Neogene-Quaternary intraforeland transpression along a Mesozoic platform-basin margin: The Gargano fault system, Adria, Italy

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ABSTRACT

We analyzed field structural data and an offshore seismic-reflection profile and compared them with previously published geological and geophysical data to constrain the tectonic evolution of the Gargano fault system, the kinematics of which have been the subject of contradictory interpretations. Field analyses show that the Gargano fault system consists of NW- to W-striking folds, thrusts, and left-lateral transpressional and strike-slip faults. A set of NW-striking solution cleavage supports the inference of an overall left-lateral kinematic regime for the Gargano fault system. Some synsedimentary structures indicate Miocene-Pliocene contractional and transpressional activity along the Gargano fault system, whereas strike-slip faults affecting Pleistocene conglomerates support a recent, left-lateral, strike-slip activity. The seismic-reflection data show that the offshore prolongation of the Gargano fault system consists of an anticline cut by high-angle faults arranged in a positive flower-like structure, which has mostly grown since middle-late Miocene times along a Mesozoic platform-basin margin. We have schematically reconstructed the tectonic evolution of the Gargano fault system between the middle-late Miocene and the present day. During this period, the Gargano fault system has mostly accommodated contractional to left-lateral transpressional and strike-slip displacements. These displacements are consistent with the regional, Neogene-Quaternary, contractional tectonics across Adria and the Apennines and Dinarides-Albanides fold-and-thrust belts. Some evidence suggests that the Gargano fault system is presently accommodating extensional or left-lateral transtensional displacements. We interpret the Neogene-Quaternary, strike-slip displacements on the Gargano fault system to be connected with the segmentation of the subducted Adriatic slab beneath the Apennines fold-and-thrust belt and with the noncylindrical evolution of this slab (i.e., differential retreating motions), which has undergone differential flexural movements in the adjacent, northern and southern Adriatic compartments.

Keywords: Adriatic region, faults, forelands, Gargano, transpression, subduction zones.

INTRODUCTION

The Gargano Promontory in southern Italy (Fig. 1) is a structural high located in the Adriatic foreland (or Adria) between the Apennines and the Dinarides-Albanides fold-and-thrust belts (Favali et al., 1993; Doglioni et al., 1994; Brankman and Aydin, 2004). The promontory consists of a thick succession of Mesozoic carbonates (Figs. 2 and 3) dissected by an active and complex fault array (the Gargano fault system). Within this system, the Mattinata fault in the southern Gargano Promontory is the most prominent fault (Ortolani and Pagliuca, 1987; Funiciello et al., 1988; Salvini et al., 1999; Brankman and Aydin, 2004). This fault has received much attention by researchers, who, however, have so far provided contradictory interpretations on its kinematics and tectonic history. In summary, the Mattinata fault has been interpreted as reverse, right-lateral, left-lateral, right-laterally inverted, or left-laterally inverted (Billi, 2003; Tondi et al., 2005).

A large body of data about the tectonics of the Gargano Promontory and surrounding regions has been acquired and published during recent years (e.g., Bertotti et al., 1999, 2001; Casolari et al., 2000; Borre et al., 2003; Brankman and Aydin, 2004; Patacca and Scandone, 2004; Milano et al., 2005; Ridente and Trincardi, 2006); however, the tectonic history and the sense of displacement of the Gargano fault system and particularly of the Mattinata fault are still strongly debated (e.g., Bertotti et al., 1999; Hunstad et al., 2003; Brankman and Aydin, 2004; Tondi et al., 2005; Di Bucci et al., 2006).

Understanding the tectonic history of the Gargano fault system provides important insights into the along-strike segmentation of the Apenninic outer deformation front (Royden et al., 1987) and, ultimately, into the evolution of the Africa-Eurasia plate boundary in the central Mediterranean region, where contractional tectonic processes have been profoundly influenced by Adria acting as a continental tectonic indenter (Channell and Horváth, 1976). Within this tectonic framework, the Gargano fault system has been regarded as a first-order tectonic boundary separating Adria into a northern block and a southern one (Favali et al., 1993) and, possibly, as the modern, northern margin of the African plate (Westaway, 1990).

The aim of this paper is to reconstruct the tectonic history of the Gargano fault system from Neogene to Quaternary times by integrating published and newly acquired data. We analyze here field data collected in the Gargano Promontory

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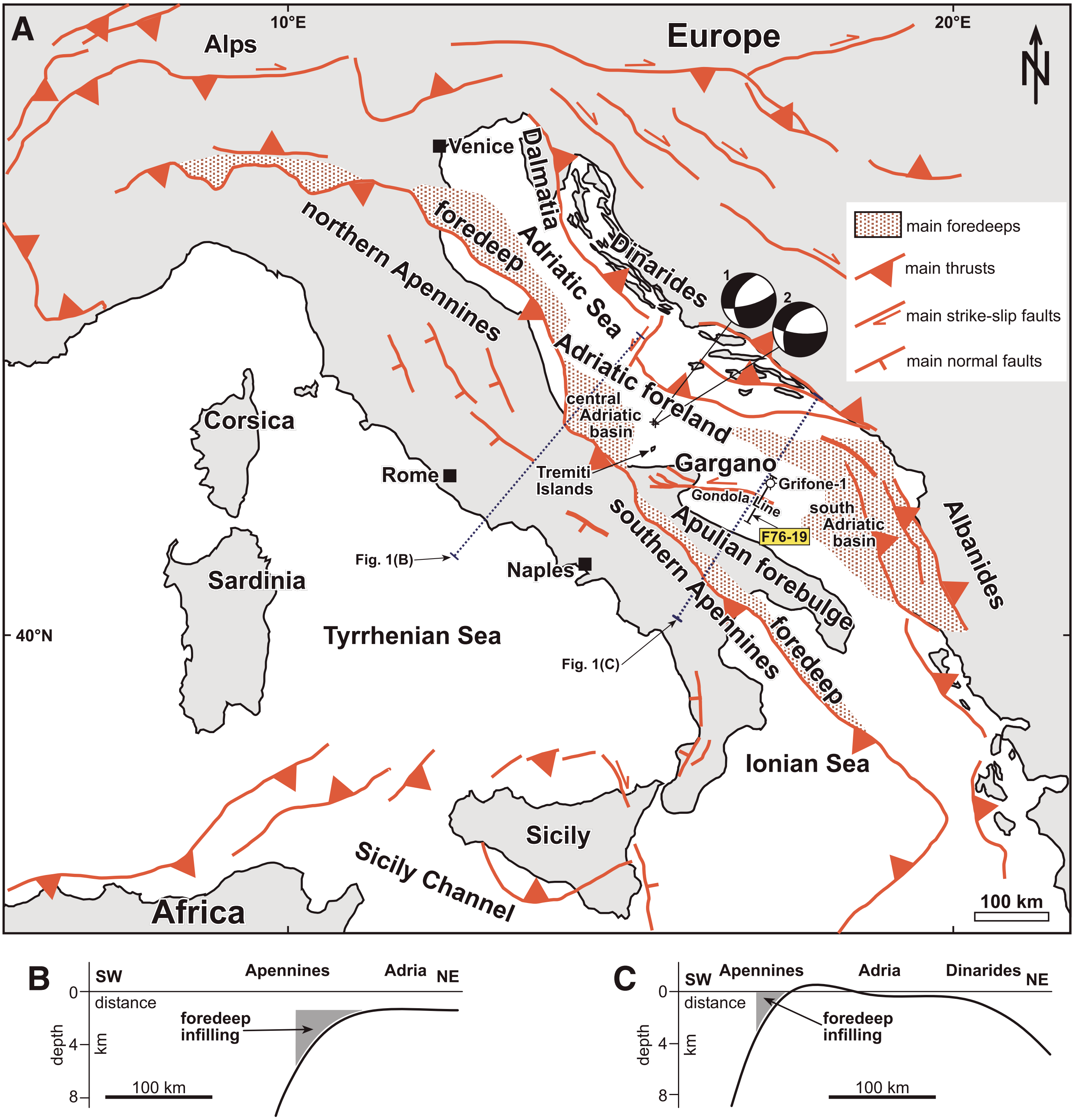

Figure 1. (A) Simplified tectonic map of Italy and surrounding regions. The Gargano fault system (GFS) is located in the central Adriatic foreland, between opposite-verging Apennines and Dinarides-Albanides fold-and-thrust belts. Major foredeep domains are shown along the belt fronts. Apulian forebulge is a NW-trending (i.e., hinge trend) peripheral bulge formed during Pliocene-Pleistocene flexure of the Adriatic foreland beneath the southern Apennines. The two earthquake fault-plane solutions in Adriatic Sea are from Console et al. (1989). Relative data are as follows. Solution 1: date = 8 January 1986; ML = 4.6; T-axis azimuth = N143°; T-axis plunge = 17°. Solution 2: date = 11 January 1986; ML = 4.8; T-axis azimuth = N163°; T-axis plunge = 19°. (B–C) Profiles (see relative tracks in Fig. 1A) showing the shape of flexed Adriatic foreland beneath the Apennines. Profiles are drawn by best-fitting data about the depth of the basal Pliocene surface in the area (Royden et al., 1987; Moretti and Royden, 1988). Note that the vertical scale is greatly exaggerated. The southern profile shows a pronounced forebulge (i.e., the Apulian forebulge) and a deep basin northeast of the forebulge. In contrast, the forebulge is much less marked in the northern profile.

and a reprocessed seismic-reflection profile across the offshore prolongation of the Mattinata fault. These results are compared with the Neogene-Present tectonic evolution of the Adriatic plate as depicted in previous papers (e.g., Doglioni et al., 1994; de Alteriis, 1995; Argnani et al., 1996; Bertotti et al., 2001). Finally, a comprehensive, regional, tectonic model is proposed. In this model, the Gargano fault system is hypothetically linked with tears across the segmented Adriatic slab beneath the Apennines fold-and-thrust belt, and the Gargano fault system strike-slip displacement is connected with the noncylindrical evolution of this slab (i.e. differential retreating motions affected adjacent, decoupled compartments of the slab), which has undergone differential flexural movements in the adjacent northern and southern compartments (Figs. 1B and 1C; Royden et al., 1987).

GEOLOGICAL SETTING

The Gargano Promontory is located on the western side of Adria (Fig. 1), which has been the common foreland for the NE-verging Apennines in the west, and the SW-verging Dinarides-Albanides in the east, during Late Cretaceous through Quaternary times (Channell et al., 1979; Platt et al., 1989). The Apennines grew in a forelandward sequence mainly between Miocene and late Pliocene–early Pleistocene times (Patacca et al., 1992). Contractional deformations at the front of the orogenic wedge terminated during late-early Pliocene times in the central Apennines (i.e., to the north of the Gargano Promontory) and during early Pleistocene times in the southern Apennines (i.e., to the south of the Gargano Promontory). The Dinarides-Albanides developed mainly during Paleogene-Neogene times as an orogenic wedge, including foreland-verging thrust sheets and back thrusts (Roure et al., 2004; Dumurdzanov et al., 2005). The northern orogenic wedge (i.e., the Dinarides) developed mainly during Eocene–early Miocene times, whereas the southern orogenic wedge (i.e., the Albanides) developed mainly during late Paleogene–middle Miocene times. A further phase of shortening involved the Albanides during post–middle Pliocene times (Nieuwland et al., 2001; Roure et al., 2004). Ongoing earthquakes characterized by NE-SW compressional axes at the front of the Albanides suggest that the contractional tectonics in this region are still slightly active (Montone et al., 2004).

Since Late Cretaceous–Paleogene times and, more intensely, since Miocene times, contractional deformation has occurred within the Adriatic foreland in response to the development of the Apennines and Dinarides-Albanides belts. Intraforeland contractional deformation has probably occurred because of the strong mechanical coupling between the subducting Adriatic plate and the overriding ones, and this mechanism has resulted in the transfer of displacement from the fold-and-thrust belt to the foreland. Bertotti et al. (2001) thoroughly reconstructed the Neogene-Quaternary main tectonic phases of the Adriatic foreland and relative basins as follows. (1) During Miocene times, basin subsidence and orogen-perpendicular contractional tectonics were active both in the northern and in the southern Adriatic (i.e., to the north and to the south, respectively, of the Gargano Promontory). Shortening in the southern sector was probably greater than in the northern sector. Contractional inversion tectonics occurred locally in the Gargano Promontory and in the Tremiti Islands (Abbazzi et al., 1996; Bertotti et al., 1999; Casolari et al., 2000). (2) During Pliocene–early Pleistocene times, the Apennines foredeep and the adjacent Apulian forebulge developed (Figs. 1B and 1C). At this stage, the orogen-perpendicular shortening across the Adriatic foreland was particularly active in the southern sector. Folds and thrusts developed in the Gargano Promontory, where late Pliocene shallow-water sediments were involved in synsedimentary contractional structures (Bertotti et al., 1999; Brankman and Aydin, 2004). Toward the east, basin subsidence terminated in the Albanide foredeep and back thrusts activated in the Albanide fold-and-thrust belt (early-middle Pleistocene times) (Nieuwland et al., 2001; Roure et al., 2004). (3) During middle Pleistocene times, tectonic uplift occurred in the Apulian forebulge and in the eastern sector of the southern Apennines foredeep, whereas subsidence was operating in northern Adria (Doglioni et al., 1994, 1996). The shape of the Adriatic flexure (Figs. 1B and 1C) in northern and southern Adria and the relative foredeep size show the spatially heterogeneous flexural behavior of Adria (Royden et al., 1987). (4) Contractional tectonics in the southern Adriatic foreland has endured until recent or present

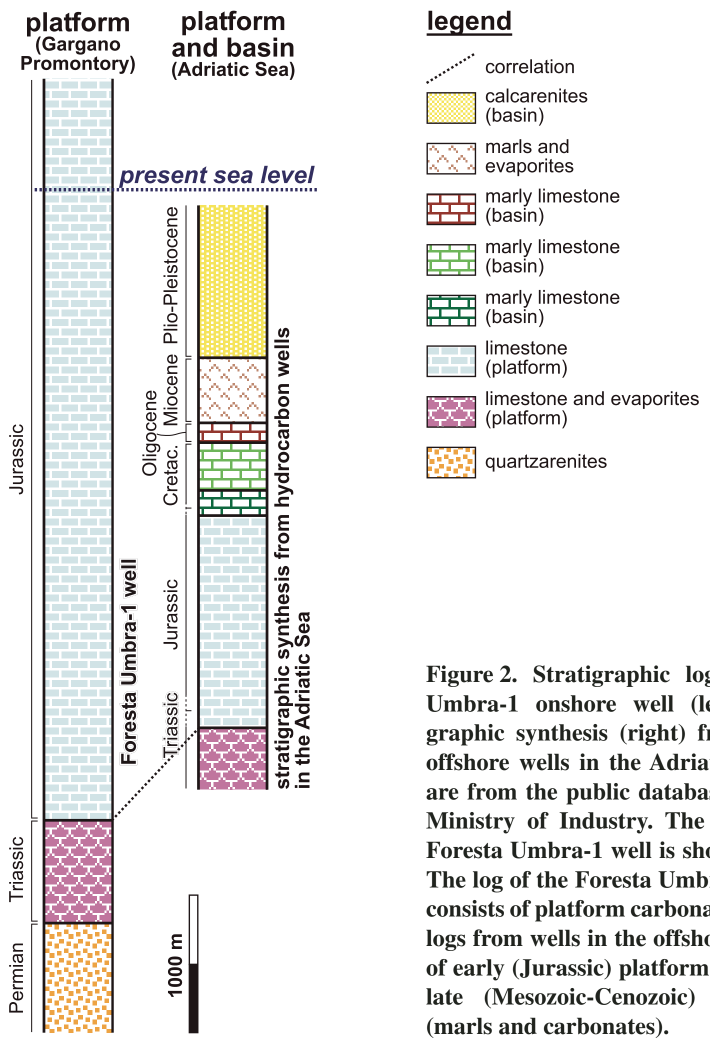

Figure 2. Stratigraphic log from Foresta Umbra-1 onshore well (left) and stratigraphic synthesis (right) from logs of the offshore wells in the Adriatic region. Data are from the public database of the Italian Ministry of Industry. The location of the Foresta Umbra-1 well is shown in Figure 3. The log of the Foresta Umbra-1 well mostly consists of platform carbonates, whereas the logs from wells in the offshore areas consist of early (Jurassic) platform carbonates and late (Mesozoic-Cenozoic) basin deposits (marls and carbonates).

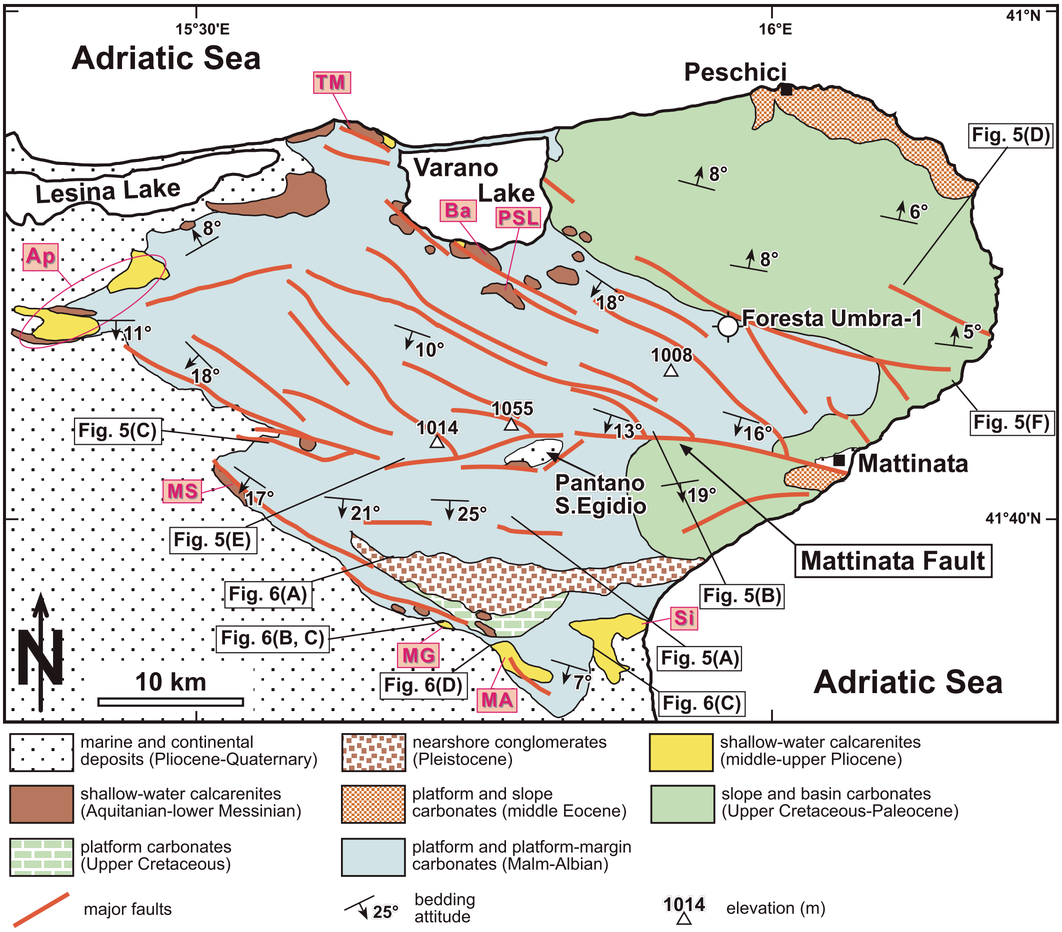

Figure 3. Geological map of Gargano Promontory. The fault pattern is simplified and will be thoroughly considered in Figure 4. Note the variability of depositional environments (i.e., from platform in west to basin in east) for Mesozoic-Paleogene rocks. List of abbreviations for localities mentioned in text: Ap—Apricena, Ba—Bagno, MA—Monte Aquilone, MG—Monte Granata, MS—Masseria Spagnoli, PSL—Poggio San Lio, Si—Siponto, and TM—Torre Mileto.

times, as shown by seismic-reflection profiles, in which a set of reverse faults and gentle folds involves sediments lying at the sea bottom (Argnani et al., 1996; Ridente and Trincardi, 2006). In contrast, the youngest contractional structures in the northern Adriatic foreland (i.e., to the north of Gargano) are late Pliocene–early Pleistocene in age.

The Gargano Promontory consists of a 3–4-km-thick succession of Jurassic to Eocene carbonates (Spalluto et al., 2005), which were formed in a platform environment toward the west and the south, and in slope-to-basin environments toward the east and the northeast (Figs. 2 and 3). Seismic-reflection profiles across Adria have shown that, during Mesozoic times, the platform-basin margin consisted of a topographically heterogeneous, transitional region where islands, troughs, and elevated sectors occurred. The low sectors acted as sedimentary traps and were systematically bounded by normal faults (de Dominicis and Mazzoldi, 1987; Morelli, 2002).

Miocene-Pliocene shallow-water sediments (i.e., mostly calcarenites) are scattered over the Gargano Promontory, particularly in the low-altitude sectors (i.e., usually lower than ~200 m above sea level [asl]) toward the south, the north, and the west (Casolari et al., 2000). In the southern sector, a marine conglomerate that consists of round carbonate clasts (i.e., derived from the weathering of the local Mesozoic carbonates) within a calcarenitic matrix (i.e., the Rignano Conglomerate; Casolari et al., 2000) occurs between ~50 and 200 m asl and unconformably overlies the Mesozoic-Neogene carbonates. This conglomerate has been dubiously dated back either to Pleistocene times by Servizio Geologico d'Italia (1970) or to late Messinian times by Casolari et al. (2000). Recent analyses have confirmed the Pleistocene age of these deposits (Spalluto, 2004).

The Gargano fault system cuts across the middle sector of the Gargano Promontory (Fig. 3). The prolongation of the Gargano fault system both toward the east in offshore areas (de Dominicis and Mazzoldi, 1987; Finetti et al., 1987; Argnani et al., 1993, 1996; de Alteriis and Aiello, 1993), and toward the west beneath the Apennines foredeep (Chilovi et al., 2000; Patacca and Scandone, 2004) has been analyzed and mapped from seismic-reflection data. Toward the east, the Gondola Line (Fig. 1) is considered the prolongation of the Mattinata fault. The Gondola Line is an E-W–trending anticline disrupted by subvertical faults. Toward the east, the Gondola Line changes to trend NW-SE. Argnani et al. (1993, 1996) interpreted this structure as a link with Eocene–early Pliocene contractional inversion of Mesozoic extensional faults marking the boundary between the basin and the carbonate platform. Toward the west, the prolongation of the Gargano fault system beneath the Apennines foredeep consists of an array of strike-slip to transpressional faults (Fig. 4A) that are progressively characterized by a NW-SE strike (Chilovi et al., 2000; Patacca and Scandone, 2004).

ONSHORE DATA

At the scale of the Gargano Promontory, the Mesozoic-Cenozoic carbonate strata form a gentle and asymmetric anticline (Fig. 3). The northern limb of the anticline dips toward the N-NE by less than 10°, whereas the southern limb dips toward the S by ~20° (Fig. 5A). The average azimuth (i.e., computed from a Gaussian best fit of data) of the carbonate strata from

123 measurements scattered across the entire promontory is N109° (G1 in Fig. 4B). This trend approximately corresponds to the azimuth of the anticline hinge, the location of which is almost coincident with the WNW–striking boundary between the platform carbonates in the southwest and the slope-to-basin carbonates in the northeast (Fig. 3).

The wide anticline of the Gargano Promontory is dissected, in its middle portion, by the WNW–trending Gargano fault system (Figs. 3 and 4). The Gargano fault system includes W-, WNW–, and NW-striking faults. Fault mapping in the Gargano Promontory (Fig. 4B) was done by combining results from the following methods: (1) the analysis of stereoscopic aerial photographs (at the approximate scale of 1:25,000); (2) the analysis of the digital elevation model shown in Figure 4A; and (3) field mapping at 1:25,000 scale. To determine the attitude and kinematics of the faults that form the Gargano fault system, mesoscopic structural data were collected along these faults (e.g., G5 to G16 in Fig. 4B). These data show a fault population that mostly consists of high-angle or subvertical slip surfaces, which mainly strike between N83° and N146° (G2 in Fig. 4B). The average azimuth (i.e., computed from a Gaussian best fit of data) of mesoscopic faults from 965 measurements is N117° (G2 in Fig. 4B). The direction and sense of slip of the analyzed faults are inferred from the relative kinematic indicators (G3 in Fig. 4B), which mostly consist of striations, slickensides, and slickolites. The inferred slip for the observed faults is either strike-slip, oblique-slip, or dip-slip (e.g., Fig. 5B). Pure or near-pure strike-slip faults usually strike about N90° (e.g., Fig. 5C). The dip-slip component of slip increases for faults striking from about N90° to about N150–160° (e.g., G5 to G16 in Fig. 4B). Except for a few NNE–striking faults, which have a right-lateral sense of slip, fault striations and other kinematic indicators on the analyzed faults show a left-lateral sense (e.g., Fig. 5C) for the horizontal component of slip and a reverse sense for the dip-slip component of slip. Within the azimuth population from the fault-slip indicators, three major sets can be recognized, namely N65°, N96°, and N125° (G3 in Fig. 4B). The N65°-trending set is mainly associated with pure or near-pure reverse fault motions, whereas the N96°- and N125°-trending sets are mainly associated with left-lateral strike-slip or oblique-slip (i.e., transpressional) fault motions.

Normal faults in the Gargano Promontory are not frequent and are restricted to particular areas. Normal and transtensional faults occur along the Mattinata fault in the Pantano S. Egidio area (Fig. 3), where a pull-apart basin occurs. This basin is filled with Pleistocene continental sediments, which unconformably overlie late Miocene shallow-water calcarenites. The Miocene calcarenites are in the hanging wall of the normal faults bounding the basin. Normal faults occur also in the northeastern Gargano Promontory, where they cut through Late Cretaceous–Paleocene slope carbonates. Most of these faults show evidence of synsedimentary growth (see the fan-shaped growth strata along normal faults in Fig. 5D) and, in some cases, are upward-sutured by the Cretaceous-Paleocene carbonates. The normal faults of the northeastern Gargano Promontory are usually intermediate- to high-angle faults that strike between N120° and N170° and dip toward the NE (Fig. 5D).

The most ubiquitous tectonic structure affecting the carbonate strata within the Gargano fault system is a solution cleavage (Figs. 5E and 5F). This consists of arrays of subvertical, closely spaced, solution surfaces along which insoluble residues may concentrate (Fig. 5E). The solution cleavage is particularly frequent in the vicinity of fault surfaces (Fig. 5F) and tends to fade away at larger distances from the major faults. Stylolitic teeth along the solution cleavage show the contractional nature of this structure and indicate the relative axis of shortening, which is usually perpendicular to the cleavage surfaces (Billi, 2003). The average azimuth of 6411 cleavage surfaces measured within the Gargano fault system is N132°, from which we infer a relative N42°-striking axis of shortening (G4 in Fig. 4B).

Some notable exposures help to constrain the chronology of deformations in the Gargano Promontory. In the southern Gargano Promontory, the Rignano Conglomerate (i.e., Pleistocene in age; Fig. 3) lies on a flat, wave-cut, erosional surface limited toward the north by the southern limb of the Gargano anticline. The Rignano Conglomerate is affected in a few places by left-lateral, strike-slip faults striking about E-W (Fig. 6A). In the Monte Granata area (southern Gargano Promontory; Figs. 3 and 6B), a growth wedge of middle-late Pliocene, shallow-water calcarenites, partially overthrust by the fold itself, is preserved in the footwall of a NW-striking thrust-related anticline of Jurassic carbonate strata. The calcarenites are gently folded and form a syncline (Fig. 6B). This structure was described in detail by Bertotti et al. (1999). The Jurassic carbonates in the hanging wall are intensely deformed, and such deformations include a NW-striking solution cleavage and NW-striking, left-lateral, strike-slip faults. In the footwall, the Pliocene strata unconformably overlie strongly deformed (i.e., faulted, folded, and cleaved) Jurassic carbonates (see also Bertotti et al., 1999). In contrast, the Pliocene strata are slightly deformed, and these deformations include NW-striking, left-lateral, strike-slip faults (Fig. 6C) and deformation band arrays in addition to the synsedimentary syncline observed in Figure 6B.

Another growth thrust-related anticline occurs in the Monte Aquilone area (Fig. 3), where near-horizontal strata of middle-late Pliocene, shallow-water calcarenites unconformably overlie faulted and folded Jurassic carbonates. The Pliocene calcarenites fill the depressions generated by the WNW–trending synclines of Jurassic carbonates. The fan-shaped organization of the Pliocene strata in the backlimb of the Monte Aquilone anticline indicates the syntectonic deposition of the Pliocene strata. In the Monte Aquilone area, the strong contrast in deformational styles between the Jurassic carbonates and the Pliocene calcarenites is visible in several exposures. Figure 6D, for instance, shows nearly undeformed Pliocene calcarenites unconformably overlying a fault-related coarse breccia developed in Jurassic carbonates. Similar features also occur in the Siponto area (Fig. 3).

In the Apricena area (Fig. 3), Abbazzi et al. (1996) observed tectonically controlled, Neogene-Quaternary, sedimentary cycles that reveal contractional events during Messinian, late Pliocene, and Pleistocene times. In the Bagno, Poggio San Lio, and Masseria Spagnoli localities (Fig. 3), Bertotti et al. (1999) and Casolari et al. (2000) observed sedimentary structures grown under contractional tectonic control during the Miocene (i.e., during Langhian–early Messinian time).

In summary, the main findings from onshore analyses are: (1) the occurrence of a regional anticline trending WNW-ESE; (2) the occurrence of the WNW–trending Gargano fault system in the axial region and southern limb of the regional anticline; (3) the occurrence, within the Gargano fault system, of faults, folds, and solution cleavages consistent with an overall NE-SW contraction; (4) the occurrence of field evidence suggesting the following ages of tectonic deformation: (i) middle-late Mesozoic time for the normal faulting along the platform margin; (ii) middle-late Pliocene for thrusting within the Gargano fault system; and (iii) from middle-late Pliocene onward for left-lateral strike-slip faulting within the Gargano fault system. These age constraints are consistent with previously published dates (cited earlier).

OFFSHORE DATA

To define the main structural highs and depressions of the Mesozoic-Cenozoic carbonate strata offshore of the Gargano Promontory, a dip magnitude map of the carbonate strata

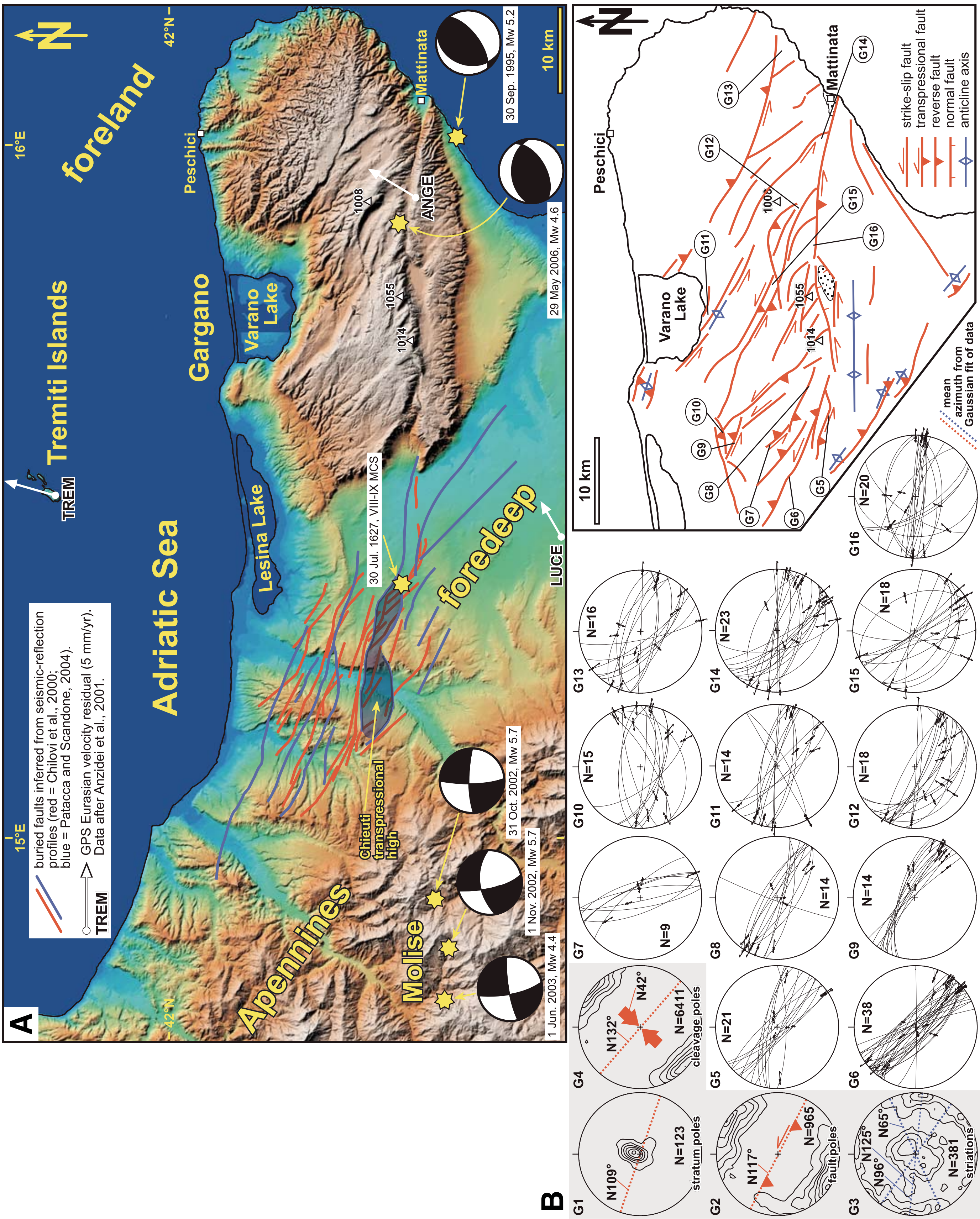
A
B
Adriatic Sea
Tremiti Islands
foreland
Gargano
foredeep
Apennines
Molise
Varano Lake
Lesina Lake
Peschici
Mattinata
TREM
ANGE
LUCE
1008
1055
1014
16°E
15°E
42°N
10 km
buried faults inferred from seismic-reflection profiles (red = Chilovi et al., 2000; blue = Patacca and Scandone, 2004).
GPS Eurasian velocity residual (5 mm/yr). Data after Anzidei et al., 2001.
Chieuti transpressional high
30 Jul. 1627, VIII-IX MCS
30 Sep. 1995, Mw 5.2
29 May 2006, Mw 4.6
31 Oct. 2002, Mw 5.7
1 Nov. 2002, Mw 5.7
1 Jun. 2003, Mw 4.4
strike-slip fault
transpressional fault
reverse fault
normal fault
anticline axis
mean azimuth from Gaussian fit of data
G1
N109°
N=123
stratum poles
G2
N117°
N=965
fault poles
G3
N125°
N65°
N96°
N=381
striations
G4
N132°
N42°
N=6411
cleavage poles
G5
N=21
G6
N=38
G7
N=9
G8
N=14
G9
N=14
G10
N=15
G11
N=14
G12
N=18
G13
N=16
G14
N=23
G15
N=18
G16
N=20

Figure 4. (A) Digital elevation model of Gargano Promontory. The elevation ranges between 0 and 1055 m above sea level (asl). The three earthquake fault-plane solutions in the Molise region are from Valensise et al. (2004). In the east, the two earthquake fault-plane solutions are the only ones available for the Gargano Promontory in the Centroid-Moment Tensor (CMT) catalogue of Harvard University. A yellow star south of Lesina Lake indicates estimated epicenter for the great 1627 A.D. earthquake (Boschi et al., 1997). The fault array located west of the Gargano Promontory is buried below the foredeep infilling and is inferred from seismic-reflection profiles (Chilovi et al., 2000; Patacca and Scandone, 2004). The blue shading indicates the area of the Chieuti transpressional high known from seismic-reflection data. The three global positioning system (GPS) velocity vectors are from Anzidei et al. (2001). (B) Tectonic map of Gargano Promontory (right) and relative structural data (left) plotted in equal-area Schmidt diagrams (lower hemisphere). Shading is for cumulative diagrams. Mapped faults are inferred from geomorphologic analyses and field mapping. Diagrams G1 to G4 show contours to total data (G1—stratum poles; G2—fault poles; G3—fault striations; and G4—cleavage poles) and average azimuths of planes (red) or lines (blue) computed from a Gaussian best fit of data (e.g., Salvini et al., 1999). In G2, the triangles and a left-lateral arrow along average azimuth of fault planes indicate the sense of displacement for major components of fault slip, i.e., reverse and left-lateral senses. In G4, the convergent arrows indicate average azimuth (i.e., N42°-trending) for the axis of maximum shortening as inferred from the attitude of solution cleavages. G5–G16 show fault planes and relative striations for selected sites shown in the tectonic map (right).

was generated by automatically running the first derivative on the isobaths of the carbonate top surface (Fig. 7). These isobaths were produced at Enterprise Oil Italiana (now Shell Italia E&P) for the southern Apennines and Adriatic foreland by interpreting a data set consisting of ~22,000 km of seismic lines and 300 wells. Data points were organized into grids by using square meshes 500 m wide. The dip values, expressed in degrees, were computed from the difference in height between two adjacent grid nodes (i.e., 500 m distant). We chose to develop a dip magnitude map because such a map is likely to be the best way to identify folds, which are notoriously frequent in the region off Gargano (i.e., thrust-related anticlines; de Dominicis and Mazzoldi, 1987; Morelli, 2002). We chose to draw the dip magnitude of the Mesozoic-Cenozoic carbonate top surface because this surface is the most distinguishable in seismic-reflection profiles and in borehole sonic logs and because most folds are younger than this surface (de Dominicis and Mazzoldi, 1987; Argnani et al., 1993). The top surface of the carbonate strata is not an isochronous horizon and does not correspond to a specific paleogeographic unit. Such a surface can, in fact, correspond either to the top of the carbonate pelagic sequence (Cretaceous-Eocene) in the basinal areas, or to the top of shallow-water carbonates (Cretaceous-Messinian) in the platform region and in the bypass and slope areas (Crescenti, 1975). In some structural highs, because of erosion, the top surface of the carbonate succession is Cretaceous or even Jurassic. The top surface of the carbonate strata is seismically characterized by a high-amplitude reflection (i.e., reflection A in Fig. DR1 in the GSA Data Repository[1]), which results from the change in acoustic impedance between the late Neogene–Quaternary siliciclastic sediments and the underlying carbonate succession.

Figure 7 shows the E-trending fold (i.e., anticline) along the easterly prolongation of the Mattinata fault (i.e., the Gondola Line, Fig. 1). Toward the east, the Gondola Line diverts into a WNW–trending array of folds and faults. Further anticlines can be recognized near the eastern portion of the Gondola Line, and most of these anticlines trend WNW-ESE. N- and NNE–trending anticlines are also present. Most anticlines inferred from Figure 7 are also imaged in previously published seismic-reflection profiles (de Dominicis and Mazzoldi, 1987; Finetti et al., 1987; Aiello and de Alteriis, 1991; Argnani et al., 1993; de Alteriis, 1995; Tramontana et al., 1995; Morelli, 2002). In the southwest (Fig. 7), a curvilinear band of steep-dip domains indicates the main margin of the Apulian Platform.

To analyze the deformational features and chronology along the offshore prolongation of the Mattinata fault (i.e., the Gondola Line), we reprocessed (i.e., filtering and migration) the F76–19 seismic-reflection profile (Fig. DR1, see footnote 1). This profile was acquired in 1976 by the Compagnie Générale de Géophysique as part of the public domain data set acquired when this region was open to hydrocarbon exploration. The main parameters for the acquisition and original processing of the F76–19 profile are listed in Table DR1 in the GSA Data Repository (see footnote 1). The F76–19 profile contains the Grifone-1 well, the stratigraphy of which is redrawn in Figure 8 after the original log elaborated by Agip. We chose the F76–19 profile among others located off the Gargano Promontory because its profile cut across a WNW–striking segment of the Gondola Line fault, the general strike of which is about E-W along the easterly prolongation of the strike-slip Mattinata fault. In such a fault, a WNW–striking segment should be affected by transpressional deformation in the case of left-lateral displacements and by transtensional deformation in the case of right-lateral displacements. The F76–19 profile should, therefore, significantly contribute to the knowledge of the sense of displacement on the Mattinata fault.

In the southwestern sector of the F76–19 profile, the main margin of the Apulian Platform can be seen. This margin is affected by a NE-dipping normal fault (Fig. 9A). In the central and northeastern sectors, two anticlines are imaged, namely the Gondola and Grifone anticlines. The Gondola anticline is strongly faulted. In particular, two systems of faults are present. One system (i.e., below 2.75 s two-way traveltime [TWTT]) affects the anticline limbs with normal displacements. A younger system (i.e., above 2.75 s TWTT) affects the axial region of the anticline and forms a flower structure where the axial zone is depressed and the limbs are elevated. The link between the two fault systems (i.e., the one below and the one above 2.75 s TWTT) is ensured by three main fault segments, at least (Fig. 9A). Two segments of the younger fault system (i.e., the one located above 2.75 s TWTT) propagate upward and involve the seafloor. Growth strata occur on the limbs of the Gondola anticline (Fig. 9A). These strata are younger than the top surface of the Bisciaro Formation (early-middle Miocene time). In particular, the deepest growth strata are between the top surfaces of the Bisciaro and Schlier Formations (i.e., middle-late Miocene time), and the shallowest ones are very close to the seabed (i.e., late Quaternary time). Several other faults occur in the southwest of the Gondola anticline. Most of these faults are arranged in a positive, flower-like structure near the seabed and originate, at deeper levels, from basin-bounding normal faults. The small vertical displacements on

[1]GSA Data Repository item 2007060, Figure DR1 and Table DR1 (Figure DR1 contains the reprocessed F76–19 seismic-reflection profile across the southern Adriatic Sea, and Table DR1 contains the relative main acquisition and processing data), is available on the Web at http://www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

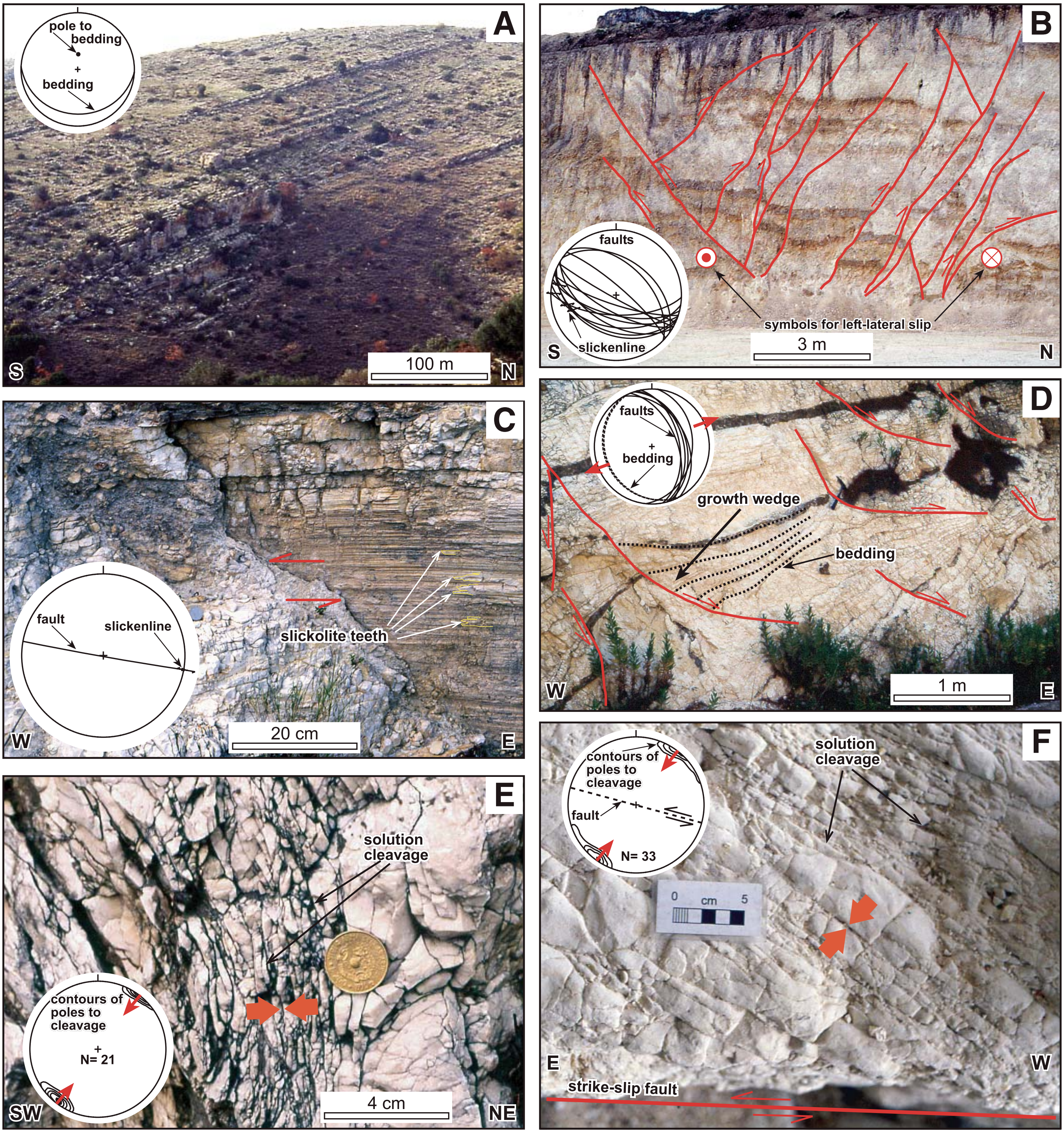

Figure 5. Photographs of rock exposures from the Gargano Promontory. See relative locations in Figure 3. Data plots are equal-area Schmidt diagrams (lower hemisphere). (A) S-dipping (~20°) Jurassic platform carbonates in the southern limb of the regional WNW–trending anticline (southern Gargano Promontory). (B) Positive flower structure (i.e., left-lateral transpressional faults) and associated fault rocks within the Mattinata fault zone. (C) Pure strike-slip fault (N97°-striking) in Jurassic carbonates of the western Gargano Promontory. Note, on the northern block, slickolite teeth (contoured in yellow) point toward the west and show a left-lateral sense of slip. (D) Synsedimentary normal faults in Cretaceous, slope-to-basin carbonates of eastern Gargano Promontory. Note fan-shaped strata (i.e., thickening toward faults) along some of the faults, indicating synsedimentary faulting. Some faults terminate upward. The two red arrows in the data plot indicate horizontal component of slip. (E) Solution cleavage in Jurassic carbonates along the Mattinata fault. Red converging arrows show relative shortening axis. (F) Strike-slip fault (map view) with an associated set of solution cleavage along the southeastern coast of the Gargano Promontory (i.e., Cretaceous slope-to-basin carbonates). Red converging arrows show relative shortening axis. From the shortening axis, a left-lateral sense of slip can be inferred for the N110°-striking fault.

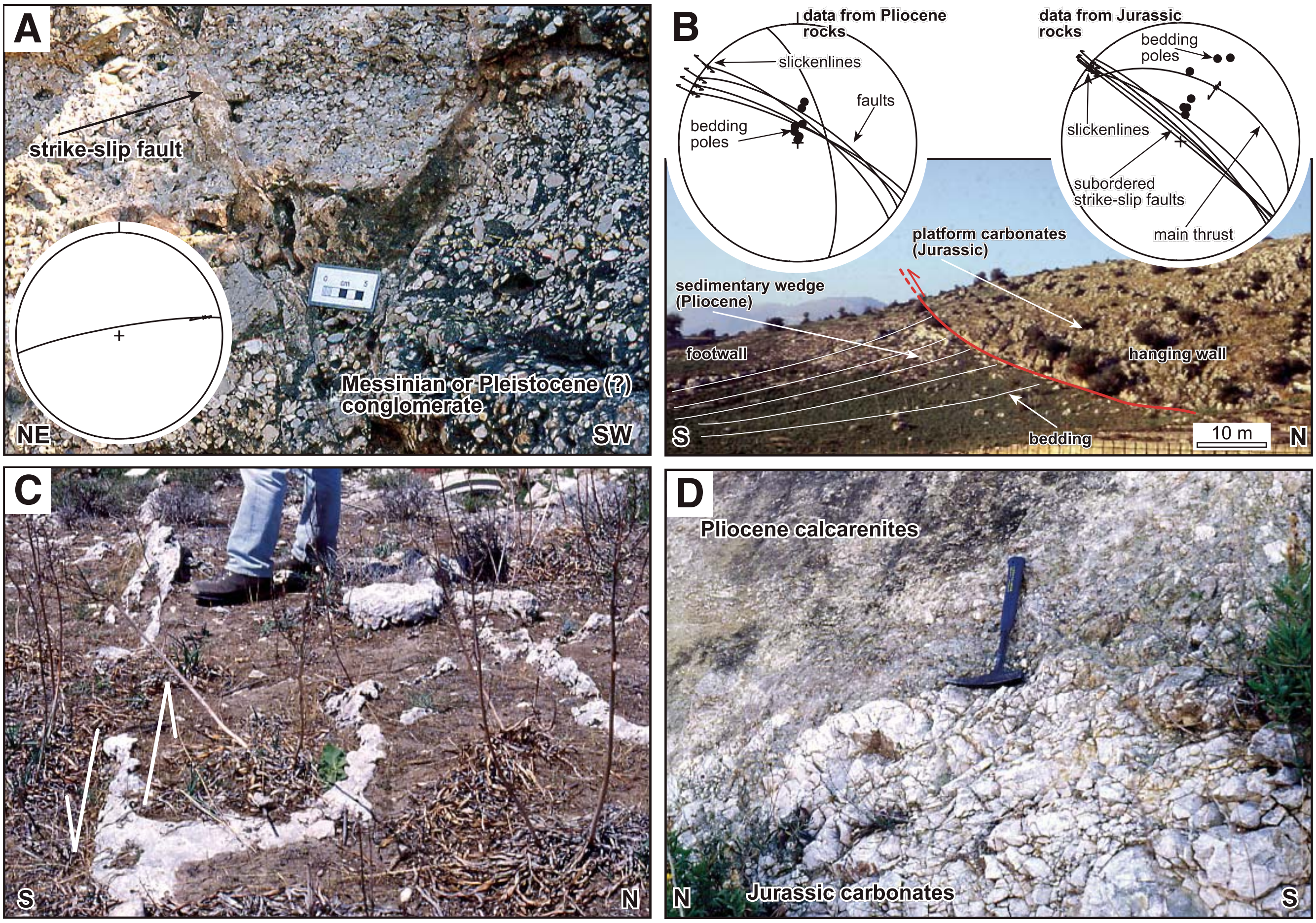

Figure 6. Photographs of rock exposures from the Gargano Promontory. See Figure 3 for locations. Data plots are equal-area Schmidt diagrams (lower hemisphere). (A) Nearshore conglomerates (dated as Pleistocene by Spalluto, 2004) unconformably overlying Jurassic carbonates in the southern Gargano Promontory. A N80°-striking, left-lateral, strike-slip fault cuts across conglomerates. (B) SW-verging synsedimentary thrust (i.e., Jurassic platform carbonates in the hanging wall and middle-late Pliocene shallow-water calcarenites in the footwall). Pliocene strata form a growth wedge as indicated also by the distribution of relative poles plotted in the Schmidt diagram (left diagram). Progressive thickening of strata toward the thrust can be inferred from the photograph. A set of NW-striking, left-lateral, strike-slip faults affects Pliocene strata (see Schmidt diagram on the left). Jurassic strata form a SW-dipping forelimb of the hanging-wall ramp anticline. Relative poles in the Schmidt diagram on right show a steepening pattern of strata toward the forelimb. A set of NW-striking, left-lateral, strike-slip faults cuts across the crest and backlimb of the hanging-wall anticline (see the Schmidt diagram on right). Compare this photograph with Figure 3b in Bertotti et al. (1999) and Figure 4a in Brankman and Aydin (2004). (C) NW-striking, left-lateral, strike-slip faults across Pliocene strata lying at the footwall of the growth thrust shown in A. (D) Middle-late Pliocene, shallow-water calcarenites unconformably overlying Jurassic platform carbonates in the southern Gargano Promontory. Jurassic carbonates are strongly fractured, whereas Pliocene calcarenites are almost undeformed.

the shallow portions of these faults are suggestive of strike-slip kinematics.

The Grifone anticline is more prominent than the Gondola anticline (Fig. 9A). Two reverse faults on the northeastern side of the Grifone anticline probably contributed to the development of the anticline itself. A normal fault (i.e., below 3 s TWTT) that involves the strata younger than the top surface of the Scaglia Formation bounds the Grifone anticline toward the southwest. Growth strata occur on both limbs of the Grifone anticline just below and above the top surface of the Schlier Formation (i.e., Messinian time).

Figure 9B shows a modified version of the F76–19 profile obtained by flattening the horizon interpreted as the top surface of the Scaglia Formation (i.e., top surface of Cretaceous carbonates) to its assumed original horizontality and height equal to 0 m. The remainder of the F76–19 profile is consistently deformed and shows the deformations older than the top surface of the Scaglia Formation. The structural highs generated by the Gondola and Grifone anticlines correspond to preexisting horst blocks (i.e., pre–Scaglia Formation) generated by normal faults (i.e., below 3 s TWTT; Fig. 9B). Extensional basins associated with these normal faults occur adjacent to the Mesozoic structural highs. Interestingly, Figure 9B shows a large section of growth strata within the Scaglia interval (Late Jurassic–Cretaceous time) on the northeastern side of the Grifone anticline. These strata are subsequently folded, and the associated normal fault is probably inverted (Fig. 9A).

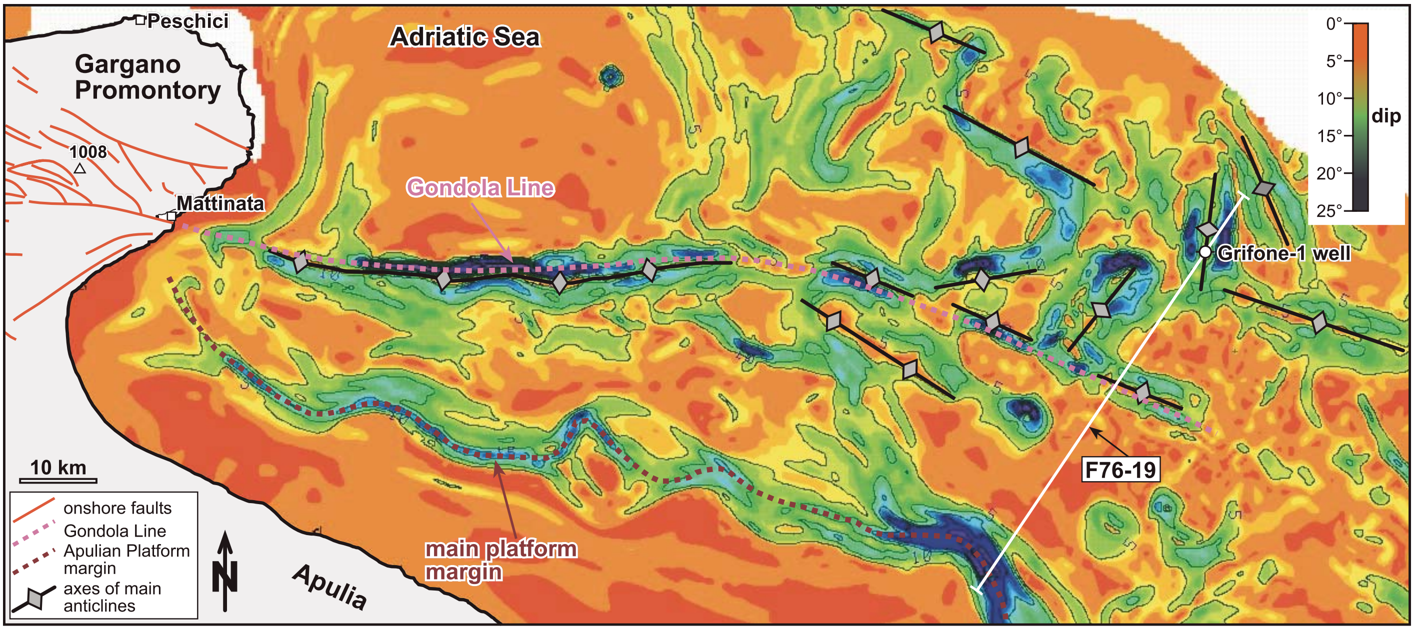

Figure 7. Dip magnitude map showing the contours to dips of top surface of Mesozoic-Cenozoic (i.e., younger than late Miocene time) carbonate strata. Dips are between 0° (red) and 25° (blue). Anticlines axes shown in the figure are also known from several wells and seismic-reflection profiles in this region (e.g., de Dominicis and Mazzoldi, 1987).

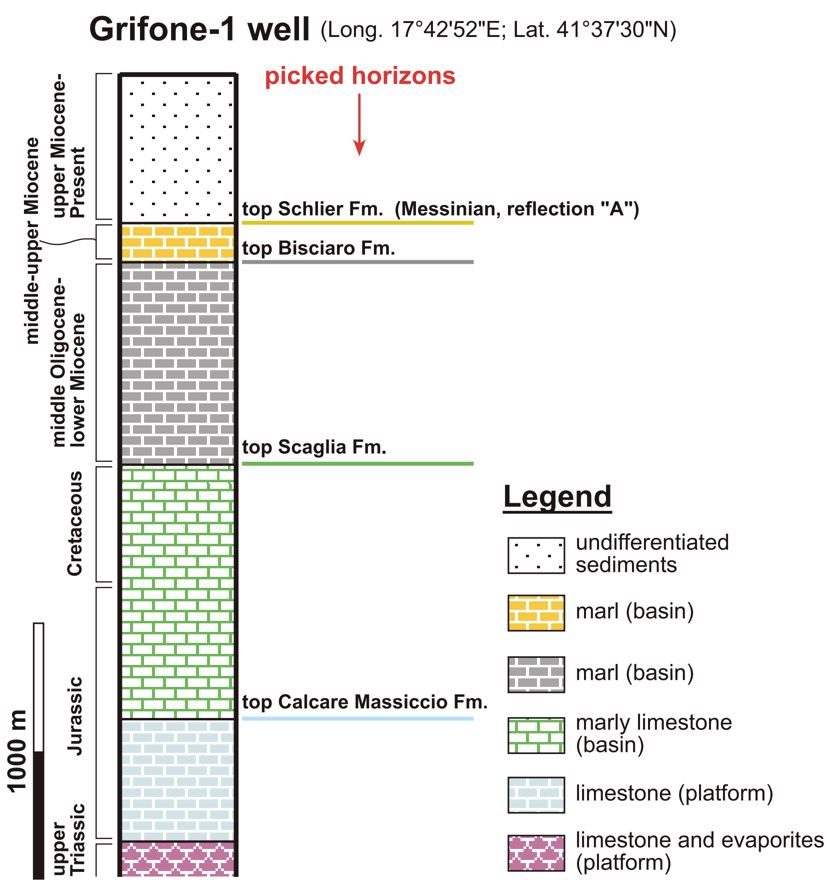

Figure 8. Stratigraphic log for the Grifone-1 well. Picked horizons are shown in Figure 9.

DISCUSSION

Geometry and Kinematics of the Gargano Fault System

The Gargano fault system (i.e., including the Gondola Line [Fig. 7] and the buried faults in the west of the Gargano Promontory [Fig. 4A]) consist of a complex array of faults and folds across the central Adriatic region, the Gargano Promontory, and the central Apennines foredeep. The western tip of the Gargano fault system is still unknown, whereas the eastern tip is located in the middle of the southern Adriatic region (Fig. 7; see also Aiello and de Alteriis, 1991). Trend and cross-sectional thickness of the Gargano fault system are heterogeneous. Although the general trend is E-W, the Gargano fault system diverts into marked WNW-ESE or NW-SE trends near the eastern tip, in the west of the Gargano Promontory, and also in the northern Gargano Promontory (Figs. 4 and 7).

The cross-sectional thickness of the Gargano fault system is ~2–3 km in the offshore area (Fig. 9), and increases to ~20 km in the onshore area (Fig. 3). This heterogeneous thickness is probably connected with the different lithologies and styles of folding. Both in onshore and in offshore areas, in fact, the Gargano fault system and its offshore prolongation cut through the axial region of an anticline, but the two anticlines (the onshore and offshore ones) are very different. The onshore anticline is wide and gentle and mainly affects platform carbonates (i.e., almost pure carbonates), whereas the offshore anticline is much narrower and mainly affects basinal carbonates (i.e., marls and marly carbonates). This suggests a control exerted by the anticline geometry on the cross-sectional architecture of the Gargano fault system.

The superposition of the Gargano fault system onto Mesozoic, basin-bounding, normal faults shows the control exerted by the Mesozoic structures (i.e., the faults controlling the platform-basin transition) on the subsequent development of the Gargano fault system. Such control can be inferred both from the geological maps (Figs. 2 and 4) and from the F76–19 seismic-reflection profile (Fig. 9), where the Mesozoic faults are physically linked with the subsequent faults forming the Gondola Line.

The subsurface attitude of the Gargano fault system can be inferred from the offshore seismic-reflection data provided in this paper (Fig. 9A) and from the onshore seismological data provided by Milano et al. (2005). In both cases, the geophysical data suggest a subvertical attitude. This is supported by the distribution of the earthquake hypocenters, which suggests that the onshore portion of the Gargano fault system is a subvertical, diffuse, fault belt as deep as ~25 km, where this depth corresponds to the base of the upper crust in this region (Milano et al., 2005).

The data presented in this paper show that the displacements accommodated on the Gargano fault system are mostly reverse and left-lateral strike-slip displacements (Figs. 4, 5, 6, and 9). In particular, folds and reverse faults developed along NW-trending segments of the Gargano fault system (i.e., the Gondola anticline in Fig. 9A, the Chieuti transpressional high in Fig. 4A, and the faults in the northern Gargano Promontory in Fig. 4B) show that the overall displacement accommodated along the E-W–trending Gargano fault system has a significant, left-lateral, horizontal component. The Pantano S. Egidio pull-apart basin on the Mattinata fault (Figs. 3 and 4B) shows even stronger evidence for the overall left-lateral kinematics of the Gargano fault system. Reverse and left-lateral displacements on the Gargano fault system are consistent with the regional pattern of displacement accommodated within the Apennines and Dinarides-Albanides fold-and-thrust belts and within the Adriatic foreland (Fig. 10A), where the major structures are NW-trending thrusts and folds formed under a perpendicular contraction during Paleogene-Quaternary time (e.g., Roure and Sassi, 1995; Roure et al., 2004). Transpressional deformation along the Gargano fault system provides a good explanation for the localized uplift of the Gargano Promontory within the Adriatic foreland (Brankman and Aydin, 2004).

Recently published global positioning system (GPS) data for the Adriatic region provide additional insights into the present kinematics of the Gargano fault system. In particular, Hunstad et al. (2003) explained their GPS data in the Gargano region with a present N53°-trending contractional axis (or with a perpendicular extensional one). The orientation of this axis is close to the N42°-trending contractional axis inferred from the solution cleavage data (G4 in Fig. 4B) and to the average N65°-trending striations on the reverse faults (G3 in Fig. 4B) in the Gargano Promontory. The recent GPS velocity data allow us to estimate the present, relative motion between the two blocks bounding the Gargano fault system. By combining the velocity vectors from the TREM station and the ANGE station (Anzidei et al., 2001), in the Tremiti Islands and in the southeastern Gargano Promontory (Fig. 4A), respectively, we find that the two blocks that bound the Gargano fault system are moving apart by ~1 mm/yr along the N97° direction (compare this datum with the fault slip in Fig. 5C). Because of the errors in the original data (Anzidei et al., 1996, 2001), this estimate should be considered as fairly accurate. Moreover, the ANGE station is probably within the Gargano fault system (Fig. 4A) and may be affected by fault-related deformations, thus providing a poorly reliable datum. This problem may be overcome by considering a remote station such as the LUCE station in the southwest of the Gargano Promontory (Fig. 4A). By using the velocity vectors from the TREM and LUCE stations (Anzidei et al., 2001), we find that the two blocks bounding the Gargano fault system are moving apart by ~3 mm/yr along the N149° direction. These estimations of the velocity vectors are consistent with a present, pure left-lateral or left-lateral transtensional kinematic regime along the Gargano fault system (Fig. 10B). These kinematics are consistent with two earthquake fault-plane solutions obtained from two M ≥ 4.6 earthquakes located 60 km north of the Tremiti Islands (Fig. 1; Console et al., 1989). Also, in the Tremiti Islands, Brozzetti et al. (2006) have recently found evidence of Pleistocene, normal and left-lateral transtensional faulting along N100°-striking faults. West of the Gargano Promontory, Patacca and Scandone (2004) proposed that the causative fault for the 1627 A.D. destructive earthquake (see the epicenter in Fig. 4A as proposed by Boschi et al. [1997]) is a shallow normal fault, which they observed in a seismic-reflection profile ~7–8 km north of the epicenter shown in Figure 4A. Ridente and Trincardi (2006), in high-resolution seismic profiles across the Gondola Line, recognized evidence of normal faulting affecting the seafloor and the upper 50 m of the sedimentary pile. Serpelloni et al. (2005), by using GPS data, inferred that the eastern Gargano fault system and the Gondola Line are undergoing NE-SW contraction, whereas the western Gargano fault system is undergoing NE-SW extension. The resulting kinematics on the Gargano fault system may be left-lateral transtensional, as estimated here by using the GPS vectors of Anzidei et al. (2001).

Some authors have proposed right-lateral displacements on the Gargano fault system and particularly on the Mattinata fault (Tondi et al., 2005, and references therein). Such a displacement is not consistent with the regional pattern of deformations and with most data presented in this paper. However, some evidence suggests a right-lateral displacement on the Gargano fault system or on faults near it. These include the fault plane solutions for the 2002–2003 Molise earthquakes (note, however, that these earthquakes did not occur on the Gargano fault system; Fig. 4A), the fault plane solution for the 1995 and 2006 earthquakes in the southeastern sector of the Gargano Promontory (Fig. 4A), and the NE-SW to ENE-WSW trend of some folds near the eastern tip of the Gondola Line (Fig. 7). Such evidence may be explained by local slip episodes not consistent with the long-standing, regional, tectonic framework. Moreover, as mentioned already, some GPS and earthquake data (Battaglia et al., 2004; Milano et al., 2005; Serpelloni et al., 2005), in partial contrast with previous GPS data (Anzidei et al., 2001; Hunstad et al., 2003) and centroid-moment tensor (CMT) focal mechanisms (Fig. 4A), are consistent with a NE-SW extension in the Gargano Promontory or in specific sectors of the promontory. These apparently contradictory evidences compel the future acquisition of earthquake and GPS data to shed light on the present kinematics of the Gargano fault system.

The amount of displacement on the Gargano fault system is still unknown because no data are available for a suitable estimate (Billi, 2003, and references therein). A maximum horizontal displacement of ~2 km on the Mattinata fault can be inferred from the geometry and size of the Pantano S. Egidio pull-apart basin, which occurs in the middle section of this fault (Fig. 3); however, because the Mattinata fault is only one element of the Gargano fault system, it is likely that the total displacement on the Gargano fault system is greater than 2 km. An estimate of the horizontal displacement on the Gargano fault system (i.e., including the offshore prolongation) can be provided by considering the general, fault length–displacement relationship:

$$D = cL^n, \quad (1)$$

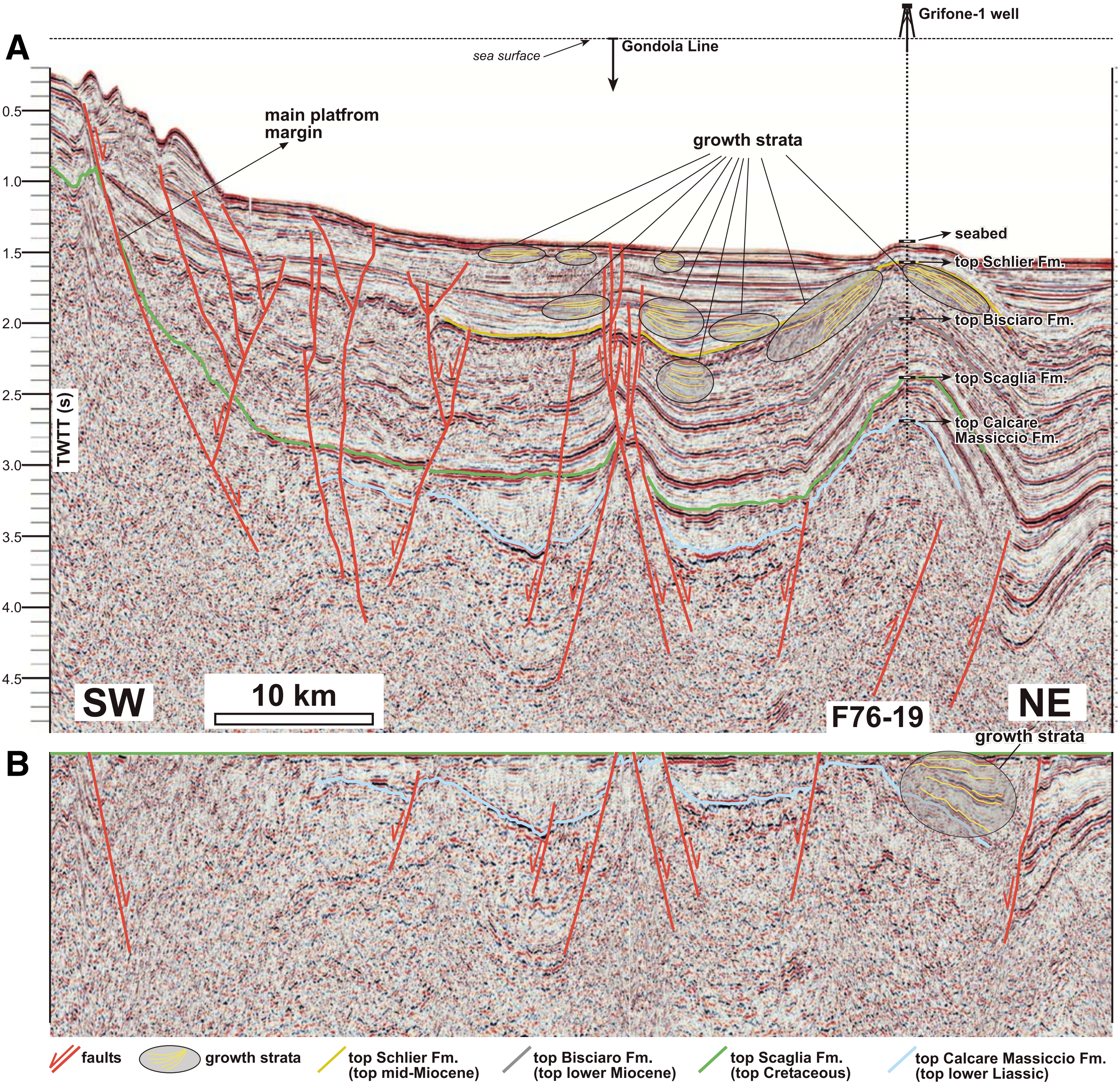

Figure 9. (A) Interpretation of the F76–19 seismic-reflection profile (see the raw data in Figure DR1 in the GSA Data Repository; see text footnote 1). TWTT is two-way traveltime. Note the growth strata bordering the Gondola and the Grifone anticlines. These strata constrain the timing of multiple episodes of deformation along these structures. (B) F76–19 seismic-reflection profile modified by flattening the horizon interpreted as the top surface of the Scaglia Formation (i.e., top surface of Cretaceous carbonates) to its original horizontality and to height = 0 m. Note that only the pre-Scaglia strata (i.e., the strata below the green horizon) are displayed. This figure shows the deformations older than the top surface of Cretaceous carbonates (i.e., top Scaglia Formation); these deformations consist of Mesozoic extensional basins bounded by normal faults.

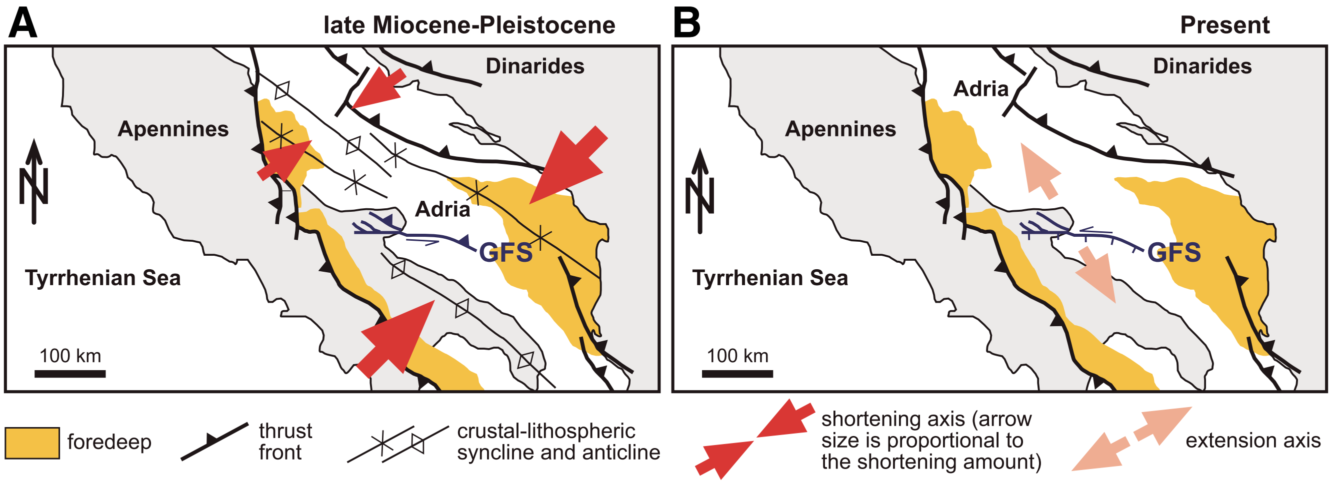

Figure 10. Simplified model for the tectonic evolution of the Gargano fault system (GFS) (modified after Bertotti et al., 2001). (A) During late Miocene–Pleistocene times, the Gargano fault system mostly accommodated left-lateral transpressional displacements induced by regional NE-SW shortening and by a disparity in the amount of shortening accommodated by the southern and northern sectors of the foreland fold-and-thrust belt. The shortening disparity between the northern and southern Adriatic compartments also reflects a disparity in the flexural retreat of the northern and southern portions of the subducting Adriatic slab (Figs. 1A and 1B). Foreland basins in the Adriatic region mostly developed since Pliocene time. (B) At present, the Gargano fault system may be accommodating mainly extensional or left-lateral transtensional displacements as shown by some global positioning system (e.g., Anzidei et al., 2001; Serpelloni et al., 2005) and earthquake (e.g., Console et al., 1989; Patacca and Scandone, 2004; Milano et al., 2005) data.

where D is the fault displacement, L is the fault length, n is a constant that may vary between 0.5 and 2.0 but is usually approximated to 1.0, and c is a constant related to the material properties of the host rock and is usually at least one order of magnitude less than 0.1 (Bonnet et al., 2001; Xu et al., 2006, and references therein). It follows that a reasonable solution for Equation 1 is $D \approx 0.01L$. In any case, $D < 0.1L$. From Equation 1 and from the total length of the Gargano fault system (i.e., ~200 km; Fig. 1), we infer that the relative horizontal displacement is ~2 km and, in any case, is less than 20 km. Uncertainty on this estimate is connected with the unknown western tip of the Gargano fault system. It follows that the Gargano fault system length (i.e., ~200 km) is uncertain. By considering fault activity along the Gargano fault system since the late Miocene (i.e., ca. 11 Ma), the estimated displacement between ~2 and 20 km corresponds to a displacement rate between ~0.2 and 2.0 mm/yr. Note that the 2–20 km of displacement on the Gargano fault system is consistent with the 2 km of maximum displacement on the Mattinata fault inferred from the size of the Pantano S. Egidio pull-apart basin.

Age of Deformation

Normal faulting along the platform-basin margin in the central and southern Adriatic region occurred in Mesozoic times (i.e., Jurassic-Cretaceous times, e.g., Figs. 5D and 9B) and probably lasted until late Paleogene times (Masse and Borgomano, 1987; Graziano, 2001). Contractional deformation in the Gargano Promontory and adjacent areas started in middle-late Miocene time at least, as shown by sets of growth strata along the southwestern limb of the Grifone anticline and along the northeastern limb of the Gondola anticline (Fig. 9A). In the Gargano Promontory, evidence of middle-late Miocene contractional deformation has been provided in previous papers (Abbazzi et al., 1996; Bertotti et al., 1999; Casolari et al., 2000). The occurrence of late Miocene calcarenites within the Pantano S. Egidio pull-apart basin (i.e., along the Mattinata fault; Fig. 3) suggests that left-lateral, strike-slip faulting along the Mattinata fault was active in late Miocene time, about concurrently with the growth of the Grifone and Gondola anticlines. The WNW–trending, nonsymmetrical anticline of the Gargano Promontory (see the southern limb in Fig. 5A) probably grew during the early phases of contraction (i.e., middle-late Miocene times) and substantially preceded the formation of the Gargano fault system, which cuts across it. Otherwise, most contractional and strike-slip faults that presently cut through the limbs of this anticline (including the Mattinata fault; Fig. 3) would have been significantly tilted (i.e., by ~20° at least) consistent with the inclination of the anticline limbs.

Growth strata along the limbs of the Gondola anticline (Fig. 9A) and along the southern margin of the Gargano Promontory (Fig. 6B) show that the study area underwent contraction also during middle-late Pliocene time. However, in some places, the disparity between the deformational state of the Mesozoic carbonates and of the late Pliocene rocks (Fig. 6D) suggests that most deformation occurred before late Pliocene time. Alternatively, such deformational disparity may be explained by a markedly different behavior of the Mesozoic and Pliocene rocks during Pliocene-Quaternary tectonics. The occurrence of late Pliocene, contractional tectonics in the Gargano Promontory was also pointed out by Abbazzi et al. (1996) on the basis of geological evidence from the W-NW Gargano Promontory. Moreover, the buried, Chieuti transpressional high along the westerly prolongation of the Gargano fault system (Fig. 4A) developed before and during the Apulian flexure (i.e., during Pliocene–early Pleistocene time by ca. 1.5 Ma; Patacca and Scandone, 2004).

A set of geological and geophysical evidence shows post-Pliocene fault activity along the Gargano fault system. These include faults involving the seafloor in the Gondola anticline (Fig. 9A) and the occurrence of left-lateral strike-slip faults in the Rignano Conglomerate (i.e., southern Gargano Promontory; Fig. 6A), the deposition of which is dated back to the Pleistocene (Spalluto, 2004). Moreover, Abbazzi et al. (1996) and Ridente and Trincardi (2006) found evidence of Pleistocene contractional tectonics in the W-NW Gargano Promontory and across the Gondola Line, respectively. The recent and present fault activity along the Gargano fault system is also demonstrated by its seismicity (e.g., Milano et al., 2005), by the different GPS velocities of the blocks bounding the Gargano fault system (e.g., Anzidei et al., 2001; Hunstad et al., 2003), and by the previously mentioned faults involving the seafloor in the Gondola anticline (Fig. 9A; see also Ridente and Trincardi, 2006).

In synthesis, at least three major tectonic phases can be inferred for the Gargano fault system: (1) a middle-late Miocene phase; (2) a middle-late Pliocene phase; and (3) a Quaternary phase, including the recent and present activity. Besides these major phases, Mesozoic-Paleogene normal faulting preceded the formation of the Gargano fault system in some sectors.

Regional Implications

The inferences discussed herein about the evolution of the Gargano fault system can be framed in a regional context by considering previous works on the regional tectonic evolution of the Adriatic foreland (e.g., Royden et al., 1987; Bertotti et al., 2001). Bertotti et al. (2001) showed that, since Miocene times, contraction in the southern Adriatic sector (i.e., south of the Gargano Promontory) has been greater than contraction in the northern sector (i.e., north of the Gargano Promontory) (Fig. 10A). This applies, in particular, to Quaternary time. Shortening in the Adriatic foreland is connected with the mechanical coupling between the subducting and overriding plates, which promotes transfer of most deformation from the subduction zone to the foreland. The different shape of the flexed Adriatic lithospheres in the northern (Fig. 1B) and southern (Fig. 1C) sectors, as drawn by Royden et al. (1987), supports the hypothesis of a greater mechanical interaction between subducting and overriding plates in the southern Adriatic foreland (see also Mariotti and Doglioni, 2000). In particular, the significant Pliocene-Pleistocene uplift of the Apulian forebulge and the contemporaneous subsidence in the central-northern Adriatic foreland (Hearty and Dai Pra, 1992; Doglioni et al., 1996; Bertotti et al., 2001) demonstrate stronger contractional tectonics in the southern Adriatic foreland (Fig. 10A). This has been interpreted as the reflection of either lithosphere buckling (Bertotti et al., 2001) or the shortening of relatively thin crustal sheets (Oldow et al., 2002). In any case, a Neogene-Quaternary stronger contraction in the southern Adriatic region explains the overall left-lateral kinematics of the Gargano fault system.

The differential flexural evolution for the northern and southern sections of the subducted Adriatic slab implies the occurrence of discontinuities (tears or gashes) across the slab itself (Royden et al., 1987). During the last years, several studies have focused on the recognition of such discontinuities both in the Adriatic and in other regions (e.g., Wortel and Spakman, 2000; Levin et al., 2002, 2005; Faccenna et al., 2005). Surprisingly, such slab discontinuities are rather well known at depth, but their prolongation at the surface is still poorly studied (Govers and Wortel, 2005). The location of the Gargano fault system right at the transition between two adjacent foreland compartments characterized by different flexural histories suggests that the Gargano fault system may represent the surface expression of a tear occurring across the Adriatic slab beneath the Apennines fold-and-thrust belt. This may also explain why the western tip of the Gargano fault system is still unknown, i.e., because the Gargano fault system would extend across the subducted slab. The evidence that the geometry and kinematics of the Gargano fault system are consistent with differential foreland lithospheric shortening (Bertotti et al., 2001) supports the hypothesis of a link between the Gargano fault system and possible slab tears. The Gargano fault system may therefore constitute a significant case history within a class of faults that are still poorly known.

CONCLUSIONS

The Gargano fault system in the central Adriatic foreland has acted as an intraforeland, left-lateral, transpressional zone since the Miocene, partly reactivating or reworking a topographically and structurally complex, Mesozoic-Paleogene platform-basin margin. The overall kinematics of the Gargano fault system are consistent with the regional pattern of contractional displacements and can be ascribed to differential amounts of shortening in the southern and northern Adriatic domains. Regardless of the geodynamic process governing deformation in the Adriatic region, the kinematic element that decouples the differential tectonic shortening and flexural behavior between the northern and southern Adriatic foreland is provided by the Gargano fault system. In this tectonic context, the Gargano fault system may extend downward across the Adriatic slab. The presented data are still too indistinct to confirm or refute the hypothesis of a first-order plate boundary separating northern and southern Adria in coincidence with the Gargano Promontory; however, the small amount of estimated horizontal displacement for the Gargano fault system suggests that this is not the main plate boundary (see also Battaglia et al., 2004), unless this boundary is still in an incipient evolutionary phase. Recent earthquake and GPS data are still rather contradictory about the present kinematics of the Gargano fault system. In the future, a monitoring system, including GPS stations recording over prolonged periods of time, is necessary to clarify the debated present kinematics of the Gargano fault system.

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