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Normal faulting, transcrustal permeability and seismogenesis in the Apennines (Italy)

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Abstract

Late Pliocene–Pleistocene tectonic evolution of the Apennines is driven by progressive eastward migration of extensional downfaulting superposed onto the Late Miocene–Early Pliocene compressional thrust belt. This process has led to distinct structural domains that show decreasing transcrustal permeability from conditions of pervasive mixing between deep and surface fluids in the hinterland (west) to conditions of restricted fluid circulation and overpressuring in the foreland (east). At present, the highest rates of normal faulting and the strongest seismicity occur in the area bounded by stretched, highly permeable crust to the west and thick, poorly permeable crust to the east. In this area, the seismogenic sources of the largest earthquakes ($5 < M_s < 7$) are potentially related to mature normal faults that deeply penetrate thick brittle upper crust, and act as transient high-permeability channels during seismic activity. In this framework, it is plausible that domains of overpressuring govern progressive inception of normal faulting and fluid redistribution in the crust, leading to eastward migration of the belt of maximum seismicity with time.

Keywords: Apennines; Normal faults; Fluids; Permeability; Seismicity

1. Introduction

Thinning of orogenic crust, magmatism, and seismogenic normal faulting are all evidence for post-collisional extensional collapse of the Apenninic thrust belt. Different mechanisms may drive this extension (e.g. plastic-rigid extrusion, passive retreat of a subducted slab, gravitational collapse) and alternative interpretations have been accordingly advanced by different authors (e.g. Malinverno and Ryan, 1986; Locardi, 1988; Channell and Mareschal, 1989; Boccaletti et al., 1997; Faccenna et al., 1997; Barchi et al., 1998; Liotta et al., 1998). Whatever the mechanism, tectonic processes operating during the last 7 Ma have led to a structural setting within the inner, western margin of the Apenninic thrust belt (Tyrrhenian basin and peri-Tyrrhenian domain) that differs strongly from the setting of the outer, eastern margin (Adriatic–Jonian foredeep and foreland). Major differences are (Fig. 1): the lithospheric thickness, the complex Pleistocene and Holocene magmatic activity of the Tyrrhenian region (Savelli, 1988) and the change in orientation of the stress field from the extensional inner domain to the compressional outer domain (Ghisetti

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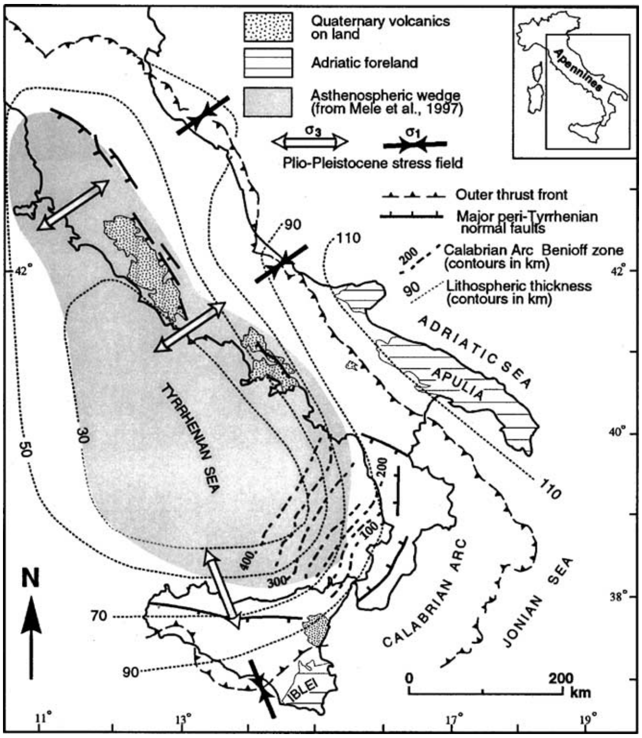

Fig. 1. Large-scale tectonic setting of the Apenninic thrust belt in relation with the inner stretched domains of the Tyrrhenian foundered basin.

and Vezzani, 1981; Amato and Montone, 1997; Frepoli and Amato, 1997). Eastward migration of magmatism and extension, accompanied by progressive collapse of the thrust belt since Late Miocene times, indicate the progressive "Tyrrhenization" of the Apennines up to the Holocene and present times.

The highest seismicity of the Apennines occurs within a belt of elevated regions close to the orographic divide (Fig. 2), i.e. areas that are in a state of critical equilibrium relative to the collapsed and foundered peri-Tyrrhenian margin. In fact, this belt coincides with sharp gradients in the Bouguer gravity anomaly (Carrozzo et al., 1991) in between the positive ($<+250$ mgals) Tyrrhenian area and the negative (>-80 mgals) Adriatic foredeep.

Within this domain, up to 1000-km long and 70–100-km wide, neotectonic and seismic information indicate that many normal faults are capable of seismic reactivation with $5<M_s<7$ earthquakes (Ambrosetti et al., 1987; Boschi et al., 1997). At particular localities, recurrence intervals of the order of 1 ka have been derived from paleoseismological studies (e.g. Vittori et al., 1991; Pantosti et al., 1993, 1996; Giraudi and Frezzotti, 1995) but the number of seismic cycles that each single fault may have undergone over time intervals longer than 15–20 ka is unconstrained.

Long-term geological deformations averaged over time intervals >3 Ma indicate that the largest active normal faults (e.g. Ghisetti, 1992; Westaway, 1992; Vezzani et al., 1997) have all comparable offsets (on average 2 km) and slip rates (on average 1 mm/year) but their ages decrease from west to east. This raises the question as to whether eastward advancement of the extensional front, accompanied by growth of newly generated normal faults, results, over geological times, in the progressive demise of activity of the earlier normal faults, which were left behind in crustal domains undergoing thinning and magmatism.

This paper investigates the role of heterogeneously distributed permeability and fluid pressure in controlling the foreland advance of seismicity during post collisional extensional collapse of an orogen. The analysis relates the structural architecture of

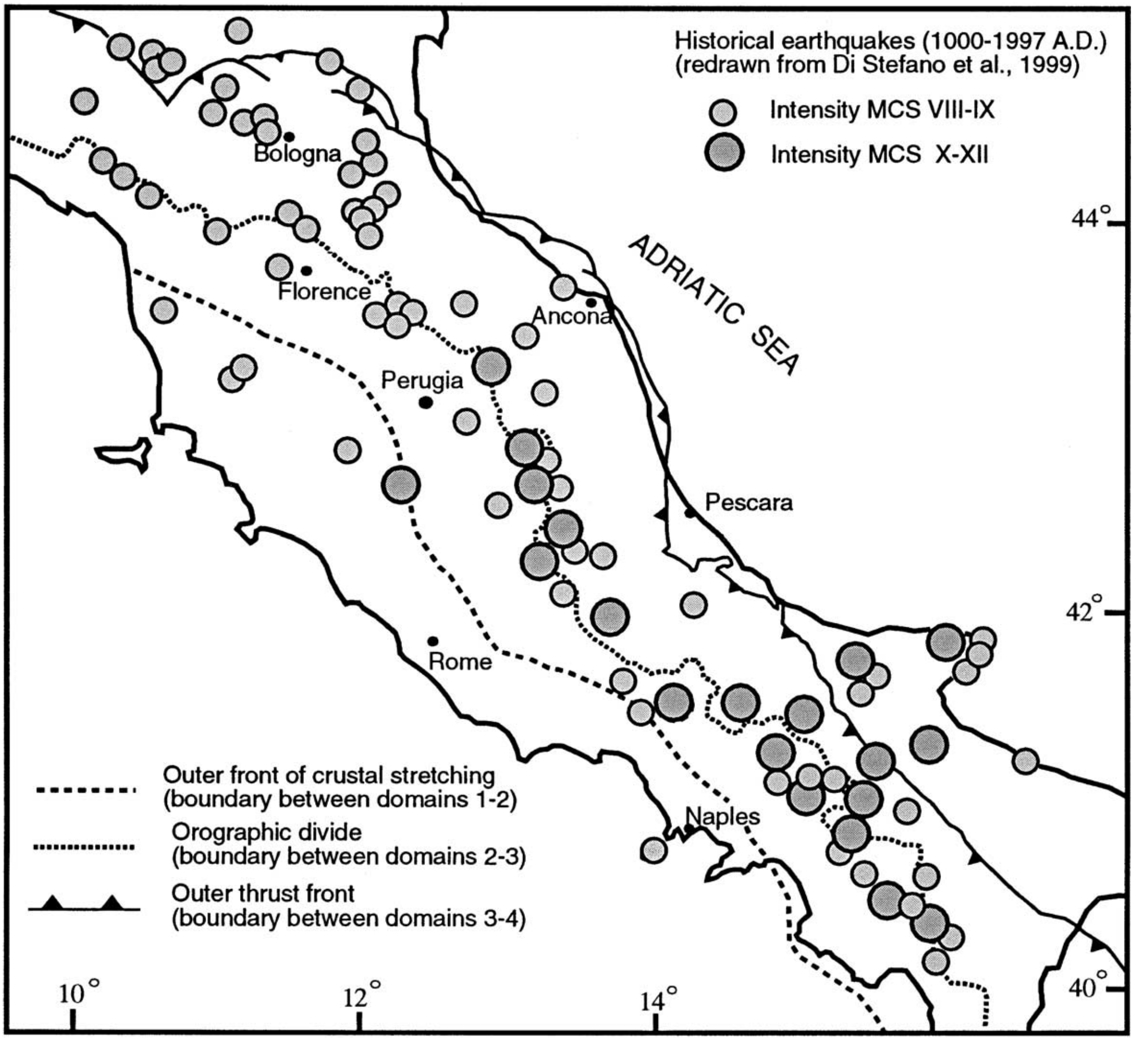

Fig. 2. Distribution of historical earthquakes that shows localization of the strongest shocks along the high elevation belt in between the foundered Tyrrhenian basin and the Adriatic foredeep. Intensity is expressed in the Mercalli Cancani Sieberg scale (MCS) (see Di Stefano et al., 1999).

seismically active normal faults in the central Apennines (Ghisetti and Vezzani, 1997, 1999, 2000) to newly acquired geochemical data for the central and southern Apennines (Chiodini et al., 2000; Ghisetti et al., 2000, 2001; Italiano et al., 2000). We suggest that normal faulting within the Apennines is a process that leads to increasing vertical permeability, connectivity and fluid mixing in progressively larger and interconnected sectors of the stretched crust, with relevant consequences on timing and style of seismic activity.

2. Geological background

Significant along-strike variations in the amount of Late Miocene–Early Pliocene shortening of the Apennines can be correlated to differential buoyancy of the subducted crust, transitional from oceanic (Jonian margin) to continental (Adriatic margin). Subduction of a residual Jonian oceanic slab is still occurring in the Calabrian arc (Fig. 1), where an active Benioff zone, dipping 70–50° west, can be traced to depths of nearly 500 km (Selvaggi and Chiarabba, 1995). In contrast, the collisional margin that involves thick Adriatic continental crust is poorly defined. Subcrustal seismicity down to 100 km and a high velocity zone in the mantle down to 250 km are suggestive of a west-dipping slab only in the region north of the 42° parallel (Selvaggi and Amato, 1992). At the rear of the collisional margin extension is heterogeneous as well. Lithospheric stretching increases south of the 42° parallel (Fig. 1), where the Tyrrhenian Moho is 10-km deep and heat flow reaches 150–200 mW/m^2. The southward increase of shortening and extension has been related to differential rollback of the segmented Adriatic–Jonian slab (Malinverno and Ryan, 1986; Royden et al., 1987), driving the ascent of an asthenospheric wedge (Fig. 1) into the thinned lithosphere of the back-arc regions (Mele et al., 1997).

A full account of the tectonic processes in the Apennines requires a three dimensional approach but large-scale similarities exist that make it possible to draw continuous boundaries between domains that differ in lithospheric thickness and in timing of normal faulting relative to thrusting.

From west to east, the four domains are (Fig. 3): (1) Peri-Tyrrhenian foundered thrust belt; (2) Inner thrust belt; (3) Outer thrust belt; (4) Adriatic–Bradanic foredeep and Apulia foreland. The surface boundaries between these domains correspond, respectively, with: (i) the outer front of crustal stretching; (ii) the oro-

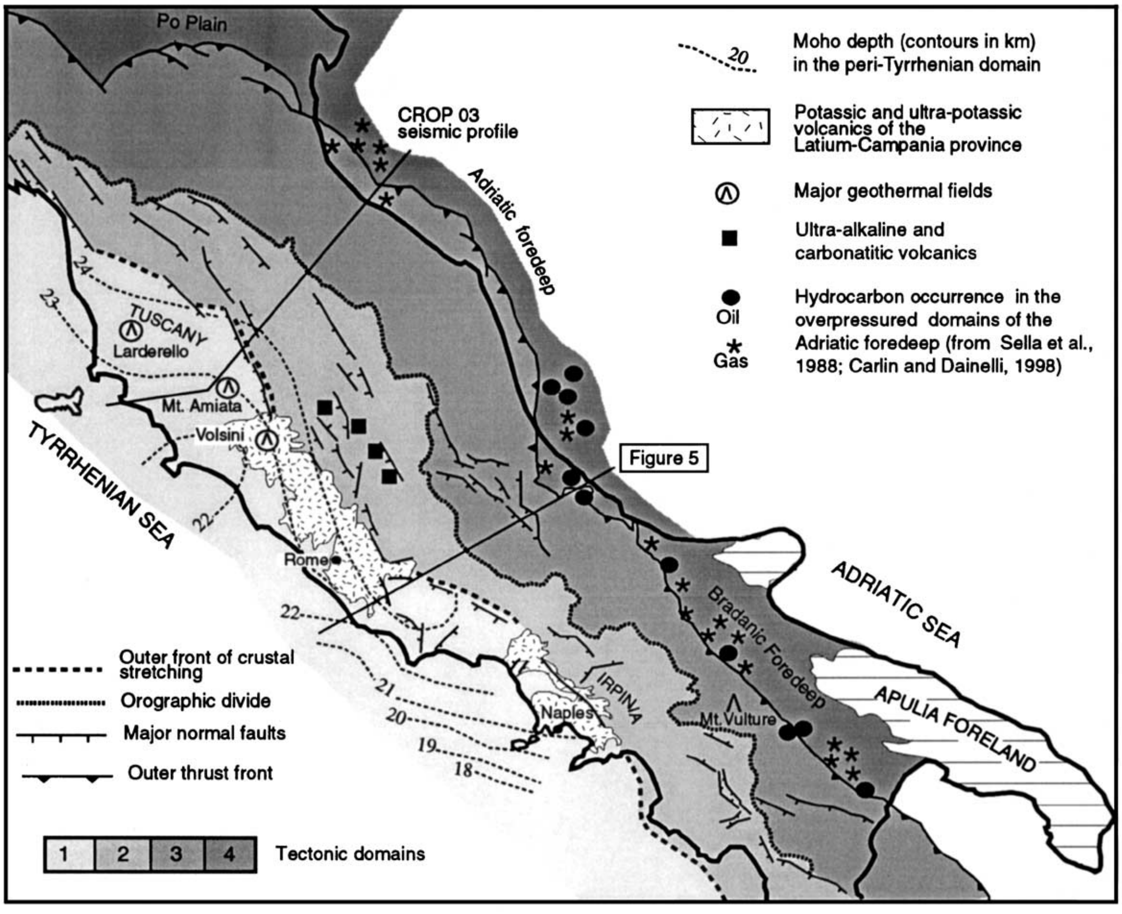

Fig. 3. Crustal and structural characters of the major tectonic domains in the central and southern Apennines. (1) Peri-Tyrrhenian domain; (2) Inner thrust belt; (3) Outer thrust belt; (4) Adriatic foredeep.

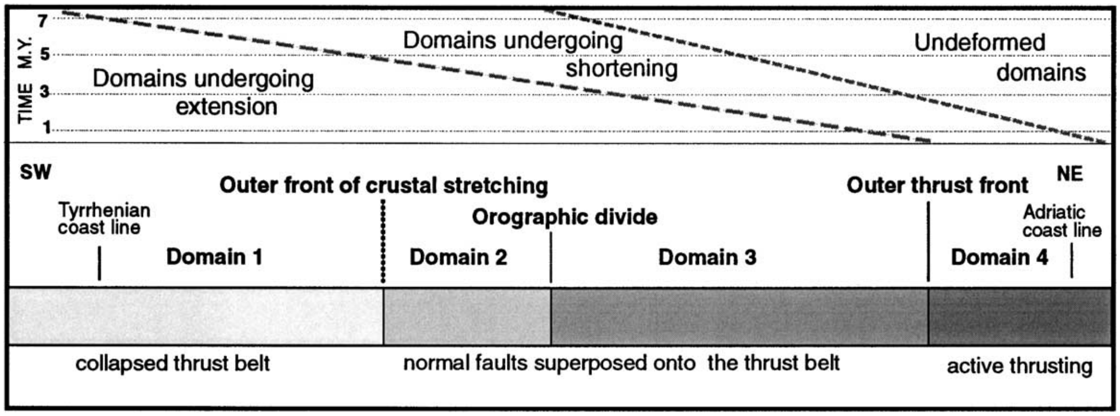

Fig. 4. Migration of extension and compression since 7 Ma from the innermost (1) to the outermost (4) tectonic domains of the central-southern Apennines.

graphic divide, and, (iii) the outer thrust front. For each domain, rates of progressive eastward migration of shortening are calibrated by the age of siliciclastic deposits in the foredeep and in thrust-top basins (Cipollari and Cosentino, 1995; Ghisetti and Vezzani, 1998). Inception and rates of extensional failure are calibrated by the ages of the continental to marine basins bounded by normal faults and superposed onto the thrust belt (Martini and Sagri, 1993; Cavinato and De Celles, 1999; Ghisetti and Vezzani, 1999). The comparison indicates that since 7 Ma, the extensional front propagated behind the compressional front and advanced to the east at a comparable rate of 4 cm/year (Fig. 4). Therefore, the present structural activity of the different domains (Figs. 3 and 4) is largely dependent on the time of inception of normal faulting. In fact, where normal faulting dates back to Late Miocene–Early Pliocene times (domain 1), the thrust belt is almost completely obliterated, whereas in the domain not yet reached by the extensional mechanisms (domain 4), shortening and thrusting are still active.

3. Tectonic differences between adjacent domains

A large number of geological and geophysical data provides consistent information for differentiating the structural and seismic styles of the domains of Fig. 3. These data are summarized in Tables 1 and 2.

The following discussion focuses on the trans-crustal permeability of these domains as inferred from structural analyses of the normal faults and circulation of deep and surficial fluids. Relevant data are summarized in Fig. 3.

3.1. Peri-Tyrrhenian domain

This domain is dissected by systems of NW–SE oriented, west-dipping normal faults that eventually merge with low-angle, NW–SE oriented, east-dipping normal faults in the Tyrrhenian offshore (Barchi et al., 1998; Jolivet et al., 1998). Inland, differential sinking of asymmetric grabens bounded by W-dipping normal faults has controlled the location and evolution of

Table 1
Structural features of the different tectonic domains of Fig. 3

	Domain 1	Domain 2	Domain 3	Domain 4
Crustal thickness (km)	20/25	25/30	30/40	25/30
Lithospheric thickness (km)	30/50	50/70	70/90	90/110
Heat flow (mW/m^2)	110/>20	80/110	40/70	40/90
Bouguer anomaly (mgals)	25/50	25/0	− 5/ − 40	− 40/ − 70
Beginning of extension (Ma)	7	5	3	No extension
Resources	Mineralization, geothermics			Oil, gas

Table 2
Seismic characteristics of the different tectonic domains of Fig. 3

	Domain 1	Domain 2	Domain 3	Domain 4
Maximum magnitude (M_s)	5	5–6	6–7	4–5
Earthquake focal mechanisms	Normal	Normal	Normal, strike-slip	Thrust, strike-slip
Extensional deformation rate (mm/year)	< 1	2	2/3	
Depth of seismicity (km)	< 10	10–30	10–100	20–25

marine to continental sedimentary basins since Late Miocene times (Martini and Sagri, 1993). In Tuscany, seismic reflection data show that normal faults root along a continuous horizon 3–6 km deep that has been correlated to a strongly fractured, fluid-saturated detachment (Liotta et al., 1998).

The peri-Tyrrhenian margin is affected by potassic and ultra-potassic magmatism 5.1–0.6 Ma old (Serri et al., 1993). Extensional downfaulting and crustal thinning precede asthenospheric upwelling and associated magma ascent of 1–2 Ma. The strong influence of these processes on fluid circulation is testified by the presence of geothermal areas, hot thermal springs with travertines and large-scale CO_2 degassing (up to $1-3 \times 10^{11}$ mol year^{-1} in Chiodini et al., 2000). According to Gianelli (1985) and Chiodini et al. (2000), CO_2 derived from both mantle sources and metamorphic reaction of carbonates is directly released at surface or is dissolved in groundwaters. Fluid inclusions and C and O isotopes from quartz and calcite veins (Gianelli et al., 1997; Ruggieri et al., 1999) and from travertines (Manfra et al., 1976) are compatible with two different fluid systems: a meteoric–hydrothermal system at surface and a juvenile-metamorphic system at depth. Circulation and mixing of these fluids in reservoirs down to depths of 2500 m is recognised in the geothermal areas and appears to be strongly controlled by fluctuations (in space and time) of pore pressure, from lithostatic to hydrostatic (Minissale, 1991).

The presence of extensive mineralization (Sb + Ba+/ – As, Ag, Zn, Pb, Au) that is mostly aligned with NW–SE oriented faults in the periphery of the geothermal fields (Lattanzi, 1999) is well explained by the tectonic features of this sector. Mineral deposits are generally associated with normal faults, travertines, gas discharges and thermal springs and probably result from hydrothermal fluid circulation from magmatic bodies emplaced at shallow depths (Lattanzi, 1999).

3.2. Inner thrust belt

In this domain, the Miocene–Pliocene thrust belt is dissected by prevailing NNW–SSE oriented normal faults dipping 50–70° west and east (Fig. 3), which bound Plio-Quaternary basins infilled by continental lacustrine sequences. Other major normal faults in this domain have E–W orientation and dip north and south at high angle. According to some authors (e.g. Lavecchia et al., 1994), crustal stretching and seismogenesis of this region are controlled by east-dipping listric normal faults onto which the W-dipping normal faults detach at depths of 7–10 km. Seismic resolution of this geometry is poor and alternative interpretations (e.g. Ghisetti et al., 1993) suggest detachment of normal faults at the intersection with earlier, low-angle west-dipping thrust faults that are eventually reactivated in the present-day stress field.

A peculiar and intriguing feature of this domain is the occurrence (Fig. 3) of small volcanic edifices younger than 0.6 Ma, where carbonate-rich pyroclastics are associated with ultra-alkaline rocks (Stoppa and Woolley, 1997; Peccerillo, 1998). Contrasting interpretations of these carbonate-rich rocks within processes of rifting (Stoppa and Lavecchia, 1992) or subduction (Peccerillo, 1998) have been proposed. The implication is a substantially different genesis of the carbonatites either from (i) original magmas or (ii) from the interaction between ultrapotassic magmas and sedimentary carbonates. In the second case, production of carbonate melts and related CO_2 emissions are expected to be associated with fluid tapping, overpressuring and mineralization in intrusion-related skarn systems (e.g. Lentz, 1999).

In this domain, CO_2 degassing is not as intense as in domain 1 but in the southern Apennines, large CO_2 discharges (up to 20–50 m^3/s) are known in the Irpinia region (Doglioni et al., 1996). At these localities, degassing of large quantities of helium of possible mantle origin or from magmatic bodies has been recently reported (Italiano et al., 2000). The presence of melts intruded into normal faults at depths of 10–8 km (Italiano et al., 2000) is in agreement with geophysical data (Mele et al., 1997) that depict partial melting of lower crust and lithosphere delaminated above the Tyrrhenian asthenospheric wedge (Fig. 1). These processes are compatible with crustal contamination of magmatic sources along the Jonian–Adriatic collision zone and generation of a wide spectrum of melts that have eventually reached the surface along high-permeability conduits provided by normal faults.

3.3. Outer thrust belt

The Late Pliocene–Pleistocene normal faults of this domain are arranged in spaced systems that separate large panels of preserved thrust units. The faults dip >60° at surface, bound large intramontane basins infilled with Early–Late Pleistocene lacustrine deposits, and merge into and reactivate earlier thrust surfaces at depths of 3–7 km (Vezzani et al., 1997). Active faults display normal mechanisms but some evidence exists for strike-slip faulting during Early–Middle Pliocene times, possibly connected with fault reactivation during progressive shifting from the compressional to the extensional stress field (Ghisetti and Vezzani, 2000). Present-day seismically active strike-slip faulting is not frequent and concentrated at the eastern boundary of this domain, close to the region undergoing active shortening (Table 2).

Structural and stable isotope sampling of thrust fault rocks in the central Apennines (Maiorani et al., 1992; Ghisetti et al., 2000, 2001) are consistent with conditions of closed fluid circulation during shortening. Tectonic interleaving of carbonate thrust slices in between low-permeability siliciclastic rocks, coupled with the development of clay-rich, foliated fault rocks along the thrust faults (Ghisetti, 1987) appears to have inhibited large-scale fluid infiltration from both surface and deep sources.

Subsequent propagation of normal faults was associated with intense fracturing. Belts of cataclasites 50–100-m wide typically show a gradient of fracture intensity that increases towards the fault core, where repeated deposition and reshear of millimeter–centimeter-thick calcite cements testifies to numerous episodes of extensional shearing and post-failure sealing during cyclic activity of the faults (Ghisetti et al., 2000). Isotopic data on the cemented cataclasites associated with normal faults (Ghisetti et al., 2000) are indicative of localized penetration of meteoric fluids along high angle normal faults down to depths of at least 3 km. Therefore, late processes of extension, uplift and erosion of the thrust belt appear to have introduced substantial changes in the fluid circulation, shifting the hydrologic system from closed to open.

3.4. Adriatic foredeep

This is the only domain of the Apennines where folding and thrusting are still active, associated with progressive eastward shifting of the Adriatic foredeep and migration of the foreland peripheral bulge at rates of 1.5–3 cm/year since Middle Pliocene times (Patacca and Scandone, 1989). In this domain, many seismic profiles (e.g. Mostardini and Merlini, 1986) depict the geometry of detached ramp folds and fault-propagation folds onlapped by siliciclastic wedges and thrust over high-porosity sediments of the foredeep. Most hydrocarbon reservoirs occur in a belt (Fig. 3) that parallels the contact between the outer thrust front and the Adriatic foredeep (Carlin and Dainelli, 1998). Hydrocarbons are trapped at the top of Middle Miocene and Mesozoic carbonates, or in structural (thrust-faulted anticlines) and stratigraphic traps (pinch-outs) located within different Pliocene sand bodies in the Adriatic foredeep. The deepest and innermost gas occurrences are in sands of Early Pliocene age (Cellino Formation). In contrast, the youngest reservoirs are confined to the outermost position, in Middle–Late Pliocene–Pleistocene sands (Casnedi, 1983). Drilling in the oil fields (Carlin and Dainelli, 1998) indicates the occurrence of fluid overpressures up to lithostatic in compartmentalized domains, which are bounded laterally by thrust faults and trapped vertically by low-permeability beds. Closed circulation of fluids within low-permeability compartments is indicative of thrust faults acting as barriers to meteoric and deep fluids and also to hydrocarbons, in agreement with isotope analyses in the adjacent domain 3 (Ghisetti et al., 2000). Progressive eastward fluid expulsion towards the toe of the Apenninic thrust wedge, connected with eastward migration of shortening (Cello and Nur, 1988), is indicated by west to east migration of gas reservoirs (Casnedi, 1983) and by eastward migration of deep and warm fluids towards the Apulian foreland (Nanni and Zuppi, 1986; Pagliarulo, 1996).

4. Discussion

4.1. Normal faulting and transcrustal permeability

The deep structural setting of the tectonic domains of Fig. 3 is summarized in the cross-section of Fig. 5. The cross-section, originally drawn at scale 1:100,000, integrates: (1) geological and structural field data of the central Apenninic thrust belt (Vezzani et al., 1997); (2) data from commercial boreholes and seismic reflection profiles in the Adriatic foredeep (Bally et al., 1988; Mostardini and Merlini, 1986); and (3) data from the seismic profile CROP 03 (trace in Fig. 3). Interpretations from seismic wave attenuation and seismic tomography have been taken into account as well (e.g. Selvaggi and Chiarabba, 1995; Mele et al., 1996, 1997).

The major interpretative points focused in Fig. 5 are given below.

(1) The normal faults of the peri-Tyrrhenian domain stretch the crust of the thrust belt and merge into a discontinuity that separates the detached upper crust from hot, partially melted (?) lower crust in the Tyrrhenian domain (see Scarascia et al., 1998). In Fig. 5, the magmatic conduits of the peri-Tyrrhenian province are depicted to follow extensional pathways along normal faults. The stretched crust of this domain is directly superposed onto thin and hot Tyrrhenian lithosphere with anomalously high seismic attenuation (Mele et al., 1996; Di Stefano et al., 1999). Pervasive extensional fracturing and faulting of the thin brittle layer may explain why this domain is highly permeable to circulation of juvenile and magmatic fluids and to mantle degassing.

(2) The transition between domains 1 and 2 is gradual and occurs in those crustal sectors delaminated above Tyrrhenian asthenosphere ascending in front of the Adriatic slab. Domain 2 is on the verge of being assimilated into the Tyrrhenian foundered zone but intrusion of melts into the upper crust has insofar been rare and volumetrically small (Stoppa and Woolley, 1997). Infiltration of "pioneer" melts along deeply penetrating normal faults may have resulted in crustal contamination and mobilization of very low viscosity carbonate melts, infilling an array of intrusion dykes during Pleistocene times. Effusion of these melts has occurred in domain 2 in the central Apennines and in a much more external (and problematic) position (Fig. 3) in the Vulture volcanic edifice in the southern Apennines (see Stoppa and Woolley, 1997).

(3) The orographic divide marks the boundary beyond which circulation of fluids becomes progressively more localized along normal faults. Within domain 3 the geometric architecture of the late Miocene–Pliocene thrust belt is still preserved in a crust over 30 km thick and normal faults appear to root into and reactivate older thrust faults at depths of 5–10 km. Since late Pliocene times progressive disruption of the thrust belt has occurred through normal faulting and was associated with high rates of footwall uplift (Ghisetti and Vezzani, 1999). As a consequence, erosion of the uppermost Late Miocene–Early Pliocene terrigenous sediments was concomitant with exhumation of highly fractured carbonates that typically make up the bulk of the Mesozoic–Tertiary tectonic units of the Apennines. These conditions likely favoured localized circulation of meteoric fluids along the fracture network of the normal faults, down to depths of at least 3 km (Ghisetti et al., 2001).

(4) In domain 4, the thrust belt is buried underneath the thick siliciclastic covers of the outermost Late Pliocene–Early Pleistocene foredeep. It is confined above a low-angle detachment at depths of 7 km, dipping gently westward (Bally et al., 1988). The apparent impermeability of thrust faults to fluids from different sources (Ghisetti et al., 2001), added to the interlayering of poorly permeable horizons in the stratigraphy, appear to be primary factors for restricting fluid circulation within compartmentalized overpressured domains.

4.2. Normal faulting and overpressuring

The character of structural permeability across the Apennines summarized in Fig. 5 is indicative of different sources of overpressuring from west to east, in a range of crustal depths.

In the westernmost domain 1, mantle fluids derived from asthenospheric upwelling may well enter the ductile lower crust at near lithostatic pressure (e.g. Kennedy et al., 1997) and infiltrate upwards through the

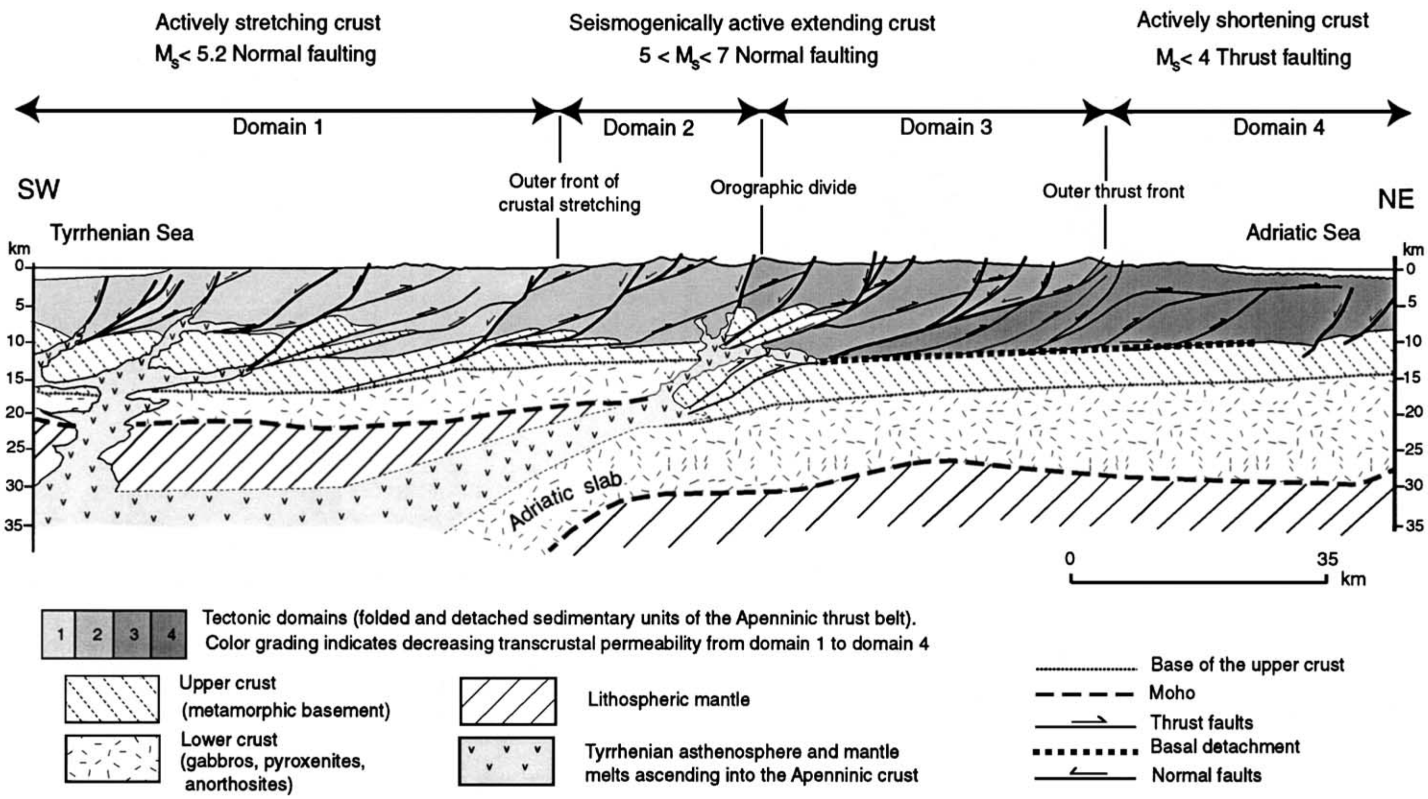

Fig. 5. Crustal section (trace in Fig. 3) highlighting the connections between deep and upper crustal deformations and the structural control on decreasing permeability and fluid mixing from the innermost domain 1 (stretched, highly permeable crust) to the outermost domain 4 (shortened, overpressured crust with restricted fluid circulation). The belt of highest seismicity is located in between domains 2 and 3 (see Fig. 2), where mature normal faults cut across the whole brittle crust. For further explanations, see text.

interconnected network of extensional fractures and normal faults. Locally, the presence of low-permeability stratigraphic and hydrothermal cemented horizons (e.g. in the geothermal fields) can contribute to maintain fluid pore pressures in excess of hydrostatic (Chiodini et al., 1999). However, widespread geochemical evidence for mixing of meteoric and deep fluids in the geothermal reservoirs and escape of free gas phase at surface testify for high levels of permeability of the strongly fractured thinned crust, where overpressuring must be episodic and ephemeral.

In contrast to this, in the easternmost domain 4, the frontal portion of the thrust belt contains numerous oil and gas reservoirs that are overpressured at shallow depths. The largest reservoirs occur in the buried outer margin of the thrust belt, in the region that has not yet undergone extensive uplift or normal faulting. Most hydrocarbons are contained in large anticlines overlapped by impermeable siliciclastic deposits of the foredeep and laterally confined by thrust faults that ramp across the folds (Ghisetti et al., 2001).

No data on overpressuring exist for domains 2 and 3 but their structural confinement between domains 1 and 4 is compatible with lateral and vertical transitions in fluid pressure regime across these domains. It is conceivable that overpressured fluids rising from magmatic dykes infiltrate deeply penetrating faults (Fig. 5, see also Italiano et al., 2000) but the extent to which elevated pore fluid pressures can be maintained at depths ≥ 10 km is unknown. Faults that detach at shallower depths (between 5 and 7 km) may well intersect overpressured horizons preserved in the cores of buried anticlines and within overthrusted low-permeability units. In contrast, hydrostatic conditions of fluid pressure prevail in the depth range from surface to 3 km, as supported by isotopic data on infiltration of meteoric fluids along the normal faults (Ghisetti et al., 2001).

4.3. Seismogenic interpretation

In the Apennines, the orientation of the contractional (Late Miocene–Early Pliocene) and extensional (Late Pliocene–Pleistocene) stress field remained fixed relative to the axial trend of the chain (Fig. 1). The inversion from compression to extension appears to be triggered by strong components of uplift consequent to shortening of imbricates, and suggests an overall low value of the differential stress during the compressional events (Ghisetti and Vezzani, 2000). Conceivably, the decrease in mean stress and lower levels of maximum sustainable overpressure consequent on extension (Sibson, 1995) are accompanied by extensive formation of distributed fault-fracture networks, with enhanced fluid circulation and transient changes in fluid overpressuring during cycles of normal fault activity (Sibson and Scott, 1998).

Long-term maintenance of overpressuring in the fractured upper crust appears unfeasible but there is evidence for localized fluid overpressure in normal fault zones, at depths nearly corresponding with the base of the seismogenic zone, apparently coupled to pressure fluctuations from near-lithostatic to hydrostatic conditions (Bruhn et al., 1990). Gas accumulation in permeable reservoirs bounded by sealed active faults leads to localized overpressures and seismic slip, followed by increased fault permeability (Brown and Bruhn, 1996). Post-seismic fluid discharge is feasibly channeled along high-angle fractures (Muir-Wood and King, 1993; Wiprut and Zoback, 2000) or along σ_2-parallel, high-permeability conduits (Sibson, 2000). Migration of fluid pressure waves along faults that cut through rocks with different permeability has been sometimes correlated to delayed sequences of aftershocks (Noir et al., 1997).

In the Apennines, rates of seismic extensional deformation increase from west to east (Table 2) and from north to south (Amato et al., 1998) but the highest seismicity remains confined in a crustal wedge 25–30-km wide and 10–15-km deep (Fig. 2).

Different authors (e.g. Pasquale et al., 1997; Negredo et al., 1999) have correlated the larger number and higher magnitude of shocks in this belt to the larger thickness and rock strength of the cold Adriatic crust, opposite to the lower rock strength of the hot and thinned Tyrrhenian domain. However, the role of transcrustal permeability and overpressuring in controlling nucleation of earthquakes is largely unexplored (Quattrocchi, 1999).

Localization of M_s>5 normal faulting earthquakes in a crustal wedge bounded by thin and highly permeable crust to the west and by thick and poorly permeable crust to the east (Fig. 5) suggests that occurrence, modes and depth of seismicity are dependent on permeability and overpressuring of fault zones relative to the surrounding crust. In the present tectonic regime, many normal faults of domain 1 are suitably oriented for reactivation but seismicity cutoff at depths <10 km and low release of seismic energy in $M_s \leq 5.2$ earthquakes (Boschi et al., 1997) are indicative of extensional deformation in a large volume of highly permeable rocks, where conditions of hydrostatic pressure prevail during the seismic cycle. In contrast, the largest earthquakes ($5<M_s<7$) that occur in between domains 2–3 (Fig. 5) are potentially triggered by conditions of overpressuring that help create new, favourably oriented normal faults or allow reactivation of unfavourably oriented inherited thrust faults. Faults that break in large earthquakes may act as transient high-permeability surfaces, thus controlling episodic fluid redistribution along preferential planar compartments.

This interpretation implies that within the process of eastward migrating, extensional faulting driven by rollback of the Adriatic plate, older faults left behind in the hot, highly stretched and permeable crust of the hinterland may well become reactivated but fail to produce large magnitude earthquakes. On the contrary, it is the existence of overpressured domains in a thick crust undergoing early stages of extension that triggers the highest seismic release, associated with eastward advancement of the extensional front with time. These processes occur in the belt localized between domains 2 and 3.

5. Conclusion

The crustal wedge of the Apenninic thrust belt subjected to extension since 5 Ma occupies an intermediate position between hot, highly permeable thinned crust of the inner peri-Tyrrhenian domain (subjected to extension since 7 Ma) and cold, thick and low-permeability crust of the Adriatic domain (not yet reached by extension). Within this wedge, (i) crustal thickness in excess of 25–30 km, (ii) growth of spaced normal faults that penetrate the crust down to seismogenic depths, and (iii) preservation of thrust structures not yet dissected by extensional fracturing favour maintenance of overpressuring conditions at depths of 10–15 km that may eventually trigger episodic seismic slip during $5<M_s<7$ normal faulting earthquakes.

Geological, geophysical and geochemical data suggest a close interconnection between amount of crustal stretching, depth of detachment of normal faults, and fluid circulation. In particular, the change of tectonic regime from folding and thrusting to normal faulting appears to drive rising levels of vertical permeability that have increased proportionally with length of time elapsed since onset of extension. Progressive build-up of extensional strain, leading to linkage of different fault systems in the stretched and thinned upper crust, appears to control redistribution and mixing of overpressured fluids that (i) migrate from mantle melts infiltrating the lower crust and (ii) are trapped in low-permeability compartments of the thrust belt.

In this framework, it is plausible that domains of fluid overpressuring in the upper crust trigger formation of new normal faults and reactivation of older thrust faults at depths of 15–10 km, with consequent eastward migration of the belt of maximum seismic release with time.

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References

Amato, A., Montone, P., 1997. Present-day stress field and active tectonics in southern peninsular Italy. Geophys. J. Int. 130, 519–534.

Amato, A., Azzara, R., Basili, A., Chiarabba, C., Ciaccio, M.G., Cimini, G.B., Di Bona, M., Frepoli, A., Hunstad, I., Lucente, F.P., Margheriti, L., Mariucci, M.T., Montone, P., Nostro, C., Selvaggi, G., 1998. Geodynamic evolution of the northern Apennines from recent seismological studies. Mem. Soc. Geol. Ital. 52, 337–343.

Ambrosetti, P., Bosi, C., Carraro, F., Ciaranfi, N., Panizza, M., Papani, G., Vezzani, L., Zanferrari, A., 1987. Neotectonic map of Italy, scale 1:500,000. Quad. Ric. Sci., CNR, 114.

Bally, A.W., Burbi, L., Cooper, C., Ghelardoni, R., 1988. Balanced sections and seismic reflection profiles across the Central Apennines. Mem. Soc. Geol. Ital. 35, 257–310.

Barchi, M., Minelli, G., Pialli, G., 1998. The CROP03 profile: a synthesis of results on deep structures of the northern Apennines. Mem. Soc. Geol. Ital. 52, 383–400.

Boccaletti, M., Gianelli, G., Sani, F., 1997. Tectonic regime, granite emplacement and crustal structure in the inner zone of the Northern Apennines (Tuscany, Italy): a new hypothesis. Tectonophysics 270, 127–143.

Boschi, E., Guidoboni, E., Ferrari, G., Valensise, G., Gasperini, P., 1997. Catalogo dei Forti Terremoti in Italia dal 461 a.C. al 1990. I.N.G., Roma, 644 pp.

Brown, S.R., Bruhn, R.L., 1996. Formation of voids and veins during faulting. J. Struct. Geol. 18, 657–667.

Bruhn, R.L., Yonkee, W.A., Parry, W.T., 1990. Structural and fluid-chemical properties of seismogenic normal faults. Tectonophysics 175, 139–157.

Carlin, S., Dainelli, J., 1998. Pressure regimes and pressure systems in the Adriatic foredeep (Italy). Am. Assoc. Pet. Geol. Mem. 70, 145–160.

Carrozzo, M.T., Luzio, D., Margiotta, C., Quarta, T., 1991. Gravity map of Italy, scale 1:500,000. Structural Model of Italy. C.N.R. Progetto Finalizzato Geodinamica, S.EL.CA., Firenze.

Casnedi, R., 1983. Hydrocarbon-bearing submarine fan systems of Cellino Formation, central Italy. Am. Assoc. Pet. Geol. Bull. 67, 359–370.

Cavinato, G.P., De Celles, P.G., 1999. Extensional basins in the tectonically bimodal central Apennines fold-thrust belt, Italy: response to corner flow above a subducting slab in retrograde motion. Geology 27, 955–958.

Cello, G., Nur, A., 1988. Emplacement of foreland thrust systems. Tectonics 7, 261–271.

Channell, J.E.T., Mareschal, J.C., 1989. Delamination and asymmetric lithospheric thickening in the development of the Tyrrhenian rift. Geol. Soc. London, Spec. Publ. 45, 285–302.

Chiodini, G., Frondini, F., Kerrick, D.M., Rogie, J., Parello, F., Peruzzi, L., Zanzari, A.R., 1999. Quantification of deep CO_2 fluxes from central Italy: examples of carbon balance for regional aquifers and of soil diffuse degassing. Chem. Geol. 159, 205–222.

Chiodini, G., Frondini, F., Cardellini, C., Parello, F., Peruzzi, L., 2000. Rate of diffuse carbon dioxide Earth degassing estimated from carbon balance of regional aquifers: the case of central Apennines, Italy. J. Geophys. Res. 105, 8423–8434.

Cipollari, P., Cosentino, D., 1995. Il sistema Tirreno–Appennino: segmentazione litosferica e propagazione del fronte compressivo. Studi Geol. Camerti 1995/2, 125–134.

Di Stefano, R., Chiarabba, C., Lucente, F., Amato, A., 1999. Crustal and uppermost mantle structure in Italy from the inversion of P-wave arrival times: geodynamic implications. Geophys. J. Int. 139, 483–498.

Doglioni, C., Harabaglia, P., Martinelli, G., Mongelli, F., Zito, G., 1996. A geodynamic model of the southern Apennines accretionary prism. Terra Nova 8, 540–547.

Faccenna, C., Mattei, M., Funiciello, R., Jolivet, L., 1997. Styles of back-arc extension in the central Mediterranean. Terra Nova 9, 126–130.

Frepoli, A., Amato, A., 1997. Contemporaneous extension and compression in the Northern Apennines from earthquake fault-plane solutions. Geophys. J. Int. 129, 368–388.

Ghisetti, F., 1987. Mechanisms of thrust faulting in the Gran Sasso chain, Central Apennines, Italy. J. Struct. Geol. 9, 955–967.

Ghisetti, F., 1992. Fault parameters in the Messina Strait (Southern Italy), and relations with the seismogenic source. Tectonophysics 210, 117–133.

Ghisetti, F., Vezzani, L., 1981. Contribution of structural analysis to understanding the geodynamic evolution of the Calabrian Arc (Southern Italy). J. Struct. Geol. 3, 371–381.

Ghisetti, F., Vezzani, L., 1997. Interfering paths of deformation and development of arcs in the fold-and-thrust belt of the central Apennines (Italy). Tectonics 16, 523–536.

Ghisetti, F., Vezzani, L., 1998. Segmentation and tectonic evolution of the Abruzzi–Molise thrust belt (central Apennines, Italy). Ann. Tecton. 12, 97–112.

Ghisetti, F., Vezzani, L., 1999. Depth and modes of Pliocene–Pleistocene crustal extension of the Apennines (Italy). Terra Nova 11, 67–72.

Ghisetti, F., Vezzani, L., 2000. Detachments and normal faulting in the Marche fold-and-thrust belt (central Apennines, Italy): inferences on fluid migration paths. J. Geodyn. 29, 345–369.

Ghisetti, F., Barchi, M., Bally, A.W., Moretti, I., Vezzani, L., 1993. Conflicting balanced structural sections across the central Apennines (Italy): problems and implications. In: Spencer, A.M. (Ed.), Generation, Accumulation and Production of Europe's Hydrocarbons III. Special Publication European Association of Petroleum Geologists, vol. 3. Springer-Verlag, Berlin, pp. 219–231.

Ghisetti, F., Kirschner, D., Vezzani, L., 2000. Tectonic controls on large-scale fluid circulation in the Apennines. J. Geochem. Explor. 69–70, 533–537.

Ghisetti, F., Kirschner, D., Vezzani, L., Agosta, F., 2001. Stable isotope evidence for contrasting paleofluid circulation in thrust faults and normal faults of the central Apennines, Italy. J. Geophys. Res. 106, 8811–8825.

Gianelli, G., 1985. On the origin of geothermal CO_2 by metamorphic processes. Boll. Soc. Geol. Ital. 104, 575–584.

Gianelli, G., Ruggieri, G., Mussi, M., 1997. Isotopic and fluid inclusion study of hydrothermal and metamorphic carbonates in the Larderello geothermal field and surrounding area, Italy. Geothermics 26, 393–417.

Giraudi, C., Frezzotti, M., 1995. Palaeoseismicity in the Gran Sasso massif (Abruzzo, central Italy). Quat. Int. 25, 81–93.

Italiano, F., Martelli, M., Martinelli, G., Nuccio, P.M., 2000. Geochemical evidence of melt intrusions along lithospheric faults of the southern Apennines, Italy: geodynamic and seismogenic implications. J. Geophys. Res. 105, 13569–13578.

Jolivet, L., Faccenna, C., Goffé, B., Mattei, M., Rossetti, F., Brunet, C., Storti, F., Funiciello, R., Cadet, J.P., D'Agostino, N., Parra, T., 1998. Midcrustal shear zones in postorogenic extension: example from the northern Tyrrhenian sea. J. Geophys. Res. 103, 12123–12160.

Kennedy, B.M., Kharaka, Y.K., Evans, W.C., Ellwood, A., De Paolo, D.J., Thordsen, J., Ambats, G., Mariner, R.H., 1997. Mantle fluids in the San Andreas fault system, California. Science 278, 1278–1281.

Lattanzi, P., 1999. Epithermal precious metal deposits of Italy—an overview. Miner. Deposits 34, 630–638.

Lavecchia, G., Brozzetti, F., Barchi, M., Menichetti, M., Keller, J.V.A., 1994. Seismotectonic zoning in east-central Italy deduced from an analysis of the Neogene to present deformation and related stress fields. Geol. Soc. Am. Bull. 106, 1107–1120.

Lentz, D.R., 1999. Carbonatite genesis: a reexamination of the role of intrusion-related pneumatolytic skarn processes in limestone melting. Geology 27, 335–338.

Liotta, D., Cernobori, L., Nicolich, R., 1998. Restricted rifting and its coexistence with compressional structures: results from the CROP 3 traverse (northern Apennines, Italy). Terra Nova 10, 16–20.

Locardi, E., 1988. The origin of Apenninic arcs. Tectonophysics 146, 105–123.

Maiorani, A., Funiciello, R., Mattei, M., Turi, B., 1992. Stable isotope geochemistry and structural elements of the Sabina region (central Apennines, Italy). Terra Nova 4, 484–488.

Malinverno, A., Ryan, W.B.F., 1986. 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.

Manfra, L., Masi, U., Turi, B., 1976. La composizione isotopica dei travertini del Lazio. Geol. Rom. 15, 127–174.

Martini, I.P., Sagri, M., 1993. Tectonosedimentary characteristics of late Miocene–Quaternary extensional basins of the northern Apennines, Italy. Earth Sci. Rev. 34, 197–233.

Mele, G., Rovelli, A., Seber, G., Barazangi, M., 1996. Lateral variations of Pn propagations in Italy: evidence for a high-attenuation zone beneath the Apennines. Geophys. Res. Lett. 23, 709–712.

Mele, G., Rovelli, A., Seber, G., Barazangi, M., 1997. Shear wave attenuation in the lithosphere beneath Italy and surrounding regions: tectonic implications. J. Geophys. Res. 102, 11863–11875.

Minissale, A., 1991. The Larderello geothermal field—a review. Earth Sci. Rev. 31, 133–151.

Mostardini, G., Merlini, S., 1986. Appennino centro-meridionale. Sezioni Geologiche e Proposta di Modello Strutturale. 73° Congresso Società Geologica Italiana, AGIP Milano, 59 pp.

Muir-Wood, R., King, G.C.P., 1993. Hydrological signatures of earthquake strain. J. Geophys. Res. 98, 22035–22068.

Nanni, T., Zuppi, G.M., 1986. Acque salate e circolazione profonda in relazione all'assetto strutturale del fronte Adriatico a Padano dell'Appennino. Mem. Soc. Geol. Ital. 35, 979–986.

Negredo, A.M., Barba, S., Carminati, E., Sabadini, R., Giunchi, C., 1999. Contribution of numeric dynamic modelling to the understanding of the seismotectonic regime of the northern Apennines. Tectonophysics 315, 15–30.

Noir, J., Jacques, E., Bekri, S., Adler, P.M., Tapponier, P., King, G.C.P., 1997. Fluid flow triggered migration of events in the 1989 Dobi earthquake sequence of Central Afar. Geophys. Res. Lett. 24, 2335–2338.

Pagliarulo, P., 1996. Migrazione di fluidi profondi nel substrato prepliocenico dell'avanfossa appenninica (bacino pugliese e lucano). Mem. Soc. Geol. Ital. 51, 659–668.

Pantosti, D., Schwartz, D.P., Valensise, G., 1993. Paleoseismology along the 1980 Irpinia earthquake fault and implication for earthquake recurrence in the southern Apennines. J. Geophys. Res. 98, 6561–6577.

Pantosti, D., D'Addezio, G., Cinti, F.R., 1996. Paleoseismicity of the Ovindoli–Pezza fault, central Apennines, Italy: a history including a large, previously unrecorded earthquake in the middle Ages (860–1300 A.D.). J. Geophys. Res. 101, 5937–5959.

Pasquale, V., Verdoya, M., Chiozzi, P., Ranalli, G., 1997. Rheology and seismotectonics in the northern central Mediterranean. Tectonophysics 270, 239–257.

Patacca, E., Scandone, P., 1989. Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab: the Lithosphere in Italy. Atti Accad. Naz. Lincei 80, 157–176.

Peccerillo, A., 1998. Relationships between ultrapotassic and carbonate-rich volcanic rocks in central Italy: petrogenetic and geodynamic implications. Lithos 43, 267–279.

Quattrocchi, F., 1999. In search of evidence of deep fluid discharges and pore pressure evolution in the crust to explain the seismicity style of the Umbria–Marche 1997–1998 seismic sequence (central Italy). Ann. Geofis. 42, 606–636.

Royden, L., Patacca, E., Scandone, P., 1987. Segmentation and configuration of subducted lithosphere in Italy: an important control on thrust belt and foredeep-basin evolution. Geology 15, 714–717.

Ruggieri, G., Cathelinau, M., Boiron, M.C., Marignac, C., 1999. Boiling and fluid mixing in the chlorite zone of the Larderello geothermal system. Chem. Geol. 154, 237–256.

Savelli, C., 1988. Late Oligocene to Recent episodes of magmatism in and around the Tyrrhenian Sea: implications for the processes of opening in a young inter-arc basin of intra-orogenic (Mediterranean) type. Tectonophysics 146, 163–181.

Scarascia, S., Cassinis, R., Federici, F., 1998. Gravity modelling of deep structures in the northern-central Apennines. Mem. Soc. Geol. Ital. 52, 337–343.

Selvaggi, G., Amato, A., 1992. Subcrustal earthquakes in the northern Apennines (Italy): evidence for a still active subduction? Geophys. Res. Lett. 19, 2127–2130.

Selvaggi, G., Chiarabba, C., 1995. Seismicity and P-wave velocity image of the southern Tyrrhenian subduction. Geophys. J. Int. 121, 818–826.

Serri, G., Innocenti, F., Manetti, P., 1993. Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene–Quaternary magmatism of central Italy. Tectonophysics 223, 117–147.

Sibson, R.H., 1995. Selective fault reactivation during basin inversion: potential for fluid redistribution through fault-valve action. Geol. Soc. London, Spec. Publ. 88, 3–19.

Sibson, R.H., 2000. Fluid involvement in normal faulting. J. Geodyn. 29, 469–499.

Sibson, R.H., Scott, J., 1998. Stress/fault controls on the containment and release of overpressured fluids: examples from gold–quartz vein systems in Juneau, Alaska, Victoria, Australia and Otago, New Zealand. Ore Geol. Rev. 13, 293–306.

Stoppa, F., Lavecchia, G., 1992. Late Pleistocene ultra-alkaline magmatic activity in the Umbria–Latium region (Italy) — an overview. J. Volcanol. Geotherm. Res. 52, 277–293.

Stoppa, F., Woolley, A.R., 1997. The Italian carbonatites: field occurrence, petrology and regional significance. Miner. Petrol. 59, 43–67.

Vezzani, L., Ghisetti, F., Casnedi, R., 1997. Carta Geologica dell'Abruzzo, scale 1:100,000. S.EL.CA., Firenze.

Vittori, E., Sylos Labini, S., Serva, L., 1991. Palaeoseismology: review of the state-of-the-art. Tectonophysics 193, 9–32.

Westaway, R., 1992. Seismic moment summation for historical earthquakes in Italy: tectonic implications. J. Geophys. Res. 97, 15437–15464.

Wiprut, D., Zoback, M.D., 2000. Fault reactivation and fluid flow along a previously dormant normal fault in the northern North Sea. Geology 28, 595–598.