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Rheological control of subcrustal seismicity in the Apennines subduction (Italy)

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[1] Different rheological behavior of continental vs oceanic lithosphere can account for the shallower and lower subcrustal seismicity below the northern Apennines with respect to the deeper and more intense seismicity below the Calabrian arc in the south along the same subduction zone. We show that, for equal temperature distribution, oceanic slabs are predicted to display brittle behavior down to depths higher than those predicted for a continental slab. This opposite rheology is likely amplified by the higher strain rates and cooler slab temperatures in the south due to the faster subduction rollback and the oceanic composition of the downgoing lithosphere. Therefore the paucity of seismicity in the central-northern Apennines might not be related to the absence of the slab, but rather to its continental nature and to lower strain rates. *INDEX TERMS:* 7230 Seismology: Seismicity and seismotectonics; 8160 Tectonophysics: Evolution of the Earth: Rheology—general; 8164 Tectonophysics: Evolution of the Earth: Stresses—crust and lithosphere; 5104 Physical Properties of Rock: Fracture and flow; *KEYWORDS:* Subduction, Apennines, Calabria, Seismicity, Rheology. **Citation:** Carminati, E., F. Giardina, and C. Doglioni, Rheological control of subcrustal seismicity in the Apennines subduction (Italy), *Geophys. Res. Lett.*, *29*(18), 1882, doi:10.1029/2001GL014084, 2002.

1. Introduction

[2] The Tertiary evolution of the central Mediterranean area (Tyrrhenian-Apennines system, Figure 1) is controlled by the eastward southeastward roll back of the hinge of a west directed subduction [*Malinverno and Ryan*, 1986; *Gueguen et al.*, 1998]. The subcrustal seismicity of the area displays a puzzling pattern (Figures 2a and 3a). A well developed Benioff plane can be recognized below the Calabrian arc down to depths of 500 km, whereas subcrustal seismicity reaches maximum depths of about 90 km in the Northern-Central Apennines [*Amato et al.*, 1997].

[3] This feature, together with images from tomographic studies (not confirmed by other studies, e.g., [*Piromallo and Morelli*, 1998; *Lucente et al.*, 1999]) showing no continuous high velocity bodies underneath the Apennines, has been interpreted by some researchers [*Wortel and Spakman*, 1992] as the evidence of detachment of the Apenninic slab. According to this view the Apenninic slab is expected to be inactive whether the Ionian lithosphere subducting underneath Calabria is considered to be on the verge of detaching or just detached. Other researchers (e.g., [*Gueguen et al.*, 1998]), however, suggest that a fairly continuous and still fastly retreating slab exists underneath the Apennines and the Calabrian arc. The existence of a lateral interruption (slab window) of the subducting slab beneath the southern Apennines, and the existence of two main arcs of subduction (norther Apenninic and Calabrian arcs) has been suggested by interpretation of the tomography of *Lucente et al.* [1999]. This view is not supported by a new tomographic model [*De Gori et al.*, 2001] which show the existence of a slab beneath the southern Apennines, favouring the continuous slab model. Both continuous and slab window scenarios, however, imply the existence, beneath the northern Apennines of a slab, in appearent contrast with subcrustal seismicity.

[4] The Apennines-Calabrian accretionary prism is primarily composed by sediments offscraped from the subducting slab. The paleogeographic reconstruction of their depositional environments permits to individuate the nature of subducted lithosphere [*Catalano et al.*, 2001]. It is inferred that, after a period of oceanic lithosphere subduction, about 200 km of continental lithosphere were subducted underneath the northern Apennines since about 25 Ma, whereas more than 500 km of Mesozoic oceanic lithosphere have been subducted underneath the Calabrian arc [*Gueguen et al.*, 1998], in agreement with analyses of magmatism [*Serri et al.*, 1993]. In this work we investigate whether differences in the rheological behavior, induced by the subduction of different types of lithosphere, can explain the above mentioned differences in the subcrustal seismicity, reconciling seismic data with the existence of undetached slabs underneath the northern Apennines and the Calabrian arc.

2. The Method

[5] Subcrustal seismicity within subducting slabs is likely to be accommodated by rupture within the brittle field down to at least 200–300 km. Deep focus earthquakes (>300 km) have been interpreted as being caused by phase transitions (from olivine to spinel) and are expected to exist in fast subducting slabs, where metastable olivine wedges can possibly occur [*Green and Burnley*, 1989]. In this work we concentrate on intermediate-depth earthquakes (50–300 km) since in that depth range a rheological control on seismicity is likely to occur. Seismicity differences at deeper depths could possibly be due to the lack of a metastable olivine wedge within the less fast (ca 1 cm/yr; the velocity is inferred from migration of the foredeep depocenters and from the amount and rates of backarc extension in the Tyrrhenian sea) subducting Apenninic slab and to the presence of such a wedge within the faster (ca 2 cm/yr) and presumably colder Ionian slab. A quantitative evalua-

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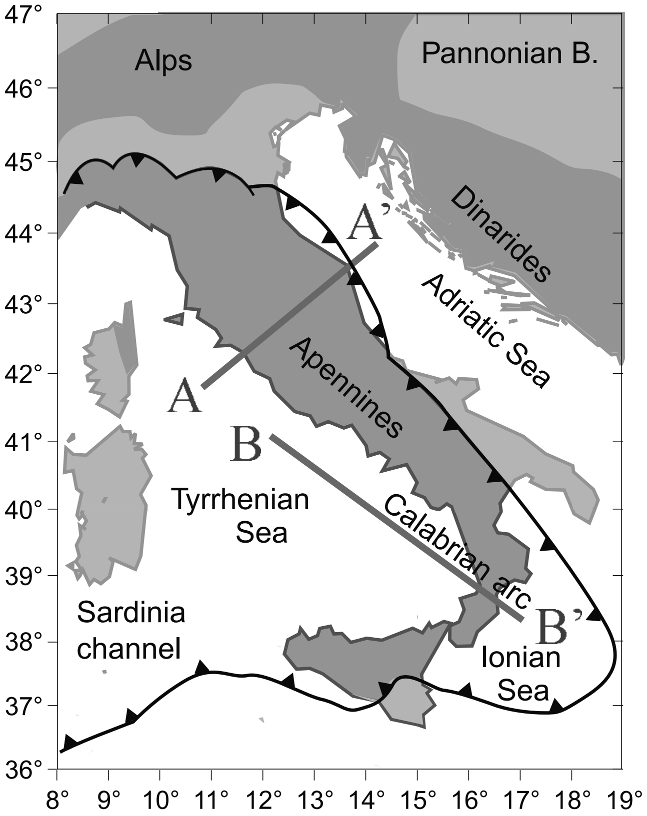

Figure 1. Sketch map of the central mediterranean area. The Apenninic subduction hinge is represented. Continental and oceanic subductions are expected to occur along sections A–A′ and B–B′ respectively.

tion of such an interpretation is however beyond the scope of this paper.

[6] Since no data on the temperature distribution within subducting slabs are available, we rely on temperature reconstructions obtained with numerical models. In order to focus solely on the effects of rheology on the earthquake distribution we decide to adopt the same temperature distribution for northern Apenninic and Calabrian slabs. We utilize the temperature distribution (Figures 2b and 3b) calculated with a finite difference model by *Ranalli et al.* [2000] for the northern Apenninic slab and produce a grid within the slab assigning to the grid nodes temperature values. For each grid point we calculate brittle and ductile yield stresses and reconstruct the spatial extension of brittle and ductile portions of the slab. Results obtained utilizing rheological parameters adequate for subducting continental and oceanic materials should reasonably describe the rheological behaviour of the northern Apennines (e.g., section A–A′ in Figure 1) and of the Ionian (e.g., section B–B′ in Figure 1) slabs respectively. The assumed slab thickness (about 60–70 km) is reasonable for both the thinned Adriatic continental lithosphere and for the Ionian oceanic lithosphere [*Calcagnile and Panza*, 1981].

[7] We use the Sibson's law for the brittle behaviour at depths shallower than 10 km. The β parameter is assumed as 3 (compressional earthquakes predominates at shallow depth within slabs), the density ρ = 2700 kg/m^3 (adequate for shallow crustal rocks), and an hydrostatic fluid pressure λ = 0.4, consistently with recentmost analysis of in-situ stress measurements. At depths higher than 10 km the brittle resistance to failure is likely not to follow Sibson's law. As a consequence brittle $\sigma_1 - \sigma_3$ is kept constant and equal to that calculated with the Sibson's law at 10 Km depth. A sensitivity analysis (not shown) on the Sibson's law parameters suggests that their influence on results is not strong, since they affect only the first 10 km of the model. For the ductile behavior we adopt the power law creep relation [*Carter and Tsenn*, 1987], which is mostly governed by temperature, strain rate and rheological parameters depending from the rock type. Since the strain rate largely affects the results we vary this parameter between 10^{-13} and 10^{-15} s^{-1}.

3. Rheology of Continental and Oceanic Subducting Slabs

[8] The choice of rhological parameters for a subducting slab clearly depends on its nature (continental or oceanic),

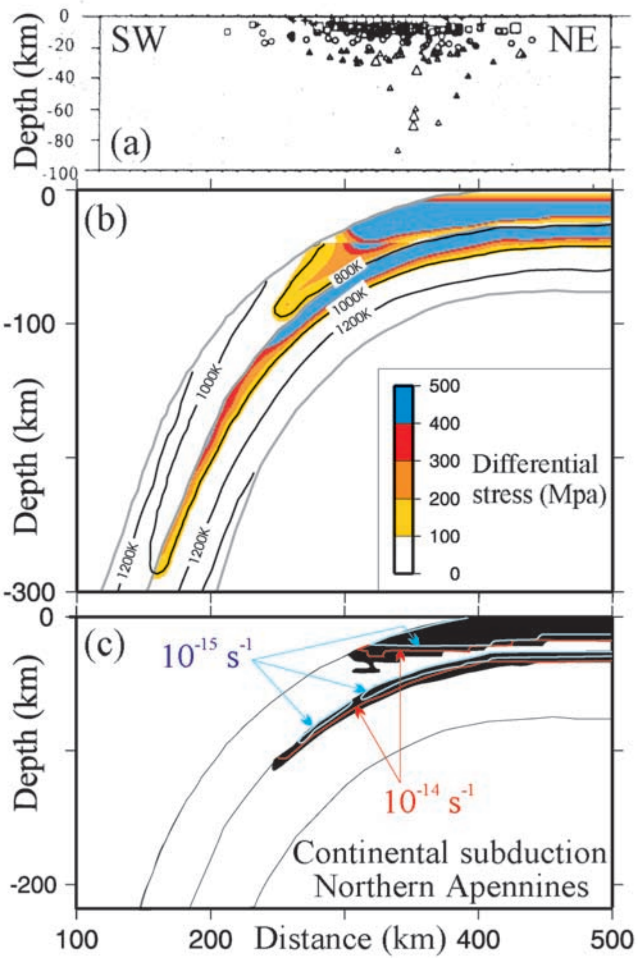

Figure 2. (a) Seismicity along section A–A′ of Figure 1, modified after *Amato and Selvaggi* [1991] (b) Yield stress calculated with a continental lithosphere rheology assuming a strain rate of 10^{-13} s^{-1} and utilized temperature distribution (K); (c) The black area represent portions of the slab where brittle behaviour is predicted assuming a strain rate of 10^{-13} s^{-1}. The red and light blue lines bound brittle areas obtained for strain rates of 10^{-14} and 10^{-15} s^{-1} respectively.

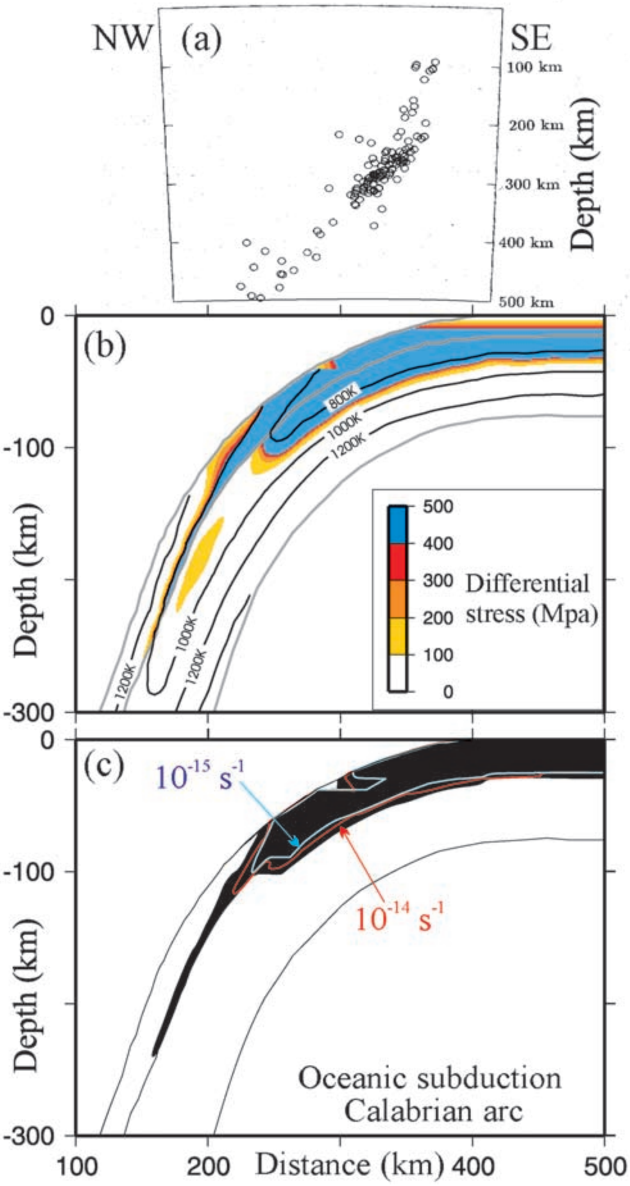

Figure 3. (a) Seismicity along section B–B′ of Figure 1, modified after *Giardini and Velonà* [1991] (b) Yield stress calculated with an oceanic lithosphere rheology assuming a strain rate of 10^{-13} s^{-1} and utilized temperature distribution (K); (c) The black area represent portions of the slab where brittle behaviour is predicted assuming a strain rate of 10^{-13} s^{-1}. The red and light blue lines bound brittle areas obtained for strain rates of 10^{-14} and 10^{-15} s^{-1} respectively.

on the slab portion which is considered (crust or lithospheric mantle) and on the P–T conditions of the slab portion, since metamorphic reactions (HP–LT metamorphism) and phase transitions are expected to occur within the crustal and mantle portions of the slab at depth.

[9] Considering the Ionian slab, the crustal portion of the slab is assumed to be 10 km thick and composed, at depths shallower than 40 km, by diabase. For diabase we utilize the following rheological parameters: A = 2.0 × 10^{-4} MPa^{-n} s^{-1}, n = 3.4, Q = 260 kJ mol^{-1} [*Ranalli*, 1997]. At depths >40 km the crust is assumed to be eclogitized. Following *Ji and Zhao* [1994], we assume the eclogite to have 60% clinopyroxene and 40% garnet mineralogical composition and use the rheological parameters obtained by these authors: A = 2430 MPa^{-n} s^{-1}, n = 2.6, Q = 449 kJ mol^{-1}. The eclogitic composition is expected to be stable down to depths of 400 km, well within the depth range of interest for this study. The depth at which metamorphic reactions are expected to occur is mainly function of P–T conditions, of composition and of deformation kinetics which affects reaction kinetics. The 40 km eclogitization depth is a reasonable estimate but variations are expected to occur. It should be however noticed that the results are very poorly affected by this parameter, as verified by calculation results not shown. The oceanic mantle is assumed to be composed of harzburgite and the following parameters are assumed: A = 1010 MPa^{-n} s^{-1}, n = 2.4, Q = 367 kJ mol^{-1} [*Ji and Zhao*, 1994]. Olivine–Spinel (β-phase) phase transitions are expected to occur within the lithospheric mantle at depths of about 400 km and are therefore not considered in this study.

[10] The Adriatic continental slab is composed by a ca 20 km thick crust and by an dunitic mantle. At shallow depths the crust is assumed to be composed of quartzdiorite. Rheological parameters for such a material are assumed to be: A = 0.0013 MPa^{-n} s^{-1}, n = 2.4, Q = 219 kJ mol^{-1} [*Ranalli*, 1997]. At depths >40 km, HP–LT metamorphism is expected to occur within crustal portions of subducting continental slabs. As an example the Sesia–Lanzo zone is mainly composed of cristalline rocks of continental crustal origin metamorphosed in eclogitic facies conditions [*Koons et al.*, 1987]. At least three mineralogical assemblages are found in the metaquartzdiorites of the Sesia–Lanzo zone: 1) 40% quartz, 40% omphacite and 20% accessories 2) 40% quartz, 40% zoisite and 20% accessories; 3) 40% quartz, 20% omphacite, 20% zoisite and 20% accessories. The first assemblege is slightly prevalent. For this reason we assume that the rheological behaviour is controlled by quartz and clinopyroxene. Volume percentages are assumed to be 50% each, i.e., minor minerals were at a first approximation neglected. We adopt the method of *Tullis et al.* [1991] to calculate the rheological parameters of multiphase rocks using experimental data (taken from *Ji and Zhao* [1994]) on the constituent phases and obtain: A = 0.00017 MPa^{-n} s^{-1}, n = 3.25, Q = 248 kJ mol^{-1}. These parameters are used for the continental crust at depths >40 km. For the dunitic continental lithospheric mantle we assume the following parameters: A = 2000 MPa^{-n} s^{-1}, n = 4, Q = 471 kJ mol^{-1} [*Ranalli*, 1997].

4. Modeling Results

[11] Figures 2b and 3b show the maximum differential stress (in MPa) which can be supported by rocks belonging to the continental and oceanic slabs respectively. Figures 2c and 3c show, in black, areas where brittle behavior is expected to occur, i.e. areas where earthquakes can possibly occur, when calculations were performed for strain rates of 10^{-13} s^{-1}. If slower strain rates (e.g., 10^{-14} and 10^{-15} s^{-1}) are assumed, the brittle area reduces, as shown by red and light blue lines.

[12] From Figures 2b and 3b it is clear that largest differential stresses are predicted to be about 500 MPa within the brittle field. The magnitude of maximum differential stress is controlled by the maximum depth at which the Sibson's law is considered to be valid. An increase of this depth would drive to higher maximum stresses.

[13] Figures 2c and 3c show that, for equal temperature distribution and strain rate values, the extension of the brittle field within oceanic slabs is expected to be larger than that within continental slabs. For a strain rate of 10^{-13} s^{-1} the brittle (and theoretically seismogenic) area reaches depths of ca 250 km and ca 110 km in oceanic and continental slabs respectively. This is in good agreement with the seismological observations of a shallower seismicity beneath the Northern Apennines with respect to Calabria.

[14] The same temperature distribution (originally calculated for the northern Apennines subduction) was utilized in the calculations of both Figures 2c and 3c. However, the higher subduction velocities and the absence of relevant radiogenic heat production within the oceanic Ionian slab should induce slightly lower temperatures, increasing the extension of the brittle areas within the oceanic slab, with a better agreement with seismological observations. This effect may also be enhanced by the faster subduction underneath Calabria which should determine higher strain rates, increasing even more the rheological differences.

5. Conclusions

[15] The low seismicity or aseismic behavior of orogenic roots or slabs may in some cases be ascribed to a ductile deformation of quartz-feldspar rich subducting continental lithosphere rather than to the absence of active subduction. Lower subduction rates, higher radiogenic heat production of continental crust would further enhance ductile behavior. The Apennines belt formed on top of a subduction involving an articulated Mesozoic paleogeography. The variable composition and thickness of the foreland lithosphere such as the Ionian ocean and the western passive continental margin of the Adriatic plate can explain most of the variations of the geophysical signatures of the Apennines subduction zone.

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