Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust-belt and foredeep-basin evolution

Leigh Royden Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology Cambridge, Massachusetts 02139

Etta Patacca, Paolo Scandone Department of Geology, University of Pisa, Pisa, Italy

ABSTRACT

The Apennine foredeep-basin system, located on continental crust, consists of four roughly parallel basin segments, each containing a flexural outer rise and an inner trough that deepens continuously toward the thrust belt. Flexural modeling of subsidence data across the basin indicates that this foredeep basin results mainly from deep subsurface loads acting on the subducted slab from within the subduction zone rather than from the topographic load of the Apennine Mountains. The geometry of the four basin segments observed within the Apennine foredeep is thus inferred to reflect subduction of segmented lithosphere, where each lithospheric segment corresponds to a segment of the foredeep basin. Beneath the basin and in the foreland the lithosphere is continuous: segmentation occurs only at depth beneath the thrust belt. This pattern of segmentation of the subducted lithosphere at depth is reflected in the large-scale geometry of the outer part of the Apennine thrust belt and appears to control it. Similarly, the pattern of segmentation also appears to control the position of the eastern limit of back-arc type extension in western Italy. These relations strongly suggest a genetic relation between subduction-zone processes, foredeep-basin geometry, and thrust-belt evolution, in which the configuration of the subducted lithosphere largely controls the large-scale surface deformation observed in the Apennine system.

INTRODUCTION

Subduction-zone processes and their control on surface deformation are poorly understood, largely because few direct methods are available for observation of such processes. One expression of the geometry of a subducted slab and the forces that act on the slab is the flexural bending of the foreland lithosphere as it enters the subduction zone. In many conti-

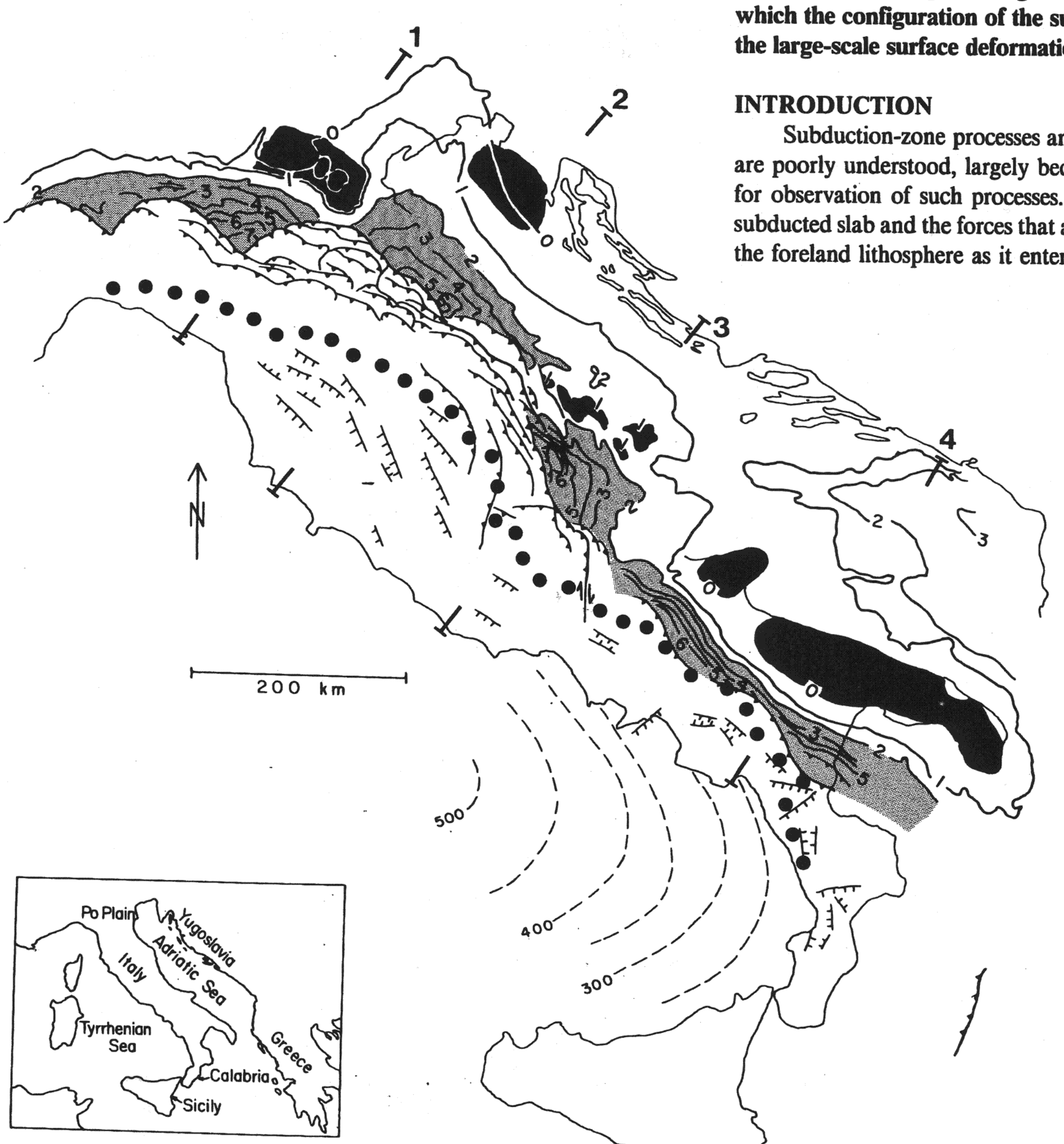

Figure 1. Generalized map of Apennine system showing depth to base of Pliocene within Adriatic and Po basins, contoured in 1-km intervals (compiled 1987 from unpub. data). Four distinct outer-rise segments (black) can be observed in morphology of basal Pliocene surface. Each outer rise is associated with southwestward-deepening basin segment analogous to a trench in an oceanic system. Stipple shows Apennine foredeep basin and basal Pliocene surface deeper than 2 km; barbed lines show position of thrust faults in outer part of Apennines; ticked lines indicate normal faults bounding Pliocene-Quaternary grabens; large dots show topographic divide of Apennines. Locations of transects 1–4 are also indicated.

nental subduction systems, the sedimentary rocks that fill the asymmetric foredeep basins adjacent (and external) to the subduction zone and the related thrust belt preserve an excellent record of this flexural history. In this respect, the Apennine Mountains of Italy and the associated foredeep-basin system offer an excellent opportunity to study the relation between foredeep-basin geometry, subduction-zone processes, and surface deformation (Fig. 1).

APENNINE OROGENIC SYSTEM

The Apennine Mountains form the northwest-trending segment of an arcuate thrust belt that continues southward and westward through Calabria and into Sicily (Fig. 1). The Apennine segment of the belt has been active from early Miocene until Pliocene and, in places, Quaternary time. The eastward- and northeastward-vergent thrust sheets of the Apennines consist of allochthonous sedimentary rocks originally deposited on the continental and transitional crust of the Adriatic plate and stripped from the basement during thrusting (e.g., Ogniben et al., 1975). Thrusting occurred in response to westward subduction of the Adriatic lithosphere beneath the Apennines, as indicated by a Benioff zone as deep as 500 km west of Calabria and the southern Apennines (Gasparini et al., 1982). Total shortening across the Apennines is generally accepted to be several hundred kilometres; perhaps 60–170 km of shortening occurred in Plio-cene–Quaternary time (Bally et al., 1986). Thrusting within the belt dies out northwestward and ends near the western end of the Po Plain. Subduction and thrusting were accompanied by back-arc type extension west of the Apennine chain, where late Miocene–Pliocene extension in the Tyrrhenian Sea generated oceanic crust (Hsü et al., 1978; Malinverno and Ryan, 1986). Extension also affected onshore areas in western Italy, where the eastern limit of Pliocene–Quaternary grabens is less than 100 km from the Pliocene thrust front (Fig. 1).

The foredeep-basin system located external to the Apennine chain is an asymmetric trough that deepens toward the Apennines and contains up to 8 or 9 km of Pliocene–Quaternary sedimentary rocks (Fig. 1; unpub. data; Pieri and Groppi, 1981). The basin system lies offshore under the northern and central Adriatic Sea and continues onshore to the west under the Po Plain and to the south under southern Italy. The basement of the foredeep basin consists of continental crust; the current depth to Moho is 25–35 km (Giese and Morelli, 1975). In map view, the geometry of this foredeep-basin system is irregular along the trend of the mountain belt, and at least four distinct segments can be identified (Fig. 1). Within each segment, the base of the Pliocene forms a broad outer rise and deepens southwestward toward the Apennine thrust belt. These roughly parallel basin segments are offset stepwise from one another by roughly 100 km across linear zones perpendicular to the Apennine mountain belt. The Bouguer gravity map of the Italy-Adriatic region shows a series of gravity highs that correspond to the morphologic highs in the base Pliocene surface (Fig. 2). A zone of negative Bouguer anomalies follows the northwest trend of the Apennine mountain belt along its entire length and parallels the trend of the gravity highs to the east.

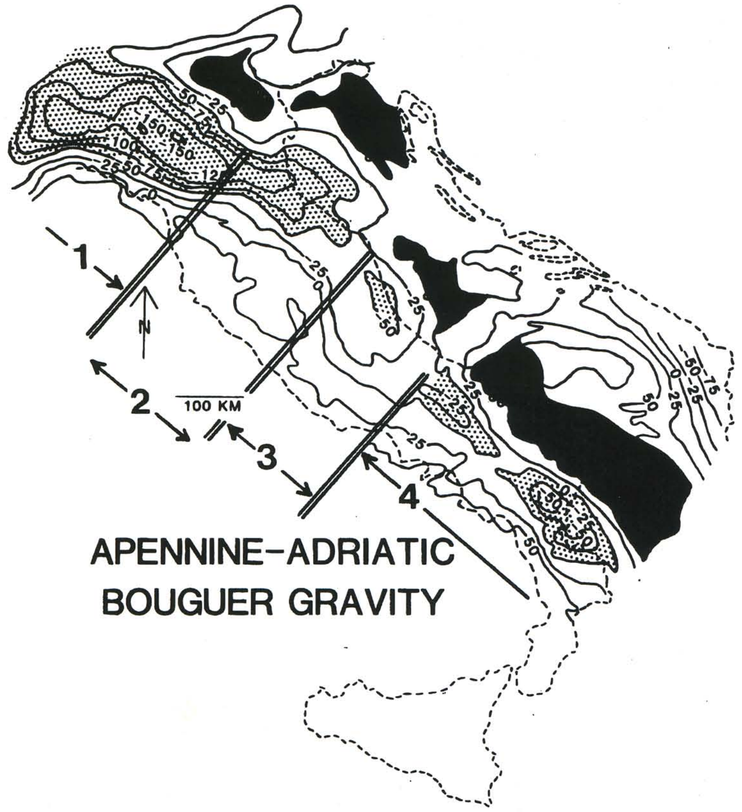

Figure 2. Simplified contour map of Bouguer gravity field in milligal. Four distinct outer-rise segments observed in morphology of basal Pliocene surface (Fig. 1) correlate with four distinct Bouguer gravity highs (black areas), indicating that these outer rises are flexurally maintained and are analogous to outer rises observed in oceanic subduction systems. Black shows gravity anomalies greater than 0 mgal in segments 1–3 and 50 mgal in segment 4; dot pattern shows gravity anomalies less than −50 mgal in segments 1–3 and 0 mgal in segment 4. Double dark lines show position of inferred tears in subducted plate and separation of subducted plate into four distinct slab segments at depth. Compiled after Ogniben et al. (1975) and Morelli et al. (1969, 1975).

FLEXURAL ORIGIN OF THE APENNINE FOREDEEP-BASIN SYSTEM

Foredeep basins form in response to flexural loading of the underlying lithosphere by the adjacent thrust belt and by subduction-related processes (e.g., Price, 1973; Beaumont, 1978, 1981; Jordan, 1981; Karner and Watts, 1983; Lyon-Caen and Molnar, 1983; Royden and Karner, 1984a, 1984b; Sheffels and McNutt, 1986). Conceptually, the loads acting on the foreland lithosphere can be divided into three categories (Fig. 3). (1) The topographic or surface load corresponds to the weight of all material present above a fixed depth, w_0, equal to the depth to the surface of the flexed plate prior to load emplacement (2) The subsurface or hidden load corresponds to any other loads applied to the foreland lithosphere that are not expressed in the topography. These loads might include a combination of unusually dense rocks obducted onto the downgoing plate, a buoyancy contrast between the subducted slab at depth and the surrounding asthenosphere, and dynamic forces associated with subduction. (3) The effects of the surface and subsurface loads are amplified by the weight of the infilling material, or of all material below the initial slab depth, w_0, and above the present slab surface, w, in the same way that tectonic subsidence of extensional basins is amplified by the weight of the sediments within the basin. In general, where the subsurface load is much smaller than the surface load, the geometry of the foredeep basin is primarily controlled by the emplacement of thrust sheets on the foreland lithosphere and creation of topographically high mountains. In contrast, where the subsurface load is much larger than the surface load, the geometry of the foredeep basin is primarily an expression of forces acting on the subducted slab.

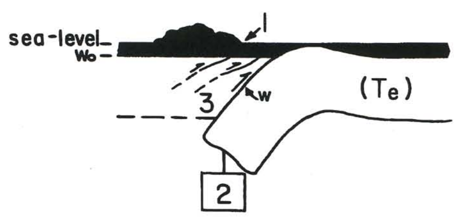

Figure 3. Illustration of three sources of load that may act on subducted slab to produce flexural bending. (1) Topographic or surface load is equal to weight of all material present above initial depth, w_0, of surface of slab prior to flexure; (2) subsurface or hidden load corresponds to any other loads applied to subducted slab at depth and not expressed in surface topography; (3) infilling material, nappes, sediments, etc., present below initial slab depth, w_0, and above final position of slab surface, w, amplifies effects of loads 1 and 2 and can be calculated from loads 1 and 2 and flexural properties of subducted lithosphere.

The base of the Pliocene surface beneath the Apennine foredeep basin corresponds to the base of the foredeep basin along most of the orogenic system and can be used as a reference horizon to measure the flexural behavior of the Adriatic plate during Pliocene-Quaternary loading. By subtracting the initial depth of this surface at the beginning of Pliocene time from its present depth, one can determine the net deflection of the Adriatic lithosphere due to all loads that currently act on the Adriatic plate and that have been emplaced since the beginning of Pliocene time. Pre-Pliocene loads acting within the Apennine system cannot be determined because Miocene subduction and thrusting and the related flexural loading of the subducted lithosphere must have occurred far to the west of the present Apennine thrust belt (except in the northern Apennines). Thus, the Miocene sediments that once recorded the Miocene bending of the Adriatic foreland have now been incorporated into the eastwardly advancing thrust belt. A clear record of pre-Pliocene deflection and loading has thus been destroyed, as the subduction zone, thrust belt, and foredeep-basin system have migrated to the east into their present position.

Figure 4 shows a basin geometry consistent in cross section with flexural bending of the foreland lithosphere due to applied loads west of the basin. In constructing the two-dimensional flexural models, the foreland lithosphere was treated as a thin elastic sheet, and the flexural rigidity (or effective elastic thickness, T_e), starting water depth, w_0, and magnitude and position of the load were determined directly from the observed deflection (and gravity) data (e.g., Royden and Karner, 1983). Except for transect 3, which appears to have smaller values of T_e, the observed deflection data are consistent with an effective elastic plate thickness of roughly 20 km, a starting water depth of about 1000 m at the beginning of the Pliocene, and a subsurface load of roughly $2–10 \cdot 10^{12}$ N/m. (This is approximately 2 to 10 times greater than the surface load.) The magnitude of this inferred load is fairly insensitive to the flexural or rheological properties assumed for the foreland lithosphere. This indicates that, along the entire length of the Apennine chain, the two-dimensional geometry of the foredeep basin can be explained quantitatively by simple flexural models if, and only if, a large subsurface load acts on the subducted slab at depth (Royden and Karner, 1984a). Additionally, the absence of a short-wavelength gravity high along the transects indicates that this large load is not present as a dense body at shallow crustal levels and implies that loading results from density contrasts at depth within the subduction zone or from dynamic effects related to subduction. This observation is critical because it suggests that the major controls on foredeep-basin geometry are processes within the subduction zone itself. Therefore, study of the Adriatic-Po basin system can yield a window into the subduction zone and presents an opportunity to investigate the relation between subduction-zone processes and thrust-belt evolution.

THREE-DIMENSIONAL LOAD CONFIGURATIONS AND SLAB GEOMETRY

In three dimensions, the geometry of the foredeep-basin system, with stepwise offsets of basin segments, clearly cannot be the result of loading by a surface load with the same distribution, in map view, as the topographically high part of the Apennines (Fig. 1). Therefore, the insufficiency of the surface load as the cause of basin subsidence is even more apparent in three dimensions than it is in two dimensions. This suggests that the along-strike variation in the geometry of the foredeep-basin system (and the Bouguer gravity field) can probably be related to a similar, along-strike variation in the configuration of and forces acting on the subducted lithosphere. In particular, the stepwise offset of basin segments 1–4 suggests that the lithosphere may be segmented at depth beneath the Apennines and within the subduction zone (e.g., Isacks and Barazangi, 1977; Barazangi and Isacks, 1976).

Figure 5A shows a simplified, three-dimensional analogue for segmentation of the subducted lithosphere beneath the Apennine system. A uniform semi-infinite elastic sheet is divided into a series of parallel seg-

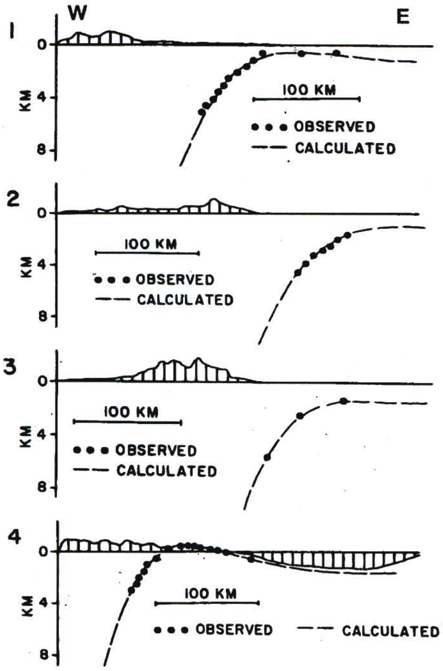

Figure 4. Observed depth of basal Pliocene surface along four transects across Apennine foredeep basin (locations in Fig. 1) plotted against best-fitting elastic solution to observed deflection, where each value of assumed plate strength (or effective elastic thickness, T_e) required particular initial water depth, w_0, in order to match deflection data. Values: 1—w_0 = -920 m, T_e = 20 km; 2—w_0 = -1000 m, T_e = 20 km; 3—w_0 = -1330 m, T_e = 15 km; 4—w_0 = -1010 m, T_e = 17.5 km.

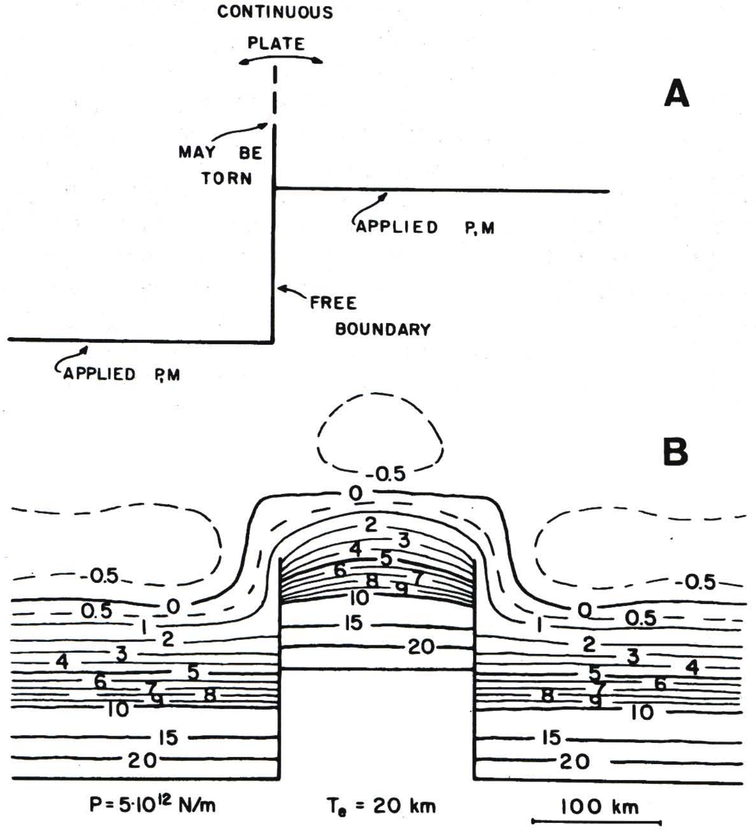

Figure 5. A: Three-dimensional flexural model used to simulate subduction of segmented lithosphere. Lithosphere is assumed to be continuous in foreland, but at depth within subduction zone, lithospheric segments are separated by free boundary or fault. Loads *P* and/or bending moments *M* are applied to effective end of each slab segment at depth. B: Contours (in km) of deflected surface assuming three slab segments initially at 1-km depth. Each segment end is subjected to subsurface load of $5 \cdot 10^{12}$ N/m, and segments are offset from one another in perpendicular direction by about 100 km. Uniform effective elastic plate thickness of 20 km is assumed throughout. Note relative positions of outer rises associated with each segment, and three-dimensional pattern of corresponding foredeep-basin area.

ments of different lengths. Along the segmented end, a downward load P acting on the free edge corresponds to the subsurface load on the plate. The slab segments are separated from one another at depth by a free boundary (fault), but at shallow depths (in the foreland) the slab is assumed to be continuous. In this particular model, the topographic load was assumed to be zero.

By using the standard equation for flexure of a thin elastic sheet having uniform flexural rigidity, solutions were obtained numerically by the successive over-relaxation method on a finite-difference grid (e.g., Dahlquist and Björk, 1969). The various parameters used were taken to be roughly equivalent to those obtained from two-dimensional modeling of transects across the Apennine system (the difference between mantle and infilling material was taken to be 0.6 g/cm^3; the load was taken to be $5 \cdot 10^{12}$ N/m, and the effective elastic plate thickness was chosen as 20 km, equivalent to a flexural rigidity of $6 \cdot 10^{22}$ Nm).

Figure 5B shows the resulting deflection of an elastic slab divided into three segments. Each segment contains an outer rise elevated about 1500 m above the original unflexed surface of the slab. Far (100–200 km) from the zones of slab segmentation, the plate deflection is about the same as that predicted by simple two-dimensional models. Nearer the zones of slab segmentation, however, the outer rises disappear and contours of constant depth to basement reflect the segmentation of the slab at depth. The amount of offset between segment ends was chosen to produce a pattern of deflection qualitatively similar to that observed in the northern end of the Adriatic foreland. Figure 5B is not meant to show an exact duplication of the deflection in the Apennine system but, rather, to show that the basin geometry is qualitatively and, in many respects, quantitatively consistent with a simple model of slab segmentation at depth beneath the thrust belt. Thus, the geometry of the Apennine foredeep-basin system is remarkably consistent with the pattern of deflection expected by subduction of a slab that is segmented at depth within the subduction zone, continuous beneath the foredeep basin and in the foreland, and has a roughly uniform flexural rigidity.

THRUST-BELT GEOMETRY VS. SLAB GEOMETRY

The three-dimensional geometry of the Apennine foredeep-basin system and the inferred geometry of the subducted lithospheric segments at depth show an interesting correlation with the geometry of the outermost and youngest part of the Apennine thrust belt (Figs. 1 and 5). Within the northern Adriatic Sea (segments 2 and 3 in Fig. 2), the flexural outer rise and the adjacent foredeep-basin segment are situated farther toward the northeast than within the adjacent Po Plain and central-southern Adriatic areas (segments 1 and 4). By inference, the lithospheric segments at depth beneath the thrust belt exhibit a similar pattern of offset. This same general pattern is loosely reflected by the geometry of the most external Apennine nappes: above segments 2 and 3 the thrust belt is farther toward the northeast, relative to the overall northwest trend of the Apennines, than are adjacent parts of the thrust belt above segments 1 and 4. This relation indicates that the thrust front has advanced farther toward the foreland in those areas where the subducted lithosphere has likewise retreated farther toward the foreland. The eastern edge of the area of Pliocene–Quaternary grabens also follows the inferred configuration of subducted lithosphere in much the same fashion.

Lateral motion between parts of the thrust belt that overlie different lithospheric segments was accommodated partly along north-northeast–trending faults by both thrust and strike-slip components of displacement. These faults may function as either lateral ramps or as tear faults, such as the dextral Maiella fault zone between segments 3 and 4. In other areas, such as between segments 1 and 2, relative motion was accomplished by counterclockwise rotation of thrust sheets during emplacement and by north-northeast–trending dextral tear faults.

The observed correlation between basin and thrust-belt geometry, together with the observation that basin geometry cannot be attributed mainly to surface loads present in the thrust belt, implies that both basin geometry and thrust-belt geometry are reflections of the configuration and segmentation of the subducted lithosphere at depth and, ultimately, of the forces acting on that subducted lithosphere. Thus, many of the large-scale features of Pliocene–Quaternary deformation within the Apennine chain, including the presence of Pliocene–Quaternary extension in northwestern Italy, can be viewed as a passive response to the retreat of the subducted slab toward the foreland.

REFERENCES CITED

Bally, A.W., Cooper, J.C., Burbi, L., and Ghelardoni, R., 1986, Thrust geometry of the Central Apennines, Italy: Geological Society of America Abstracts with Programs, v. 18, p. 533.

Barazangi, M., and Isacks, B., 1976, Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America: Geology, v. 4, p. 686–692.

Beaumont, C., 1978, The evolution of sedimentary basins on a viscoelastic lithosphere: Theory and examples: Royal Astronomical Society Geophysical Journal, v. 55, p. 471–497.

——1981, Foreland basins: Royal Astronomical Society Geophysical Journal, v. 65, p. 291–329.

Dahlquist, G., and Björk, A., 1969, Numerical methods: Englewood Cliffs, New Jersey, Prentice-Hall, 573 p.

Gasparini, C., Iannaccone, G., Scandone, P., and Scarpa, R., 1982, Seismotectonics of the Calabrian Arc: Tectonophysics, v. 84, p. 267–286.

Giese, P., and Morelli, C., 1975, Crustal structure in Italy, *in* Ogniben, L., Parotto, M., and Praturion, A., eds., Structural model of Italy: Rome, Consiglio Nazionale Delle Ricerche, no. 90, p. 453–490.

Hsü, K., Montadert, L., et al., 1978, Initial reports of the Deep Sea Drilling Project, Volume 42: Washington, D.C., U.S. Government Printing Office, 1249 p.

Isacks, B., and Barazangi, M., 1977, Geometry of Benioff zones: Lateral segementation and downwards bending of the subducted lithosphere, *in* Talwani, M., and Pitman, W., eds., Island arcs, deep sea trenches, and back-arc basins: American Geophysical Union, Maurice Ewing Series, v. 1, p. 99–114.

Jordan, T.E., 1981, Thrust loads and foreland basin evolution: Cretaceous, western United States: American Association of Petroleum Geologists Bulletin, v. 65, p. 2506–2520.

Karner, G.D., and Watts, A.B., 1983, Gravity anomalies and flexure of the lithosphere at mountain ranges: Journal of Geophysical Research, v. 88, p. 10449–10477.

Lyon-Caen, H., and Molnar, P., 1983, Constraints on the structure of the Himalaya from an analysis of gravity anomalies and a flexural model of the lithosphere: Journal of Geophysical Research, v. 88, p. 8171–8191.

Malinverno, A., and Ryan, W.B.F., 1986, Extension of the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking lithosphere: Tectonics, v. 5, p. 227–245.

Morelli, C., et al., 1969, Regional geophysical study of the Adriatic Sea: Bolletina di Geofisica, Teorica ed Applicata, v. 11, p. 3–56.

Morelli, C., Gantar, G., and Pisani, M., 1975, Bathymetry, gravity and magmatism in the strait of Sicily and in the Ionian Sea: Bolletina di Geofisica, Teorica ed Applicata, v. 11, p. 3–190.

Ogniben, L., Parotto, M., and Praturion, A., editors, 1975, Structural model of Italy: Consiglio Nazionale Delle Ricerche, no. 90, 502 p.

Pieri, M., and Groppi, G., 1981, Subsurface geological structure of the Po Plain, Italy: CNF Final Geodynamic Project, Publication 414, 13 p.

Price, R. A., 1973, Large scale gravitational flow of supracrustal rocks, southern Canadian Rockies, *in* DeJong, K.A., and Scholten, R., eds., Gravity and tectonics: New York, Interscience, p. 491–501.

Royden, L., and Karner, G.D., 1984a, Flexure of the lithosphere beneath Apennine and Carpathian foredeep basins: Evidence for an insufficient topographic load: American Association of Petroleum Geologists Bulletin, v. 68, p. 704–712.

——1984b, Flexure of the continental lithosphere beneath Apennine and Carpathian foredeep basins: Nature, v. 309, p. 142–144.

Sheffels, B., and McNutt, M., 1986, Role of subsurface loads and regional compensation in the isostatic balance of the Transverse Range, California: Evidence for intracontinental subduction: Journal of Geophysical Research, v. 91, p. 6419–6431.

ACKNOWLEDGMENTS

Supported by National Aeronautics and Space Administration Geodynamics Project Grant NAG 5-532. We thank Bert Bally and Marcia McNutt for helpful comments and suggestions.

Manuscript received January 7, 1987
Revised manuscript received April 14, 1987
Manuscript accepted April 17, 1987