JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. B6, PAGES 11,863-11,875, JUNE 10, 1997

Shear wave attenuation in the lithosphere beneath Italy and surrounding regions: Tectonic implications

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Abstract. More than 700 waveforms produced by 51 shallow earthquakes and recorded at regional distances (250-1400 km) by the Italian seismic network have been analyzed to characterize the amplitude and frequency contents of the crustal and uppermost mantle shear waves *Lg* and *Sn*, respectively. The crustal phase *Lg* efficiently propagates through the relatively stable Adriatic continental crust, while it is not observed along propagation paths crossing major physiographic features, like the Apennine chain and the basinal domain of the Tyrrhenian and Ionian Seas. Similar to *Lg*, efficient *Sn* propagation is observed in the uppermost mantle beneath the Po plain and the Adriatic Sea. Efficient *Sn* transmission is also observed across the northern Ionian Sea and Sicily and in the area between Sardinia and the northern coasts of Africa. *Sn* are efficiently transmitted across the Sicily Channel, and rather efficient *Sn* propagate beneath the Ligurian Sea. On the contrary, inefficient *Sn* transmission characterizes the uppermost mantle beneath the Apennines, the western margin of the Italian peninsula, and the southern Tyrrhenian Sea. Shear wave attenuation suggests the presence of asthenospheric material in the uppermost mantle, probably related to the present-day extension along the Apennine chain and in the Tyrrhenian basin. This interpretation is consistent with the presence of extensive Neogene and Quaternary volcanic activity in these areas and related high heat flow. Proposed lithospheric delamination processes beneath the Apennines and subduction beneath the Tyrrhenian Sea can reasonably explain the observed high-attenuation zones in the uppermost mantle. In contrast, a high-strength mantle lid is inferred to underlay the Po plain, the Adriatic Sea, and the northern Ionian Sea. The available waveforms also indicate that a continuous mantle lid is present beneath Sicily and the extensional domain of the Sicily Channel, as well as in the marine area south of Sardinia.

Introduction

The aim of this study is to analyze the propagation characteristics in the Italian peninsula and surrounding seas of crustal and uppermost mantle high-frequency shear waves, namely, *Lg* and *Sn*, produced at regional distances by shallow earthquakes.

In the range of distances considered (250 to 1400 km), the crustal shear phase *Sg* experiences multiple reflections within the crust, producing the high-amplitude, high-frequency *Lg* wave trains [e.g., *Knopoff et al.,* 1973]. It has been observed that *Lg* propagates efficiently within the continental crust, being detected several thousand kilometers from the source, while major variations in the crustal structure within continental regions, as well as oceanic paths, have a severe scattering effect on its propagation [e.g., *Press and Ewing,* 1952; *Knopoff et al.,* 1974; *Ruzaikin et al.,* 1977].

The seismic phase *Sn* is a high-frequency shear wave traveling in the uppermost mantle at an apparent velocity of 4.5-4.7 km/s. *Sn* propagation has significant tectonic implications, because it is sensitive to temperature and thickness of the mantle lithosphere. While *Sn* propagates efficiently within the high-velocity lid, that is, the mantle part of the lithosphere between the Moho and the upper mantle low-velocity zone (LVZ), it is strongly attenuated within the LVZ, where temperatures exceed the solidus and partial melt is present [e.g., *Molnar and Oliver,* 1969; *Walker,* 1977; *Ni and Barazangi,* 1983]. In fact, high-frequency, high-amplitude *Sn* are observed to propagate across stable lithospheric domains, while they are not observed where the asthenosphere is present immediately below the Moho, as in the case of some extensional tectonic settings or in the mantle wedge of a subduction zone [*Molnar and Oliver,* 1969]. Owing to these properties, *Sn* propagation has been extensively used to map lateral variations of the uppermost mantle attenuation structure [e.g., *Fuchs and Schulz,* 1976; *Chinn et al.,* 1980; *Kadinsky-Cade et al.,* 1981; *Ni and Barazangi,* 1983; *Whitman et al.,* 1992; *Seber et al.,* 1996]. Furthermore, because *Lg* can be the phase which produces the largest ground shaking, its attenuation pattern might influence the spatial distribution and the amplitude of shaking around the epicentral area. Therefore these kinds of studies are also important for seismic hazard assessment.

A major objective of this study is to map the propagation pattern of the shear waves in the uppermost mantle. Before the present study, a few paths crossing the Italian area were given by *Molnar and Oliver* [1969]. Owing to the intense shallow seismicity in and around Italy and to the density of the modern

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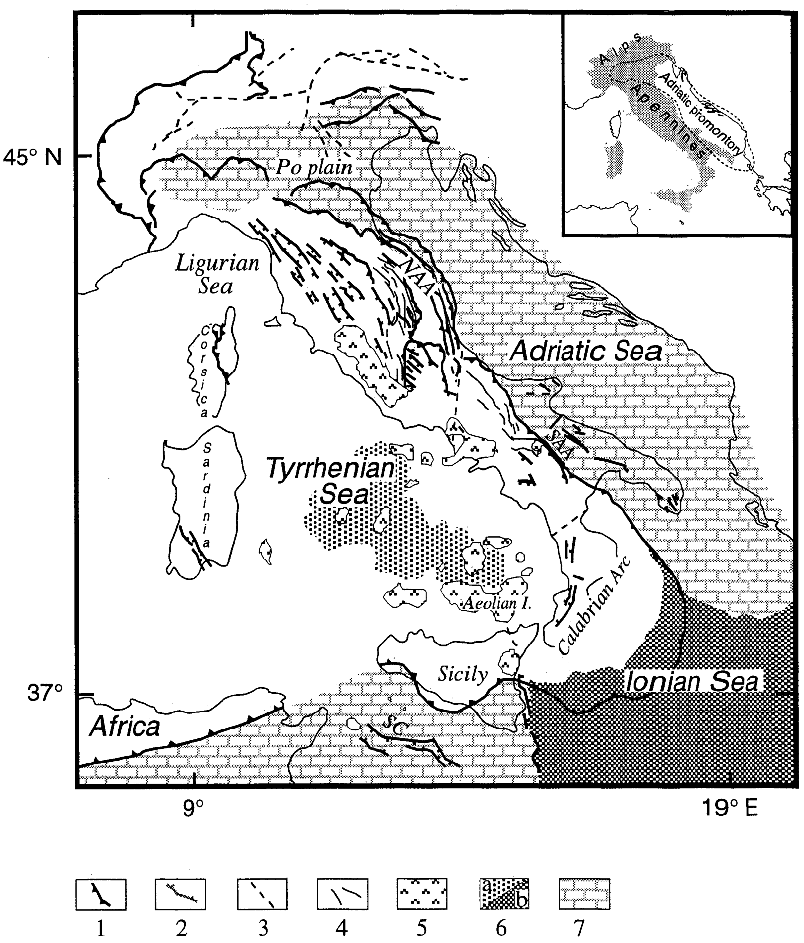

Figure 1. Map of Italy (shaded in the inset) showing major tectonic and physiographic features (NAA, Northern Apennine Arc; SAA, Southern Apennine Arc; and SC, Sicily Channel) (1, thrust faults; 2, normal faults; 3, strike-slip faults; 4, folds; 5, Plio-Pleistocene volcanics; 6, a) Cenozoic oceanic-like crust and b) Mesozoic oceanic crust; and 7, African continental lithosphere).

seismic network operated by the Istituto Nazionale di Geofisica (ING) in the Italian territory, a large collection of regional waveforms is now available.

Tectonic Setting and Seismicity

The tectonics of Italy and its surroundings (Figure 1) is mainly controlled by the convergence of Africa and Eurasia, which started about 80 Ma. While the collision between the Adriatic promontory of the African plate and the southern margin of the Eurasian plate caused the formation of the Alps in the late Cretaceous-Eocene [e.g., *Dewey et al.*, 1973; *Laubscher*, 1975; *Dewey et al., 1*989], deformations of the Apennines started in the Oligocene [e.g., *Civetta et al.*, 1978; *Channell et al.*, 1979; *Patacca et al.*, 1990]. In late Oligocene to Miocene, extension in the Ligurian Sea was accomplished by an eastward migration of the Corsica-Sardinia continental block, which separated from the European continent. Miocene extension west of the Apennines lead to the emplacement of new oceanic crust in the central and southeastern Tyrrhenian basin, while in the northern part of the basin less intense extension occurred [e.g., *Malinverno and Ryan*, 1986; *Sartori et al.*, 1987]. The extensional tectonics affecting the Tyrrhenian basin progressively migrated eastward, as testified by extensional deformations along the western peninsula [e.g., *Elter et al.*, 1975; *Lavecchia*, 1988; *Patacca et al.*, 1990].

Intense magmatic activity related to the formation of the Tyrrhenian-Apennine system has persisted since the Plio-Pleistocene. The main volcanic deposits are located within the Tyrrhenian basin and along the western margin of the Italian peninsula. In the Pleistocene, subduction-related volcanism in the southern Tyrrhenian Sea produced a calc-alkaline volcanic arc which includes the Aeolian Islands [e.g., *Barberi et al.*, 1973; *Civetta et al.*, 1978; *Beccaluva et al.*, 1989]. The heat flow in Italy increases westward, with isograds roughly parallel to the Apennine chain. The highest values, locally exceeding 200 mW/m^2, are found in the Tyrrhenian basin and western Italy, while lower values characterize the Adriatic side of the peninsula [*Loddo and Mongelli*, 1978; *Della Vedova et al.*, 1984].

The Apennine mountain belt comprises two major arcs merging in the central part of the chain [*Locardi*, 1988; *Patacca and Scandone*, 1989], although a certain degree of segmentation is recognized [*Royden et al.*, 1987; *Locardi*, 1988]. Compression started in the Oligocene in the Northern Apennine Arc and in the middle Miocene in the Southern Apennine Arc [e.g., *Patacca et al.*, 1990]. The Apennines are now dominated by extensional deformations across the chain accomplished by widespread normal faulting, as shown by surface geology and focal mechanisms [e.g., *Ritsema,* 1969; *Anderson and Jackson,* 1987; *Lavecchia,* 1988; *Pantosti and Valensise,* 1990]. A foredeep basin east of the Apennines is filled by 6-8 km of Plio-Quaternary sediments; a slightly deformed continental foreland underlies the Adriatic Sea and the Po plain. It is hypothesized that the Adriatic continental lithosphere experienced Jurassic extension as the last tectonic/thermal event [*McNutt,* 1984]. If so, a fairly undeformed and cold Mesozoic uppermost mantle is expected beneath this region. South of Italy, the Ionian basin attains more than 4000 m of maximum depth. In the Ionian abyssal plain, sparse geological and geophysical data indicate that a thin oceanic crust of Mesozoic age is overlain by a 6 km thick sedimentary cover [*Weigel,* 1974; *Rossi and Sartori,* 1980]. Little is known about the structure of the underlying mantle.

In the central Mediterranean, Italy and surrounding regions have a high rate of seismicity typical of many of the plate-boundary regions. Along the Italian peninsula, intense crustal seismicity follows the trend of the Apennine belt; relatively little seismicity occurs in the western Alps. Subcrustal seismicity has recently been recognized in the northern Apennines within the first 100 km of depth [*Selvaggi and Amato,* 1992]. Intermediate and deep hypocenters, reaching about 600 km in depth, occur in the southern Tyrrhenian Sea. This deep seismic zone, which is overlain by the Quaternary volcanic arc of the Aeolian Islands, is interpreted as a Benioff zone related to a subducting slab steeply dipping toward the Tyrrhenian basin [e.g., *McKenzie,* 1972; *Gasparini et al.,* 1982; *Giardini and Velonà,* 1991].

Data and Method of Analysis

The data consist of digital waveforms recorded within epicentral distances of 250-1400 km by the Italian Telemetered Seismic Network, which includes at present more than 80 stations. Most of the station sites are equipped with short-period (1 s) vertical seismometers, and only a few have three-component sensors.

The seismic sources used in this study include 51 shallow earthquakes from within and around Italy (see Table 1). Locations and origin times are from the ING seismic bulletin. The uncertainties on the epicenter location are always less than 10 km and are not relevant for the purpose of this study.

More than 700 waveforms have been analyzed for the presence or absence of high-frequency seismic wave arrivals. Identification of seismic phases is based on the velocity values commonly found for *Pn* (8.1 km/s), *Pg* (6.7 km/s), *Sn* (4.6 km/s), and *Lg* (3.5 km/s) [e.g., *Huestis et al.,* 1973; *Knopoff et al.,* 1973; *Kadinsky-Cade et al.,* 1981; *Barazangi and Ni,* 1982]. The shortest epicentral distance included is 250 km, in order to avoid crustal phase contamination on the regional arrivals. The poor signal-to-noise ratio of many of the regional shear wave recordings did not allow the application of quantitative methods of analysis. However, the abundance of recordings used in this study allowed us to consider the presence or absence of the *Sn* phase on the seismogram as a criterion for a qualitative analysis.

Waveforms have then been classified in terms of "efficiency" of shear wave propagation according to the frequency and amplitude character of *Lg* and *Sn* with respect to *Pg* and *Pn*. Even on vertical sensor recordings, efficiently transmitted shear waves *Lg* and *Sn* show amplitudes comparable to or greater than the compressional counterparts *Pg* and *Pn*. In contrast, inefficient propagation is characterized by weak (low-frequency and low-amplitude) or absent shear waves.

Apart from propagation path effects, shear wave recordings can be affected by radiation pattern and site effects at the receiving station. As for the former, weak or no *Sn* will be recorded at stations lying on a nodal plane for *S* waves. However, a large number of waveforms have been analyzed in the present study, from different azimuths and seismotectonic regions, in order to ensure redundancy and to filter out the radiation pattern as the main cause of weak shear wave signals. Site effects are also considered not to significantly affect our observations, because at least some high-frequency, high-amplitude shear waves from local and regional distances were observed at most stations, even though the geological structure varies among the station sites. Therefore lateral variations of the lithospheric structure are considered a primary cause for the observed shear waves attenuation or, at least, for the relatively high attenuation of shear waves (i.e., site effects may attenuate both *P* and *S*).

Three main classes of signals have been recognized among the available waveforms: (1) impulsive arrivals of high-frequency *Sn* characterized by amplitude larger than one half of *Pn*; (2) low-frequency ($f < 1$ Hz), low-amplitude *Sn* with respect to *Pn*; and (3) poorly defined or absent *Sn*. Class (1)-type signals have been considered as *Sn* phases efficiently transmitted in the uppermost mantle, while both (2)- and (3)-type signals have been considered as inefficiently transmitted *Sn* waves. In Figures 2 to 6 seismograms characterized by efficient (EF) and inefficient (NE) propagation of *Sn* waves are shown. The same criteria have been applied to classify the *Lg* propagation.

Observations and Results

In this study, the appearance of regional phases at a given station is clearly dependent on the azimuth of the propagation path, as shown in the example seismograms of Figures 2-6. Figures 2 and 3 show that high-frequency *Sn* waves from the Ionian Islands area are transmitted best to stations located in northern Italy when they travel within the Adriatic lithosphere. In contrast, low-amplitude or indeterminate *Sn* signals are recorded in northwestern Italy at BOB, CKI, and DOI stations, when their propagation paths cross the Apennine and western Italy lithosphere. It is noteworthy that, along the same azimuth, high-frequency *Sn* is recorded at FG3 station, while farther north *Sn* is very weak or absent at CRE, MME, and BOB (Figure 2), suggesting that the attenuation zone in the uppermost mantle starts somewhere between these stations. Note also that *Sn* recordings at BOB and VAI stations, both located in northern Italy, show dramatic differences even though their propagation paths differ by a small angle: where BOB recorded very poor shear waves that traveled in the uppermost mantle beneath the Apennines, VAI recorded high-frequency, high-amplitude *Sn* from the Adriatic lithosphere. The same contrast applies to BOB and ORO in Figure 3. These and other examples clearly show that the radiation pattern can be excluded as a major effect on the observed *Sn* attenuation. Several ray paths (e.g., SC9 and MEU, Figure 2) sample the northern Ionian Sea and reveal high-frequency *Sn*. *Lg* waves are not transmitted along these ray paths, while they are observed to propagate across the

Table 1. Parameters of Earthquakes Used in This Study

	Date	Origin Time, UT	Latitude, °N	Longitude, °E	M_L	Depth, km
1	Dec. 19, 1989	14 28:20	41°64'	12°70'	3.2	27
2	Dec. 22, 1989	06 48:14	43°02'	12°77'	4.0	9
3	Dec. 26, 1989	09 35:55	42°53'	13°23'	3.0	10
4	Dec. 26, 1989	19 59:57	43°53'	07°55'	4.3	13
5	Jan. 24, 1990	00 45:05	39°13'	16°51'	2.5	7
6	Jan. 31, 1990	20 22:11	42°12'	15°69'	3.4	11
7	Jan. 31, 1990	22 58:17	42°09'	15°57'	3.4	10
8	Feb. 11, 1990	07 00:36	44°97'	07°55'	4.0	14
9	Feb. 13, 1990	09 15:29	42°12'	15°53'	3.8	10
10	Feb. 18, 1990	20 10:50	42°10'	16°51'	4.0	5
11	Feb. 20, 1990	21 43:07	42°96'	13°78'	2.8	13
12	Apr. 03, 1990	22 02:38	43°37'	17°43'	4.4	9
13	Apr. 11, 1990	21 38:33	44°75'	09°98'	3.6	9
14	Apr. 15, 1990	07 50:35	43°59'	07°75'	3.7	13
15	Apr. 24, 1990	19 30:40	42°08'	19°25'	4.7	9
16	Apr. 26, 1990	11 27:42	40°97'	19°82'	4.7	10
17	May 06, 1990	04 00:32	40°65'	15°89'	3.2	10
18	May 06, 1990	05 43:27	40°68'	15°76'	2.9	9
19	May 08, 1990	22 33:17	43°60'	12°10'	3.4	11
20	May 14, 1990	17 04:24	40°68'	19°90'	5.2	12
21	Jun. 03, 1990	11 39:14	44°66'	17°63'	4.5	21
22	Jun. 16, 1990	02 16:21	39°28'	20°58'	5.4	14
23	Jul. 31, 1990	15 50:54	42°96'	17°86'	4.5	11
24	Jul. 31, 1990	23 15:17	42°98'	17°85'	3.9	12
25	Aug. 04, 1990	07 29:25	39°23'	20°52'	5.0	18
26	Aug. 26, 1990	13 41:26	40°45'	15°69'	3.4	11
27	Aug. 27, 1990	13 48:42	43°36'	17°40'	4.2	11
28	Aug. 27, 1990	23 24:43	44°02'	13°18'	3.6	9
29	Aug. 28, 1990	19 02:53	40°70'	15°88'	3.8	13
30	Sep. 03, 1990	00 27:01	42°87'	13°04'	3.1	9
31	Sep. 03, 1990	10 48:34	45°91'	15°94'	4.5	32
32	Sep. 12, 1990	02 59:44	42°73'	12°64'	3.5	9
33	Oct. 29, 1990	08 16:17	36°41'	14°78'	3.9	36
34	Nov. 11, 1990	22 16:24	46°16'	14°08'	4.2	10
35	Feb. 11, 1991	15 43:44	44°88'	06°70'	4.1	5
36	Feb. 23, 1991	06 21:49	40°42'	20°39'	4.2	14
37	Feb. 26, 1991	13 49:04	43°98'	08°69'	2.7	17
38	Mar. 19, 1991	02 37:07	39°35'	20°44'	4.8	17
39	Mar. 30, 1991	03 04:58	39°37'	16°39'	3.5	7
40	Jan. 02, 1992	13 44:59	44°97'	09°98'	3.1	9
41	Jan. 23, 1992	04 24:18	38°50'	20°43'	4.8	14
42	Feb. 18, 1992	03 30:10	42°40'	14°23'	3.7	12
43	Mar. 15, 1992	23 43:37	41°38'	14°00'	2.9	22
44	Mar. 16, 1992	05 45:35	41°42'	13°99'	3.2	14
45	Mar. 18, 1992	16 29:54	41°22'	14°80'	3.5	14
46	Mar. 19, 1992	23 34:13	41°49'	14°60'	3.4	11
47	Apr. 17, 1992	11 59:08	44°43'	11°03'	3.6	8
48	May 27, 1992	18 13:57	44°15'	11°54'	3.2	9
49	Jun. 05, 1992	02 15:03	43°05'	12°98'	3.5	12
50	Jul. 11, 1992	17 22:00	36°49'	10°87'	3.7	10
51	Jul. 16, 1992	05 38:55	42°34'	14°22'	3.8	15

Locations and origin times are taken from the seismic bulletin of the Istituto Nazionale di Geofisica.

continental crust of the Adriatic basin (see FG3 recordings, Figures 2 and 3).

Remarkable differences can be seen among the *Sn* phases produced south of Italy before and after they cross the Tyrrhenian Sea (events 50 and 52, Figure 4). *Sn* propagation is generally very inefficient in the Tyrrhenian Sea, as shown by all the stations located within the peninsula; even on the two horizontal components of station MU9 (MU9E and MU9N recordings shown in Figure 4a), the shear *Sn* wave is absent. A low-energy *Sn* arrival can be observed at MAO, while some high-frequency *Sn* propagates to BNI station in northwestern Italy, indicating that the western Tyrrhenian Sea is less attenuative compared to the eastern part. High-frequency, high-amplitude *Sn* do propagate to Sardinia (CGL station) and across Sicily (MEU and MNO) as far as the Ustica island (USI), north of Sicily.

High-frequency, high-amplitude shear waves from central Italy (Figure 5) are recorded at ORO, SAL, and CTI stations to the north. High-frequency *Sn*, with amplitude lower than *Pn*, are transmitted over the Ligurian Sea at DOI and CKI stations, while no *Sn* propagate southward to MGR and TDS. Finally, Figure 6 shows the *Sn* propagation characteristics in the northern part of the study area: while high-energy *Sn* are observed at MAO, PII, ARV, and TRI stations, attenuated *Sn* waves are recorded at ASS, MNS, and SDI, their propagation paths crossing the Apennines and western Italy. We can

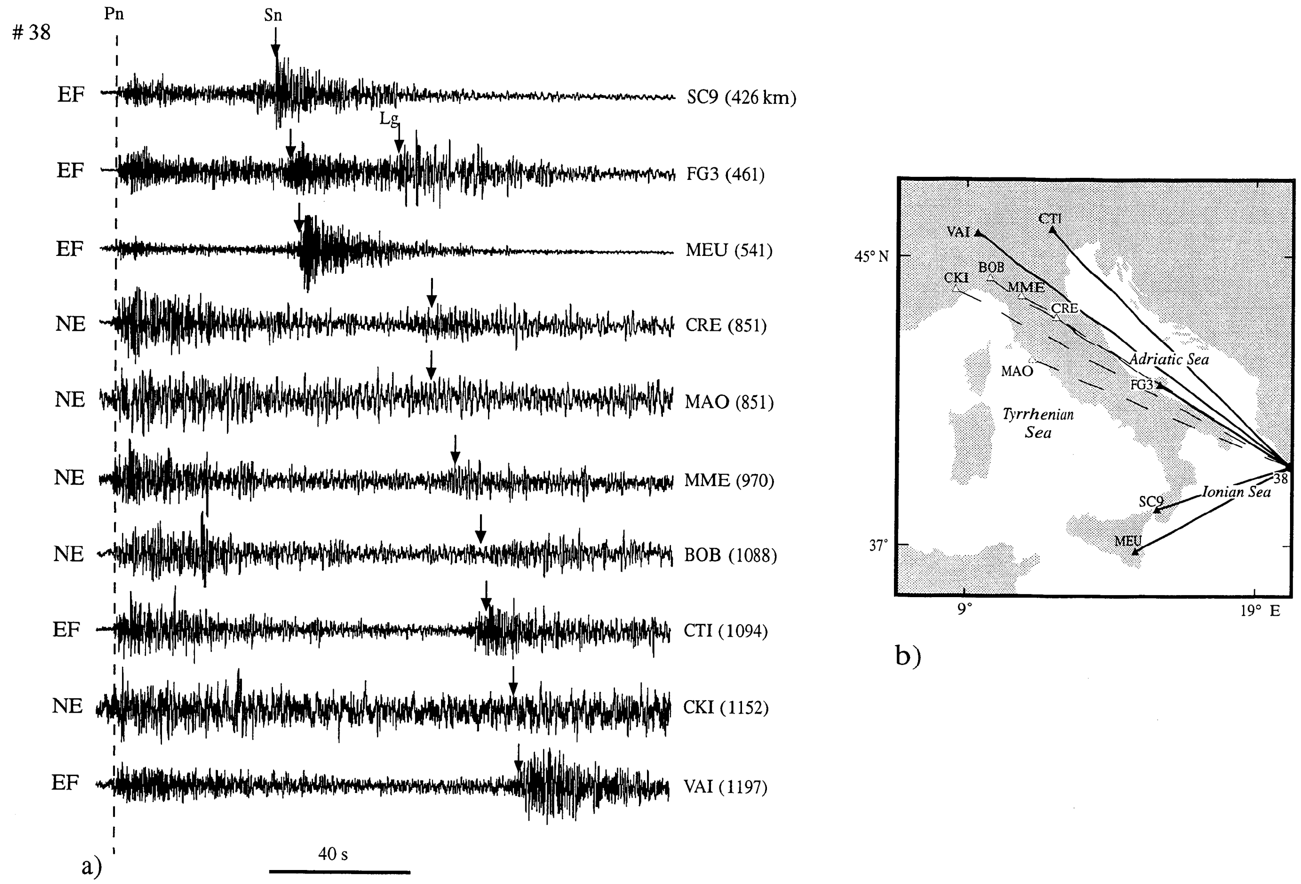

Figure 2. (a) Example of short-period seismograms recorded on the vertical component, showing different efficiency of *Sn* wave propagation (EF, efficient; and NE, not efficient) for earthquake 38. Arrows indicate the expected *Sn* arrival times. Station code, epicentral distance, and the event number referred to Table 1 are indicated. (b) Map showing epicenter (circle), stations (triangles) and propagation paths of the seismograms shown in Figure 2a. Solid and open triangles indicate stations recording efficient and inefficient *Sn*, respectively. Heavy solid lines represent high-frequency, high-amplitude *Sn* propagation; dashed lines represent low-frequency, low amplitude or absent *Sn* signals. Note that *Sn* recordings at BOB and VAI differ dramatically, even though the azimuth to the source is only slightly different.

observe that the *Sn* phase gradually disappears as the wave propagates to the south within the Apennine lithosphere (from north to south: PII, ASS, MNS, and SDI).

The *Sn* propagation characteristics resulting from the analysis of the 51 earthquakes used in this study are shown in Figure 7.

Using the same methodology, the propagation of crustal phases has been analyzed. The waveforms recorded at local distances, that is, within 250 km, reveal that high-frequency, high-amplitude shear waves *Sg* are recorded at most of the Italian stations. On the contrary, the propagation of crustal phases at regional distances (*Lg*) is strongly affected by major variations in the crustal structure. *Lg* phases produced along the eastern peri-Adriatic region are observed to propagate across the continental crust of the Adriatic Sea and Po plain (Figure 8a), except when their propagation paths intersect the Apennine chain (Figure 8b). Also, *Lg* waves produced northwest of the Apennines propagate over the Ligurian Sea, being recorded at stations lying west of the chain, while they are not transmitted farther on the other side of the Apennines. *Lg* are not produced along the Tyrrhenian margin of Italy. One possible explanation is that *Sg* waves do not travel enough distance to generate *Lg* before crossing the Apennine belt; alternatively, local sources of attenuation might be present within the crust. *Lg* are not observed to propagate in the southern Tyrrhenian crust nor in the northern Ionian crust. These observations confirm that major physiographic features along continental paths, as well as oceanic paths, have strong scattering and attenuation effects on the *Lg* wave train.

Discussion and Tectonic Implications

After *Molnar and Oliver* [1969], lateral variations in the *Sn* propagation have been interpreted as due to rheological heterogeneities in the lithospheric mantle. High attenuation of the shear waves are thought to correlate with high temperature and low strength in the uppermost mantle. If asthenospheric material is present below the Moho, it behaves as a low-pass filter attenuating the high-frequency components of the shear waves. Thus low-frequency, low-amplitude *Sn* waves are interpreted to imply the presence of anomalously hot uppermost mantle material somewhere along the propagation path. Consequently, the efficient

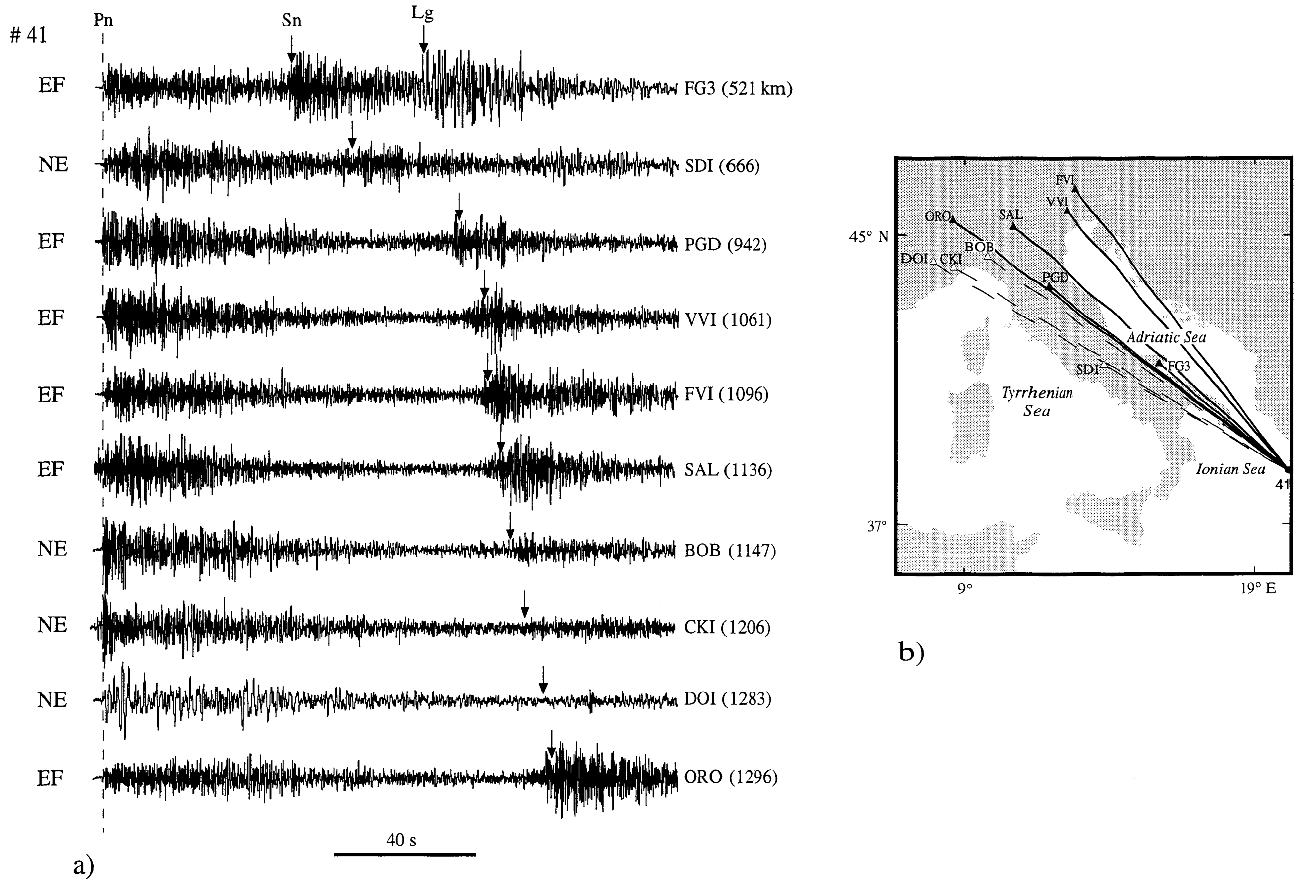

Figure 3. As in Figure 2, except seismograms are of event 41. The *Lg* arrival is clear on the FG3 seismogram. Note the different *Sn* propagation to BOB and ORO, even though the azimuth to the source is about the same for both stations.

transmission of *Sn* is interpreted to imply a typical high-strength, relatively cool mantle lid along the entire path.

Our results shown in Figure 7 are remarkably consistent. They outline a first-order rheological boundary between the eastern side of the Italian peninsula, where *Sn* is efficiently transmitted for all the epicenter-station combinations, and the western side, where significant loss of seismic energy is observed along the propagation paths. Beneath the Po plain and the Adriatic and Ionian Seas, *Sn* waves are efficiently transmitted, indicating that a high-strength uppermost mantle is present. In contrast, a high-attenuation zone is inferred in the uppermost mantle beneath the Apennines and the southern Tyrrhenian Sea. Seismic rays crossing the southernmost part of the peninsula and eastern Sicily show efficient *Sn* transmission, probably due to their propagation within the high-strength lithosphere underlying the Calabrian Arc.

Most of the earthquakes used in this study are produced within the Italian peninsula and east-southeast of Italy; low seismic activity occurs north-northwest and south of Italy, so that a few propagation paths are available from these azimuths. However, their propagation characteristics show that *Sn* transmission is rather efficient either in the Ligurian Sea or in the area between Sardinia and the northern African coasts. Furthermore, *Sn* waves produced south of Italy are efficiently transmitted to Sicily, while they are strongly attenuated within the Tyrrhenian upper mantle. These observations suggest that the thermal structure of the mantle lithosphere beneath the Ligurian Sea, as well as south of Sardinia and beneath the Sicily Channel, has not been significantly modified by the extensional tectonic processes.

In a previous paper, *Mele et al.* [1996] applied the spectral ratio method to *Pn* phases produced by Greek earthquakes in order to estimate the apparent quality factor *Q* in the uppermost mantle for ray paths through the Italian peninsula. In their study, seismic *Q* is of the order of 1000 along propagation paths crossing the Adriatic lithosphere, and it ranges from 250 to 650 beneath the Apennines and western Italy. The present *Sn* study allows us to better define the spatial extent of the low-*Q* zone beneath the peninsula and to extend the high-attenuation zone in the uppermost mantle beneath the southern Tyrrhenian Sea. The high-attenuation zones inferred from the analysis of both *Pn* and *Sn* phases are shown in Figure 9.

The extent of the high-attenuation zone in the uppermost mantle has been projected on two cross sections perpendicular to the major arc structures of Italy where subcrustal seismicity occurs, that is, the Northern Apennine Arc and the Calabrian Arc (Figure 10a). The observed shear wave attenuation suggests that the lithospheric mantle beneath the internal units of the Apennines and western Italy is contaminated by advection of relatively hot material at shallow depth, which drastically changes its thermal structure. The lowermost part of the crust might also be affected by this process. Moreover, the occurrence of subcrustal seismicity along the Northern

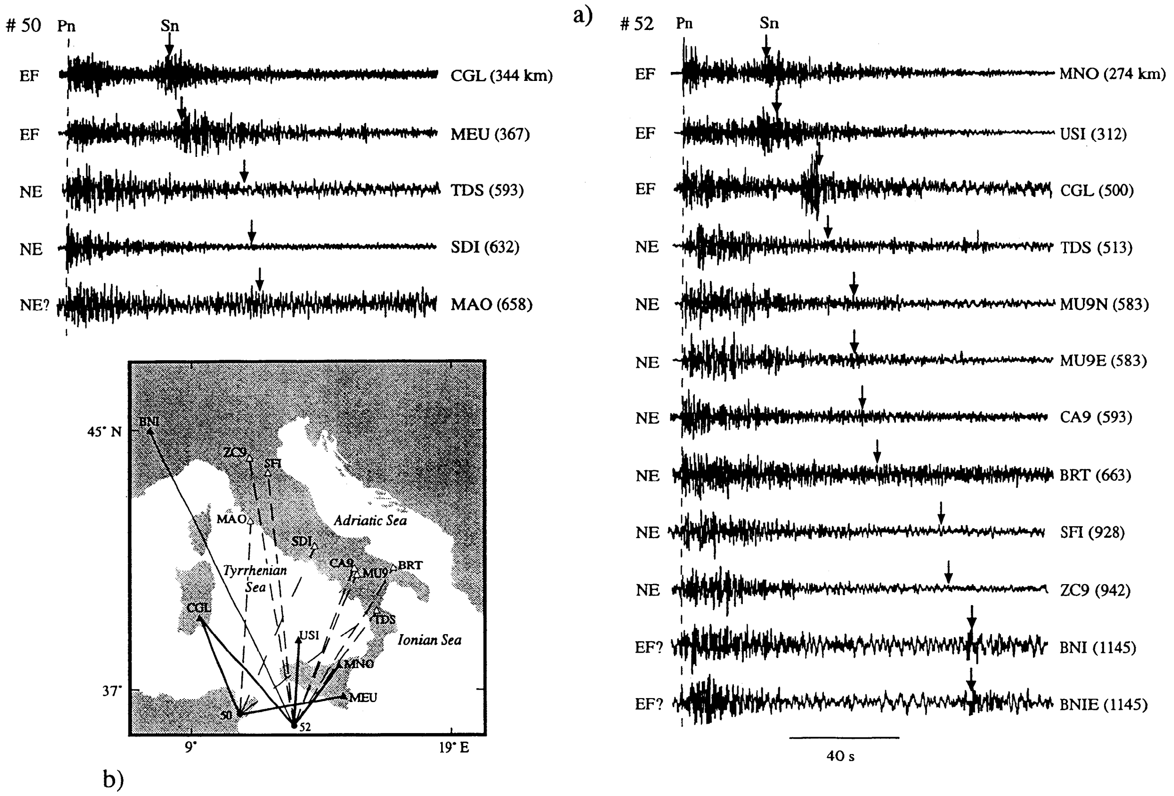

Figure 4. As in Figure 2, except seismograms are of events 50 and 52. Horizontal components are shown for stations MU9 (MU9E and MU9N) and BNI (BNIE). Heavy solid lines represent high-frequency, high-amplitude *Sn* propagation; a thin solid line is drawn along a propagation path transmitting some *Sn* energy; dashed lines represent inefficient *Sn* propagation.

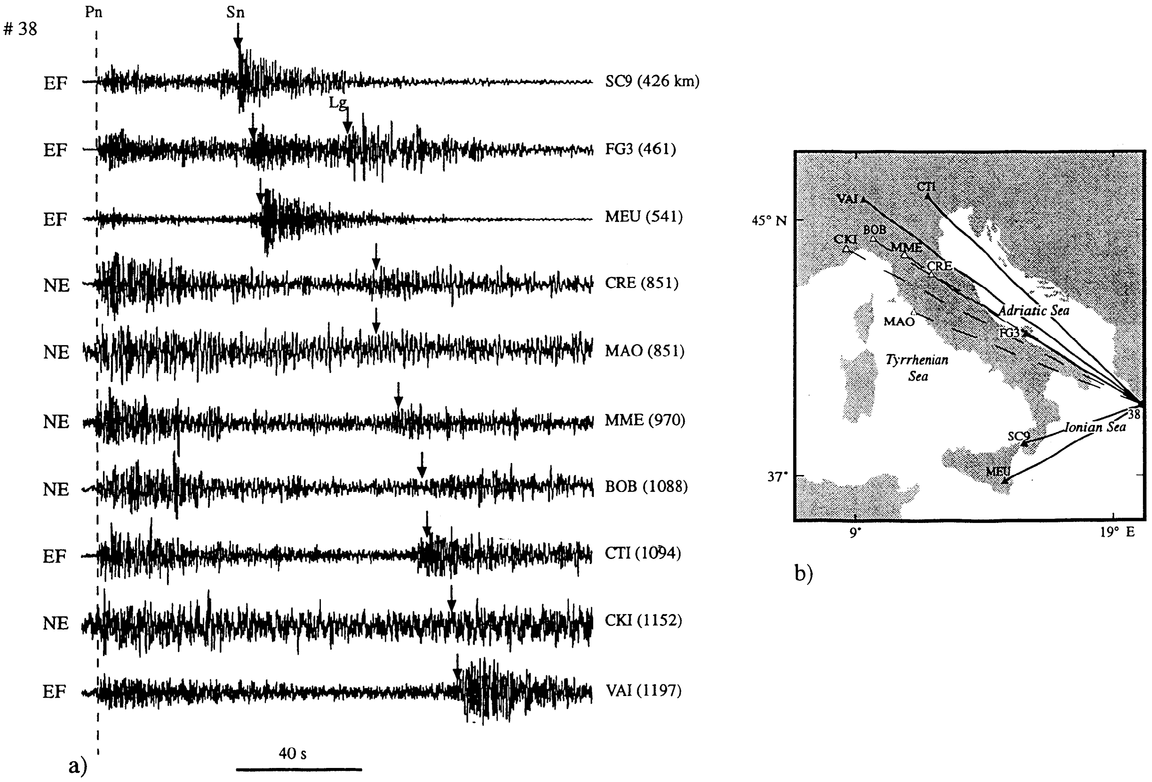

Figure 5. As in Figure 2, except seismograms are of event 2. High-frequency *Pg* and *Sg* at MAO station are shown. Heavy solid lines represent high-frequency, high-amplitude shear wave propagation; thin solid lines represent propagation paths where both *Pn* and *Sn* arrivals are observed, with the *Sn* amplitude less than that of *Pn*; dashed lines represent indeterminate *Sn* signals.

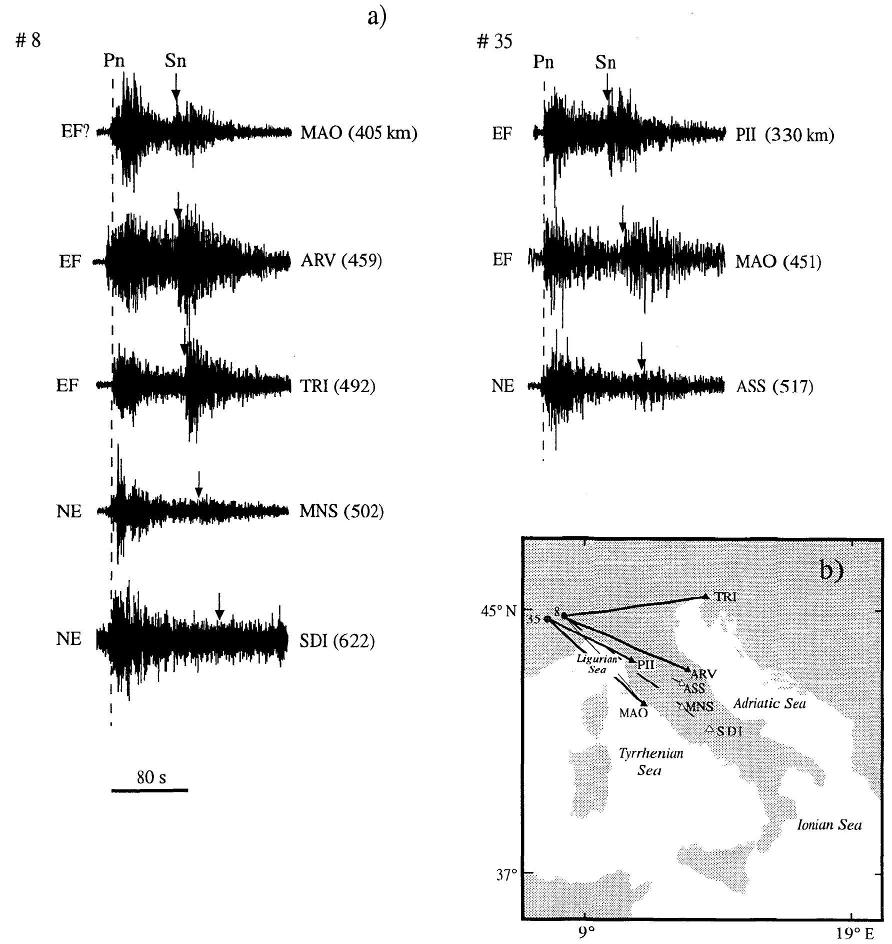

Figure 6. As in Figure 2, except seismograms are of events 8 and 35. Heavy solid lines represent high-frequency, high-amplitude *Sn* propagation; a thin solid line is drawn along a propagation path trasmitting the *Sn* wave with amplitude lower than that of *Pn*; dashed lines represent low-frequency, low amplitude or indeterminate *Sn* signals.

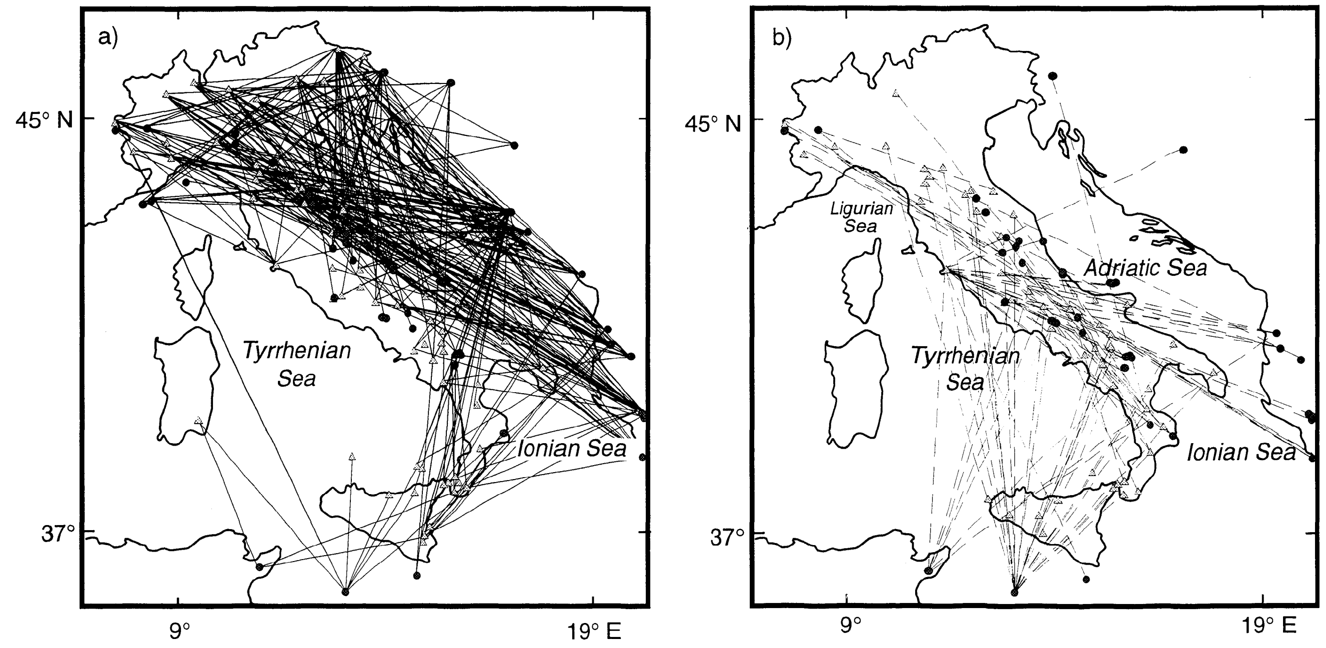

Figure 7. Pattern of *Sn* propagation in the Italian peninsula and surrounding regions: (a) efficient *Sn* propagation paths; (b) inefficient *Sn* propagation paths. Seismic stations (triangles) and epicenters (circles) used in this study are shown. Note that the uppermost mantle beneath the Ligurian, Adriatic, and northern Ionian Seas is quite efficient in transmitting high-frequency shear waves. Efficient *Sn* propagation characterizes also the Sicily Channel, Sicily, and the area between Sardinia and Africa. Inefficient *Sn* propagation characterizes the southern Tyrrhenian Sea and the internal Apennine units.

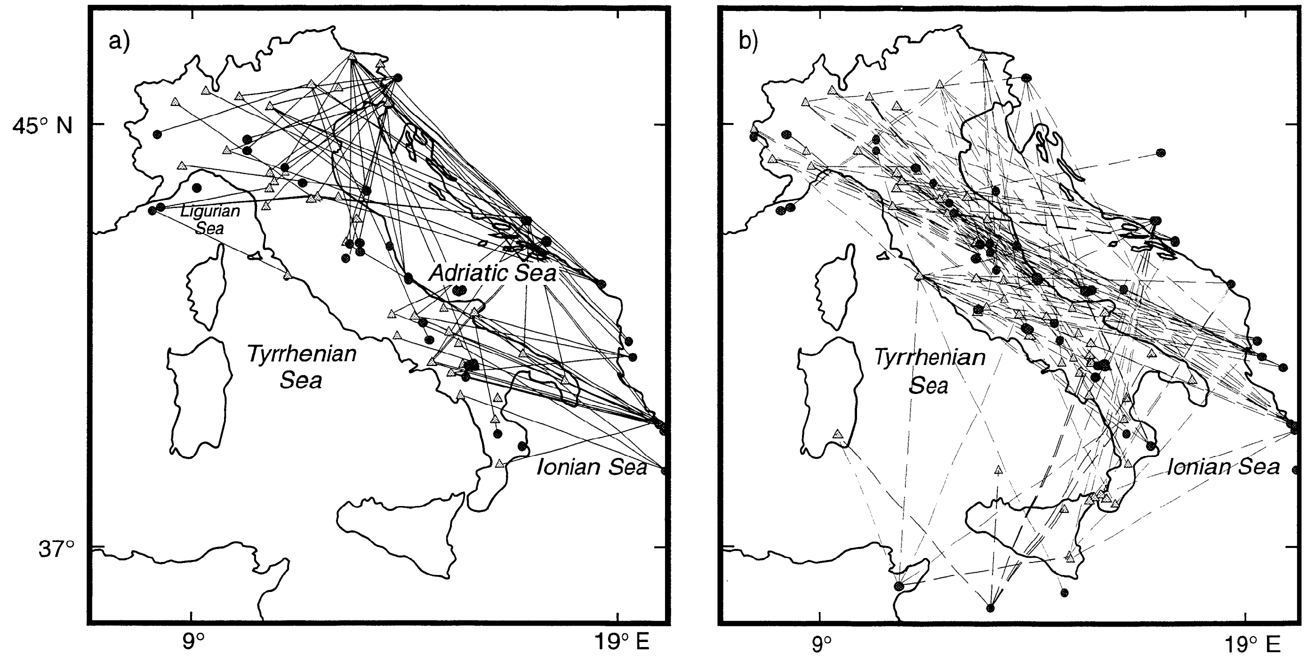

Figure 8. Map of Italy and surrounding regions showing the *Lg* propagation characteristics: (a) efficient *Lg* propagation paths and (b) inefficient *Lg* propagation paths. Triangles indicate seismic stations, and circles indicate epicenters. Note that propagation paths crossing the Apennine mountain belt, as well as oceanic paths, show inefficient *Lg* propagation.

Apennine Arc (Figure 10b) implies that the mantle lithosphere beneath the internal part of the orogen is thermally unstable and that seismic energy is not accumulated at subcrustal depth in this area. We hypothesize that lithospheric instability is a primary cause of the low-Q zone we observe beneath the Apennines and that it is related to the present-day extension of this chain. Collision-induced delamination of the lithosphere underthrusting the Apennines might reasonably explain our observations in this part of Italy. In such a process, the lithospheric mantle is replaced by the asthenospheric mantle [e.g., *Bird,* 1979; *Seber et al.,* 1996], so that its thermal structure drastically changes. In a continental collision zone, a critical amount of shortening is required for the underthrusting lithosphere to become gravitationally unstable and delaminate into the asthenosphere [e.g., *Houseman et al.,* 1981; *Dewey*, 1988]. Decoupling of the crust from the sinking Adriatic lithosphere has been hypothesized beneath northern Apennines [*Laubscher,* 1971; *Reutter et al.,* 1980]. This model [*Reutter et al.,* 1980, Figure 2c] predicts the injection of asthenospheric material beneath the orogen, which is consistent with the high shear wave attenuation we find beneath this chain. Lithospheric delamination beneath northern Apennines is also hypothesized by *Serri et al.* [1993] on the basis of petrological evidences. Delamination processes have been recently proposed to explain similar high *Sn* attenuation beneath the Rif-Betic mountain belt [*Seber et al.,* 1996].

The presence of asthenosphere at shallow depths beneath the southern Tyrrhenian Sea is consistent with the proposed geodynamic models, which can be grouped as back arc processes [e.g., *Barberi et al.,* 1973; *Scandone,* 1979; *Boccaletti et al.,* 1980; *Malinverno and Ryan,* 1986; *Mantovani et al.,* 1996], active rifting due to mantle uplift [e.g., *Van Bemmelen,* 1972; *Locardi,* 1988], lithospheric extension [*Lavecchia,* 1988; *Wang et al.,* 1989], and post collisional lithospheric delamination [*Channell and Mareschal,* 1989]. However, the existence of a well-defined Benioff zone (see Figure 10c), together with the presence of a calk-alcaline volcanic arc in the Aeolian Islands, lead us to interpret the high-attenuation zone beneath the southern Tyrrhenian Sea in terms of back arc processes in the concave side of the Calabrian Arc. It is important to notice that no significant shear wave attenuation is found east of Corsica, that is, in the northern Tyrrhenian Sea, indicating that the mantle lithosphere is currently in thermal equilibrium in this area. This may suggest that extensional processes did not significantly affect the mantle lithosphere beneath the northern Tyrrhenian Sea or that extension in the north is older than in the south, supporting the hypothesis of a different evolution between the northern and the southern part of this basin [see *Sartori et al.,* 1987; *Serri,* 1990].

Conclusions

Using shear wave propagation characteristics, a high-attenuation zone has been mapped in the uppermost mantle beneath the Apennine chain and western Italy and beneath the southern Tyrrhenian Sea. We interpret these observations to indicate the presence of asthenospheric material in the mantle lid. Present-day extension in the Apennines and the widespread Plio-Quaternary volcanism and high heat flow in western Italy and nearby Tyrrhenian Sea support this view, indicating, in turn, that such extensional features are controlled by uppermost mantle processes. Delamination processes of the Adriatic lithosphere underthrusting the Apennines reasonably explain our observations beneath this chain, while back arc spreading related to lithospheric subduction beneath the Calabrian Arc would account for the presence of anomalously hot and partially melted material beneath the southern Tyrrhenian Sea. In contrast, a high-

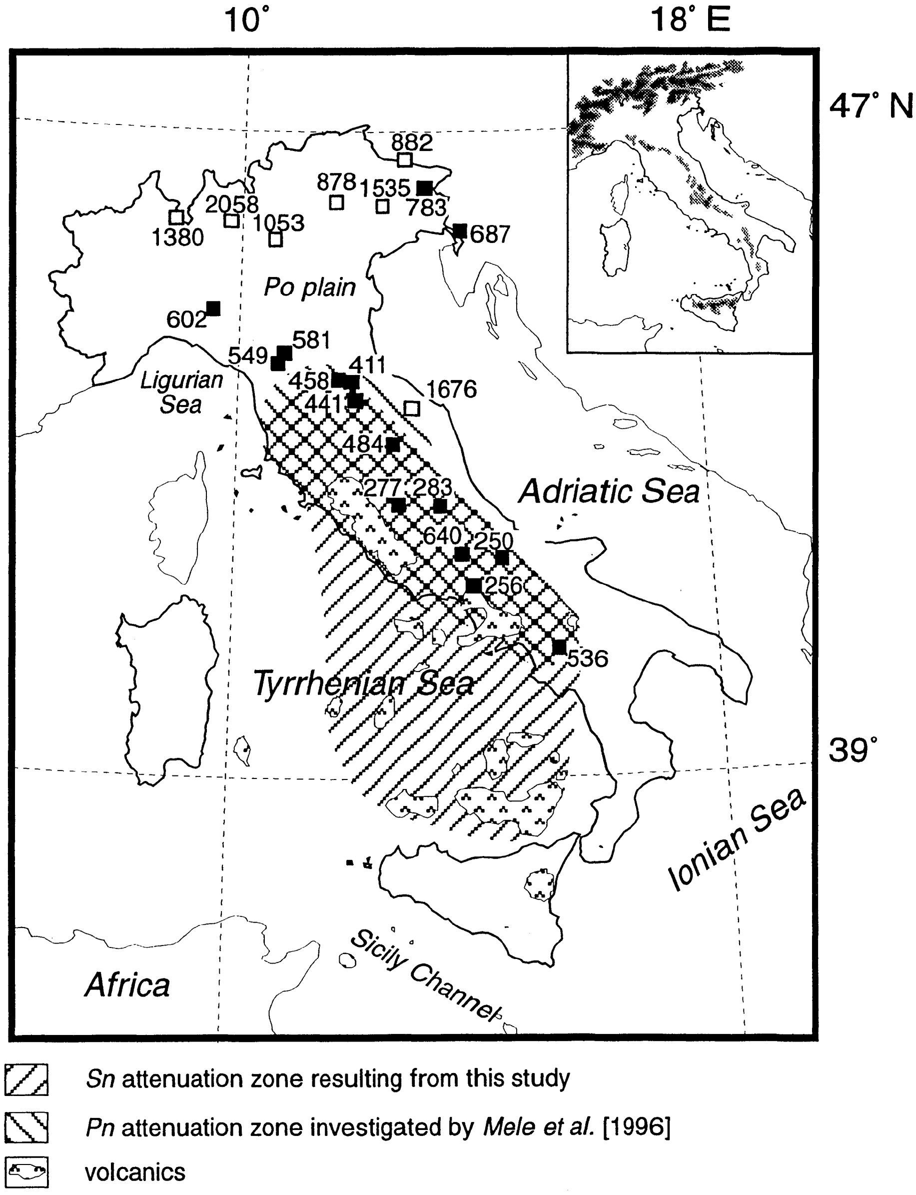

Figure 9. Map of Italy showing the *Sn* attenuation zone inferred from the present study. The uppermost mantle *Q* estimated by *Mele et al.* [1996] from *Pn* spectral ratios and the inferred attenuation zone are also shown. Open and solid squares indicate seismic stations where high- and low-*Q* values, respectively, have been estimated along the ray paths to the stations. The areas with elevations greater than 1000 m above sea level are shown in the inset.

strength mantle lid is present beneath the Po plain and the Adriatic Sea, as well as beneath the northern Ionian Sea. From the relatively few *Sn* observations, a normal mantle lid is also suggested beneath the Ligurian Sea and the northern Tyrrhenian Sea, in the area between Sardinia and the northern African coasts, as well as beneath the Sicily Channel and Sicily.

The analysis of crustal shear phases *Sg* and *Lg* has been included in this study to evaluate possible effects of crustal attenuation on the *Sn* propagation. Our analysis shows that crustal shear waves are efficiently transmitted at local distances all over the peninsula and that they are recorded as high-frequency, high-amplitude *Sg* at most of the stations used in this study. Thus inefficient propagation of *Sn* implies that the attenuation zone is in the uppermost mantle. We also observed that propagation of crustal phases at regional scale (i.e., the *Lg* phase) is primarily affected by major variations in the crustal structure, such as the presence of mountain belts and the transition from continental to oceanic crust. In fact, *Lg* waves are observed to propagate efficiently, unless their propagation paths intersect the Apennines or the oceanic domain of the Tyrrhenian Sea. *Lg* does not propagate over the northern Ionian Sea.

The first-order observation of significant lateral variations in the propagation of high-frequency shear waves in Italy is important for earthquake hazard studies. The present results imply that, generally, seismic waves produced by an earthquake in eastern Italy will propagate farther and, potentially, will be more damaging than a similar-size earthquake in western Italy.

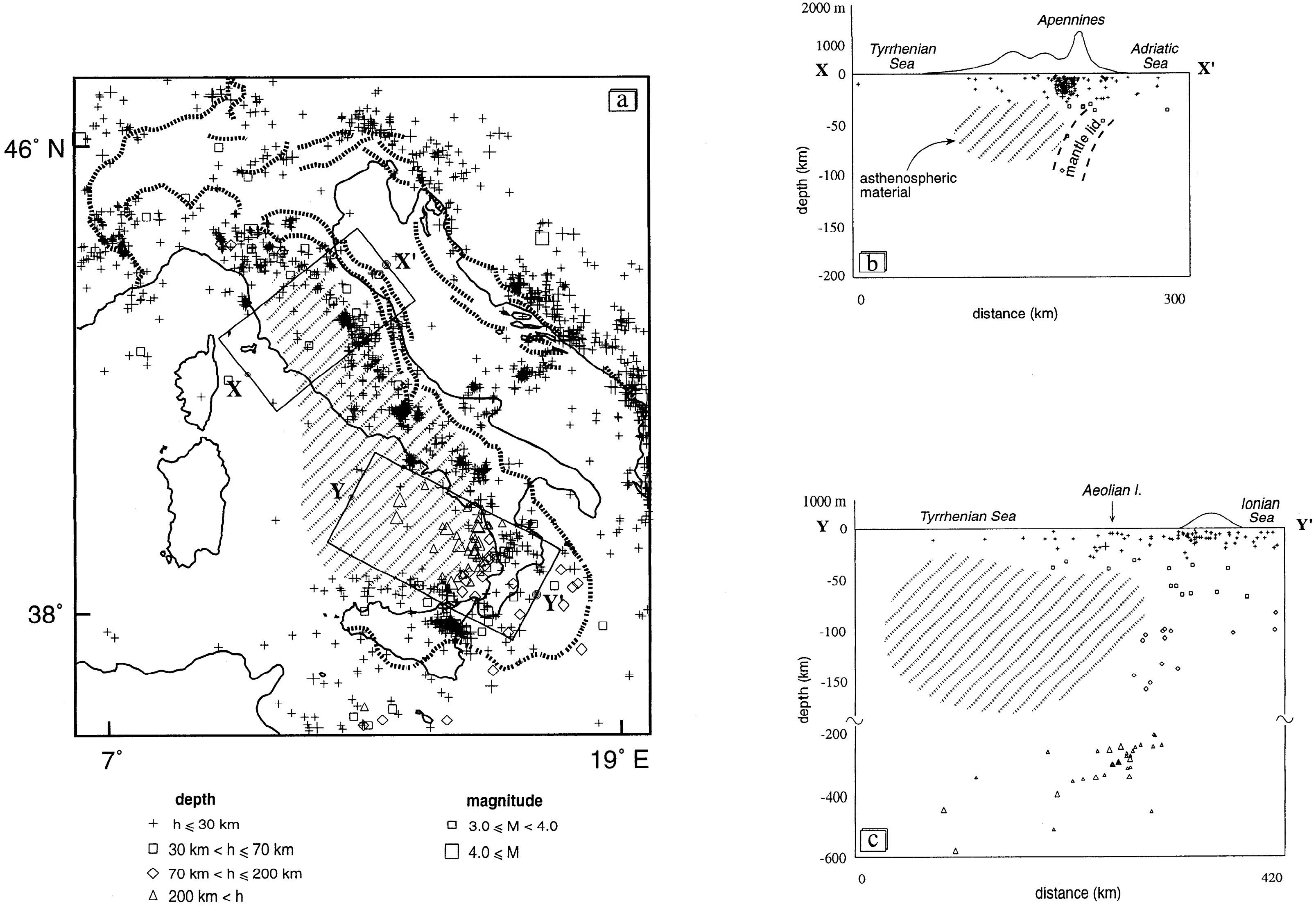

Figure 10. (a) Map of the study area showing the *Sn* attenuation zone (dashed area), together with the 1982-1992 seismic activity and the main thrusts. The projection areas along the vertical sections X-X' and Y-Y' are indicated. (b) X-X' cross section perpendicular to the Northern Apennine Arc. The approximate spatial extent of the attenuation zone beneath the Apennines and western Italy and the distribution of seismicity within the projection area shown in Figure 10a are projected. (c) Y-Y' cross section perpendicular to the Calabrian Arc. The approximate spatial extent of the attenuation zone beneath the southern Tyrrhenian Sea and the distribution of seismicity within the projection area shown in Figure 10a are projected.

Acknowledgments. We thank Enzo Boschi for encouraging this study, which has been supported by ING internal research funds. Thanks are due to Klaus Mosegaard, Leonardo Seeber, and an anonymous reviewer for their critical review and helpful comments and to Andrea Argnani for his helpful suggestions. Part of this work was done during a several-months stay of one of the authors (G.M.) at the Institute for the Study of the Continents (INSTOC) of Cornell University in Ithaca. During her stay, she greatly benefited from stimulating conversations and the friendship of many people. Thanks are due to all of them and in particular to Naomi Ussami and Elias Gomez. This is INSTOC contribution 222.

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(Received May 28, 1996; revised November 26, 1996;
accepted January 27, 1997.)