Geological Society of America
Special Paper 409
2006

# *Active faulting in the north Aegean basin*

**Dimitrios Papanikolaou***
*University of Athens, Department of Geology, Panepistimioupoli Zografou, 15784 Athens, Greece*
**Matina Alexandri***
*Hellenic Centre for Marine Research, 19014 Anavyssos, Greece*
**Paraskevi Nomikou***
*University of Athens, Department of Geology, Panepistimioupoli Zografou, 15784 Athens, Greece*

## ABSTRACT

**Detailed analysis of air gun lithoseismic profiles in the north Aegean basin has permitted construction of a tectonic map on the pre-existing detailed bathymetric map. The basin is structurally subdivided into three parts. (1) A continental platform borders the basin at ~200 m depth and shows no significant internal deformation. (2) Continental slope areas, usually occurring at 400–900 m depth, are shaped by major marginal faults (>1 km throw) trending mainly northeast-southwest and secondarily northwest-southeast. The dominant structure of the basin is a 160 km–long northeast-southwest-trending fault extending from Skopelos to Limnos, which borders the basin's southern margin and accommodates more than 2 km of throw. This structure probably represents the continuation of the North Anatolian fault. (3) Basinal areas at ~900–1650 m depth include a complex alternation of ridges and basins bordered by active faults. The main structural trend within the basinal areas trends east-west and dominates in the western part of the basin. In the central and eastern parts, northeast-southwest structures become more important. Late Pliocene–Quaternary fault throw ranges between a few tens of meters and 200 m, with higher vertical throws occurring only on northeast-southwest marginal faults bordering the intermediate horst structure. Several northeast-southwest shear zones occur in the central part of the basin parallel to the major southern northeast-southwest marginal fault. A distinctive east-west shear zone occurs in the southwestern part of the basin, where maximum subsidence is observed. An angular unconformity occurs within the Plio-Pleistocene sequence linked to uplifted/tilted neotectonic blocks and anticlinal hinges. The overall interpretation of the mapped structures indicates oblique opening of the basin marked by northeast-southwest strike-slip on both marginal and internal faults, east-west strike-slip faults only in the basinal areas, and northwest-southeast normal faults on the southwestern (Pelion) and northeastern (Athos) margins. This structural architecture is the combined result of the WSW escape of Anatolia on dextral northeast-southwest and east-west strike-slip faults due to Eurasia-Arabia collision and the extension on northwest-southeast normal faults associated with the southwest pull of**

*E-mails: Papanikolaou—dpapan@geol.uoa.gr; Alexandri—matina@ncmr.gr; Nomikou—evi@ncmr.gr.

Papanikolaou, D., Alexandri, M., and Nomikou, P., 2006, Active faulting in the north Aegean basin, *in* Dilek, Y., and Pavlides, S., eds., Postcollisional tectonics and magmatism in the Mediterranean region and Asia: Geological Society of America Special Paper 409, p. 189–209, doi: 10.1130/2006.2409(11). 

**the retreating Hellenic subduction zone in the Ionian Sea to the west. The main effect of this complex deformation is an increase in the normal character of fault structures from northeast to southwest.**

**Keywords:** marine geology, tectonics, geomorphology, northern Greece, north Anatolian fault

## INTRODUCTION

The north Aegean basin is one of the most important tectonic areas in the eastern Mediterranean, yet it remains relatively unknown because of its off-shore nature. Most structural interpretations have been based on rough bathymetric maps and scattered profiles (Needham et al., 1973; Brooks and Ferentinos, 1980; Mascle and Martin, 1990; Pavlakis et al., 1993; Laigle et al., 2000). This article presents the first tectonic map of the basin, based on several lithoseismic profiles superimposed on a detailed digital bathymetric map obtained during the first stage of our research (Papanikolaou et al., 2002).

The north Aegean basin is located in the northern part of the Aegean Sea behind the main morphostructural elements of the Hellenic orogenic arc, which has formed within the convergence zone between the northward-subducting Africa plate and the Hellenic margin of the Eurasia plate (Fig. 1). The development of the north Aegean basin has been related to neotectonic movements in the eastern Mediterranean that followed the collision of Arabia with Eurasia in the late Miocene and the subsequent westward escape of Anatolia accommodated by dextral strike-slip motion of the North Anatolian fault (McKenzie, 1970, 1972; Brunn, 1976; Angelier, 1979; Dewey and Şengör, 1979; Le Pichon and Angelier, 1979, 1981; Şengör, 1979; Taymaz et al., 1991; Jackson, 1994; Armijo et al., 1999).

GPS data obtained in the eastern Mediterranean over the past ten years (Le Pichon et al., 1995; Barka and Reilinger, 1997; Reilinger et al., 1997; Kahle et al., 2000) have, in general, confirmed this geotectonic model with the following average motions relative to stable Africa (Fig. 1): (1) Arabia is moving at a rate of 10 mm/yr to the north, resulting in a collision zone with the Caucasus, which is moving at 10 mm/yr to the south; (2) the Eurasia plate north of the North Anatolian fault and the north Aegean basin is also moving at 10 mm/yr to the south; (3) Anatolia is moving at 20 mm/yr to the west; (4) the Aegean area south of the north Aegean basin is moving at 40–50 mm/yr to the southwest; and (5) the Apulian block in the southern Adriatic Sea is moving eastward at 10 mm/yr, converging with the northern Hellenides.

These GPS data suggest that a difference in convergence rate of ~25 mm/yr is localized in the north Aegean basin between the slowly southward-moving Eurasia plate on its northern margin in the Chalkidiki Peninsula and the rapidly southwest-retreating Hellenic subduction zone system on its southern margin in the northern Sporades and Limnos islands.

The opening of the present-day north Aegean basin is generally accepted to have started during the late Miocene–early Pliocene (LePichon et al., 1984; Armijo et al., 1999; Papanikolaou et al., 2002; Kreemer et al., 2004), largely over a pre-existing Early Tertiary molassic sedimentary basin (Dermitzakis and Papanikolaou, 1981; Papanikolaou, 1993; Roussos, 1994).

Nevertheless, a major problem that has existed since plate tectonic reconstructions were first proposed for this area (McKenzie, 1970, 1972) has been the lack of field evidence for the continuation of the northeast-southwest north Aegean strike-slip structures through the Alpine chain of the Hellenides in continental Greece to the northern end of the present-day Hellenic trench near Preveza. Distributed deformation models involving rotating blocks and related opening of Plio-Quaternary grabens have been proposed as an alternative (e.g., Jackson, 1994). But the link between the north Aegean basin and the tripartite western segment of the North Anatolian fault has generally been accepted (McKenzie, 1972; LePichon and Angelier, 1979; Şengör, 1979; Armijo et al., 1999; Kahle et al., 2000; Koukouvelas and Aydin, 2002; McNeill et al., 2004).

Another problem is that the westward escape of Anatolia is not balanced by the much faster-retreating Hellenic subduction zone, as was postulated before the recent GPS data became available (e.g., Jackson, 1994). Hence, the tectonics of the north Aegean can be understood only as a combination of the Anatolian strike-slip kinematics and those produced by the retreat of the Hellenic subduction zone (e.g., Armijo et al., 2003).

The strike-slip character of the ENE-WSW faults within the north Aegean basin has been shown on the basis of negative and positive flower structures—e.g., the Sithonia fault (Mascle and Martin, 1990) and the Athos tault (Roussos and Lyssimachou, 1991). However, normal movement has been documented for the northwest-southeast fault east of Pelion (Mascle and Martin, 1990) and more generally for the northwest-southeast faults of the basin and surrounding islands (Koukouvelas and Aydin, 2002).

Morphotectonic analysis of the north Aegean basin, based mainly on detailed swath bathymetric data, has revealed its general geometry, which forms an almost orthogonal quadrangle that is elongate in a northeast-southwest direction (Papanikolaou et al., 2002). The subsided part of the north Aegean basin occurs below 300–500 m depth of the continental platform, which surrounds it in all directions (Fig. 2). The margins of the basin are marked by steep morphological slopes from the edge of the continental platform to ~900 m depth, where the basinal

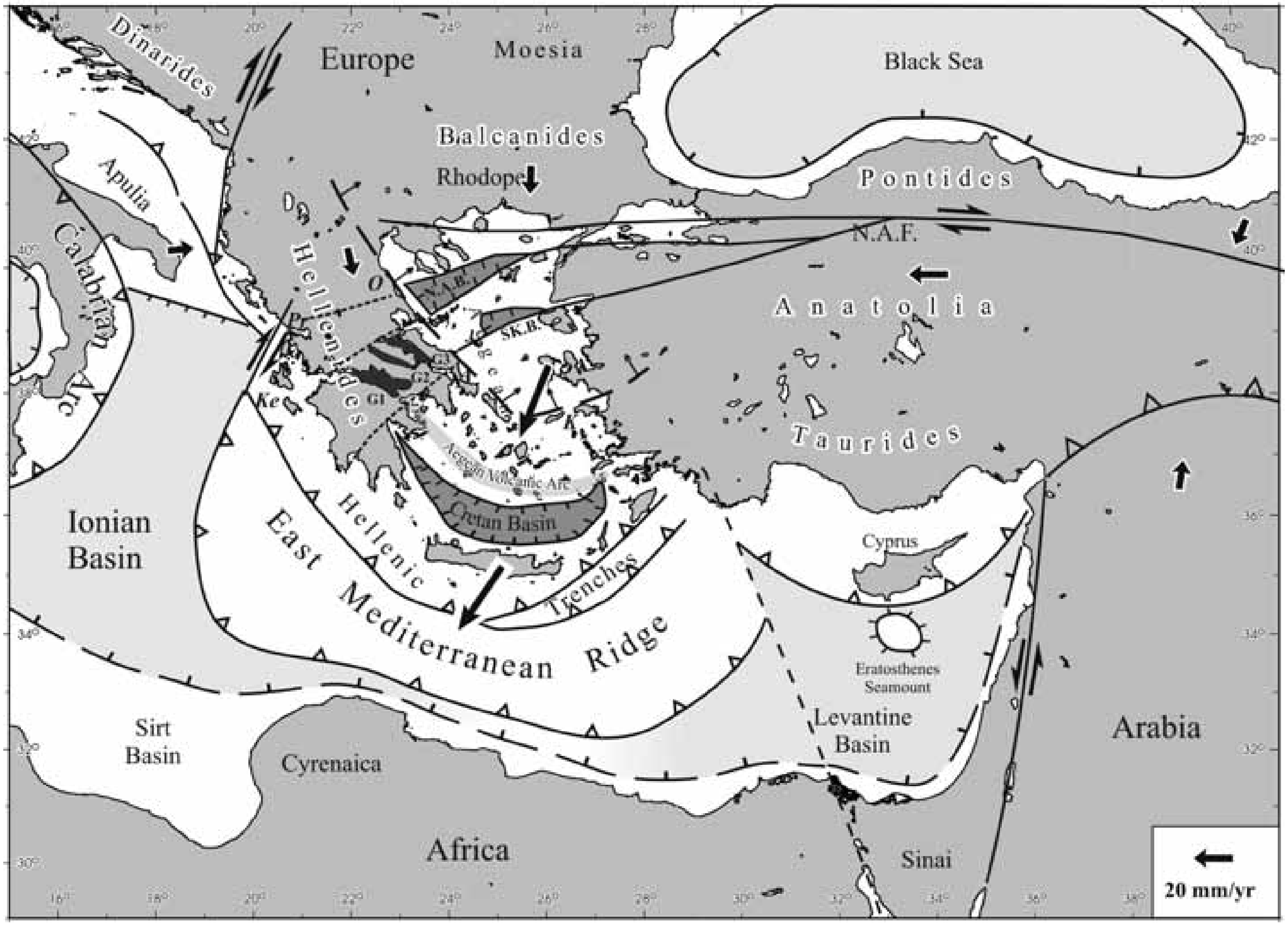



Figure 1. Geotectonic position of the north Aegean basin (N.A.B.) within the plate tectonic framework of the eastern Mediterranean. The arrows correspond to GPS annual rates. Thrusts are indicated by lines with teeth on the upper plate, strike-slip faults by lines with parallel opposing arrows, and normal faults by lines with barbs on the subsiding blocks. The dashed line with arrows on the downthrown side corresponds to the late Alpine detachment. The three Plio-Quaternary grabens of north Evoikos (G3), Viotikos Kifissos (G2), and Corinthos (G1) are shown in dark gray. A—Almyropotamos; K—Kerketeas; Ke—Kephalonia; N.A.F.—North Anatolian fault; O—Olympos; Pr—Preveza; SK.B.—Skyros basin.

areas occur up to the maximum depth of ~1650 m. Other characteristics revealed by our previous research include (1) the planar geometry and strong morphotectonic impact of the marginal faults, principally on the prominent 160-km-long northeast-southwest southern boundary fault, but also on faults of 20–60 km length that border the basin's other three boundaries in northeast-southwest and northwest-southeast directions; (2) the existence of numerous east-west structures occurring exclusively within the basin, (3) the general increase of opening and deepening of the basin toward its southwest part, where the width increases from 20 to 40 km and the depth increases from 950 to 1650 m; and (4) the early Pliocene age inferred for the main onset of basin opening.

This article presents new data obtained from air gun lithoseismic profiles of the basin obtained during an oceanographic cruise on the research vessel *AEGAEO* of the National Center for Marine Research of Greece in April 2002. The air gun was operated in 10 $in^3$ at an average speed of 5 knots. The penetration depth of the air gun was several hundred meters, with a maximum of 700–800 m. The detailed stratigraphy of the lithoseismic units of the basin is unknown, because no correlation to off-shore drilling data is available. Data from Thermaikos Gulf indicate a Plio-Quaternary thickness of 2 km (Roussos, 1994). Taking into account the penetration depth, the sediments studied in this article correspond, in general, to the upper Pliocene–Quaternary. Even though accurate fault-slip rates cannot be extracted due to the uncertainties concerning the age of the reflectors, a rough approximation is possible by using Holocene sedimentation rates for the basinal areas (18–34 cm/k.y.; Roussakis et al., 2004). The profiles were selected on the basis of the

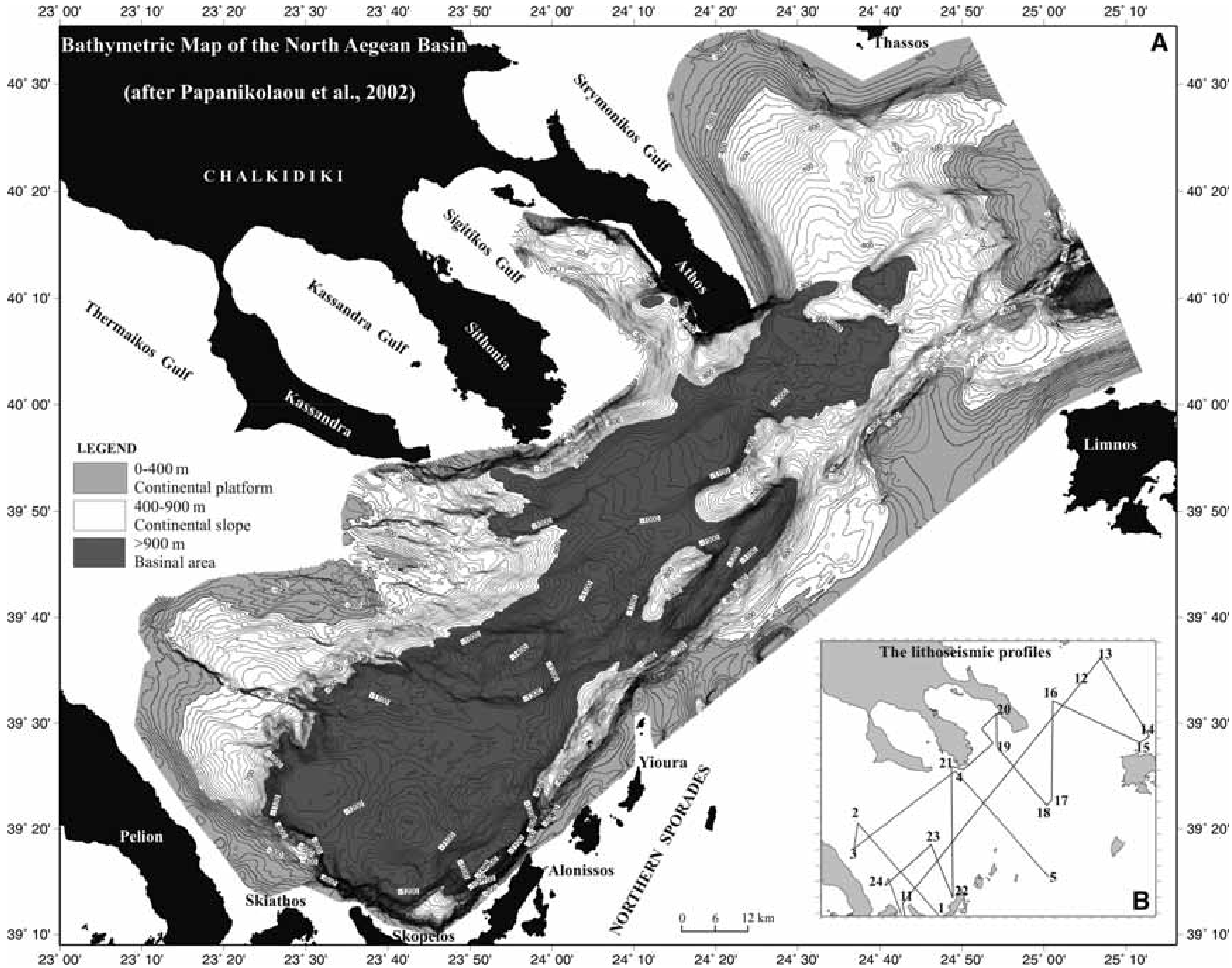



Figure 2. (A) Bathymetric map of the north Aegean basin (after Papanikolaou et al., 2002) with distinction of three levels: (1) Continental platform (0–400 m), (2) Continental slope (400–900 m), and (3) Basinal area (>900 m). (B) Location of air gun lithoseismic profiles.

pre-existing morphotectonic map (Papanikolaou et al., 2002) in order to cross all important marginal faults and all areas with interesting morphotectonic structures. The locations of the lithoseismic profiles are given in Figure 2B. The basin is divided into three bathymetric levels: the continental platform, the continental slope, and the basinal parts. These are described in the following sections, and then the overall tectonic structure is analyzed.

## CONTINENTAL PLATFORM

The edge of the continental platform toward the steep slopes of the basin's margins is marked by a well-developed slope discontinuity that usually exceeds 15%. This abrupt change of slope from an average of 1% on the continental platform to the >20% average slope of the margins is the top of a destructive surface that follows the morphotectonic surface of the fault controlling the margin from the edge of the platform to the edge of the basin at depth. The lower part of the slope becomes steeper, reflecting the planar geometry of the fault, whereas the upper part becomes less geometric and gradually deviates toward the footwall, with smaller values of morphological slope, as a result of gravitational phenomena caused by the submarine instability of the steep slopes and consequent rock sliding.

The depth of the continental platform differs on the four sides of the basinal quadrangle. An average depth of 200 m is observed along the northern margin, around the Chalkidiki Peninsula and south of Thassos island, on the western margin along the Pelion slopes, and on the southern margin along the northern Sporades slopes. However, a greater average depth of ~400–500 m is observed in the eastern part of the southern margin, between Yioura and Limnos islands (Fig. 2). This is due to the existence of a northeast-southwest fault with a throw of more than 500 m, along which a narrow zone (90 × 4–8 km) of the continental platform has subsided parallel to the main marginal fault (Fig. 3). South of this fault the continental platform once again lies at ~200–300 m depth.

There are only two segments where the edge of the continental platform does not run parallel to major marginal faults. (1) The northeastern part between Thassos and Limnos islands represents the transition area between the western basin of the north Aegean and the much smaller eastern basin that starts north of Limnos island and extends ENE into the Saros basin as a very narrow trough. The maximum depth of this transitional area is 500 m and the northeast-southwest structures of the western basin do not continue, but rather are replaced by ENE-WSW structures east of this critical area (Papanikolaou et al., 2002). Transpressional deformation has been proposed for this area (Koukouvelas and Aydin, 2002; Armijo et al., 2003). (2) In the northwestern part of the basin at its junction with Thermaikos Gulf, east-west structures dominate. However, the overall deformation becomes less important to the west and the submarine topography gradually becomes smoother and shallower as the east-west folds plunge east (as is discussed later). The depth of the continental platform in both cases remains ~200–300 m.

## CONTINENTAL SLOPE

The continental slope defines the boundaries of the basin between 300–400 m and 900–1000 m depth. The margins of the basin are controlled by major faults that are tens of kilometers long and have significant throws (>1 km). The tectonic map of the basin (Fig. 4) shows only fault throws, because strike-slip offsets cannot be quantified. In most cases, the Alpine basement is reflected in lithoseismic profiles in the footwall of the marginal faults, but it is buried beneath several hundreds of meters of sediments and cannot be traced in the hangingwall. Thus, the throw indicated on the tectonic map is the minimum offset of the top of the Alpine basement. This can be seen in some characteristic lithoseismic profiles across the main marginal faults of the basin (Fig. 5).

The dip of the marginal faults lies in the range of 40°–60°, and adjacent sediments in the basin are in some cases flat-lying and undisturbed, whereas in others they thicken toward the fault plane, indicating rapid synsedimentary subsidence (e.g., the profile of the Sithonia marginal fault, Fig. 5C). There are also some cases, such as that of the Pelion marginal fault (Fig. 5B), where the sediments dip away from the fault toward the basin, indicating a smaller rate of fault slip than of overall basin subsidence. In this particular case, the sediment-fault relationship can be explained by the strike-slip motion of the dominant east-west-trending shear zone on the southwestern corner of the basin (Fig. 4; see next section).

The most impressive structure is the northeast-southwest fault that forms the southern basin's margin from its southwestern corner, east of Skopelos Island, to its southeastern corner, northwest of Limnos island, a distance of 160 km. This major marginal fault in places splays into two parallel faults, forming a narrow step zone 2–5 km in width. In other segments, it is linked to a parallel antithetic fault forming a subsided tectonic wedge, the upper surface of which forms small elongated basins at depths of between 900 and 1200 m. The most representative example is observed north of Alonnisos island, where the basin is 15 km long and 3 km wide and has a maximum depth of 1650 m (Fig. 5A).

## BASINAL AREA

The basinal area of the north Aegean basin is characterized by a complex sea bottom morphology in which a number of flat-floored basins are separated by several ridges or platformlike domes. The boundaries of the small basins are fault controlled, with average values of throw ranging from a few tens of meters to several hundred meters.

The most important faults occur in the central part of the basin, opposite the Sithonia and Athos Peninsulas. Here they

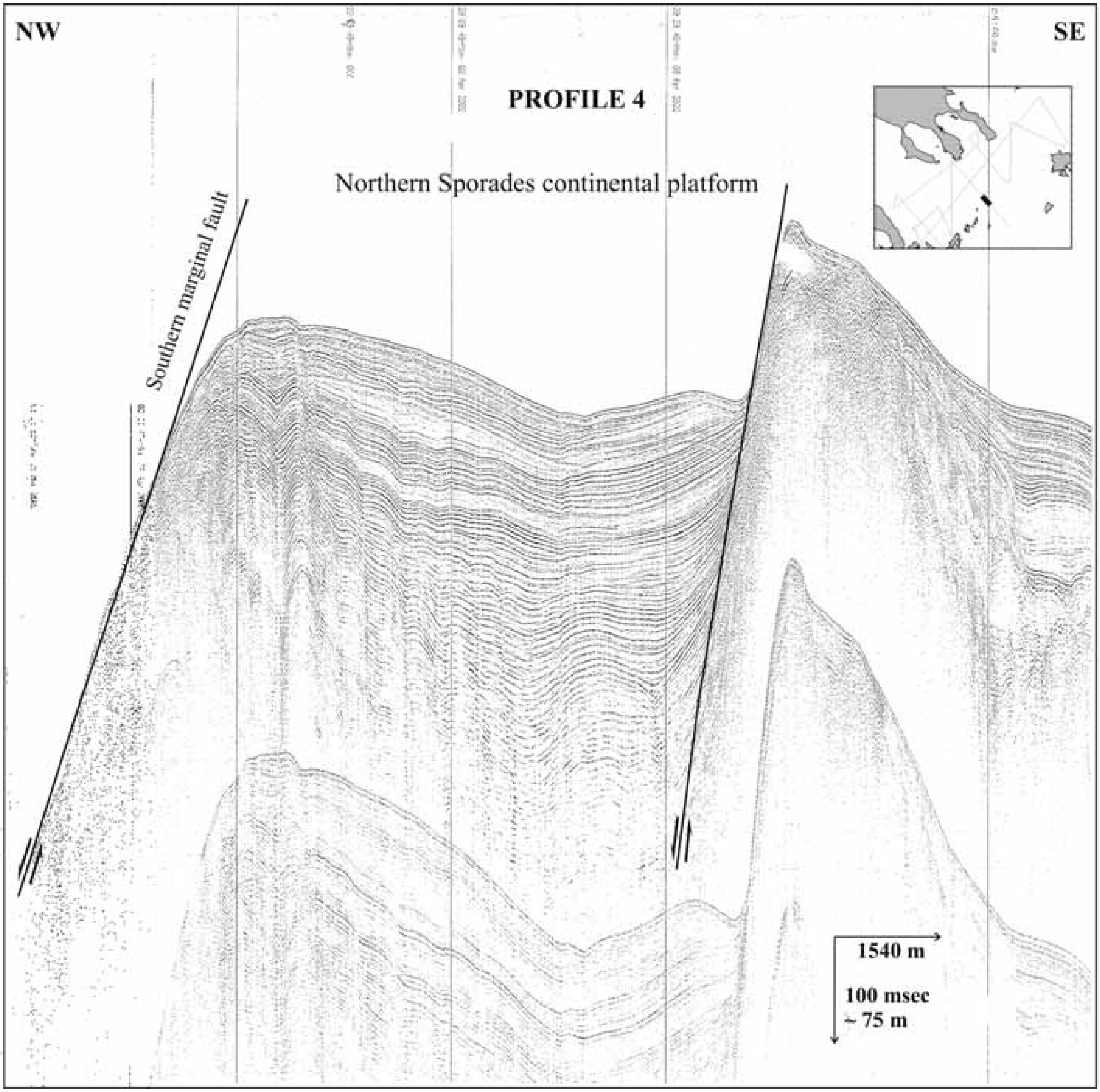



Figure 3. Northwest-southeast profile across the southern marginal fault of the north Aegean basin showing the subparallel fault that has produced a narrow zone of subsidence along the northern margin of the Northern Sporades–Limnos continental platform. The location of each profile is indicated by the dark rectangle on the inset map.

form a pronounced northeast-southwest tectonic horst structure in which the Alpine basement can be detected below 150–200 m of sediments (Fig. 6). This intermediate horst lies parallel to and a distance of only 3–4 km from the southern marginal fault of the basin. Northwest of the horst, the Alpine basement is buried below 400–500 m of sediments. This is the thickness penetrated by the air gun, and thus a minimum throw of 900 m is indicated. On the other hand, the southeast-dipping faults observed along the Sithonia slopes toward the northern side of the basin display 100–200 m throws.

Several east-west-trending faults located within the basin have only a minor morphotectonic impact of ~100–200 m in the

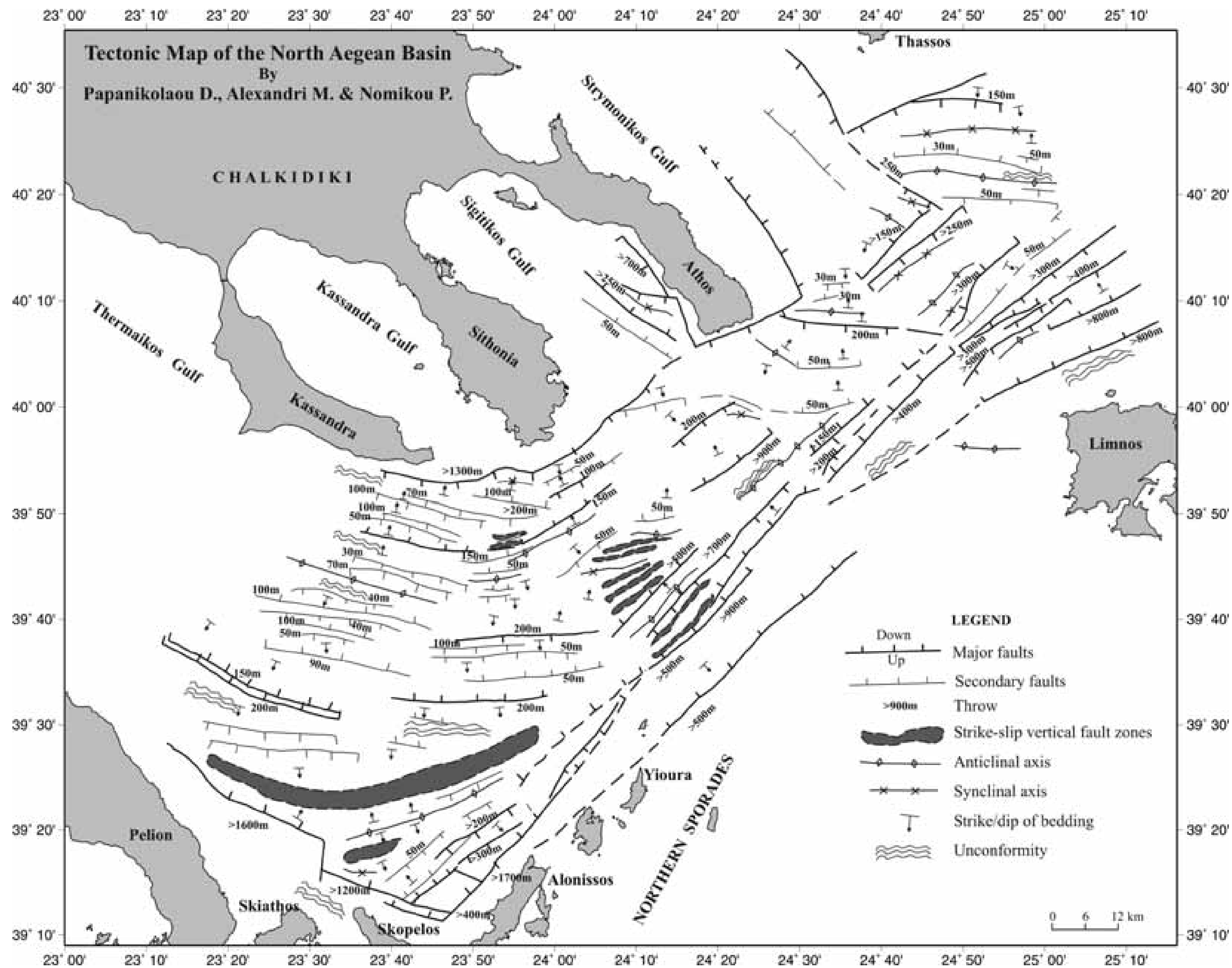
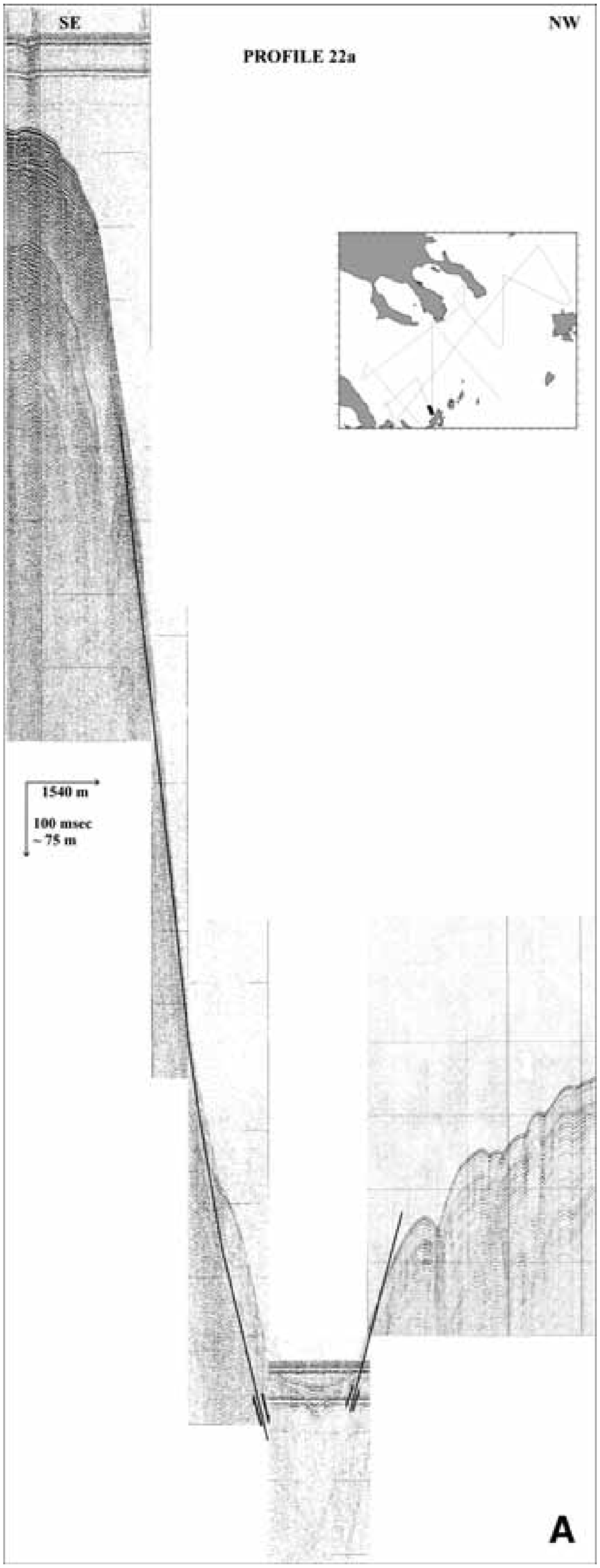
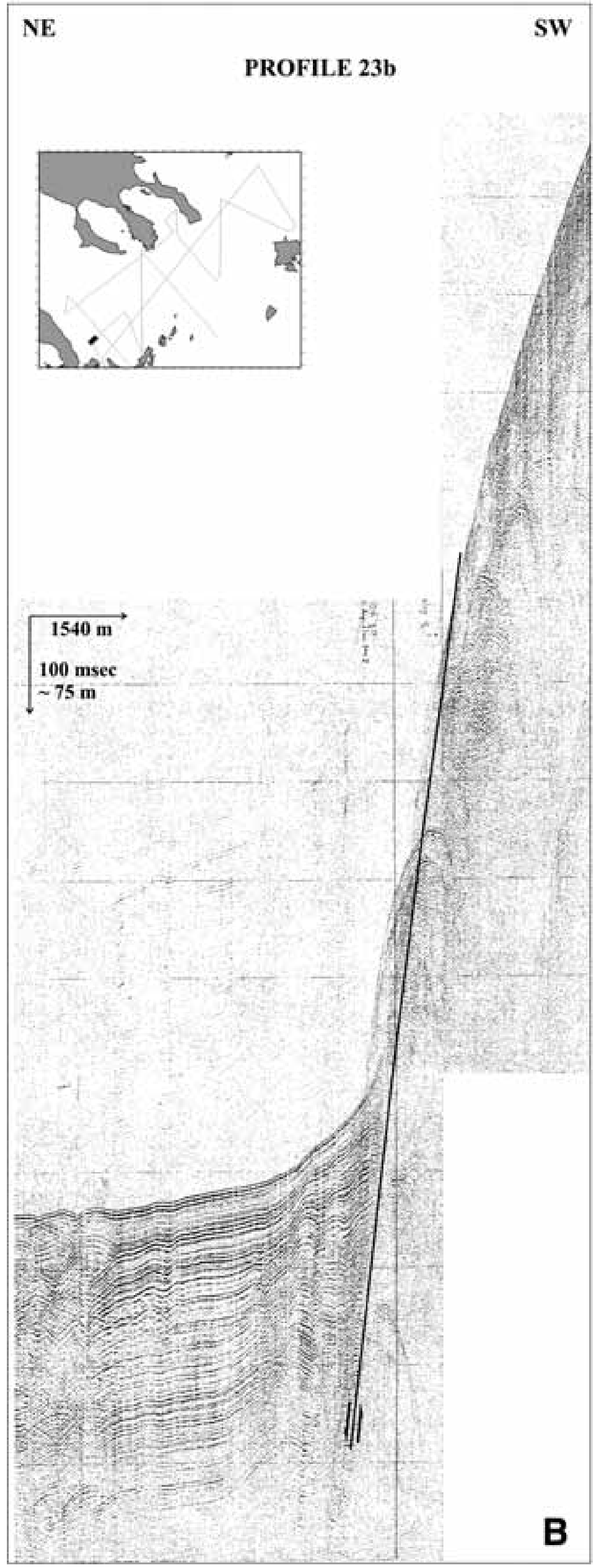
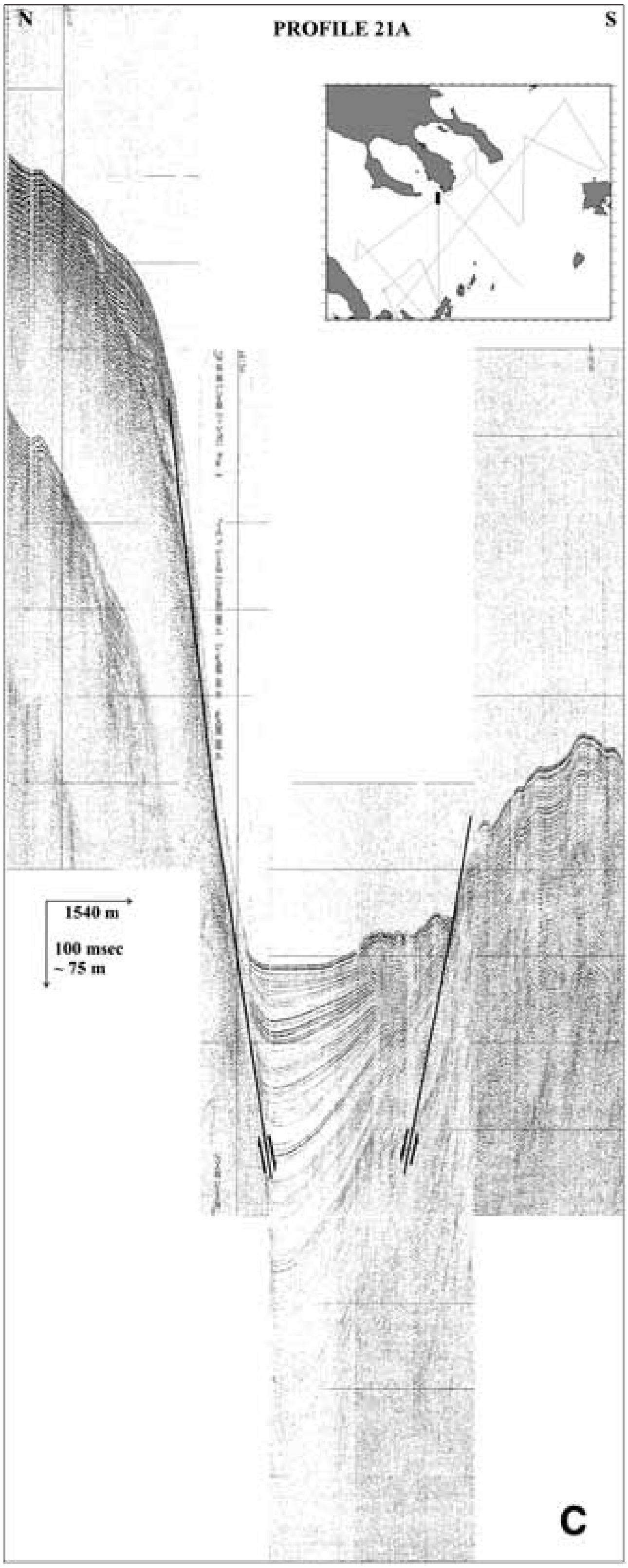



Figure 4. Tectonic map of the north Aegean basin deduced from the analysis of air gun lithoseismic profiles.


SE
NW
PROFILE 22a
1540 m
100 msec
~ 75 m
A


NE
SW
PROFILE 23b
1540 m
100 msec
~ 75 m
B




sea bottom bathymetry. One example is shown in the lithoseismic profile of Figure 7, which traverses a rather symmetric tectonic graben. The central subsided part of the basin with horizontal strata lies at 1400 m depth, whereas the two relatively uplifted margins of the graben lie at 1100 m depth.

In other cases, however, the east-west faults vertically disrupt monoclinal sedimentary sequences, locally uplifting or subsiding the mean bedding surface and the subparallel sea bottom surface by a few tens of meters (Fig. 8). The bedding within these vertical fault zones is also tilted in one direction or the other by several degrees, and in some cases it is folded into small, narrow anticlinal domes. It is noteworthy that these vertical east-west faults cannot be traced along strike for more than 10 km, but are replaced by similar east-west faults with the opposite sense of vertical motion. This geometry, together with the presence of several shear zones between the faults, implies strike-slip movement. Between the elongated blocks bordered by the east-west faults and shear zones are several cases of folded strata with east-west anticlinal or synclinal fold axes (Fig. 4).

One major east-west fold structure is observed in the northeast-southwest lithoseismic profile across the western part of the basin between the Pelion and Sithonia marginal faults (Fig. 9). The anticlinal fold hinge area occurs at 300 m depth, whereas the disrupted flanks gradually subsided to 600–700 m. An angular unconformity was detected along this profile that is best expressed at the top of the structure, in the uplifted parts of the two marginal fault zones and the median area of the anticlinal fold hinge. The thickness of the sedimentary sequence above the unconformity is estimated to be ~80 m, implying a broadly Pleistocene age for these topmost sediments. Thus, local uplift and erosion must have occurred in the late Pliocene–early Pleistocene, followed by an important recent episode of subsidence to present-day water depths of 300–700 m. However, the east-west fault and open fold structures remained active before and after the tectonic event that created the unconformity, for the only difference in the structures of the lower and upper stratigraphic sequences is the higher dip of the lower sequence. The previously described fold corresponds to one reported by Brooks and Ferentinos (1980) in another northwest-southeast profile several kilometers away, where those authors relate the folding to the fracturing. The same authors also reported intraformational unconformities in the growth folds of the Thermaikos Gulf.

The most important tectonic structure at the southwestern corner of the basin is an impressive east-west vertical shear zone extending from the northwest-southeast Pelion marginal fault to the west to the northern Sporades northeast-southwest marginal

Figure 5. Lithoseismic profiles across the main marginal faults of the north Aegean basin: (A) Northeast-southwest fault north of Alonissos, (B) northwest-southeast fault east of Pelion, and (C) northeast-southwest fault south of Sithonia. The location of each profile is indicated by the dark rectangle on the inset map.

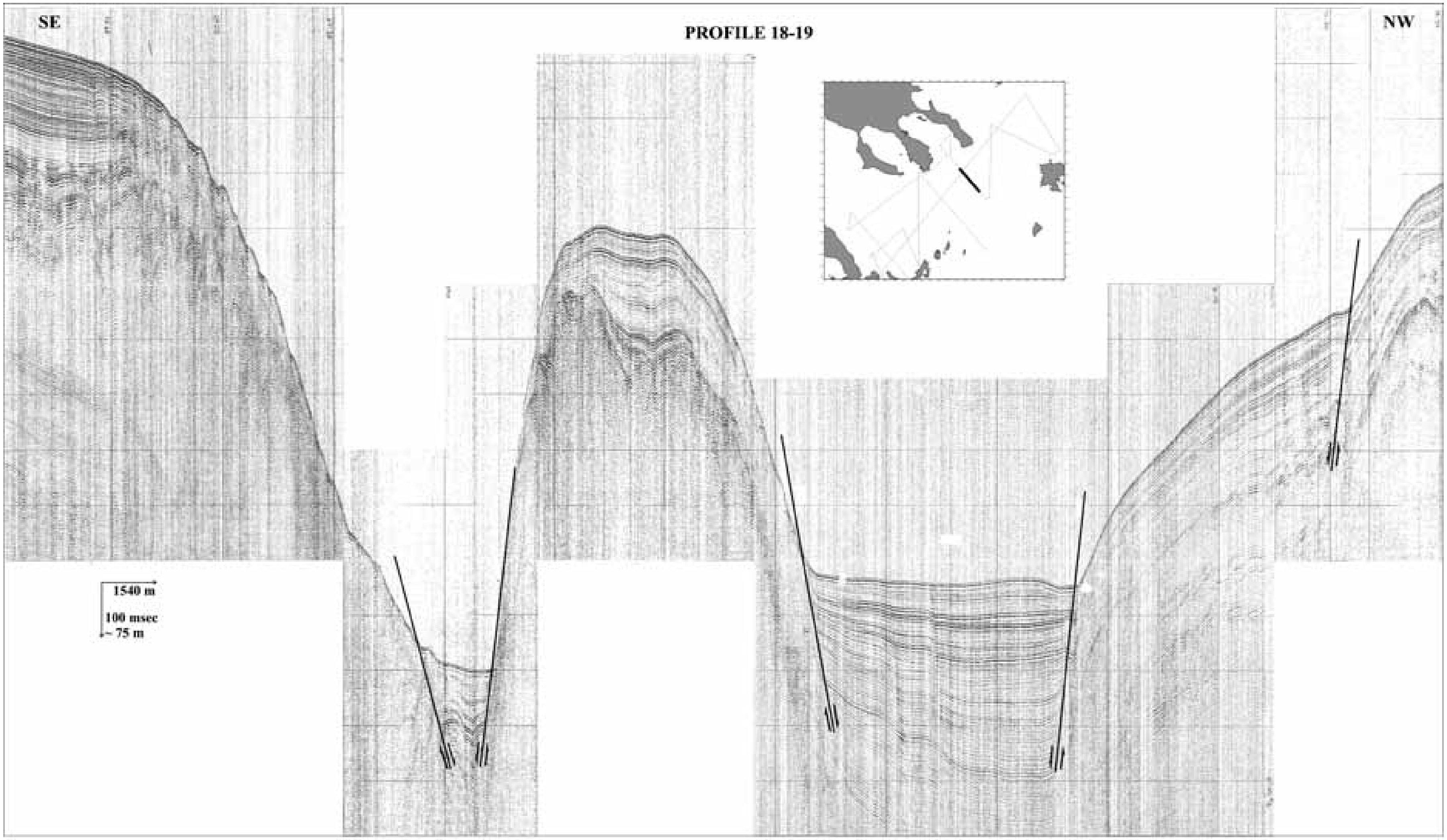



Figure 6. Air gun lithoseismic profile showing the northeast-southwest structures forming the intermediate tectonic horst in the central part of the basin. The location of the profile is indicated by the dark elongated rectangle on the inset map.

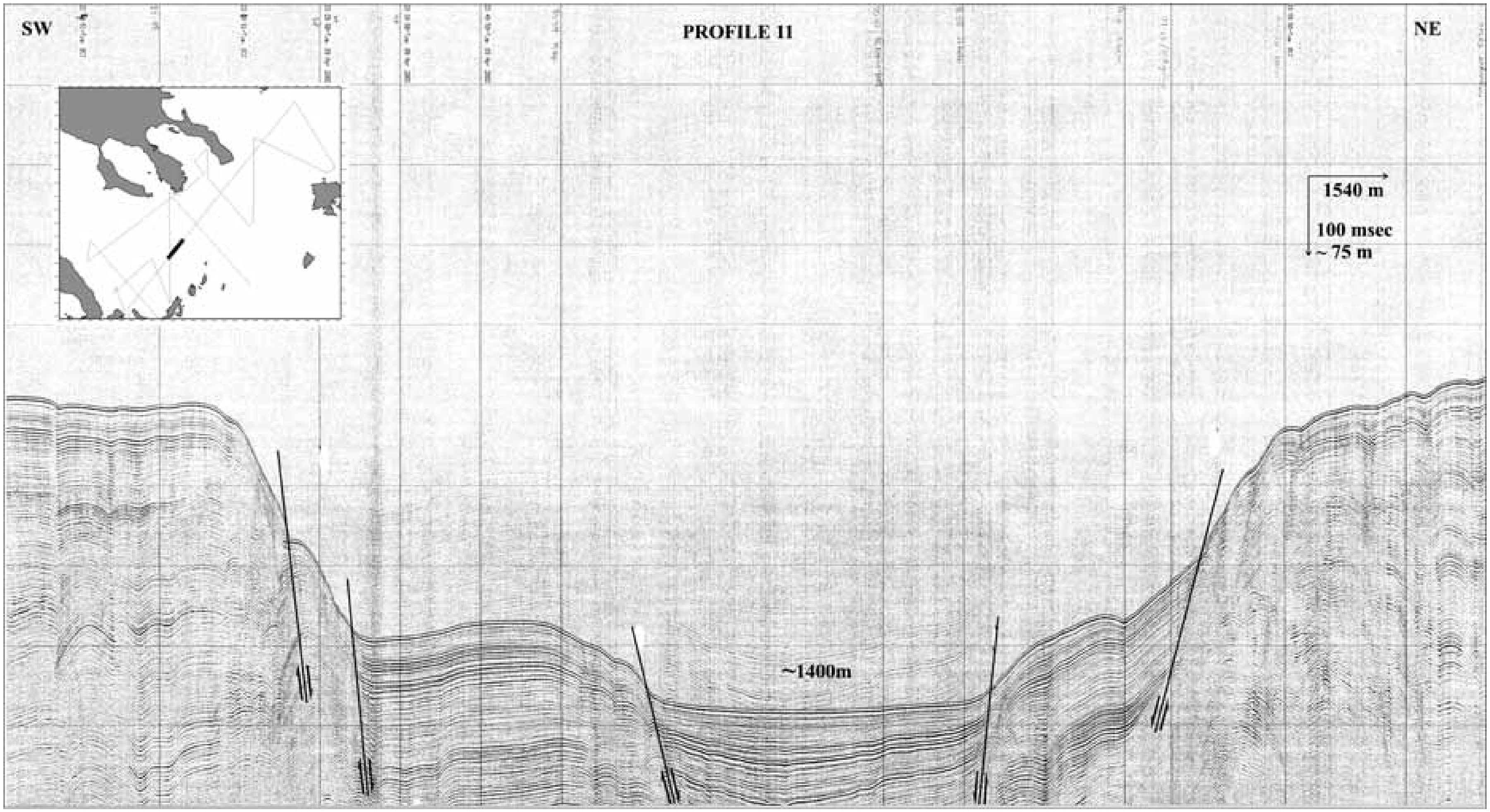



Figure 7. Air gun lithoseismic profile across the east-west structures in the central basinal area (~1400 m depth). The location of the profile is indicated by the dark elongated rectangle on the inset map.

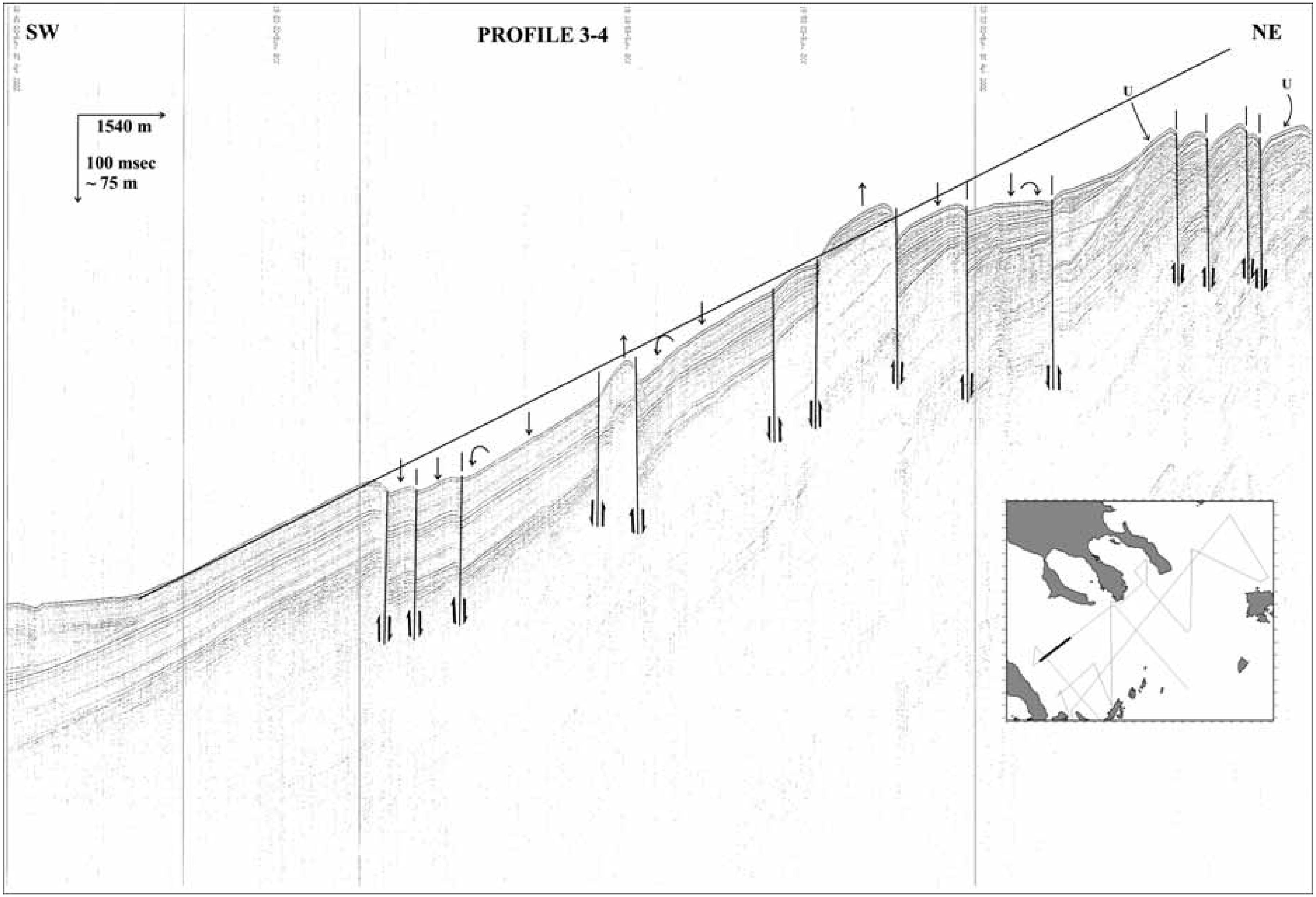



Figure 8. Air gun lithoseismic profile across the east-west vertical fault zones disrupting the monoclinal sequence forming the western flank of a broader anticline (see also Fig. 9) southwest of Sithonia Peninsula. The relative vertical motion and tilt are indicated for each tectonic block by small arrows. Unconformities (U) can be seen. The average top surface of the monoclinal sequence is drawn as a reference level. The location of the profile is indicated by the dark elongated rectangle on the inset map.

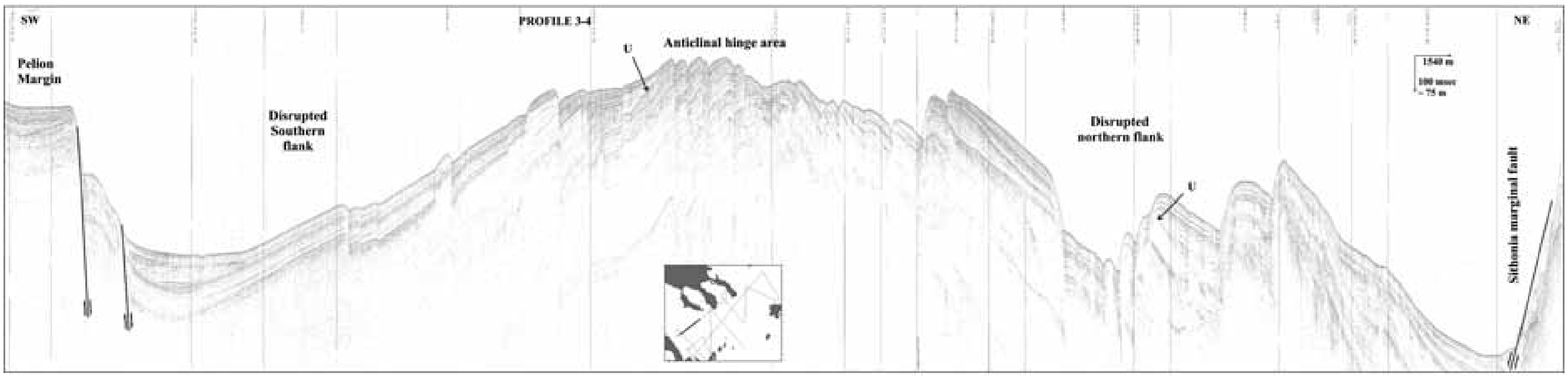



Figure 9. Air gun lithoseismic profile across the western part of the north Aegean basin between Pelion and Sithonia marginal faults showing a major anticlinal east-west fold that separates the basin into southern and northern flank. Numerous subvertical east-west faults disrupt the fold structure. An unconformity (U) can be seen in the fold hinge and in higher parts of the tilted blocks. The dip values for the reflectors are higher in the lower sequence across the anticline. The location of the profile is indicated by the dark rectangle on the inset map.

fault to the east. Its length is ~50 km, and its width ranges between 3 and 5 km (Figs. 4 and 10). The shear zone does not create any systematically significant vertical offset to the north and south, but crosses the sea bottom at depths of between 1150 and 1250 m. The vertical fractures of the shear zone heavily disrupt the planar sedimentary structures, which look chaotic, with multiple hyperbolic reflections. To the north of the shear zone, the south-dipping sediments have a distinct geometry, and within the relatively uplifted area north of the shear zone, the previously described unconformity is detected. South of the shear zone, an anticlinal ENE-WSW fold hinge is followed by another northeast-southwest shear zone. A number of parallel synclinal folds also occur adjacent to the corner of the basin formed by the intersection of the two major marginal faults trending northeast-southwest and northwest-southeast, respectively (Fig. 4). The opposing dip of the bedding on either side of the shear zone forms an open synclinal fold (Fig. 4) that may represent the upper part of a negative flower structure.

It is noteworthy that the eastern part of this shear zone coincides with the major north-dipping normal fault detected by Laigle et al. (2000). However, the suggested northwestward continuation of this fault corresponds not to the shear zone but rather to a pair of east-west normal faults with Pleistocene throws of ~200 m seen in the western part of the section of Figure 9.

Other shear zones have been mapped in the central parts of the basin, where the sediments are squeezed between the parallel major northeast-southwest faults of the intermediate horst and the southern marginal fault. Anticlinal fold hinges along the tectonic horst zones and synclinal fold hinges in the tectonic graben zones are also observed. Besides these strike-slip zones of extremely sheared sediments, there are several cases in which the sediments have been disrupted by a very closely spaced system of northeast-southwest or east-west-trending subvertical faults that resemble, on a macroscopic scale, the fracture cleavage seen under the microscope (Fig. 11).

These shear zones, as well as the change of relative vertical motion along strike observed in many of the northeast-southwest and east-west faults and the parallel folds, imply that strike-slip structures dominate the active deformation inside the basin. The measured values of throw are in most cases only a small portion of the overall tectonic slip of the faults. This explains why sediments become thinner adjacent to some faults, although significant subsidence would be expected on the basis of their apparent normal fault character (Fig. 12). Additionally, the occurrence of anticlinal folds running parallel to the faults reveals positive flower structures indicative of the strike-slip character of the deformation (Fig. 12). If we consider the lateral slip of the faults, it is obvious that the sediments now in contact with a given fault may once have been several kilometers away along the fault's strike, whereas the actual profile of the fault shows a contrasting kinematic picture with, for example, subsidence of the northern block instead of the southern and vice versa, as is the case in the area southeast of Sithonia (Fig. 13). In this particular area, the enechelon tilted northeast-southwest blocks corresponds to a deep flower structure reported by Mascle and Martin (1990).

## TECTONIC STRUCTURE OF THE BASIN

Based on previous analysis of the lithoseismic profiles of the basin, we attempted to distinguish the major neotectonic blocks bordered by active faults. However, this attempt failed because, within the basin and inside the frame formed by the marginal faults, there are no major faults that can be traced for more than 15–20 km. Additionally, in several cases the same fault lines correspond to opposite kinematics, with the downfaulted block in one location becoming the upfaulted block in another over a distance of 5–10 km (Fig. 13). In other cases, fault continuity gradually decreases in one direction, with the extra slip taken up on other subparallel faults, sometimes in enechelon zones. These zones interrelate with anticlinal and synclinal folds that occur along elongate faulted blocks, with the anticlinal fold hinges occurring along the crest zone of tectonic horsts, whereas the synclinal fold hinges occupy the bottom of elongate tectonic grabens. In several cases, these anticlinal and synclinal folds correspond to positive and negative flower structures, as can be seen when deep structures are also available (e.g., Mascle and Martin, 1990; Roussos and Lyssimachou, 1991).

Additionally, the frequent occurrence of subvertical shear zones and their macroscopic zones of fracture cleavage, interfingering with these fold and fault structures, gives an additional flow character to the transtensional deformation of the thick Plio-Quaternary sedimentary sequence. This style of brittle plastic deformation characterizes the actual tectonics of the basin, with the absence of neotectonic rigid blocks emphasizing the plasticity of the deformed sediments, which are deforming in intermediate conditions between folding and fracturing.

The overall tectonic structure of the north Aegean basin is shown on the simplified tectonic map of Figure 14, in which most of the secondary faults with throws of less than 50 m are omitted. A special representation of the morphotectonic surface of the major faults that create important submarine scarps has been included on the tectonic map. Thus, the width of the fault outcrops can be observed across strike, sometimes exceeding 3–4 km. Additionally, four 3-D tectonic sections across the basin are shown in Figure 15. Although the tectonic structure in each section is different, there is a general geometric scheme for the basin that can be seen in all sections, involving: (1) a tectonic graben filled with post-Alpine sediments formed between the two marginal fault zones of Chalkidiki and northern Sporades–Limnos, with an east-west trend that becomes northeast-southwest to the east, and (2) an anticlinal or horst median structure with the same geometry as the graben. Along this median zone of relative uplift, there is either elevated Alpine basement (in the central part of the basin) or anticlines in which the previously described unconformity underlies older anticlinal structures (Fig. 15).

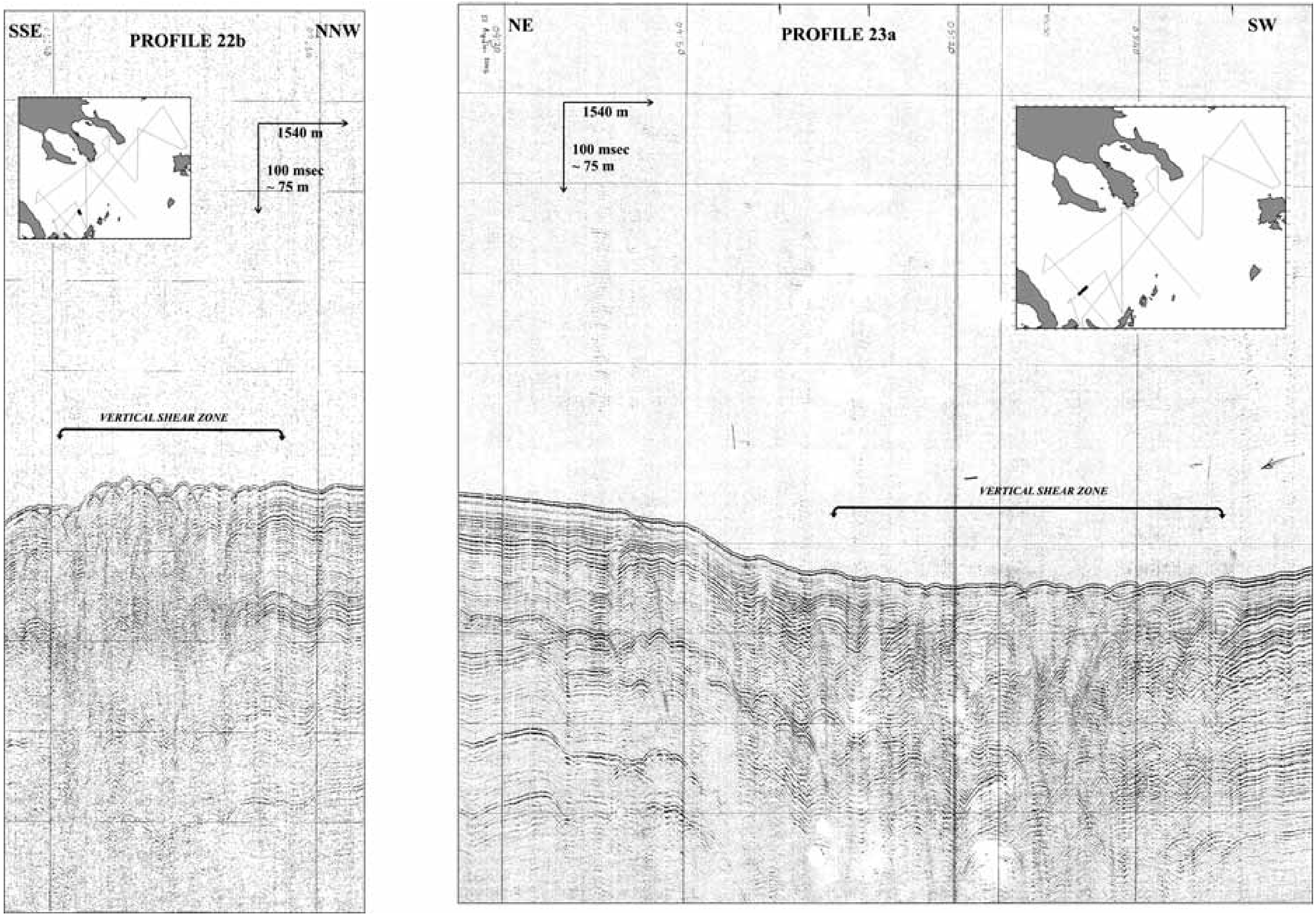



Figure 10. Air gun lithoseismic profiles across the east-west shear zone in the southwestern part of the basin. The location of the profile is indicated by the dark rectangle on the inset maps.

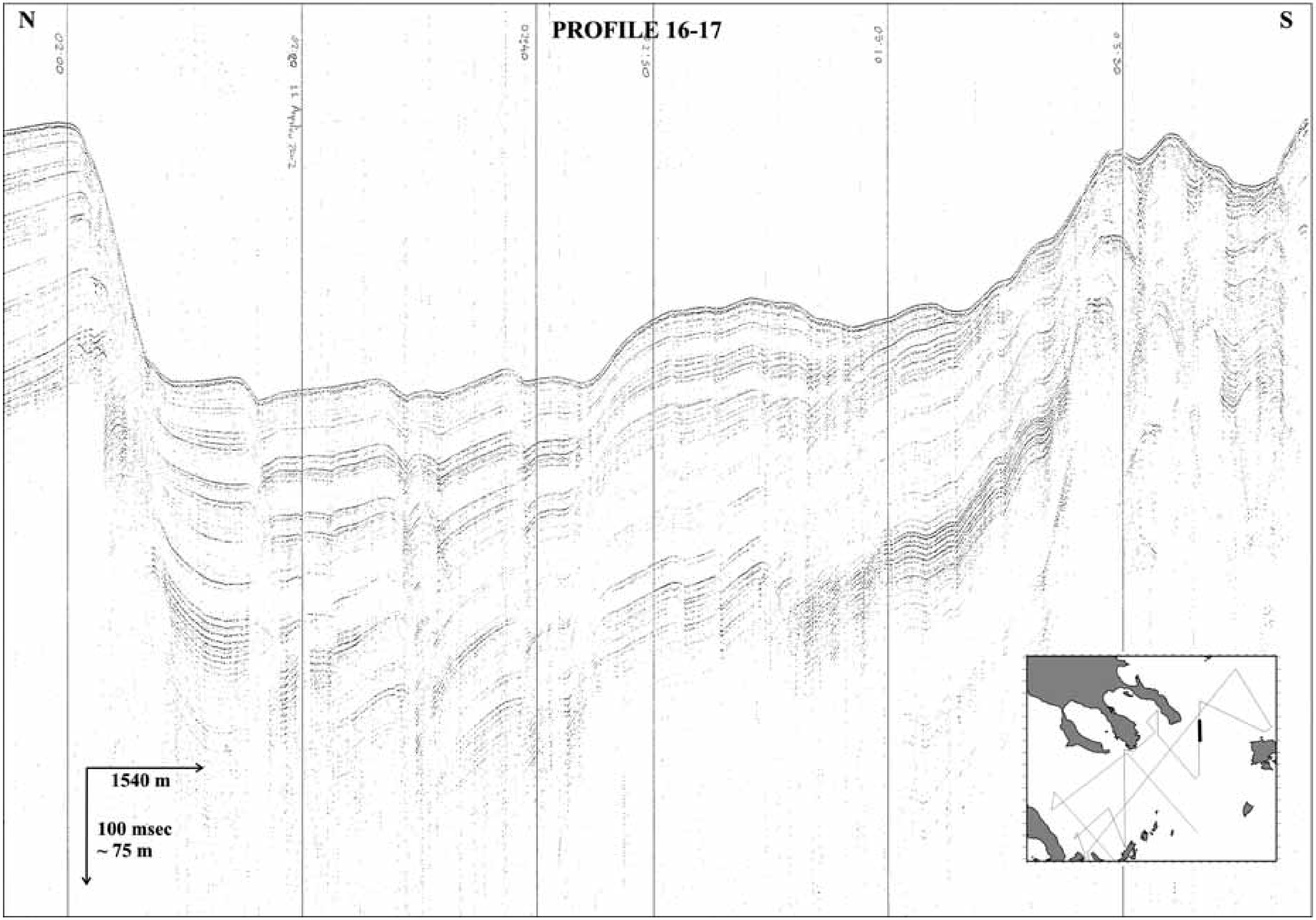



Figure 11. Air gun lithoseismic profile across the closely spaced east-west vertical faults in the eastern part of the basin. The location of the profile is indicated by the dark rectangle on the inset map.

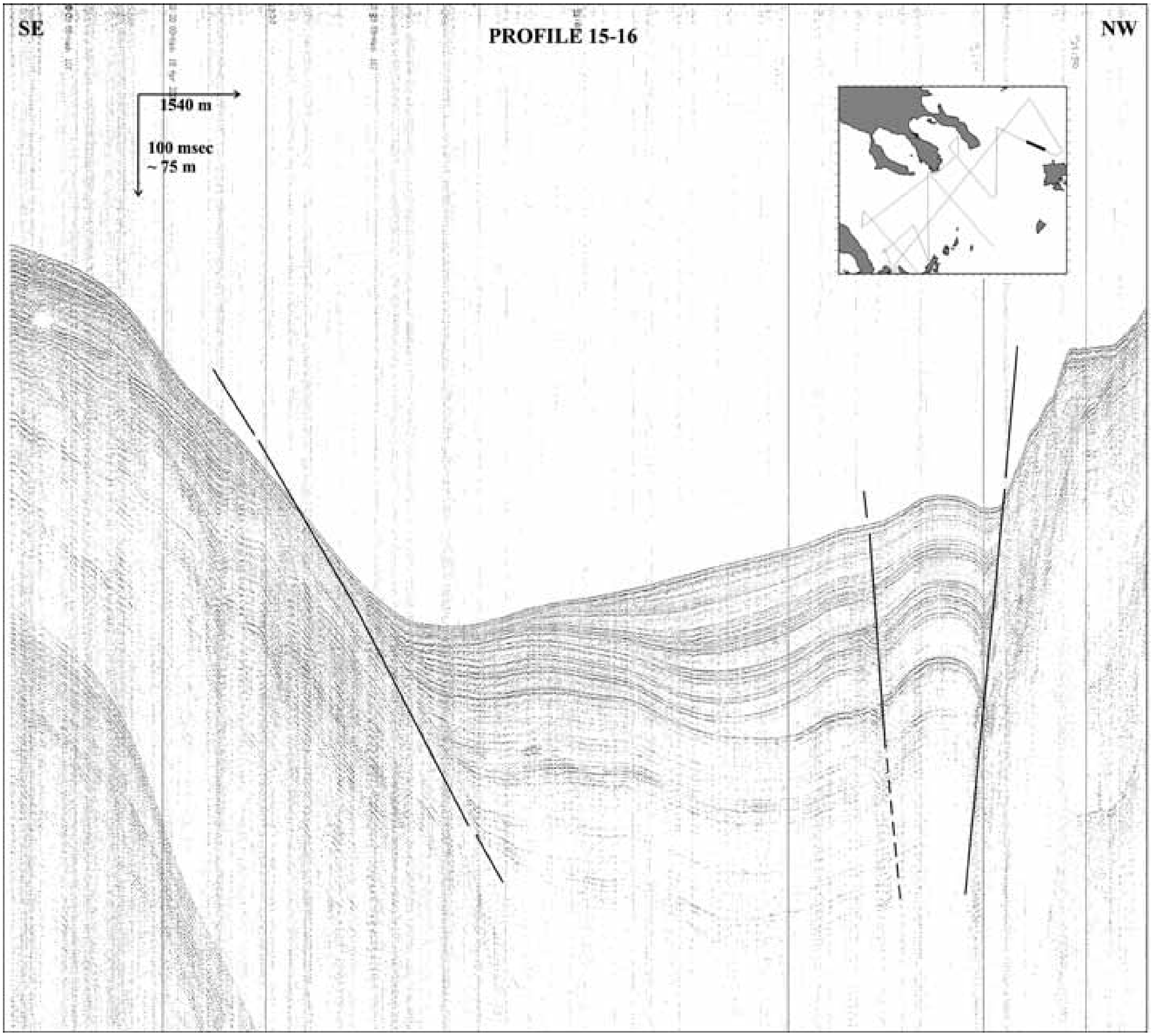



Figure 12. Air gun lithoseismic profile across the northeast-southwest strike-slip faults northwest of Limnos, showing thinning of the sedimentary sequence on one side of the apparent graben structure and an anticlinal fold (positive flower structure) on the other. The location of the profile is indicated by the dark rectangle on the inset map.

A distinct structure within this general tectonic scheme occurs in the southwestern corner of the basin, which is bounded by the ends of the northeast-southwest and northwest-southeast marginal faults and by the east-west major shear zone (Fig. 14). This triangular area is the most deeply subsided part of the basin, with depths of between 1000 and 1650 m and significant vertical displacements. Additionally, it corresponds to the area where maximum sediment thicknesses (>5 km) have been reported (Lalechos and Savoyat, 1979; LePichon et al., 1984). The segments of the two marginal faults forming the triangular area are therefore largely normal rather than strike-slip faults.

## DISCUSSION AND CONCLUSIONS

The tectonic structure of the basin we have described is in agreement with the existing kinematic and dynamic data for the surrounding area. The dextral shear produced by the escape of Anatolia to the WSW is evident in the dominant northeast-

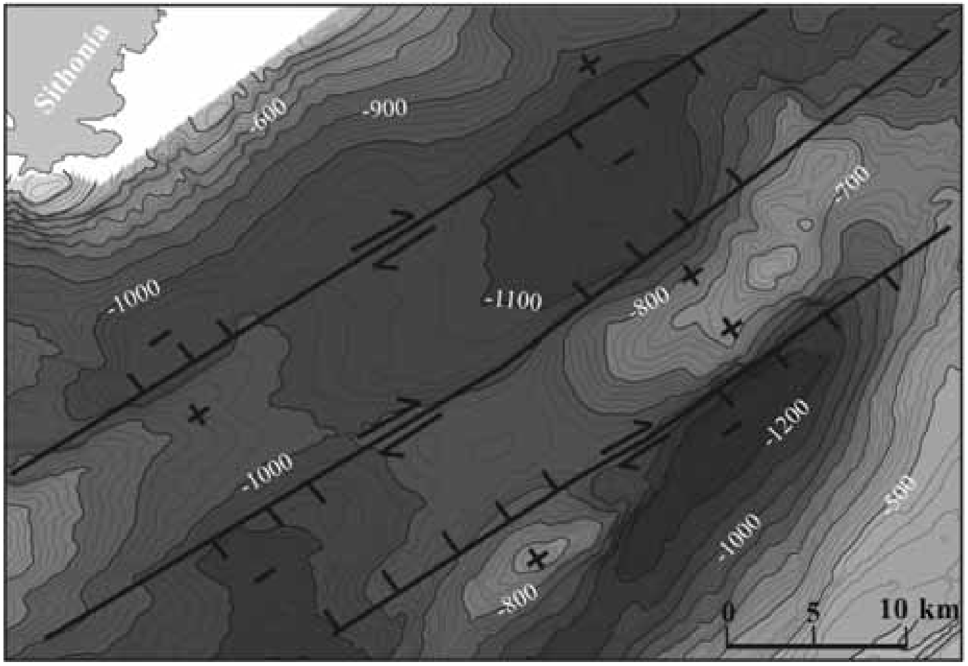



Figure 13. Detail of the bathymetric map southeast of Sithonia Peninsula, showing three parallel northeast-southwest strike-slip faults that change their sense of vertical displacement within a few km along strike, resulting in an enechelon tilted block structure.

southwest structures of the north Aegean basin, which forms a transtensional zone of dextral shear between the Eurasia plate to the north and the Aegean block to the south. However, westward propagation of the northeast-southwest strike-slip structures of the north Aegean basin into mainland Greece is not observed.

The western barrier of the northeast-southwest strike-slip structures coincides with the major northwest-southeast Alpine tectonic structure delineating the internal tectonic boundary of the medial tectonometamorphic belt to the west from the Axios (Vardar) oceanic zone to the east (Papanikolaou, 1984, 1986). This northwest-southeast tectonic zone can be followed from the inner Dinarides to the northwest to southern Evia, the northern Cyclades, and Samos to the southeast and east, and it borders the deep tectonic windows of Olympus, Almyropotamos, and Kerketeas (Fig. 1). These relatively autochthonous units belong to the internal parts of the huge External Carbonate platform of the Hellenides, forming their basal tectonostratigraphic unit (Papanikolaou, 1997; Papanikolaou et al., 2004). This major Alpine tectonic zone was transformed to a large-scale extensional detachment in the Miocene (Kilias et al., 2002). Thus, uplift of the basal units to the top of the mountain ranges of Olympus (2918 m), Almyropotamos, and Kerketeas (1450 m) has occurred in the footwall, whereas the topmost tectonic units of Axios origin are found in the hangingwall.

Geophysical and drilling data from the northern Aegean (Roussos, 1994) have revealed the existence of an Early Tertiary molassic sequence several kilometers in thickness, overlain by thick Late Tertiary sediments. The western margin of the Thermaikos basin is shown to be a low-angle normal fault that can be followed to a depth of 6 km below the sediments. However, the overall geometry of Thermaikos basin reveals a synclinal structure, the southeastern end of which corresponds to the anticline between Pelion and Kassandra-Sithonia shown in Figure 9.

The off-shore data from along this northwest-southeast tectonic zone presented by Mascle and Martin (1990) show a different tectonic structure in the northern segment (Olympus) than in the southern segment off Pelion. Thus, several kilometers of throw on the ENE-dipping fault zone are observed off Pelion, whereas a positive flower structure is observed east of Olympus. This difference may well be the result of the interfingering effect of the east-west shear zone detected at the southwestern corner of the basin (Figs. 4, 10, and 14) that may distribute the strike-slip motion northwest of the shear zone, leaving areas to the southeast with normal motion.

It is interesting to note that the geometric continuation of the major northeast-southwest strike-slip structure of the north Aegean basin, which forms its 160-km-long southern margin, lies in the direction of Maliakos Gulf, reaching the northwestern coast of the Peloponnesus in Patraikos Gulf via the Sterea Hellas (Fig. 1). This tectonic line has been proposed to be a major boundary of the Aegea microplate (e.g., McKenzie, 1972); the area south of it should be moving southwest with dextral strike-slip motion and should create compression all the way to the Hellenic trench. However, the area south of the Maliakos and Patraikos Gulfs is characterized by the opening of three subparallel grabens that form the Plio-Quaternary basins of the northern Evoikos, Viotikos Kifissos, and Corinthos Gulfs. This particular area, therefore, shows northeast-southwest extension

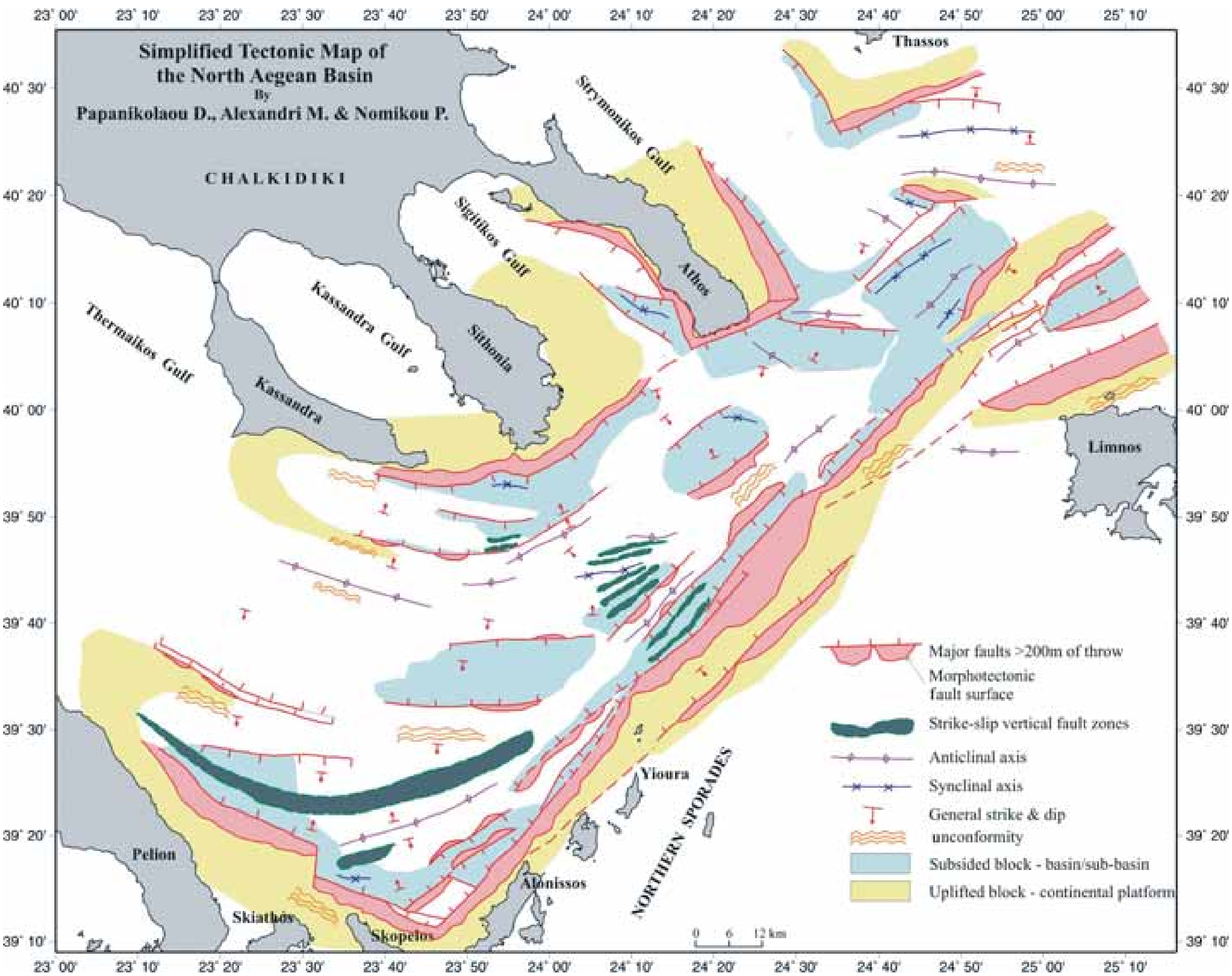



Figure 14. Simplified tectonic map of the north Aegean basin based on the interpretation of the air gun lithoseismic profiles (faults with throws of less than 50 m are generally omitted).

in contrast to the area north of this zone, where no opening of Plio-Quaternary basins is observed (Fig. 1). Extensional structures in central continental Greece probably belong to the central Hellenic shear zone, which has resulted from the difference in subduction rates north (continental subduction at 5–10 mm/yr) and south (oceanic subduction at 35–40 mm/yr) of the Kephalonia transform fault (Royden and Papanikolaou, 2004).

These observations, together with the lack of balance in the GPS rates between Anatolia and the western Aegean area, indicate that the north Anatolian strike-slip kinematics end within its triple bifurcation in the north Aegean area. The extensional deformation of southern continental Greece and the central southern Aegean is the result of Hellenic subduction zone dynamics driven by the retreat of the subducted slab of the Ionian Sea.

In conclusion, the tectonic structure of the north Aegean basin is the result of oblique opening produced by the combination of (1) dextral shear along the northeast-southwest structures of the basin due to the westward escape of Anatolia (and possibly the central Hellenic shear zone) and (2) southwestward pull due to the retreat of the Hellenic subduction zone. The model of gradual increase of opening and deepening of the basin from northeast to southwest (Papanikolaou et al., 2002) has been confirmed by the new tectonic data, which show a gradual southwestward increase of the normal character of the faults, especially at the basin's triangular southwestern corner.

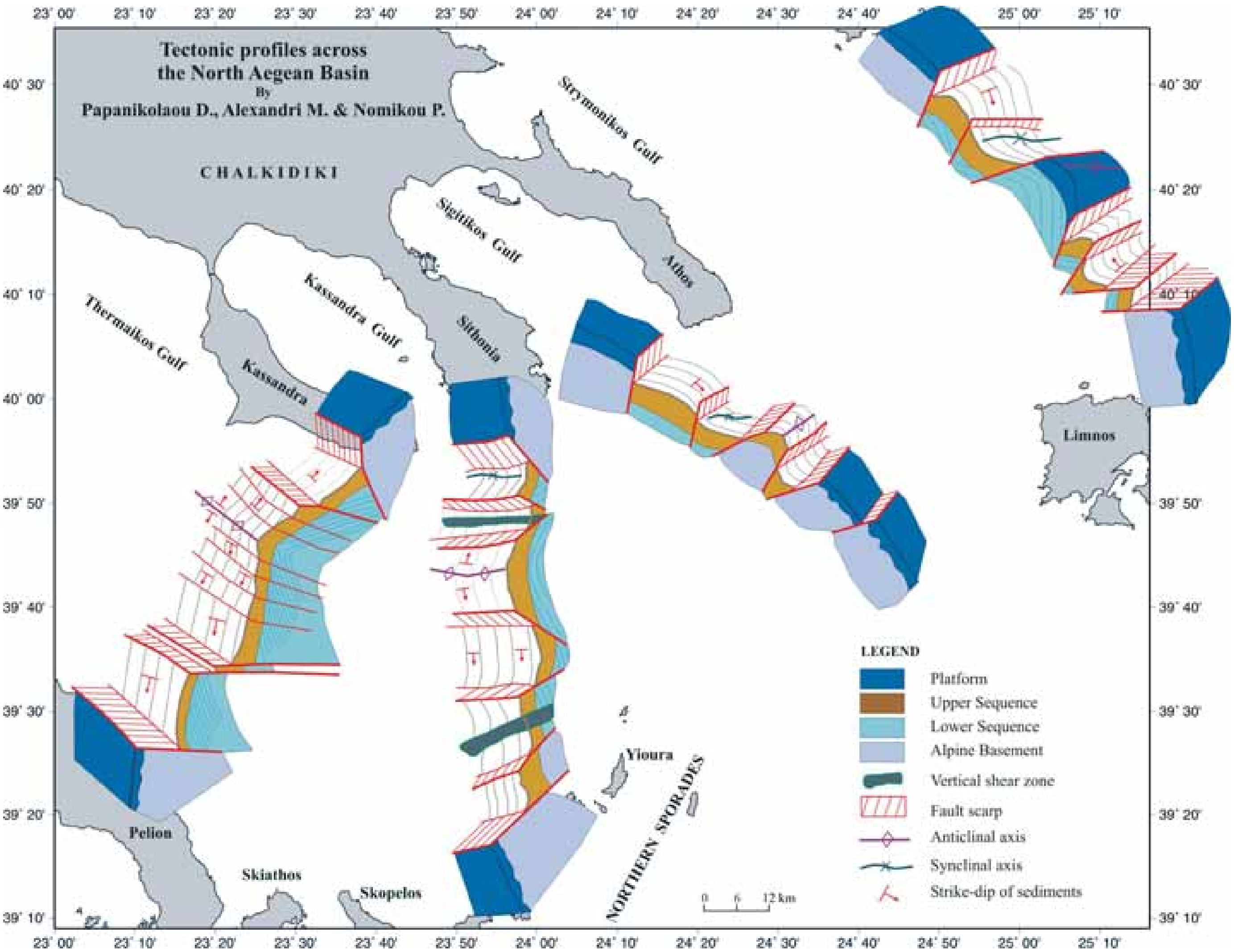



Figure 15. 3-D tectonic profiles across the north Aegean basin based on the analysis of the air gun lithoseismic profiles. The overall structure shown is that of an arcuate graben oriented east-west in the west and northeast-southwest in the east, with an intermediate zone of uplift in the form of either an anticline or a horst.

## ACKNOWLEDGMENTS

The Earthquake Planning and Protection Organization of Greece is acknowledged for financing the research project on the tectonic structure of the north Aegean basin. The officers and the crew of the R/V *AEGAEO* are gratefully acknowledged for their effective contribution in acquiring the seismic data. Constructive comments made by Damian Nance and an anonymous reviewer greatly improved the manuscript.

## REFERENCES CITED

Angelier, J., 1979, Neotectonique de l'arc Egéen: Societé Géologique du Nord, Publications, v. 3, p. 1–417.

Armijo, R., Meyer, B., Hubert, A., and Barka, A., 1999, Westward propagation of the North Anatolian Fault into the northern Aegean: Timing and kinematics: Geology, v. 27, no. 3, p. 267–270, doi: 10.1130/0091-7613(1999)027<0267:WPOTNA>2.3.CO;2.

Armijo, R., Flerit, F., King, G., and Meyer, B., 2003, Linear elastic fracture mechanics explains the past and present evolution of the Aegean: Earth and Planetary Science Letters, v. 217, p. 85–95, doi: 10.1016/S0012-821X(03)00590-9.

Barka, A., and Reilinger, R., 1997, Active tectonics of the Eastern Mediterranean region: Deduced from GPS, Neotectonic and seismicity data: Annali di Geofisica, v. XL, no. 3, p. 587–610.

Brooks, M., and Ferentinos, G., 1980, Structure and evolution of the Sporades basin of the North Aegean Trough, Northern Aegean Sea: Tectonophysics, v. 68, p. 15–30, doi: 10.1016/0040-1951(80)90006-2.

Brunn, J.H., 1976, L'arc concave Zagro-taurique et les arcs convexes tauriques et égéen: Collision des arcs induits: Bulletin de la Société Géologique de France, v. 18, p. 553–567.

Dermitzakis, M., and Papanikolaou, D., 1981, Paleogeography and geodynamics of the Aegean region during the Neogene: Annales Géologiques des Pays Helléniques, *in* Proceedings, vol. IV, VIIth International Congress on the Mediterranean Neogene, Athens, 1979, p. 245–289.

Dewey, J., and Şengör, A.M.C., 1979, Aegean and surrounding region: Complex multiplate and continuum tectonics in convergent zone: Geological Society of America Bulletin, v. 90, p. 84–92, doi: 10.1130/0016-7606(1979)90 <84:AASRCM>2.0.CO;2.

Jackson, J., 1994, Active tectonics of the Aegean region: Annual Review of Earth and Planetary Sciences, v. 22, p. 239–272, doi: 10.1146/annurev.ea .22.050194.001323.

Kahle, H.G., Cocard, M., Peter, Y., Geiger, A., Keilinger, R., Barka, A., and Veis, G., 2000, GPS—derived strain rate fixed within the boundary zones of the Eurasian, African and Arabian Plates: Journal of Geophysical Research, v. 105, p. 23,353–23,370.

Kilias, A.A., Tranos, M.D., Orozco, M., Alonso-Chaves, F.M., and Soto, J.I., 2002, Extensional collapse of the Hellenides: A Review: Revue Societa Geologica Espana, v. 15, p. 129–139.

Koukouvelas, I., and Aydin, A., 2002, Fault structure and related basins of the North Aegean Sea and its surroundings: Tectonics, v. 21, no. 5, p. 1046, doi: 10.1029/2001TC901037.

Kreemer, C., Chamot-Rooke, N., and Le Pichon, X., 2004, Constraints on the evolution and vertical coherency of deformation in the North Aegean from a comparison of geodetic, geologic and seismologic data: Earth and Planetary Science Letters, v. 225, p. 329–346, doi: 10.1016/j.epsl.2004.06.018.

Laigle, M., Hirn, A., Sachpazi, M., and Roussos, N., 2000, North Aegean crustal deformation: An active fault imaged to 10 km depth by reflection seismic data: Geology, v. 28, p. 71–74, doi: 10.1130/0091-7613(2000)028<0071: NACDAA>2.3.CO;2.

Lalechos, N., and Savoyat, E., 1979, La sedimentation Neogène dans le Fosse Nord Egéen: Proceedings, 6th Colloquium on the Geology of the Aegean region, Athens, 1977, v. 2, p. 591–603.

Le Pichon, X., and Angelier, J., 1979, The Hellenic arc and trench system: A key to the neotectonic evolution of the Eastern Mediterranean area: Tectonophysics, v. 60, p. 1–42, doi: 10.1016/0040-1951(79)90131-8.

Le Pichon, X., and Angelier, J., 1981, The Aegean sea: Philosophical Transactions of the Royal Society of London, v. A300, p. 357–372.

Le Pichon, X., Lyberis, N., and Alvarez, F., 1984, Subsidence history of the North Aegean Trough, *in* The geological evolution of the Eastern Mediterranean: Geological Society of London Special Publication 17, p. 727–741.

Le Pichon, X., Chamot-Rooke, N., Lallement, S., Noomen, B., and Veis, G., 1995, Geodetic determination of the kinematics of central Greece with respect to Europe: Implications for Eastern Mediterranean tectonics: Journal of Geophysical Research, v. 100, p. 12,675–12,690, doi: 10.1029/ 95JB00317.

Mascle, J., and Martin, L., 1990, Shallow structure and recent evolution of the Aegean Sea: A synthesis based on continuous reflection profiles: Marine Geology, v. 94, p. 271–299, doi: 10.1016/0025-3227(90)90060-W.

McKenzie, D., 1970, Plate tectonics in the Mediterranean Region: Nature, v. 226, p. 239–243, doi: 10.1038/226239a0.

McKenzie, D., 1972, Active tectonics in the Mediterranean region: Geophysics, Journal of the Royal Astronomical Society, v. 30, p. 109–185.

McNeill, L.C., Mille, A., Minshull, T.A., and Kenyon, N.H., 2004, Extension of the North Anatolian Fault into the North Aegean Trough: Evidence for transtension, strain partitioning, and analogues for Sea of Marmara basin models: Tectonics, v. 23, p. TC2016, doi: 10.1029/2002TC001490.

Needham, H.D., Le Pichon, X., Melguen, M., Pautot, G., Renard, V., Avedik, F., and Carre, D., 1973, North Aegean sea trough: 1972 Jean Charcot cruise: Bulletin of the Geological Society of Greece, v. 10, p. 152–153.

Papanikolaou, D., 1984, The three metamorphic belts of the Hellenides: A review and a kinematic interpretation, *in* The geological evolution of the Eastern Mediterranean: Geological Society of London Special Publication 17, p. 551–561.

Papanikolaou, D., 1986, The Medial Tectonometamorphic Belt of the Hellenides: 3rd Congress, Geological Society of Greece, May 1986: Bulletin of the Geological Society of Greece, v. 20, no. 1, 1988, p. 101–120.

Papanikolaou, D., 1993, Geotectonic evolution of the Aegean: Bulletin of the Geological Society of Greece, v. 28, no. 1, p. 33–48.

Papanikolaou, D., 1997, The tectono-stratigraphic Terranes of the Hellenides: Annales Géologiques des Pays Helléniques, v. 37, p. 495–514.

Papanikolaou, D., Alexandri, M., Nomikou, P., and Ballas, D., 2002, Morphotectonic structure of the western part of the North Aegean Basin based on swath bathymetry: Marine Geology, v. 190, p. 465–492, doi: 10.1016/ S0025-3227(02)00359-6.

Papanikolaou, D., Bargathi, H., Dabovski, C., Dimitriu, R., El-Hawat, A., Ioane, D., Kranis, H., Obeidi, A., Oaie, G., Seghedi, A., and Zagorchev, I., 2004, Transect VII: East European Craton–Scythian Platform–Dobrogea–Balkanides–Rhodope Massif–Hellenides–East Mediterranean–Cyrenaica, *in* The TRANSMED atlas: The Mediterranean Region from crust to mantle: Geological and Geophysical Framework of the Mediterranean and the Surrounding Areas: 32nd International Geological Congress, Florence, August 2004.: Berlin, Springer, CD-ROM.

Pavlakis, P., Makris, J., and Alexandri, S., 1993, Proceedings of Marine Geophysical Mapping of Aegean Sea: 2nd Congress of the Geophysical Union of Greece, v. 2, p. 400–411.

Reilinger, R., McClusky, S., Oral, M., King, R., Toksöz, N., Barka, A., Kinik, I., Lenk, O., and Sanli, I., 1997, Global Positioning System measurements of present day crustal movements in the Arabia-Africa-Eurasia plate collision zone: Journal of Geophysical Research, v. B 102, no. 5, p. 9983–9999.

Roussakis, G., Karageorgis, A.P., Conispoliatis, N., and Lykousis, V., 2004, Last glacial-Holocene sediment sequences in N. Aegean basins: Structure, accumulation rates and clay mineral distribution: Geo-Marine Letters, v. 24, p. 97–111, doi: 10.1007/s00367-004-0167-0.

Roussos, N., 1994, Stratigraphic and paleogeographic evolution of the Paleocene molassic basins of the North Aegean Sea: Bulletin of the Geological Society of Greece, v. 30, p. 275–294.

Roussos, N., and Lyssimachou, T., 1991, Structure of the Central North Aegean Trough: An active strike-slip deformation zone: Basin Research, v. 3, p. 39–48.

Royden, L., and Papanikolaou, D., 2004, Subduction zone dynamics and the recent evolution of the Hellenic Subduction System: American Geophysical Union, annual meeting, Dec. 2004, Abstracts.

Şengör, A.M.C., 1979, The North Anatolian transform fault: Its age, offset and tectonic significance: Journal of the Geological Society of London, v. 136, p. 269–282.

Taymaz, T., Jackson, J., and McKenzie, D., 1991, Active tectonics of the North and Central Aegean Sea: Geophysical Journal International, v. 106, no. 2, p. 433–490.

Manuscript Accepted by the Society 30 December 2005

Geological Society of America Special Papers

## Active faulting in the north Aegean basin

Dimitrios Papanikolaou, Matina Alexandri and Paraskevi Nomikou

*Geological Society of America Special Papers* 2006;409; 189-209
doi:10.1130/2006.2409(11)



Notes