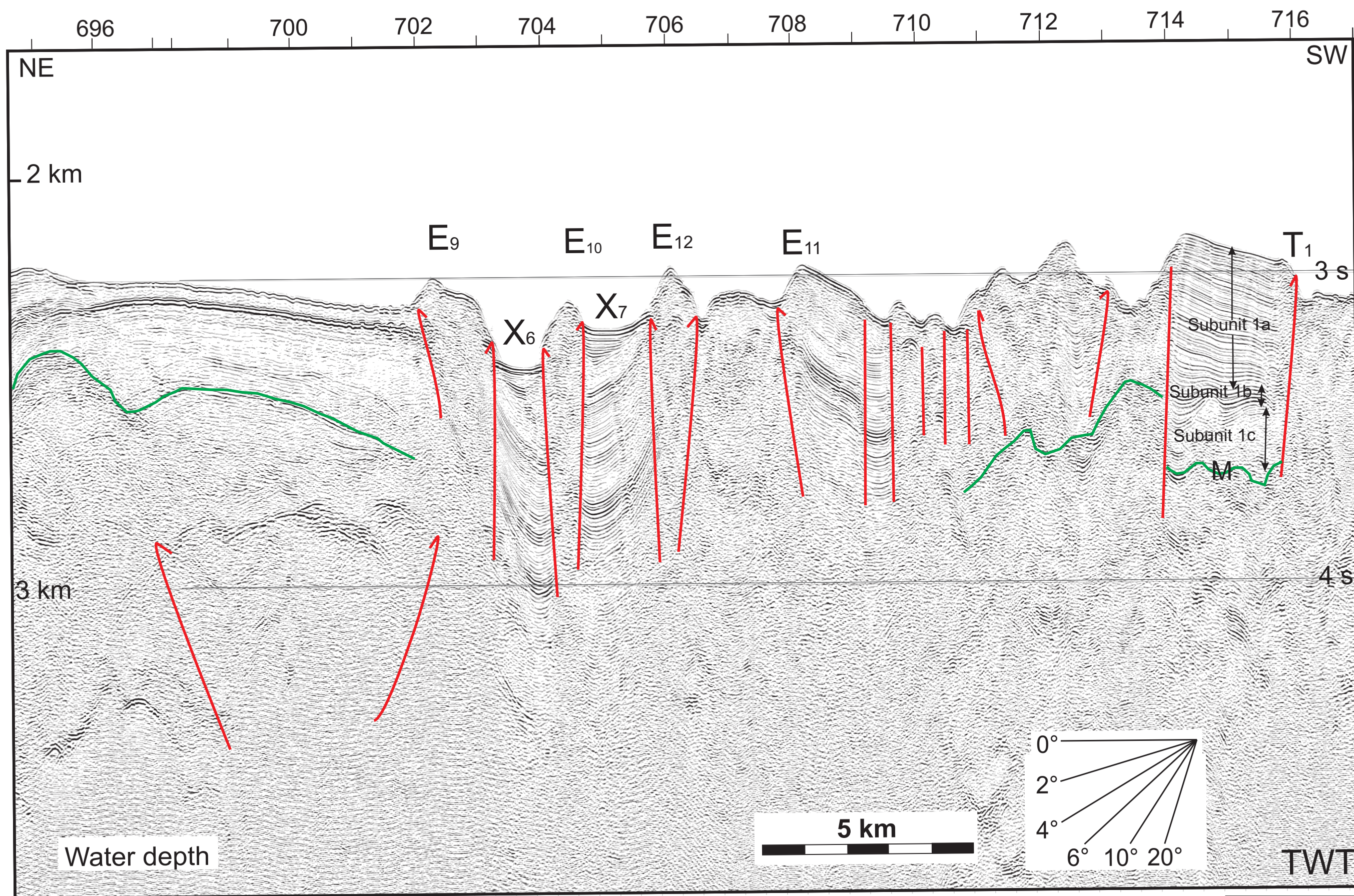


Figure 5.16 Seismic reflection profile (FIX 693-717).

These structures trend parallel to the overall strike of the Florence Rise, which defines the western segment of the Cyprus Arc. The anticlines display notably long, gently northeast-dipping backlimbs and shorter, but steeply southwest-dipping forelimbs, suggesting that these structures define a large southwest-verging fold system. In seismic reflection profiles where the folds are well imaged, the hinge traces of the folds invariably show moderate to gentle northeast dips, further supporting the southwest vergence of the fold system.

The geometry of structures within the core of the anticlines is poorly resolved in most seismic reflection profiles. However, there are several key profiles where the geometry is better imaged, allowing the delineation of the structural architecture of the anticline-syncline pairs (Figs. 5.15, 5.16). The stratigraphic framework and the structural architecture observed within the syncline-anticline pairs resemble the geometries observed in the previously-described fold-thrust belts (McClay, 1981; Jackson and McKenzie, 1984; Ori and Friend, 1984). Therefore, the discontinuities imaged within the core of the ridges are interpreted to represent thrusts, with the ridges defining ramp anticlines (Fig. 5.17). In this framework, the basins situated on the backlimb and forelimb of the thrust culminations represent the trailing and leading synclines, respectively. Careful correlation of seismic markers within Unit 3 between the leading syncline to the southwest and the crest of the anticline indicates ~ 400 -500 ms vertical separation. Similarly, correlation of seismic markers in Unit 3, as well as the M-reflector between the trailing syncline to the northeast and the leading syncline to the southwest, indicates ~ 100 -200 ms vertical separation (Fig. 5.16). This overall architecture of the anticlines, the stratal relationship within the leading and trailing synclines and the growth stratal architecture on both the backlimb and forelimb of the anticlines indicate the presence of northeast-dipping and southwest-verging thrusts seated deep in the core of the anticlinal structures.

In some profiles, the tips of the thrusts can be readily and invariably traced to the base of the M-reflector cutting the strata within the leading syncline, thus representing thrusts (Fig. 5.19). Yet in others, the thrust tips are inferred to lie well within Unit 3 in the partially imaged leading syncline, suggesting that these

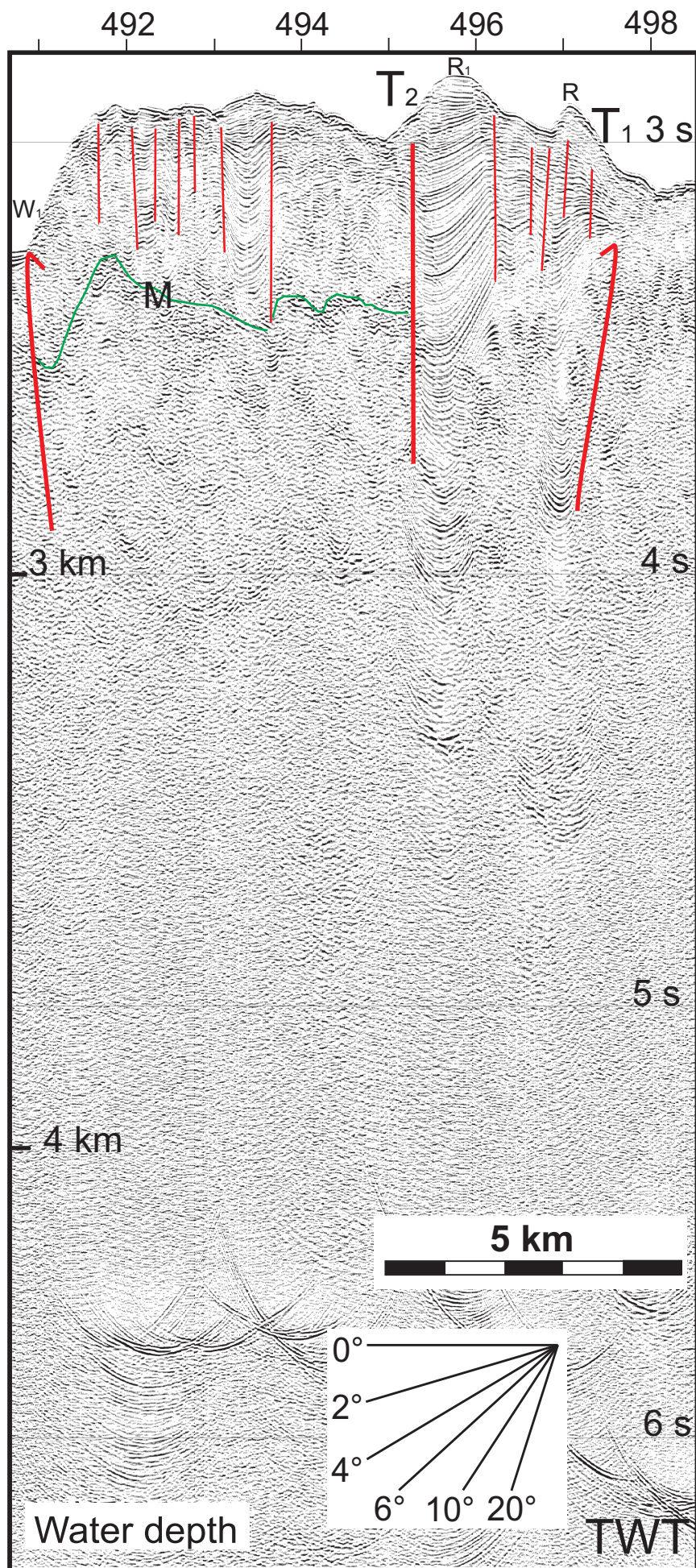


Figure 5.17 Seismic reflection profile (FIX 491-498).

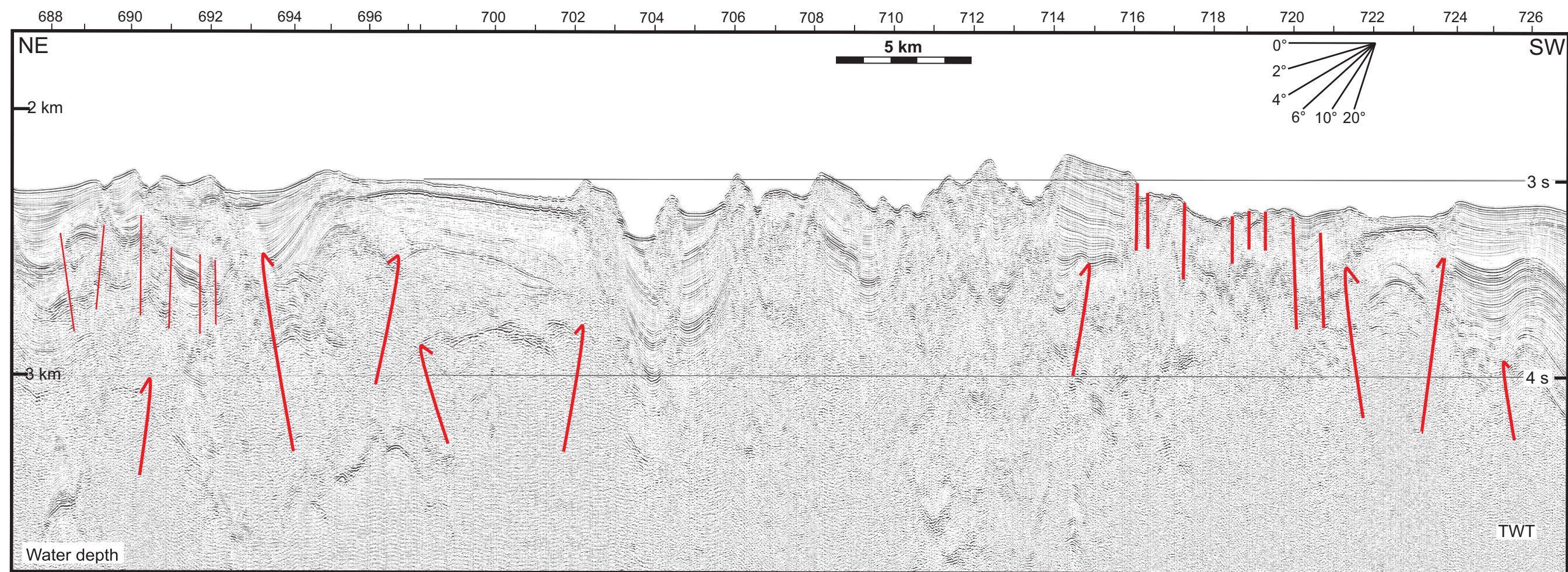
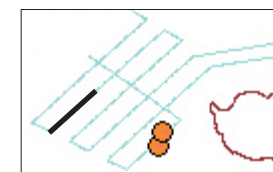


Figure 5.19 Seismic reflection profile (FIX 688-726).



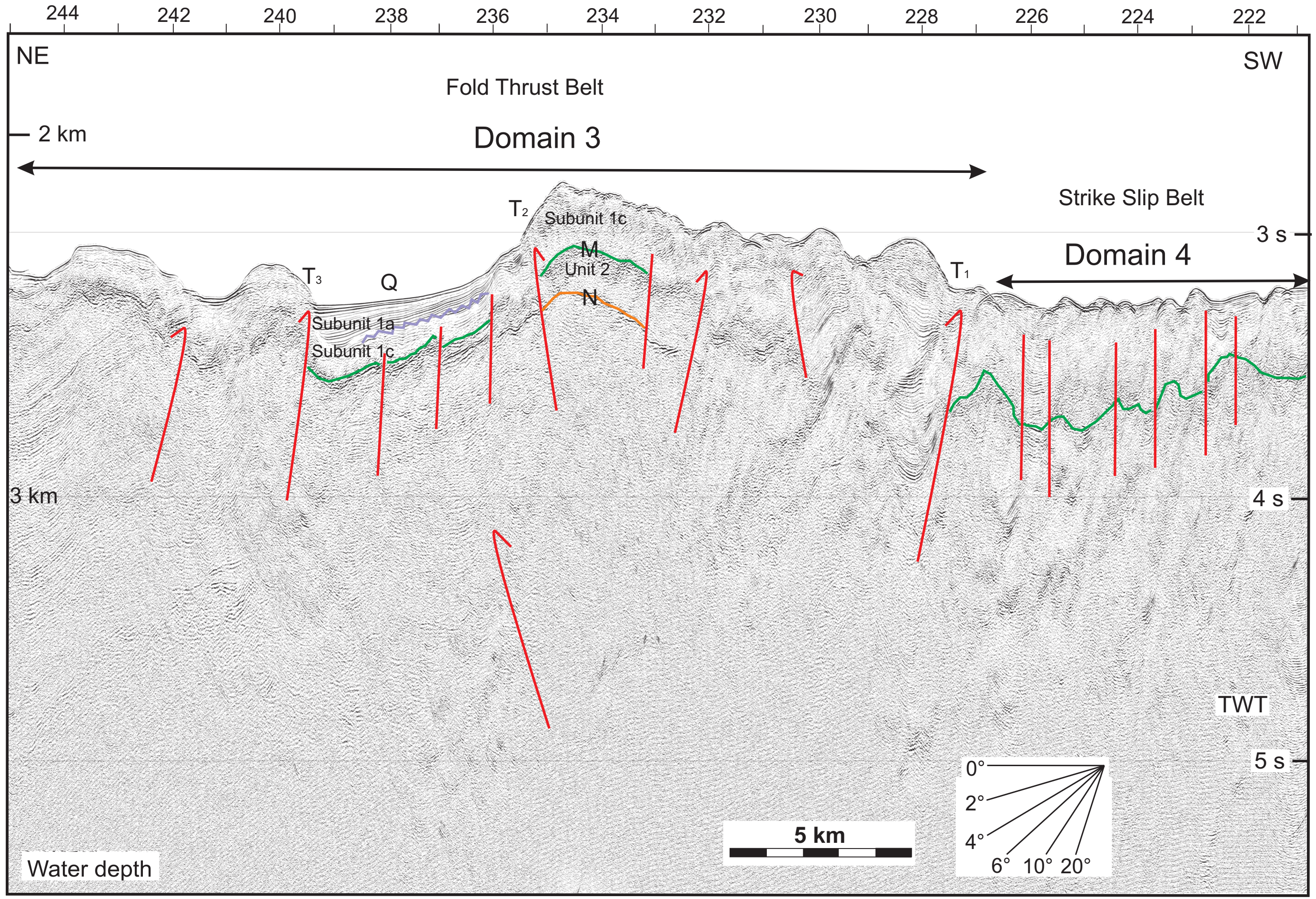
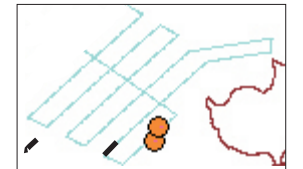


Figure 5.20 Seismic reflection profile (FIX 228-244).



represent blind thrusts (Fig. 5.19). The ridges described in Domain 3 are, thus interpreted to represent the apex of the hanging-wall ramp anticlines. Some well-imaged examples of these are illustrated in Figures 5.17 and 5.19. Note that in all these images, ridge $R_0 + R_1$ defines the crestal region of the hanging-wall ramp anticline of thrust T_2 , whereas the gently to moderately northeast-dipping backlimbs represent hanging-wall flats above the thrust surfaces. The large Pliocene-Quaternary depocentre basin Q, which is nestled on the backlimb of the ramp anticline, thus represents a piggyback basin carried by thrust T_2 (Fig. 5.20). The individual thrusts T_1 , T_2 and T_3 of the fold-thrust system occur beneath the most prominent ridges, E_9 , E_{10} , E_{11} and E_{12} , E_{13} , E_{14} respectively (Figs. 5.16, 5.19, 5.20). Splays with southwest-verging sense stem from thrusts T_1 , T_2 in the northwest and southeast from thrust T_3 in the south portion of the study area, and display map traces mostly parallel to the trend of the associated main faults (Fig. 5.2). They exhibit low-angle trajectories similar to that of the main thrusts and the tip points mostly lie below the middle Pliocene-Quaternary and below the M-reflector.

The intervening basins between the ramp anticlines, are referred to as piggy-back basins, which are carried above the imbricate thrust fault system. The sedimentary fill of these piggy-back basins contain Messinian to Recent deposits. The deposition of the Messinian to Recent strata is mostly contemporary with the activity of thrust faults, suggested by the growth strata wedges recognized throughout the sedimentary column of the piggy-back basins. Although, the mainly undeformed character of the lower Pliocene-Quaternary subunit through most of the study area provides evidence of a period of quiescence in the fault activity. However, occasionally, this subunit locally shows thinning towards the crest of the ridges, suggesting that the faults continued to grow during the deposition of this succession (Fig. 5.19). Various intra-stratal unconformities developed within the Pliocene-Quaternary succession separate growth strata packages and mark the stages of hiatus in the growth of the thrusts. These growth strata wedges developed on the backlimb and forelimb of the fold-thrust structures are bounded by several unconformities delineated by the prominent onlap of the mostly the lower/middle Pliocene to Recent succession over the flanks of the

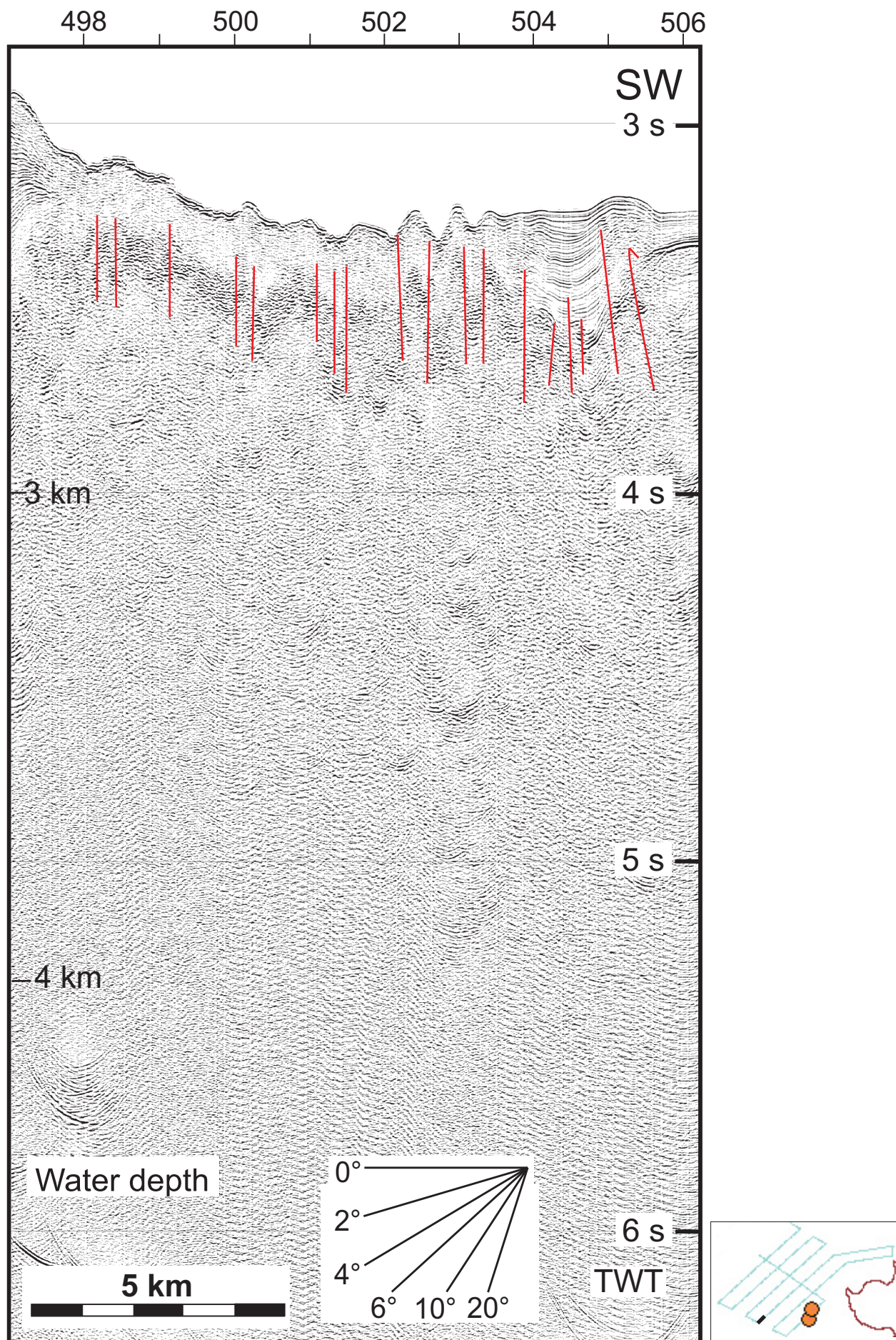


Figure 5.21 Seismic reflection profile (FIX 498-506).

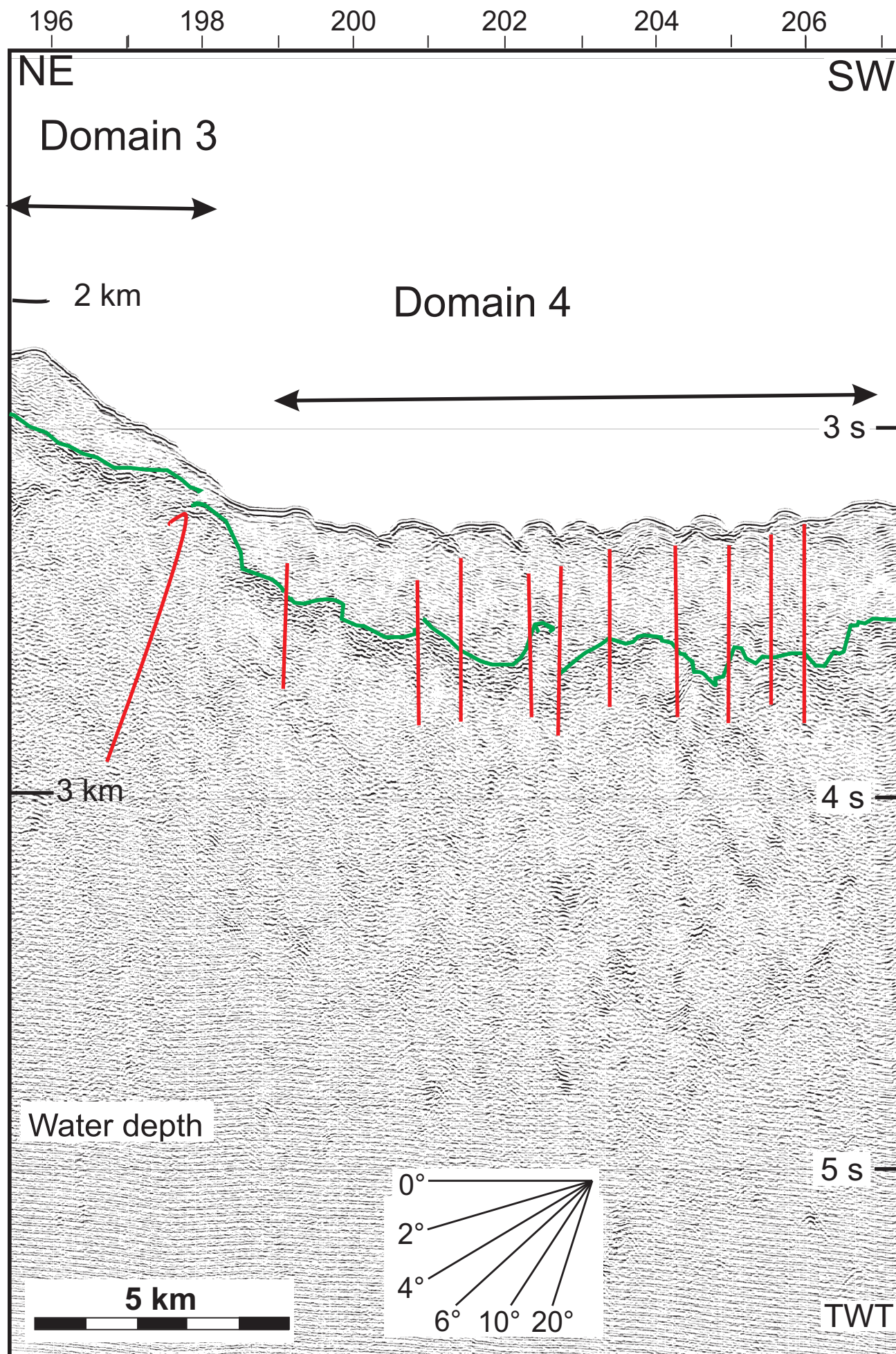
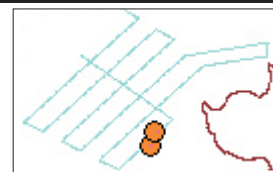


Figure 5.22 Seismic reflection profile (FIX 199-207).



ridges or the underlying pre-growth strata (Fig. 5.19). This character of the unconformities show remarkable resemblance to that of progressive unconformities as described by Riba (1976). Progressive unconformities are inferred to develop associated with growth of the thrust-related folds during sedimentation (Suppe et al., 1992; Hardy and Poblet, 1994) and they represent changes in rate of uplift assuming constant sedimentation rate.

In summary, the overall structural framework of Domain 3 is characterized by three prominent northwest-southeast striking, southwest-verging thrust and northeast-verging thrust faults with several minor splays, which display curvilinear, south-convex traces on the map throughout the study area (Fig. 5.2). The thrust sheets are 900-1200 ms thick and consist of sediments of Units 3 and 2. These thrusts override one another in the transport direction and define a stacked imbricate fan. The thrust faults exhibit low-angle trajectories, of which only the uppermost portion could be imaged in the seismic reflection profiles. Except a small number of break thrusts, most represent blind thrusts with tip points located mostly within Unit 3 below the M-reflector.

5.2.4 Domain 4

This structural domain lies immediately south of the Florence Rise and associated with the Mediterranean Ridge accretionary complex. It is characterized by corrugated seabed, indicative of closely-spaced sub-vertical faults that displays highest degree of deformation, both on the surface (Multibeam bathymetry of the Florence Rise and environs, from Loubrieu et al., 2000) and the seismic lines (Figs. 5.2, 5.20). In this domain, deformation is clearly still active because sea floor is affected caused by strike-slip faulting on the northern margins of the ridge, in agreement with the earlier findings of Woodside et al. (2002).

The northernmost thrust and backthrust panels in domain 3 delineate the boundary between domain 4 in the southwest (Figs. 5.20, 5.21, 5.22,) and these thrust panels in Domain 3 sharply offset the M-reflector, creating 800 ms vertical separation from the central of the Florence Rise to outer Florence Rise in Domain

4 south of the study area. In seismic profiles, this domain appears narrowly-spaced imbricates and are characterised by faint discontinuous reflections showing tight regular fold geometries (Fig 5.20).

The Pliocene-Quaternary architecture of Domain 4 is characterized by a corrugated seafloor morphology that is created by a series of small tightly-spaced depressions and ridges (Fig. 5.20, 5.21) The M-reflector is also folded and sharply segmented across adjacent synclines and anticlines. The overall folded appearance, and the segmentation of the M-reflector and several distinct markers within the Pliocene-Quaternary succession, are created by a series of strike-slip faults. These faults produce 50-150 ms vertical separation on the M-reflector and extend into the underlying Unit 3. The faults also extend into Unit 1, and form progressively smaller vertical offsets of distinct markers from the base toward the top of the Pliocene Quaternary succession. Tip points of these faults generally lie within the upper portion of Unit 1 ; however, in several instances, the tip.

CHAPTER SIX

DISCUSSION

In Chapters 2-3 the results of multi-channel seismic reflection profiles from the Florence Rise in eastern Mediterranean Sea were presented. These results show that the Florence Rise varies along strike in sometimes complicated fashion. The feature is generally composed of a 'core' ridge (Fig. 1.1, 4.2) which narrows and deepens westward, but generally follows the arcuate form of the Florence Rise from Cyprus to the Anaximander Mountains, which are commonly associated with plate tectonic activity. Within the regional tectonic setting of the eastern Mediterranean, a number of hypotheses have previously been proposed for the Neogene evolution of the Florence Rise, mostly concentrated around of the Antalya Basin and the Anaximander Mountains. However the Miocene to Recent kinematic evolution of the Florence Rise is still poorly understood, primarily because most previous investigations have been exploratory in nature, and lack rigorous and systematic mapping of large-scale structural elements. In this chapter the results presented above will be combined with previous investigation in order to delineate the kinematic history of the Florence Rise.

6.1. Kinematic evolution of the Florence Rise

The data presented in this study provide information on the seismic stratigraphic architecture of the Pliocene-Quaternary basins-ridges and the Miocene structures. In addition the temporal tendency of the structural results reveals a tectonic model of the Miocene to Recent evolution of the Florence Rise within the tectonic framework of the eastern Mediterranean. The deformation in the Florence Rise transpired primarily as the result of compressional stresses (Figs. 5.1 and see Appendix). Mobilization of the Messinian evaporites also played an important role in basin evolution, although it is not yet possible to quantify the amount of deformation caused by halokinesis.

6.1.1. Miocene (*pre-Messinian*)

The architecture of the pre-Messinian fold/thrust structures within the core of the Florence Rise are characterised by broadly ESE–WNW trending large ramp anticlines above SSW-verging blind thrusts developed within Unit 3 (Fig.5.1). The large thrust sheets T₁, T₂, T₃ and T₄, and their associated ramp anticlines R₁, R and carrying piggyback basins Q to the south, S₃, S₄, Y₁, Y₂ and X₁, X₂, X₃, X₄ to the north, collectively show a protracted contractional deformation throughout the deposition of Miocene Unit 3. During the middle-late Miocene, the uppermost segment of Unit 3 is tentatively correlated with the Karpuzçay, Geceleme and Oymapınar formations of the onland Aksu and Manavgat Basins (Fig. 4.4; Akay et al., 1985; Karabıyıkoglu et al., 2000). The uppermost segment of Unit 3 is also correlated with the predominantly turbidite succession (marls and marly chalks) of the Kythrea Group in the Kyrenia Range and its lateral equivalent, the Pakhna Formation of the Mesaoria Basin (Fig. 3.5; Robertson, 1998). During the middle-early Miocene, the lower portion of Unit 3 may include a diverse collection of regional lithostratigraphic units ranging from the lower Mesozoic to upper Oligocene.

Middle to late Miocene regional compression led to the development of a major northwest-southeast-oriented arcuate fold-thrust belt, which can be traced west across of the Cyprus Arc (Fig. 5.1). The structures associated with this late Miocene compression are clearly documented in the core of the Florence Rise. During the early-middle Miocene, the convergence vector between the African Plate and the Anatolian segment of the then Eurasian Plate was nearly orthogonal to this trend (e.g., Wdowinski et al., 2006) and the entire region was situated within a predominantly compressional tectonic regime. During the late Miocene, the northwestern Florence Rise and the Anaxagoras Mountain probably experienced a small amount of clockwise rotation to assume a broadly NW–SE trend, associated with the Aksu Phase of deformation that also shaped the eastern margin of the Isparta Angle (e.g. Poisson et al., 2003). This NW-SE trend is documented both in this study and in the previous studies of the Anatolia Basin (İşler et al., 2005) (Fig. 4.2). The

clockwise rotation is complemented by a counterclockwise rotation in the western portion of the Anaximander Mountain (e.g. Aksu et al., 2009). These tectonic deformation are related to the progressive adjustment of the collisional/compressional plate interaction along the Florence Rise, between the westward moving Cyprus domain and the northeast moving African Plate.

6.1.2. Messinian

The majority of eastern Mediterranean Basins contain a thick sequence of Messinian evaporites (e.g. the Antalya, Cilicia, and Ionian basins), which formed as a result of the Messinian salinity crisis during the isolation of the Mediterranean from the rest of the world oceans. In the Florence Rise this event is represented by the M-reflector (top of the Messinian) and the N-reflector (base of the Messinian), which is an angular unconformity truncating the folded strata of the Miocene Unit 3. Based on the multi-seismic data presented here the thickness of the Messinian evaporites range between ~2500-3000m. This is comparable with observed thickness of the Messinian evaporites elsewhere in the Eastern Mediterranean, which range from 3000 m in the Herodotus Basin, to ~2500 m in Antalya Basin (Biju-Duval et al., 1978), to ~1000 m in the Cilicia and Latakia Basins (Aksu et al., 2005 ; Hall et al., 2005).

The generally interpretation of the existing seismic reflection profiles show that the Messinian salt unit (Unit 2) can be divided into two subunits, termed Subunit 2a and Subunit 2b. Overall Unit 2 show a variable distribution across the Florence Rise, from west of the Cyprus to southeast of the Anaxagoras Mountain. The presence of subunit 2a on the flanks of the early subunit 2b highs, or on Miocene fold structures where subunit 2b is absent, show that local re-activation of the fold-thrust belt occurred during the deposition of the upper evaporitic subunit 2a.

6.1.3. Pliocene-Quaternary

A number of the pre-Messinian structures were reactivated during the Pliocene-Quaternary. These structures define the present-day morpho-tectonic domain

boundaries in the study area (Fig. 5.1). The base of the Unit 1 is marked by a major angular unconformity. On the basis of its acoustic character and stratigraphic position at the base of the upper unit, this unconformity is correlated with the M-reflector, which is representing the ultimate desiccation of the Mediterranean basin during the Messinian (Ryan et al., 1966; Hsü et al., 1978). The M-reflector truncates the underlying folded strata of Unit 3, or Unit 2 where the Messinian evaporites are present, suggesting that the fold-thrust activity continued into the Messinian and this activity pre-dates the development of the M-unconformity. The Pliocene-Quaternary subunits were deposited above the M-reflector as the post-growth strata relative to the Miocene fold/thrust activity in the core of the Florence Rise.

During the deposition of the early/middle Pliocene-Quaternary to Recent strata, the fault activity in the Florence Rise is constricted to four morphological and structural domains, located in the northern, central and southern portions of the Florence Rise. The thickness of the Pliocene-Quaternary is represented on isopac map result of the correlation of the DSDP Sites 375-376 and seismic reflection profiles (Fig. 4.9).

The northern portion of the Florence Rise in Domain 1 occupying the northern portion of the study area is correlated with south of the Antalya Basin. This portion is characterized by a corrugated seafloor morphology which broadly delineate numerous E-W trending quasi linear deep troughs and their intervening ridges (Fig. 4.1). The external geometry within Units 2 and 3 of the ridges are still preserved in the lower to upper Pliocene-Quaternary succession, with the reflectors showing dramatic thinning and occasionally draping over the M-reflector. Similar structures are described by Işler et al. (2005) in the Antalya Basin, as well as Hall et al. (2005) in the Cyprus Basin. Such structures are usually associated with transpressional deformation (e.g. Harding and Lowell, et al., 1983). Domain 2 is located above the core of the Florence Rise and is characterized by complex stratigraphic and structural architecture expressed primarily in the Pliocene-Quaternary succession (Figs. 5.10, 5.11), primarily prominent high-angle faults (Figs. 5.10, 5.11). The central region of the Florence Rise (Domain 3) is a Pliocene- Quaternary succession interpreted as a

broad, arcuate and narrow WNW-ESE trending high on a morpho-bathymetric map (Fig. 5.1). The Pliocene-Quaternary succession in this region (Unit 1) is correlated with DSDP Sites 375-376 (Shipboard Scientific Party, 1978). On the basis of its internal seismic character and stratigraphic architecture Unit 1 is divided into three subunits. The deposition of the Messinian to Recent strata is mostly contemporary with the activity of thrust faults, suggested by the growth strata wedges recognized throughout the sedimentary column of the piggy-back basins.

In summary, the comparison of seismic reflection profiles of the Pliocene-Quaternary successions show that the period of activity on the flower structures is highly variable spatially and temporally. Where present, the Recent fault activity is represented by small-scale inflections on the sea-floor (Figs. 5.1, 5.6a, 5.6b, 5.10, 5.19). The transpressional fault activity is interpreted to be related to the collision of the Eratosthenes Seamount with Cyprus during the early Pliocene to Recent (Ben Avraham et al., 1988). Eratosthenes Seamount is continental in character (Robertson, 1998), thus, has choked the subduction along the Cyprus Arc, generating a transpressional stress field (Harding et al., 1983). The overall deformation history of the Pliocene-Quaternary strata suggests that the plate strain is strongly partitioned in the Pliocene-Quaternary.

6.2 Previous Models and Comparisons with the Author's Model

Woodside (1977) interpreted widely-spaced single channel seismic reflection profiles and gravity data across the eastern Mediterranean Sea to show that the large scale tectonic elements, such as the Florence Rise, the Kyrenia-Misis Mountains and the Eratosthenes Seamount partitioned the eastern Mediterranean into several separately-evolving basins. He combined other geological and geophysical data to show that the crust across the eastern Mediterranean is transitional in character (i.e. between oceanic and continental) and suggested that it probably represents the thinned and attenuated northern margin of the African Plate. Woodside (1977) also pointed out the presence of several prominent features of the African-Anatolian convergence, which suggest underthrusting of the Turkish Plate by the African Plate

These include the morpho-tectonic character of the Florence Rise and Anaximander Mountains, the northward tilting and subsidence of the Antalya and Finike Basins and the apparent continuation of the Strabo Trench south of the Florence Rise. However, he further noted that there is insufficient seismicity across the African-Anatolian Plate boundary, no active volcanic arc and that the trench is rather poorly developed, which is not consistent with active subduction. Therefore, he speculated that normal subduction probably ended within the past 5 Ma and that along the northern fringe of the African Plate former oceanic crust has disappeared. Woodside (1977) argued that modern plate convergence continues with only limited underthrusting of African Plate along the Cyprus Arc, with regional deformation along zones of weakness within a ~300 km wide band stretching from the Herodotus Basin eastward along the northern edge of the African/Arabian Plates. The model presented in this study partially supports the findings of Woodside (1977). For example, the broad northwest-southeast trending imbricated thrust sheets show a protracted contractional deformation from Miocene until Recent, compatible with continued, although limited, convergence and contraction between the African Plate and the Aegean-Anatolian Microplate.

Woodside et al. (2002) analyzed the PRISMED II data set, comprising of full EM12D multibeam bathymetric coverage between Cyprus and the Anaximander Mountains, high resolution seismic reflection data, and continuous gravity and magnetic observations. Lines were run perpendicular to the rise between the Antalya Basin in the north and the Herodotus Basin in the south. The main findings of Woodside et al. (2002) and their reinterpretation in light of the data presented in this study are as follows:

1. The Florence Rise, which separates the passively subsiding Antalya Basin from the collisional tectonics to the south and southwest, was considered to be a relict of prior subduction. The model presented in this study partially supports these findings of Woodside et al. (2002).
2. Woodside et al. (2002) argued that the boundary between the Anatolian and African plates in this region was likely to be more or less sutured. However continuing deformation would have broadened into a zone which extends

right across the Florence Rise, but which is a wrench zone (inferred to be a dextral wrench system) (Fig. 6.1a). In contrast, according to the our seismic data interpretation, continuing deformation has broadened into Domain 3 which extends across the Florence Rise as a shear zone which inferred thrusts that uplifting core of the Florence Rise in Domain 3 (Fig. 6.1b).

3. Tectonic deformation was related to the progressive adjustment along the Florence Rise of the collisional/compressional plate interaction between the westward moving Cyprus domain and the northeast moving African Plate (Woodside et al. 2002). Our observations supports and evidences result of the interpreted multi channel seismic data and to contracted a detailed tectonic architecture on maps of tectonic structures
4. A large proportion of the current deformation was considered to be passive superficial deformation caused by the invasion of thick sediments from the Herodotus Basin and Mediterranean Ridge into the area of the Florence Rise (Woodside et al. 2002), and that a large part of the ‘shearing’ in Zone C was only superficial shearing in a ‘flowing’ mass of Mediterranean Ridge sediments. As known, in the eastern portion of the Cyprus Arc, a sinistral sense of shearing was suggested along the northern margin of the African Plate. The transition from sinistral movement in the east to the dextral movement in the west probably occurs immediately west of Cyprus where a large fault zone with thrust component is inferred from focal mechanisms solutions (Papazachos and Papaioannou, 1999). This interpretation is substantiated by the interpreted detailed tectonic architecture and on maps of isopac of Pliocene-Quaternary and tectonic structures presented during this study.
5. Mud volcanoes on the Florence Rise were found by Woodside et al. (2002) within the principal zones of shearing and on associated faults. Our seismic reflection profiles show no evidence for any significant mud/gas diapirs in boundary of this thesis study area.

Sage and Letouzey (1990) used ~6500 km of industry seismic reflection data and documented the presence of at least two northwest-trending, north-dipping, south-verging crustal-scale thrust panels in Antalya Basin north of the Florence Rise. They linked these thrust panels with the schematic stratigraphic cross-sections of Biju-Duval and Dercourt (1980) and further correlated these crustal-scale elements with the major onland Upper Cretaceous to Recent thrusts of the Kyrenia Range of Cyprus, which dominate the geology of the onland segment of the north-eastern Mediterranean. Sage and Letouzey (1990) further suggested that this arcuate imbricate thrust belt defines the basement of the Oligocene to Quaternary deep basins such as the Rhodes, Antalya, Cilicia and Adana Basins. They also delineated several south-verging crustal-scale thrust panels across the present-day boundary of the African Plate and Aegean-Anatolian Microplate and suggested that the Florence Rise constitutes the topographic expression of the accretionary prism. The crustal-scale contractional deformation presented by Sage and Letouzey (1990) is entirely compatible with the model presented in this study. However, the detailed architecture of the contractional deformation in the Antalya Basin marked by four to five imbricate thrust panels presented by İşler et al, (2005) and the three to four imbricate thrust panels present on north of the Florence Rise where in this study, is not found in the Sage and Letouzey (1990) maps. Furthermore, Sage and Letouzey (1990) only presented an instantaneous kinematic solution, and therefore the temporal and spatial partitioning of strain is not discussed by these authors.

Papazachos and Papaioannou (1999) used the spatial distribution of shallow-and intermediate-depth earthquake data to document a continuous boundary between the Eurasian and African Plates across the eastern Mediterranean Sea. They calculated fault plane solutions using recent earthquake data and determined the character of relative plate motion. Papazachos and Papaioannou (1999) plotted the focal depth of intermediate earthquakes along a line that crosses the Antalya Basin in a southwest-northeast direction and observed that the plot points out the presence of a well-defined Benioff Zone dipping in a northeast direction. They also demonstrated the presence of a north-northeast striking dextral transform fault with a thrust component west of Cyprus, the Paphos Transform Fault. They suggested that this fault connects

two concave segments of the plate boundary: the east-northeast trending Cyprian Arc which links with the Eastern Anatolian Transform Fault in southeastern Turkey, and the west-northwest striking Florence Rise which joins with the Rhodes Fault further northwest.

Mascle et al. (2000) used multibeam swath bathymetry in conjunction with single channel seismic reflection profiles from offshore Egypt and showed the presence of a belt of N145°E trending, crustal-scale right-lateral transtensional faults that obliquely transect the eastern Nile deep-sea fan. They interpreted this fault zone as to define the western boundary of a newly-defined Sinai-Levantine Microplate which represents a segment of the African craton disconnected from the African plate as a consequence of the collision between the Eratosthenes Seamount and Cyprus. They showed that this microplate moves independently from the surrounding Arabian and African Plates, and the Anatolian-Aegean Microplate, along the Dead Sea Transform Fault to the east, the Cyprus Arc to the north and the Suez Rift System in the west-southwest. Although the N145°E trending transtensive faults identified by Mascle et al. (2000) does not overlap geographically with the north-northeast striking transform right-lateral fault with a thrust component identified in offshore southwestern Cyprus by Papazachos and Papaioannou (1999), they display similar characteristics in terms of their relative sense of movement, hence yield a possibility that they may represent a common boundary. Despite considerable efforts, the anatomy of this complex plate boundary is still not completely understood. The data presented by Papazachos and Papaioannou (1999) and Mascle et al. (2000) bring us a step closer to resolving geometric relationships of large tectonic elements in this region. Clearly, new data are needed to confirm the linkage between the Paphos Transform Fault, the unnamed western boundary fault of the Levantine-Sinai Microplate and the Florence Rise. The transpressional deformation documented in the northern segment of the study area is believed to be somehow related to these right-lateral faults, although a better understanding of these structures again requires denser seismic grid as well as additional more seismic reflection data are needed direction of northwest-southeast or west-east.

The most recent study by Aksu et al, (2009) postulate that during the Pliocene-Quaternary the Anaximander Mountain (*sensu stricto*) and the Anaximenes Mountain developed as the result of reactivation and uplift and rotation of a linked, thick-skinned pre- Messinian imbricate thrust fan. In both regions, the development of back thrusts accentuated the morphology of these submarine mountains. At this time, the Anaximenes Mountain experienced a progressive counterclockwise rotation, while the Anaxagoras Mountain and the Florence Rise experienced a clockwise rotation creating the present-day arrowhead-shaped morphology of the Anaximander Mountains (*sensu lato*). Also they delineated NW-SE trending thrust southern boundary of the Florence Rise. These major thrusts also defined in this study and southern margin of the Anaxagoras Mountain. The late Miocene structural framework across the Anaxagoras Mountain and the Florence Rise was characterised by an approximately E–W trending fold–thrust belt, in keeping with the structural architecture across the northeastern Mediterranean region, such as the Antalya Basin (İşler et al., 2005), Cilicia Basin (Aksu et al., 2005), Cyprus Arc and Tartus Ridge (e.g. Hall et al., 2005). On the seismic reflection profiles, structural map and the morpho-bathymetric map presented in this study show the same observations as Aksu et al, (2009).

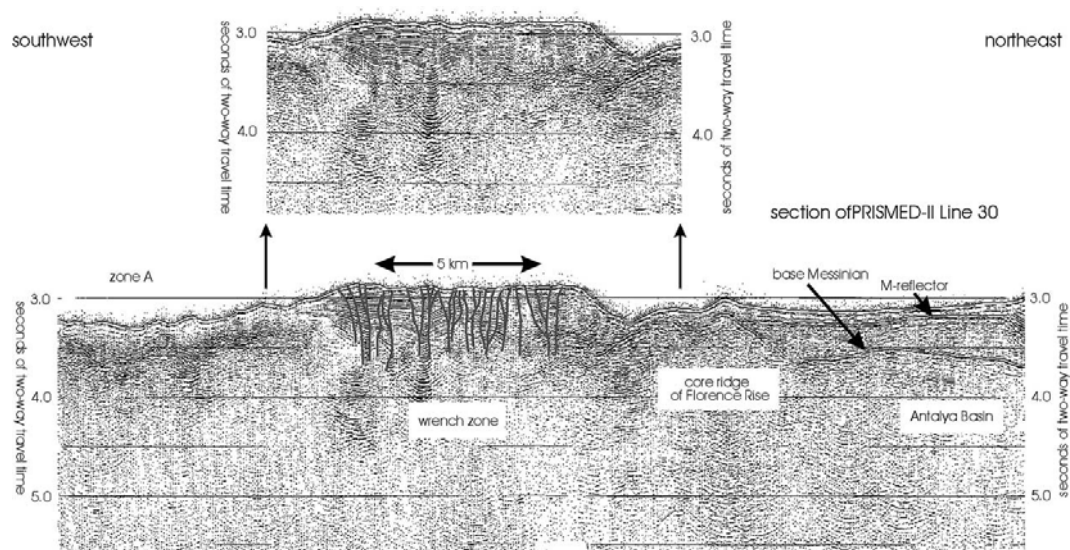


Figure 6.1a (Woodside et al, 2002).

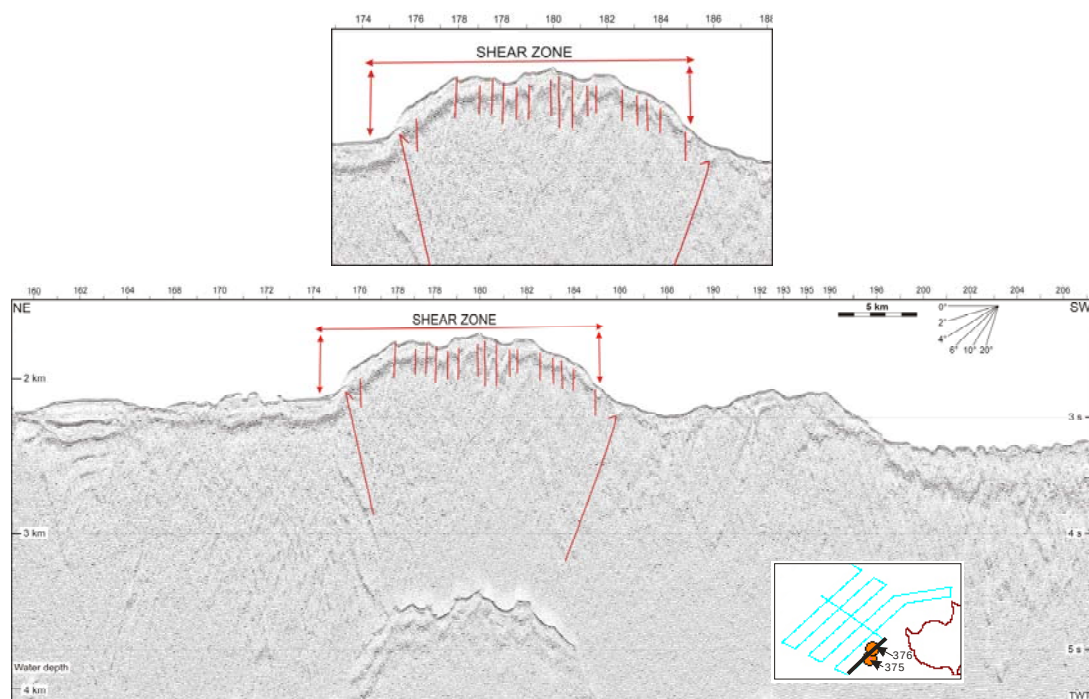


Figure 6.1b Showing the reflection profile on Line 2.

CHAPTER SEVEN

CONCLUSIONS

The Florence Rise in the eastern Mediterranean Sea were surveyed by high resolution seismic profiling during a research cruise in 2007. Based on detailed mapping of the prominent structural conclusions of the Florence Rise, thorough interpretation of the temporal and spatial development of these structural elements and the analysis of the seismic stratigraphic of the Pliocene-Quaternary architecture a number of salient conclusions can be made regarding the Miocene to Recent tectonic evolution of the Florence Rise.

1. Regional compressions during the Middle to Late Miocene resulted in the development of several major northwest-southeast trending and northeast verging thrust culminations in Unit 2 and Unit 3. These culminations define the ramp anticlines of the underlying buried thrust faults. This overall structural architecture is interpreted to define a crustal-scale imbricate fold/thrust belt.
2. The deposition of the evaporites (Unit 2) in the Florence Rise took place during the Messinian. The final desiccation of the Mediterranean Sea at the end of the Miocene and the subaerial exposure of the sea-floor at that time resulted in the development of a major erosional surface, represented by the well-defined angular unconformity on the seismic reflection profiles, the M-reflector.
3. The stable southwest-verging character of the fold/thrust belt throughout the study area suggested a major phase of contractional deformation during the middle-late Miocene. A fundamental change in kinematic regime occurred during the transition from the Miocene to Pliocene-Quaternary. In the central portion of the Florence Rise, the fold-thrust belt displayed a protracted activity from the early Pliocene to Recent with intervals of accelerated

growth during the middle Pliocene-Quaternary. Whereas, in the central portion of the Florence Rise the cessation of the fold/thrust activity occurred in the latest Miocene.

4. From the northern portion of the Florence Rise to the southern portion of the Antalya Basin, the Recent fault activity is represented by small-scale inflections on the sea-floor. The transpressional fault activity is related to the collision of a continental fragment, the Eratosthenes Seamount, with Cyprus during the early Pliocene to Recent. As a result subduction along the Cyprus Arc was choked, generating a transpressional stress field. The overall deformation history of the Pliocene-Quaternary strata suggests that the plate strain is strongly partitioned in the Pliocene-Quaternary.
5. Four morphologic and structural domains are recognised in the study area, based on multibeam bathymetry (Fig. 5.1). These domains are inferred that have shared a common origin prior to end of Miocene, but have followed separate deformation paths during the Pliocene-Quaternary.
6. The boundary between the Anatolian and African plates in this region is not considered to be sutured or halted. In contrast continuing active deformation has broadened into dextral shear zone, which extends right across the Florence Rise, but which is a zone.

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