GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 7, PAGES 709-712, APRIL 1, 1996

Lateral variations of Pn propagation in Italy: Evidence for a high-attenuation zone beneath the Apennines

Giuliana Mele, Antonio Rovelli
Istituto Nazionale di Geofisica, Rome, Italy

Dogan Seber, Muawia Barazangi
Institute for the Study of the Continents (INSTOC), Cornell University, Ithaca, New York

Abstract. Pn phases recorded by 40 stations of the Italian seismic network are analyzed using the spectral ratio technique to estimate the Q structure of the uppermost mantle beneath the Italian peninsula and nearby Adriatic Sea. A total of 344 digital waveforms are analyzed from 22 earthquakes that occurred within distances of 300 to 1600 km. The calculated apparent Q values are grouped into two categories: $Q > 800$ characterizes the Adriatic side of the Italian peninsula, indicating that the Adriatic lithosphere is very efficient in propagating Pn phases through the uppermost mantle; $Q < 600$ characterizes the uppermost mantle beneath the Apennines and western Italy, indicating less efficient wave propagation. The presence of asthenospheric mantle material at shallow depths beneath the Apennines can explain the observed Q.

Introduction

The Italian Telemetered Seismic Network (ITSN) is composed of more than 80 short period stations. Many waveforms are recorded owing to active tectonism in the central Mediterranean. Seismograms from regional earthquakes show great variability in efficiency of propagation for both Pn and Sn phases, seemingly correlated with surface geology and tectonics.

The geology of Italy has been strongly influenced since the upper Cretaceous by the convergence of the Eurasian and African plates [e.g., *Dewey et al.,* 1973]. Since late Miocene, rifting predominated in the internal (Tyrrhenian) domain, while compressional deformations initiated the Apennine thrust-and-fold system. Substantial magmatic activity has taken place since the Plio-Pleistocene in and around the Tyrrhenian basin [e.g., *Barberi et al.,* 1973]. The Adriatic continental block represents the undeformed foreland of the Apennine orogen [e.g., *Lowrie and Alvarez,* 1974; *Channell et al.,* 1979].

The aim of this paper is to estimate the uppermost mantle Q using Pn phases recorded by the Italian seismic network. Previous attenuation studies in the Italian peninsula have been focused on seismic hazard assessment in volcanic and seismogenic areas [e.g., *Rovelli,* 1983; *Del Pezzo et al.,* 1985; *Mayer-Rosa and Schenk,* 1989]. The present study, together with an ongoing study of shear wave attenuation [*Mele et al.,* 1995], is the first to evaluate the efficiency of high-frequency seismic energy transmission at a regional scale. The attenuation of Sn waves is very strong, so that poor signal-to-noise ratios do not allow quantitative evaluation for Sn efficiency.

Paper number 96GL00480
0094-8534/96/96GL-00480$03.00

Data

The data used in this study are Pn waveforms recorded by the ITSN which is operated by the Istituto Nazionale di Geofisica (ING). Signals from the station sites are transmitted to the ING via phone lines and then A-D converted by an automatic procedure [*Barba et al.,* 1995]. The sampling rate is 40 sps. All stations are equipped with short-period (1 s) S-13 Teledyne seismometers. Most of the stations operate with only a vertical-component sensor while a few are in triaxial configuration.

Earthquakes occurring along the western coast of Greece and in the Ionian Sea (Fig. 1) are favorably situated for this study. Their ray paths cross the Italian peninsula along its longitudinal axis and the station azimuths are similar for each event. Thus, amplitude variations due to the radiation pattern are minimal, allowing unbiased estimates of attenuation between the northern and the southern parts of the Italian peninsula. The attenuation of Sn waves is very strong, so that poor signal-to-noise ratios do not allow quantitative evaluation for Sn efficiency.

We analyzed the vertical components of 344 waveforms produced by 22 shallow earthquakes with local magnitude greater than 4 and epicentral distances ranging from 325 to 1620 km. Earthquake locations and origin times are from the ING bulletin.

Analysis and Results

The spectral ratio approach was used to estimate the attenuation of Pn waves which propagate in the uppermost mantle (i.e., in the mantle lid of the lithosphere). The amplitude spectrum of the Pn phase is expressed as a function of frequency f and epicentral distance R,

$$A(f,R) = H(f) \cdot A_S(f,\vartheta) \cdot G(R) \exp\left(-\frac{\pi f R}{vQ}\right)$$

where $H(f)$ is the instrument transfer function, $A_S(f,\vartheta)$ is the source spectrum whose radiation pattern is dependent on azimuth ϑ, and $G(R)$ is a geometrical spreading function; v and Q are the average values of Pn wave velocity and quality factor, respectively, in the uppermost mantle. Q is assumed to be frequency-independent since we are dealing with a narrow frequency band.

Let us consider two stations (denoted by the subscripts i and j) aligned along a ray path. In this case the spectral ratio $R_{i,j}(f)$ of

[1]An electronic supplement of this material may be obtained on a diskette or Anonymous FTP from KOSMOS.AGU.ORG. (LOGIN to AGU's FTP account using ANONYMOUS as the username and GUEST as the password. Go to the right directory by typing CD APEND. Type LS to see what files are available. Type GET and the name of the file to get it. Finally, type EXIT to leave the system.) (Paper 94JB00000, Title of paper, by author(s)of paper). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009; $15.00. Payment must accompany order.

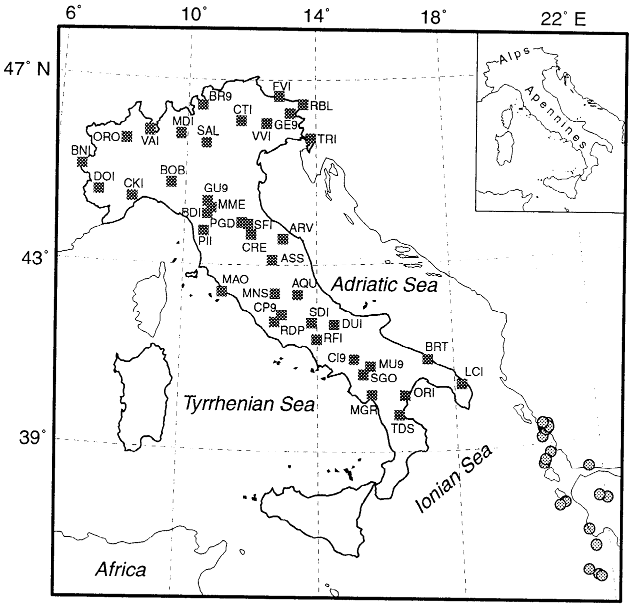

Figure 1. Map of Italy showing the seismic stations (squares) used to estimate Q. Circles indicate the epicenters of the earthquakes used in this study (see Table 1).

the Pn waves can be written as

$$\mathrm{R}_{i,j}(f) = \frac{A_i(f,R_i)}{A_j(f,R_j)} = \frac{H_i(f)}{H_j(f)} \cdot \frac{G(R_i)}{G(R_j)} \exp\left(-\frac{\pi f L_{i,j}}{vQ} \right) \quad (1)$$

where $L_{i,j}$ is the distance between the two stations. Uniform attenuation along the crustal paths beneath the two stations is implicitly assumed in (1). For this reason the quality factor Q estimated through (1) is usually called "apparent Q". The breakdown of this assumption has to be considered in interpreting our results.

In our case, all the station sites are equipped with the same type of receiver and the amplifier-modulator-demodulator chain differs among stations only by a frequency-independent amplification factor,

$$H_{i,j}(f) = C_{i,j} \cdot H_0(f) \qquad f_1 \le f \le f_2$$

where $C_{i,j}$ is the amplification factor at *i-th* or *j-th* station. The restriction $f_1 \le f \le f_2$ is motivated by the possibility of station-variable low- and high-pass filters outside of this band. Equation (1) is then simplified to

$$\mathrm{R}_{i,j}(f) = \frac{C_i}{C_j} \cdot \frac{G(R_i)}{G(R_j)} \exp\left(-\frac{\pi f L_{i,j}}{vQ} \right) \quad (2)$$

and, taking the logarithm of both sides of the equation, we obtain a linear relation between the amplitude ratios and frequency

$$\log \mathrm{R}_{i,j}(f) = a - bf \quad (3)$$

where $a = \log \dfrac{C_i G(R_i)}{C_j G(R_j)}$, and $b = \dfrac{\pi L_{i,j}}{vQ} \log e$.

Equation (3) allows us to estimate the apparent Q from the spectral ratios of Pn phases recorded at aligned stations. The slope b of a straight-line fit to the spectral ratios is related to Q

$$Q = \frac{\pi L_{i,j}}{vb} \log e. \quad (4)$$

Many of the unknown parameters of the initial equation (1) are cancelled by the ratioing operation, while others appear only in the intercept value a, which is not an essential term in estimating Q. Therefore, using this methodology the source properties, as well as the geometrical spreading of regional phases, are not required. As far as the instrument response is concerned, no correction is needed, provided that the only difference in station responses is a static gain factor in a sufficiently broad frequency band (f_1, f_2).

The analysis was performed in the frequency band 0.5 - 5 Hz which guarantees $H_0(f)$ to be the same for all stations. Amplitude spectra were computed from only the first 10 s of the Pn phase. This prevents contamination from the Pg phases into the Pn spectra. After windowing, the seismograms were tapered (5% of the total window length) and the spectra were calculated using a standard FFT technique. The analysis was restricted to stations whose signal-to-noise ratio was higher than 10 over the selected frequency band. The background noise was measured in a 10 s window before the Pn arrival. A mean value of 8.2 km/s was used for the uppermost mantle Pn velocity in calculating the Q values. Even though *Mele et al.* [1995] show that Pn velocity values in the study area range between 7.9 and 8.4 km/s, this variation would affect the estimated Q by about 5%, which is small compared to uncertainty of this parameter.

Instead of computing spectral ratios for all possible station pairs lying on the available ray-paths, we preferred to compute a reference spectrum for each earthquake and use it as the denominator in equation (1)

$$\mathrm{R}_n(f) = \frac{A_n(f,R_n)}{A_0(f,R_0)}. \quad (5)$$

In fact, depending on earthquake location, stations LCI, BRT, TDS, ORI and MGR (see Figure 1) tend to lie at epicentral distances not differing by more than few tens of kilometers. In general, we selected among the above mentioned stations those lying within ± 50 km from an average epicentral distance R_0. In (5) R_0 and $A_0(f,R_0)$ were computed as the average values

$$R_0 = \frac{\sum_{m=1}^{M} R_m}{M}, \qquad M \le 5 \quad (6)$$

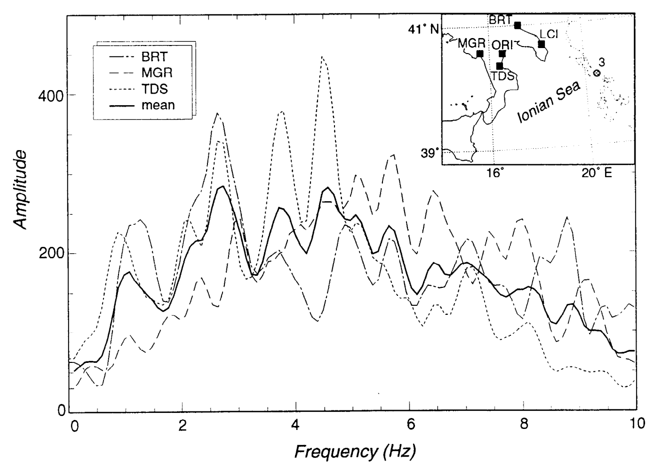

Figure 2. Example of computation of the reference Pn spectrum for event #3 of Table 1. Amplitude spectra from three stations are averaged to obtain the reference spectrum (solid line). Stations used in this study to calculate the reference spectra (squares) and the #3 earthquake location (circle) are shown in the upper corner.

and

$$A_0(f, R_0) = \frac{\sum_{m=1}^{M} A_m(f, R_m)}{M}, \qquad \left|R_m - R_0\right| \leq 50 \text{ km} \quad (7)$$

respectively. The subscript m was run over the reference stations lying within $R_0 \pm 50$ km (see Figure 2). In (5), the subscript n was run over all stations, excluding LCI, BRT, TDS, ORI and MGR. This procedure yielded one estimate of Q at each station for each of the 22 earthquakes in Table 1 (electronic supplement).

The reference spectrum was used, rather then all possible station pairs, in order to have a more stable spectrum in the denominator of (5) and to avoid problems arising from small distances between station pairs. Pairs of nearby stations would predict a very small slope in (3) so that spectral fluctuations for the different station response would mask the spectral decay when measured in a narrow frequency-band. Figure 3 shows an example of the application of (5) for one earthquake (event #3 in Table 1). Assuming that calculated values of Q^{-1} are normally distributed, the average value $\langle 1/Q \rangle$ and its standard deviation σ were computed for each station. To minimize effects of unreliable outliers, the average was recalculated excluding values exceeding $\pm\,\sigma$ from the mean. Listed in Table 2 (electronic supplement) are the inverse of the final mean value, percent errors, and an interval of statistical uncertainty I_Q computed from the final standard deviation. The lower and upper limits of I_Q are defined as the inverse of $\langle 1/Q \rangle + \sigma$ and $\langle 1/Q \rangle - \sigma$, respectively.

Figure 4 shows the pattern of the apparent Q in Italy as estimated through the inverse of $\langle 1/Q \rangle$. Only values averaged over at least 5 recordings were mapped. These values represent the average Q along the uppermost mantle path between each station site and the reference stations. Evidence for a spatial variation of Q emerges with a high statistical reliability, indicating that the uppermost mantle structure is not homogeneous in the study area.

Discussion

Regional seismic phase attenuation studies show that high Q characterizes regions of lower temperature and high-strength upper mantle materials, while low Q corresponds to higher temperature and low strength materials [e.g., *Kadinsky-Cade et al.,* 1981; *Barazangi and Ni,* 1982]. Accordingly, partial melting in the uppermost mantle is thought to be the main cause for attenuation in the mantle lid [e.g., *Brunn,* 1986]. Several estimates of the upper mantle Q indicate that values of the order of 1000 and higher are typical for efficient propagation paths within the lithosphere. In contrast, low Q values ($\approx$ 500 or less) characterize inefficient propagation paths [e.g., *Molnar and Oliver,* 1969; *Whitman et al.,* 1992].

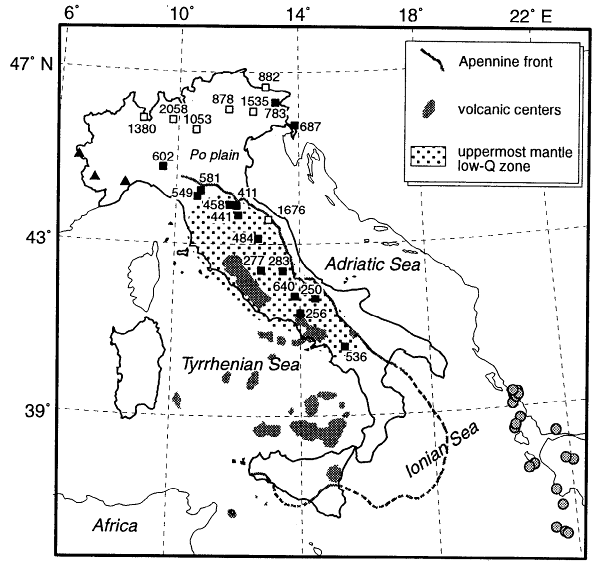

Figure 4. Map of Italy showing Pn apparent-Q values. Each value represents the average Q between reference stations (Fig. 2) and the station of interest. Open squares indicate high-Q stations, solid squares indicate low-Q stations; triangles indicate stations recording low signal-to-noise ratio Pn phases; circles indicate epicenter locations. A minimal extent of the low-Q zone in the uppermost mantle is indicated (dotted area).

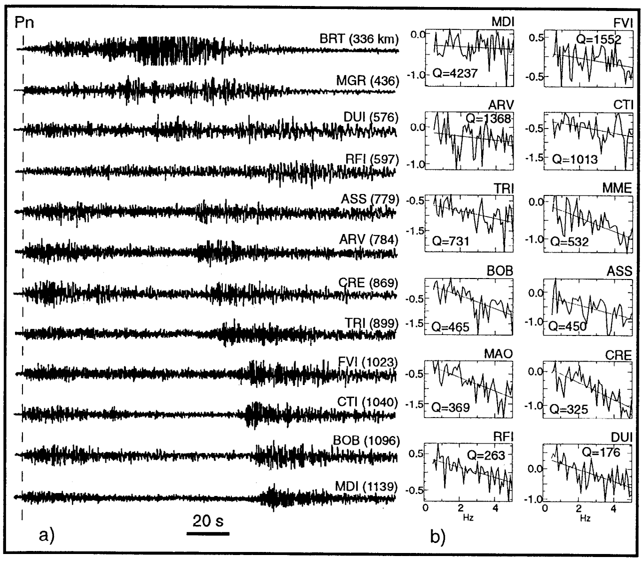

Figure 3. Examples of computation of Pn apparent-Q for event #3. Seismograms (a) and spectral ratios (b) are shown for most recording stations. Station codes and epicentral distances are indicated.

Figure 4 shows two subsets of Q values with spatial dependency. High apparent Q values, ranging from 850 to 2000, were estimated for propagation paths crossing the undeformed Adriatic lithosphere below the Po plain and the Adriatic basin, indicating that a high-strength mantle lid is present beneath these regions. This is observed at most of the stations located in northern Italy as well as station ARV (see Figs. 1 and 4). Significantly, lower apparent Q values (250 to 650) characterize the Apennine belt and western Italy. The low Q values are interpreted as due to a high attenuation zone in the uppermost mantle beneath the Apennines (dotted area in Fig. 4), probably due to partial melting below the Moho. Present-day extension in the Apennines, as well as volcanism and high heat flow in western Italy, may be related to this high-temperature uppermost mantle.

One of the assumptions made in writing equation (1) was that crustal attenuation is the same for all stations. Because this is not the case and high temperature materials are probably injected into the crust beneath some stations, local attenuation in the crust may affect the estimated uppermost mantle Q. Hence, lower apparent Q values can be observed locally. However, the poor signal-to-noise ratio we have found for Pn phases recorded in northwestern Italy (stations DOI, BNI and CKI in Figure 1) is a strong evidence that propagation paths crossing the Apennine uppermost mantle are attenuated. This is because the crust beneath northwestern Italy is very different (less attenuating) from the crust beneath the Tyrrhenian margin (more attenuating) [e.g., *Boriani et al.,* 1989].

In a recent study of Sn attenuation and Pn velocity, *Mele et al.* [1995] show that regional shear waves propagate neither beneath the Apennines nor along the Tyrrhenian side of the peninsula, and that low Pn velocities (about 7.9 km/s) are present in both regions. These findings are consistent with geodynamic models involving asthenospheric mantle at shallow depths, such as subduction and back-arc spreading [e.g., *Malinverno and Ryan,* 1986; *Patacca et al.,* 1990; *Mantovani,* 1996], mantle diapirism [*Locardi,* 1988] and post-orogenic lithosphere delamination [e.g., *Channell and Mareschal,* 1989].

The lateral variations of regional wave propagation in Italy have important implications for earthquake hazard. We find that high frequencies are strongly attenuated along paths crossing the central and western parts of the Italian peninsula. On the contrary, seismic energy is efficiently transmitted through the Adriatic lithosphere.

Conclusions

We find large lateral variations in the rheological properties of the uppermost mantle beneath Italy. The continental Adriatic lithosphere is characterized by high apparent Q values (850 to 2000) that are interpreted to indicate high-strength and low-temperature uppermost mantle material (mantle lid) below the Moho. In contrast, anomalously high seismic wave attenuation (Q ranging from 250 to 600) is found beneath the Apennines and the western part of the Italian peninsula, where extensional tectonic processes and volcanism have been active since late Miocene. Partial melting processes caused by decompression melting in extensional regime might be responsible for the high attenuation zone observed in the study area.

Acknowledgements. We are grateful to Enzo Boschi for encouraging this study. We thank Andrea Argnani, Paul Delaney and Robert Litak for a critical reading of the manuscript. Thanks are due to Thomas Hearn, Leonardo Seeber and an anonymous referee for their critical reviews and helpful suggestions. INSTOC contribution # 219.

References

Barazangi, M. and J. Ni, Velocities and propagation characteristics of Pn and Sn beneath the Himalayan arc and Tibetan plateau: possible evidence for understanding of Indian continental lithosphere beneath Tibet, *Geology, 10,* 179-195, 1982.

Barba, S., R. Di Giovambattista, G. Smriglio, Italian Seismic Databank allows on-line access, *EOS*, Transactions, Am. Geophys. Un., *76*, 9, 89, 1995.

Barberi, F., P. Gasparini, F. Innocenti and L. Villari, Volcanism of the Southern Tyrrhenian Sea and its geodynamic implications, *J.Geoph. Res., 78,* 5221-5232, 1973.

Boriani, A., M. Bonafede, G.B. Piccardo and G.B. Vai (Eds.), *The lithosphere in Italy: Advances in Earth Science Research*, 544 pp., Accademia Nazionale dei Lincei, Roma, 1989.

Brunn, J. H., The sublithospheric mantle, the generation of magmas and tectonics, *Revue de Geologie Dinamique et de Geographie Physique, 27,* 3-4, 149-161, 1986.

Channell, J.E.T., B. D'Argenio and F. Horvath, Adria, the African promontory in Mesozoic Mediterranean paleogeography, *Earth Sci. Rev., 15,* 213-292, 1979.

Channell, J.E.T. and J.C. Mareschal, Delamination and asymmetric lithospheric thickening in the development of the Tyrrhenian Rift, in *Alpine Tectonics,* edited by M.P. Coward, D. Dietrich and R.G. Park, pp. 285-302, Geol. Soc. London Spec. Publ. 45, 1989.

Del Pezzo, E., G. De Natale, G. Scarcella and A. Zollo, Q_c of three component seismograms of volcanic microearthquakes at Campi Flegrei volcanic area, *Pure Appl. Geophys., 123,* 5, 683-696, 1985.

Dewey, J.F., W.C. Pitman, W.B.F. Ryan and J. Bornin, Plate tectonics evolution of the Alpine system, *Geol. Soc. Am. Bull., 84,* 3137-3180, 1973.

Kadinsky-Cade, K., M. Barazangi, J. Oliver and B. Isacks, Lateral variations of high-frequency seismic wave propagation at regional distances across the Turkish and Iranian plateau, *J. Geophys. Res., 86,* 9377-9396, 1981.

Locardi, E., The origin of the Apenninic arcs, Tectonophysics, *146, 105-123,* 1988.

Lowrie, W. and W. Alvarez, Rotation of the Italian peninsula, *Nature, 251,* 285-288, 1974.

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

Mantovani, E.., D. Albarello, C. Tamburelli and D. Babbucci, Evolution of the Tyrrhenian basin and surrounding regions as a result of the Africa -Eurasia convergence, *J. Geodynamics, 21,* 1, 35-72, 1996.

Mayer-Rosa, D. and V. Schenk, TERESA; test regions for evaluation of algorithms for seismic hazard assessment in Europe, *Natural Hazards,* 2, 3-4, 215-407, 1989.

Mele, G., A. Rovelli, D. Seber, M. Barazangi and T. Hearn, High-frequency seismic wave propagation in the uppermost mantle beneath Italy (abstract), IUGG XXI General Assembly, Boulder (Colorado), July 2-14, *Vol. B*, 92, 1995.

Molnar, P. and J. Oliver, Lateral variations of attenuation in the upper mantle and discontinuities in the lithosphere, *J. Geophys. Res., 74,* 2648-2682, 1969.

Patacca , E., R. Sartori and P. Scandone, Tyrrhenian basin and Apenninic arcs: kinematic relations since late Tortonian times, *Mem. Soc. Geol. It., 45,* 425-451, 1990.

Rovelli, A., Time-frequency analysis of seismic excitation and estimates of attenuation parameters for the Friuli (Italy) local earthquakes, *Phys. of the Earth Int., 33,* 2, 94-110, 1983.

Whitman, D., B. Isacks, J.L. Chatelain, J.M. Chiu and A. Perez, Attenuation of high-frequency seismic waves beneath the Central Andean Plateau, *J. Geophys. Res., 97,* B13, 19929-19947, 1992.

G. Mele and A. Rovelli, Istituto Nazionale di Geofisica, Via di Vigna Murata, 605, 00143, Rome, Italy. (e-mail: meleg@ing817.ingrm.it)

D. Seber and M. Barazangi, Institute for the Study of the Continents and Department of Geological Sciences, Snee Hall, Cornell University, Ithaca, New York 14853-1504. (e-mail: seber@geology.cornell.edu)

(Received July 10, 1995; revised November 6, 1995; accepted December 4, 1995.)