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Faults linkage, damage rocks and hydrothermal fluid circulation: Tectonic interpretation of the Rapolano Terme travertines (southern Tuscany, Italy) in the context of Northern Apennines Neogene–Quaternary extension

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Key words: Neogene–Quaternary extensional tectonics, tectono-stratigraphical relationships, structural analysis, travertines, Pliocene deposits, Northern Apennines

ABSTRACT

The tectonic history of Neogene–Quaternary extensional structures has been documented in the inner part of the Northern Apennines (Rapolano Terme area) from Quaternary travertines and faults relationships. In particular, structural studies, field mapping and tectono-stratigraphical considerations on the pre-Neogene, Pliocene and Quaternary units indicate two fault populations of different ages. The travertines, broadly exposed in the Rapolano Terme area, were related to hydrothermal fluid circulation and upwelling along the damage zones of Pleistocene normal faults. These structures were superimposed upon normal (mainly NNW–SSE and SW–NE oriented) and transtensional (mainly SW–NE oriented) faults, Early–Middle Pliocene in age, related to development of the Siena Basin. The age of such Pliocene normal and transtensional faults has been inferred on the basis of the relationships between tectonic elements and Pliocene deposits. In fact, Middle Pliocene marine sandy and gravelly sediments suture the faults. The Pleistocene normal faults (mainly SW–NE oriented) reactivated the oldest SW–NE transtensional faults, cut the NNW–SSE normal faults, and displaced Middle Pliocene marine deposits. Pleistocene–Holocene travertines and present-day thermal springs mainly occur at the intersection points between the Pleistocene SW–NE faults and the Pliocene NNW–SSE normal faults, or along the SW–NE Pleistocene normal faults.

RIASSUNTO

Un nuovo studio basato sull'analisi strutturale di faglie collegate con la tettonica distensiva noegenico-quaternaria, sulla realizzazione di un nuovo rilevamento geologico di dettaglio condotto nell'area di Rapolano Terme e sulla considerazione dei rapporti tettono-stratigrafici tra le faglie ed i depositi pliocenico-quaternari, ha permesso di individuare la presenza di una evoluzione articolata delle strutture collegate con la tettonica distensiva. In particolare sono state individuate due popolazioni di faglie sviluppate in età diversa. I travertini che affiorano ampiamente nell'area di Rapolano Terme sono collegati alla circolazione ed alla emergenza di fluidi idrotermali lungo le zone intensamente fratturate associate a faglie di età Pleistocenica. Queste strutture si sono sovrapposte a faglie normali (principalmente orientate NNW-SSE) ed a faglie transtensive (principalmente orientate SW-NE) di età Pliocenica inferiore-media, collegate con lo sviluppo del Bacino di Siena. La sovrapposizione delle due popolazioni di faglie e la loro parziale riattivazione è stata documentata dallo studio degli indicatori cinematici riconosciuti lungo i piani di alcune faglie. L'età pliocenica della prima popolazione di faglie è stata dedotta mediante l'analisi dei rapporti tra tettonica e sedimentazione nei depositi pliocenici. Infatti sedimenti del Pliocene medio suturano le faglie dirette e transtensive. Le faglie dirette di età Pleistocenica, principalmente orientate in direzione SW-NE, hanno riattivato le più antiche faglie transtensive ugualmente orientate ed hanno dislocato le faglie dirette principalmente orientate in direzione NNW-SSE oltre che i depositi del Pliocene medio. Inoltre i travertini e le attuali sorgenti termali sono collocati sia in corrispondenza delle zone di intersezione tra le faglie dirette di età pleistocenica, orientate in direzione SW-NE, e le faglie dirette plioceniche, orientate in direzione NNW-SSE, sia lungo faglie orientate SW-NE di età pleistocenica.

Introduction

Travertine deposition is normally associated with thermal springs, which, in most cases, are very important indicators of tectonic activity (Pavlides & Kilias 1987; Minissale 1991; Altunel & Hancock 1993a, 1993b; Sibson 1996). Thermal springs and travertines can be related to brittle structures, normal fault systems and associated damage zones, allowing the upwelling and circulation of hydrothermal fluids (Barazzuoli et al. 1986, 1991; Hancock et al. 1999; Cello et al. 2001; Bellani et al. 2004). In fact, fluid flow along the faults may be channelled within regions of highly fractured rocks (damage zones) (e.g. Caine et al. 1996). Hydrothermal activity is dependent upon the interaction among heat sources, circulation of fluids and permeable

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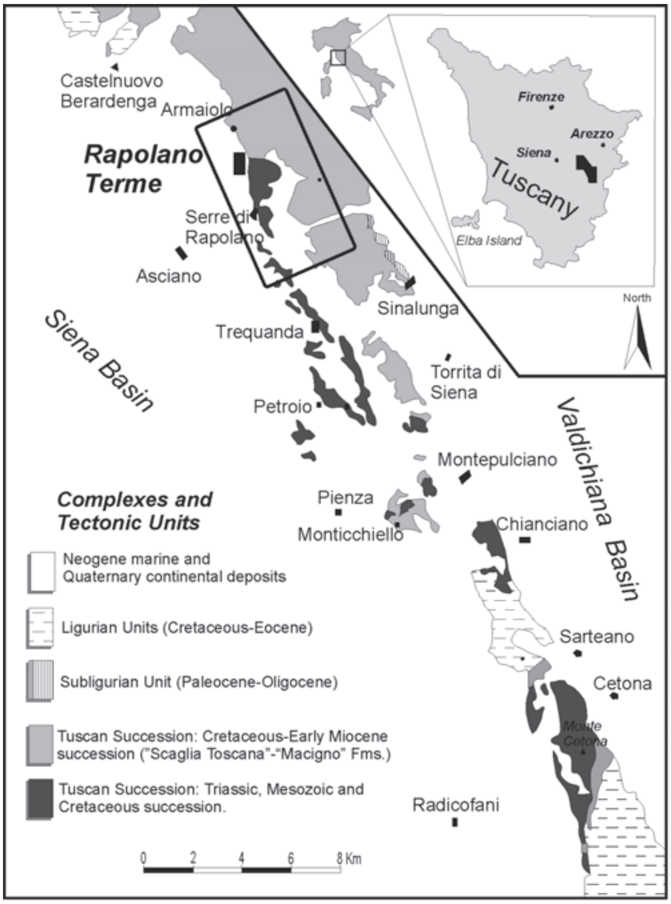

Fig. 1. Location of study area. The black rectangle shows the enlarged area of figure 2.

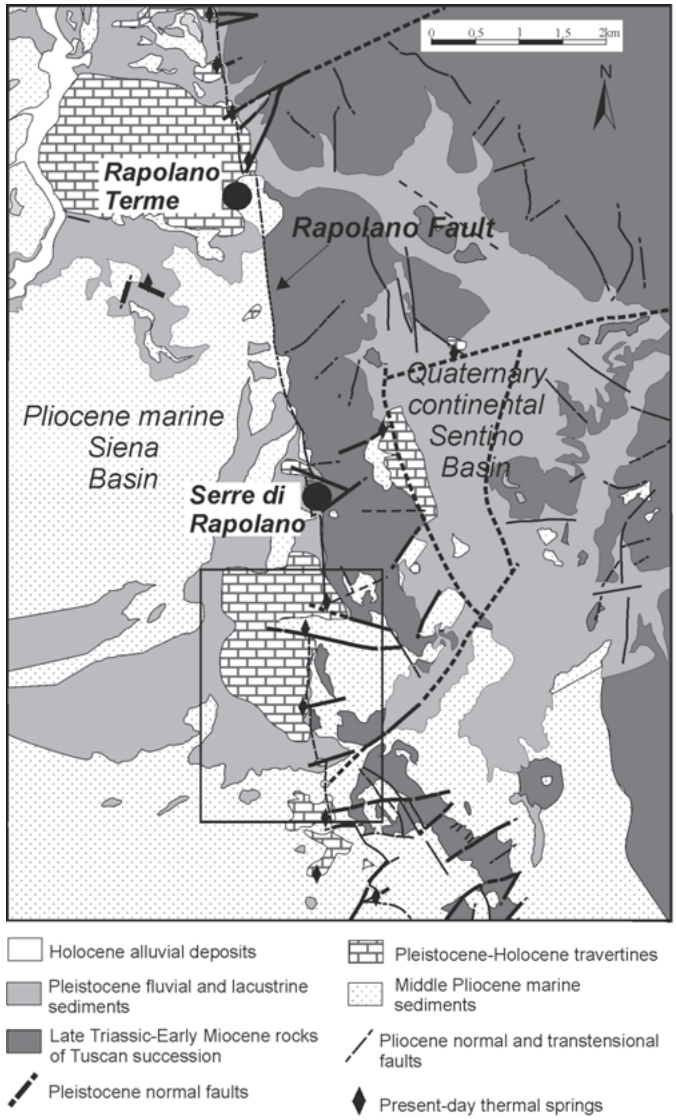

Fig. 2. Geological sketch map of the Rapolano and Serre di Rapolano areas showing the relationships between the faults, travertines and present-day thermal springs. Thermal springs and Pleistocene–Holocene travertines are located at the intersection points between the NNW–SSW striking faults of the first population and the SW–NE striking faults of the second population. The black rectangle indicates the area enlarged in figure 6.

pathways (Curewitz & Karson 1997). These processes are favoured where high geothermal gradients occur, such as in southern Tuscany and northern Latium (Della Vedova et al. 2001). The permeability of the damage zone is time-dependent: after fractures open in the damaged rocks, new generation of minerals, mainly consisting of carbonates and oxides (sulphides can also occur in the hydrothermal systems of the Tuscan metallogenic province, Arisi Rota et al. 1971; Tanelli 1983), fill the fractures and close them, preventing the circulation of fluids. Consequently, thermal springs can be considered contemporaneous or quasi-contemporaneous with the fault activity (Hancock et al. 1999 and references therein). In fact, it is known that the thermal springs are aligned along some important active faults, and hydrological changes commonly accompany earthquakes (Muir-Wood 1993). Therefore travertines are very important indicators of the timing of fault activity, and their location can suggest fault geometries in the ancient hydrothermal systems. Consequently, the study of travertines, their mapping and age determination represent an important tool to reconstruct the activity of faults and understanding their tectonic history.

New structural information on the tectonic evolution of the Neogene–Quaternary extensional structures, affecting the inner part of the Northern Apennines, have been collected by a new geological study in the Rapolano Terme area (Fig. 1), where broad exposures of Pleistocene–Holocene travertines are found in association with normal fault systems. Integrated field mapping, stratigraphical considerations and structural analyses on a large dataset of fault-striae measurements indicate that Pleistocene travertines of Rapolano Terme are related to hydrothermal circulation in carbonate rocks, along damage zones located at the intersection points between two generations of faults, different in age, related to the Neogene-Quaternary extension.

Geological Framework

The Northern Apennines thrust belt has formed during the Tertiary from the collision between the African (Apulia microplate) and European (Sardinia–Corsica massif) continental margins (Boccaletti et al. 1971; Castellarin et al. 1992; Faccenna et al. 2001). It comprises a stack of east-verging thrust sheets superimposed on the western margin of the Apulia foreland. They are composed of, from top to bottom: (a) Ligurian l.s. units consisting of remnants of Jurassic oceanic crust and Cretaceous–Oligocene sedimentary cover; (b) Tuscan Units including sedimentary and metamorphic (greenschist) sequences ranging from Palaeozoic to Early Miocene in age. The Tuscan sedimentary covers were thrust eastward over the Umbria-Marchigian units (Carmignani et al. 2001, and references therein). In the inner part of the Northern Apennines, the metamorphic substratum (Tuscan Metamorphic Basement) of the sedimentary covers is mainly known through the drilling of geothermal wells (e.g. Larderello-Travale and Mt. Amiata geothermal areas), penetrating the crust down to about 3.5 km (Batini et al. 2003, and references therein). The stacking processes of the Northern Apennines were overprinted by subsequent extensional tectonics (e.g. Carmignani et al. 1994; Jolivet et al. 1998; Brunet et al. 2000). According to Bertini et al. (1991), Carmignani et al. (1994) and Liotta et al. (1998), in the inner Northern Apennines (i.e. northern Tyrrhenian Basin and southern Tuscany) the extensional tectonics started in the Early–Middle Miocene and produced thinning of the continental crust down to 22 km (Decandia et al. 1998, and references therein).

The Rapolano Terme area is located in southern Tuscany (Figs. 1 and 2) and it is characterised by widespread extensional structures related to the Pliocene–Quaternary extensional tectonics (Brogi et al. 2002). The Rapolano Terme area exposes pre-Neogene rocks belonging to non-metamorphic Tuscan succession (Lazzarotto 1973), deformed during the Northern Apennines tectogenesis, and Pliocene–Holocene post-orogenic deposits (Losacco, 1952) (Fig. 3). The pre-Neogene rocks are characterised by the Late Triassic–Early Miocene Tuscan succession (see figure 3 for keys): “Calcari a *Rhaetavicula contorta*” Fm. (Rhaetian) (Cre), “Calcare Massiccio” Fm. (Hettangian) (Mas), “Calcare Selcifero” Fm. (Middle–Late Lias) (Sel), “Calcare Rosso ammonitico” Fm. (Late Lias) (Rsa), “Marne a *Posidonomya*” Fm. (Dogger) (Pod), “Diaspri” Fm. (Malm) (Rad), “Maiolica” Fm. (Early Cretaceous) (Mai), “Scaglia Toscana” Fm. (Cretaceous–Oligocene) (Sca) and “Macigno” Fm. (Late Oligocene–Early Miocene) (Mac). The Neogene deposits are characterised by Early–Middle Pliocene marine sediments (sands (Ps), clays (Pa) and gravels (Pc)) and Pleistocene–Holocene continental sediments (travertines (Tr), sands, clays, gravels (Dq)).

In the Rapolano area the travertines cover about 14 km^2 and are up to 50 m thick (Brogi et al. 1999). They are intensely quarried for ornamental stone, mainly in the Serre di Rapolano area (Fig. 4). The travertines, Pleistocene and Holocene in age (Carrara et al. 1998), are deposited by hot fluids issuing from thermal springs and flowing into adjacent morphological depressions. They are deposited in palustrine and fluvio-lacustrine environments, and in thin water layers running off slopes. Varying depositional geometries characterise these carbonate rocks: tabular and fan-slope bodies, fissure ridges, terraced mounds, cones and waterfall deposits (Guo & Riding 1992, 1994, 1996).

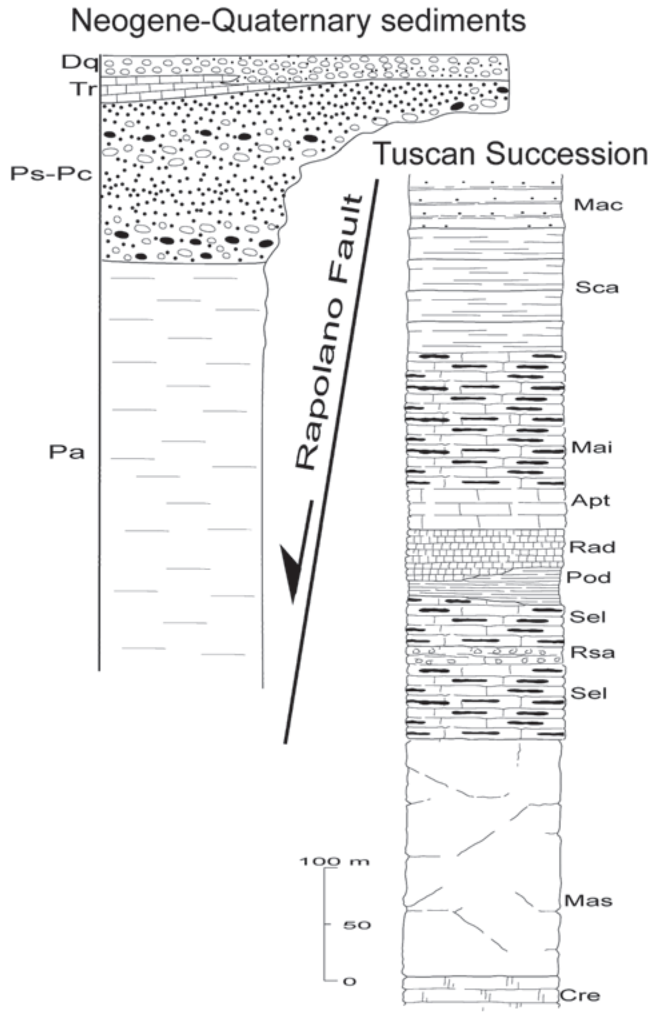

Fig. 3. Tectonic and stratigraphic relationships among the Neogene-Quaternary sediments and Tuscan succession exposed in the Rapolano area. For symbols see the text.

Structural setting of the Rapolano Terme area

Different generations of deformation features have been recognised in the rock succession cropping out in the Rapolano area. Early structures affected only the pre-Neogene (Late Triassic–Early Miocene) rocks of the Tuscan succession. The latter were involved in large-scale east-verging folds, mainly NNW–SSE oriented, as described in Brogi et al. (2002)

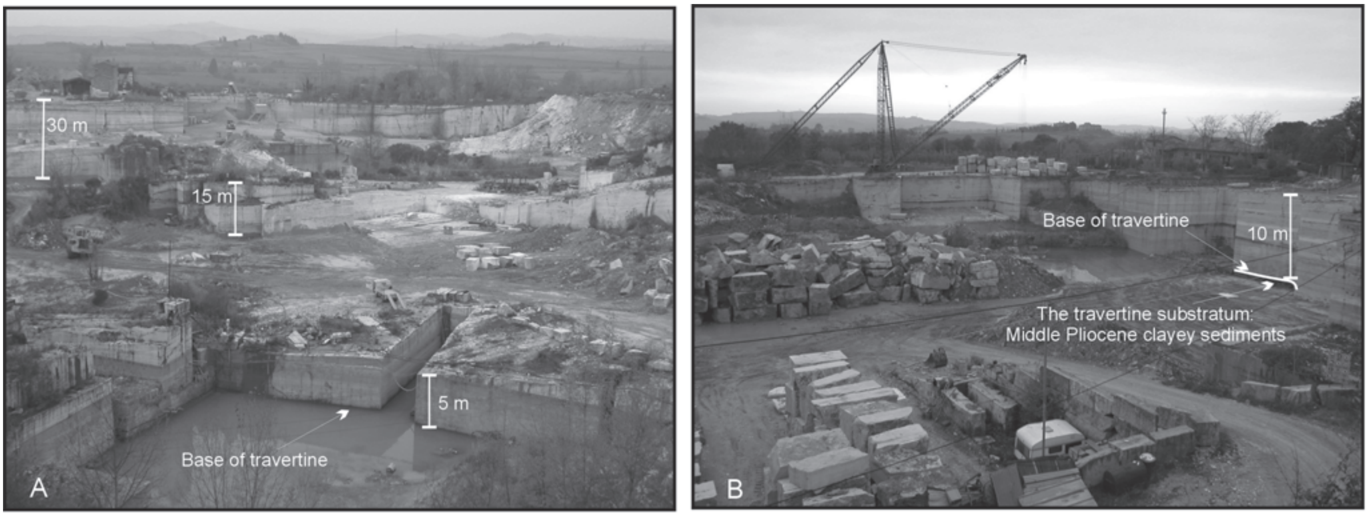

Fig. 4. Travertines are intensely quarried, mainly for ornamental purposes. The quarries are mainly located in the Serre di Rapolano area (A and B) and have been worked since the Etruscan period. The travertine deposits cover about 14 km^2 and are up to 50 m thick (A). The travertine substratum, consisting of Middle Pliocene marine clay, locally crops out in some quarries.

Tab. 1. Structural data collected in the "S. Alberto" quarry.

Location	Strike and dip	Pitch	Deformed rocks	Kinematics	Age
Quarry1	N10 60ESE		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N15 80WNW	90°	Calcare Selcifero	normal fault	Early-Middle Pliocene
Quarry1	N20 50ESE		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N170 55W		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N165 70W		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N140 60NE	90°	Calcare Selcifero	normal fault	Early-Middle Pliocene
Quarry1	N150 70SW		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N152 65SW		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N50 80NW	25°	Calcare Selcifero	right-hand transtensional fault	Early-Middle Pliocene
Quarry1	N155 89SW	90°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry1	N165 70NE	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry1	N180 80W		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N180 70W	75°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry1	N174 60W	80°	Calcare Selcifero	normal fault	Early-Middle Pliocene
Quarry1	N170 62W		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N163 70NE	85°	Calcare Selcifero	normal fault	Early-Middle Pliocene
Quarry1	N165 75W		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N60 80NW		Calcare Ros. Amm.		Early-Middle Pliocene
Quarry1	N140 85NE	85°	Calcare Selcifero	normal fault	Early-Middle Pliocene
Quarry1	N140 80SW		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N30 64WNW	70°	Calcare Selcifero	normal fault	Early-Middle Pliocene
Quarry1	N45 75NW	50°	Calcare Selcifero	right-hand transtensional fault	Early-Middle Pliocene
Quarry1	N142 75SW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N145 89SW		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N20 75WNW	40°	Calcare Selcifero	left-hand transtensional fault	Early-Middle Pliocene
Quarry1	N10 48W	75°	Calcare Selcifero	normal fault	Early-Middle Pliocene
Quarry1	N50 70NW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N70 85NW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N60 80NW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N60 70NW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N63 75NW		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N85 60N		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N140 75NE		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N90 89N		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N95 75S		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N40 72SE	15°	Calcare Massiccio	left-hand transtensional fault	Early-Middle Pliocene
Quarry1	N58 80NW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N85 85S		Calcare Massiccio		Early-Middle Pliocene

Tab. 1. Structural data collected in the "S. Alberto" quarry.

(Continue)

Location	Strike and dip	Pitch	Deformed rocks	Kinematics	Age
Quarry1	N90 88S		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N70 80NW		Calcare Massiccio		Early-Middle Pliocene
Quarry1	N45 72NW	20°	Calcare Selcifero	left-hand transtensional fault	Early-Middle Pliocene
Quarry1	N45 80SE		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N50 85NW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N60 70SE	30°	Calcare Selcifero	left-hand transtensional fault	Early-Middle Pliocene
Quarry1	N65 65NW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N175 65W		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N160 60 SW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N145 60SW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N150 60SW		Calcare Selcifero		Early-Middle Pliocene
Quarry1	N50 80NW	80°	Calcare Selcifero	normal fault	Quaternary
Quarry1	N50 75NW	75°	Calcare Selcifero	normal fault	Quaternary
Quarry1	N52 80NW	90°	Calcare Selcifero	normal fault	Quaternary
Quarry1	N35 75NW	85°	Calcare Selcifero	normal fault	Quaternary
Quarry1	N90 90	90°	Calcare Selcifero	normal fault	Quaternary
Quarry1	N95 80S	80°	Calcare Selcifero	normal fault	Quaternary
Quarry1	N85 85S	85°	Calcare Selcifero	normal fault	Quaternary
Quarry1	N85 65N	75°	Calcare Selcifero	normal fault	Quaternary
Quarry1	N130 75NE	90°	Calcare Selcifero	normal fault	Quaternary

Tab. 2. Structural data collected in the "Madonnino dei Monti" quarry.

Location	Strike and dip	Pitch	Deformed rocks	Kinematics	Age
Quarry2	N45 75SE	15°	Calcare Rhaet cont	Right-hand transtensional fault	Early-Middle Pliocene
Quarry2	N150 46SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N140 90		Calcare Rhaet cont		Early-Middle Pliocene
Quarry2	N150 52SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N50 68NW	35°	Calcare Massiccio	left-hand transtensional fault	Early-Middle Pliocene
Quarry2	N55 73NW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N40 49SE	25°	Calcare Rhaet cont	Right-hand transtensional fault	Early-Middle Pliocene
Quarry2	N130 65SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N140 84SW	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N126 78SW	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N160 73NE	65°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N125 60SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N160 71NE	70°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N155 80SW	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N168 65NE	70°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N140 52SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N158 36SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N170 36W		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N142 52SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N180 60W	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N180 46W	75°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N162 65NE		Calcare Rhaet cont		Early-Middle Pliocene
Quarry2	N170 63E	70°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N162 52NE		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N146 85SW	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N154 66SW	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N155 64SW	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N154 75SW	90°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N142 45SW		Calcare Rhaet cont		Early-Middle Pliocene
Quarry2	N130 54SW	90°	Calcare Rhaet cont	normal fault	Early-Middle Pliocene
Quarry2	N125 78SW	80°	Calcare Rhaet cont	normal fault	Early-Middle Pliocene
Quarry2	N149 80SW	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N175 80NE		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N180 63W		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N175 85W	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N174 36W		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N169 59SW		Calcare Rhaet cont		Early-Middle Pliocene
Quarry2	N172 49W	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N175 49W		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N170 49W		Calcare Massiccio		Early-Middle Pliocene

Tab. 2. Structural data collected in the "Madonnino dei Monti" quarry.

(Continue)

Location	Strike and dip	Pitch	Deformed rocks	Kinematics	Age
Quarry2	N170 50W		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N170 55W	70°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N165 50SW	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N170 55W		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N174 49W		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N165 45SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N85 70S	35°	Calcare Massiccio	left-hand transtensional fault	Early-Middle Pliocene
Quarry2	N80 80S	35°	Calcare Rhaet cont	left-hand transtensional fault	Early-Middle Pliocene
Quarry2	N40 75SE	10°	Calcare Rhaet cont	left-hand transtensional fault	Early-Middle Pliocene
Quarry2	N45 70SE		Calcare Rhaet cont		Early-Middle Pliocene
Quarry2	N55 70NW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N60 60NW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N55 70NW	75°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N150 60SW	80°	Calcare Rhaet cont	normal fault	Early-Middle Pliocene
Quarry2	N155 65SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N150 75SW	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N140 45SW		Calcare Rhaet cont		Early-Middle Pliocene
Quarry2	N133 55SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N120 50SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N135 45SW	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N140 80SW	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N126 70SW		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N170 50W	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N165 70SW	70°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry2	N170 65W		Calcare Rhaet cont		Early-Middle Pliocene
Quarry2	N170 55W	90°	Calcare Rhaet cont	normal fault	Early-Middle Pliocene
Quarry2	N174 59W		Calcare Massiccio		Early-Middle Pliocene
Quarry2	N30 90	85°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N35 90		Calcare Rhaet cont		Quaternary
Quarry2	N80 60N	90°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N60 50NW	80°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N50 90	85°	Calcare Rhaet cont	normal fault	Quaternary
Quarry2	N45 75SE	85°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N55 70SE	90°	Calcare Rhaet cont	normal fault	Quaternary
Quarry2	N70 80SE	90°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N60 70NW	90°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N65 75NW	85°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N80 90		Calcare Massiccio		Quaternary
Quarry2	N55 50NW	85°	Calcare Rhaet cont	normal fault	Quaternary
Quarry2	N65 80NW	80°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N50 65NW	90°	Calcare Rhaet cont	normal fault	Quaternary
Quarry2	N55 85NW	80°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N70 85NW	90°	Calcare Massiccio	normal fault	Quaternary
Quarry2	N65 75NW	85°	Calcare Rhaet cont	normal fault	Quaternary

Tab. 3. Structural data collected in the "Montefollonico" quarry.

Location	Strike and dip	Pitch	Deformed rocks	Kinematics	Age
Quarry3	N70 80SE	20°	Calcare Massiccio	right-hand transtensional fault	Early-Middle Pliocene
Quarry3	N50 90	5°	Calcare Massiccio	left-hand transtensional fault	Early-Middle Pliocene
Quarry3	N80 85S	15°	Calcare Massiccio	right-hand transtensional fault	Early-Middle Pliocene
Quarry3	N10 75W	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry3	N25 85NW	85°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry3	N175 85W	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry3	N170 80E	80°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry3	N168 80E		Calcare Massiccio		Early-Middle Pliocene
Quarry3	N170 90		Calcare Massiccio		Early-Middle Pliocene
Quarry3	N165 65SW	90°	Calcare Massiccio	normal fault	Early-Middle Pliocene
Quarry3	N165 68SE		Calcare Massiccio		Early-Middle Pliocene
Quarry3	N160 75NE		Calcare Massiccio		Early-Middle Pliocene
Quarry3	N162 70NE		Calcare Massiccio		Early-Middle Pliocene
Quarry3	N145 70NE		Calcare Massiccio		Early-Middle Pliocene
Quarry3	N75 75SE	85°	Calcare Massiccio	normal fault	Quaternary
Quarry3	N65 85SE	90°	Calcare Massiccio	normal fault	Quaternary

Tab. 4. Structural data collected in the "Riccia" quarry.

Location	Strike and dip	Pitch	Deformed rocks	Kinematics	Age
Quarry4	N80 85S	20°	Diaspri	left-hand transtensional fault	Early-Middle Pliocene
Quarry4	N30 80NW	90°	Diaspri	normal fault	Early-Middle Pliocene
Quarry4	N20 75WNW	85°	Diaspri	normal fault	Early-Middle Pliocene
Quarry4	N5 85W	75°	Diaspri	normal fault	Early-Middle Pliocene
Quarry4	N180 75E		Diaspri		Early-Middle Pliocene
Quarry4	N1 75E	75°	Diaspri	normal fault	Early-Middle Pliocene
Quarry4	N165 75ENE		Diaspri		Early-Middle Pliocene
Quarry4	N170 80ENE		Diaspri		Early-Middle Pliocene
Quarry4	N65 80SE	90°	Diaspri	normal fault	Quaternary

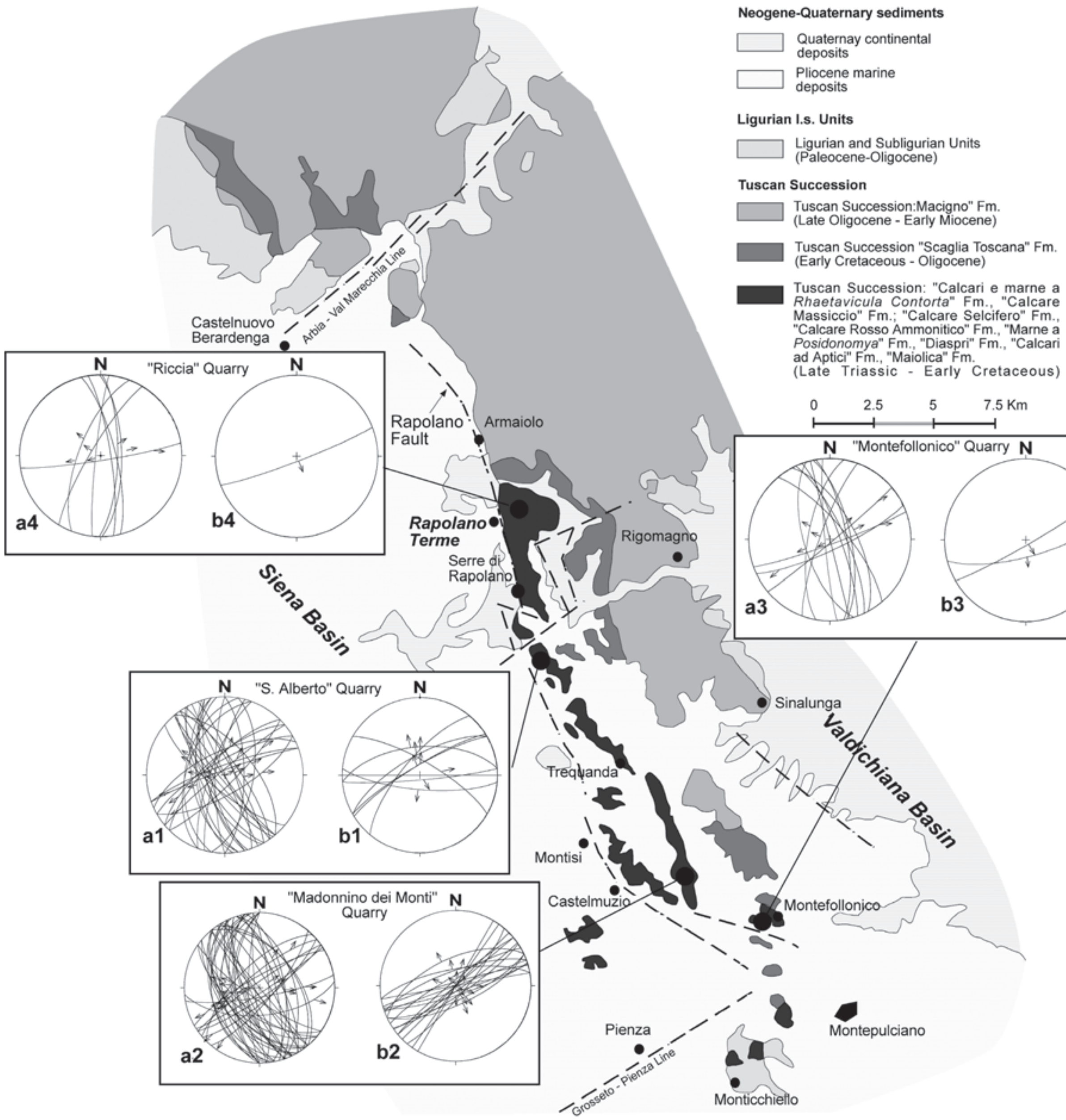

Fig. 5. Geological sketch map of the Rapolano Terme area, and stereonets (Schmidt diagram, lower hemisphere) showing structural data on faults collected in four quarries where Mesozoic carbonatic rocks belonging to the Tuscan succession are exposed. a and b diagrams show cyclographic and pitch of the faults (the arrows indicate the hangingwall movement) belonging to the first (a) and second (b) fault populations. a1 (49 data) and b1 (9 data) were collected in the "S. Alberto" quarry; a2 (66 data) and b2 (17 data) were collected in the "Madonnino dei Monti" quarry; a3 (14 data) and b3 (2 data) were collected in the "Montefollonico" quarry; a4 (7 data) and b4 (1 data) were collected in the "Riccia" quarry.

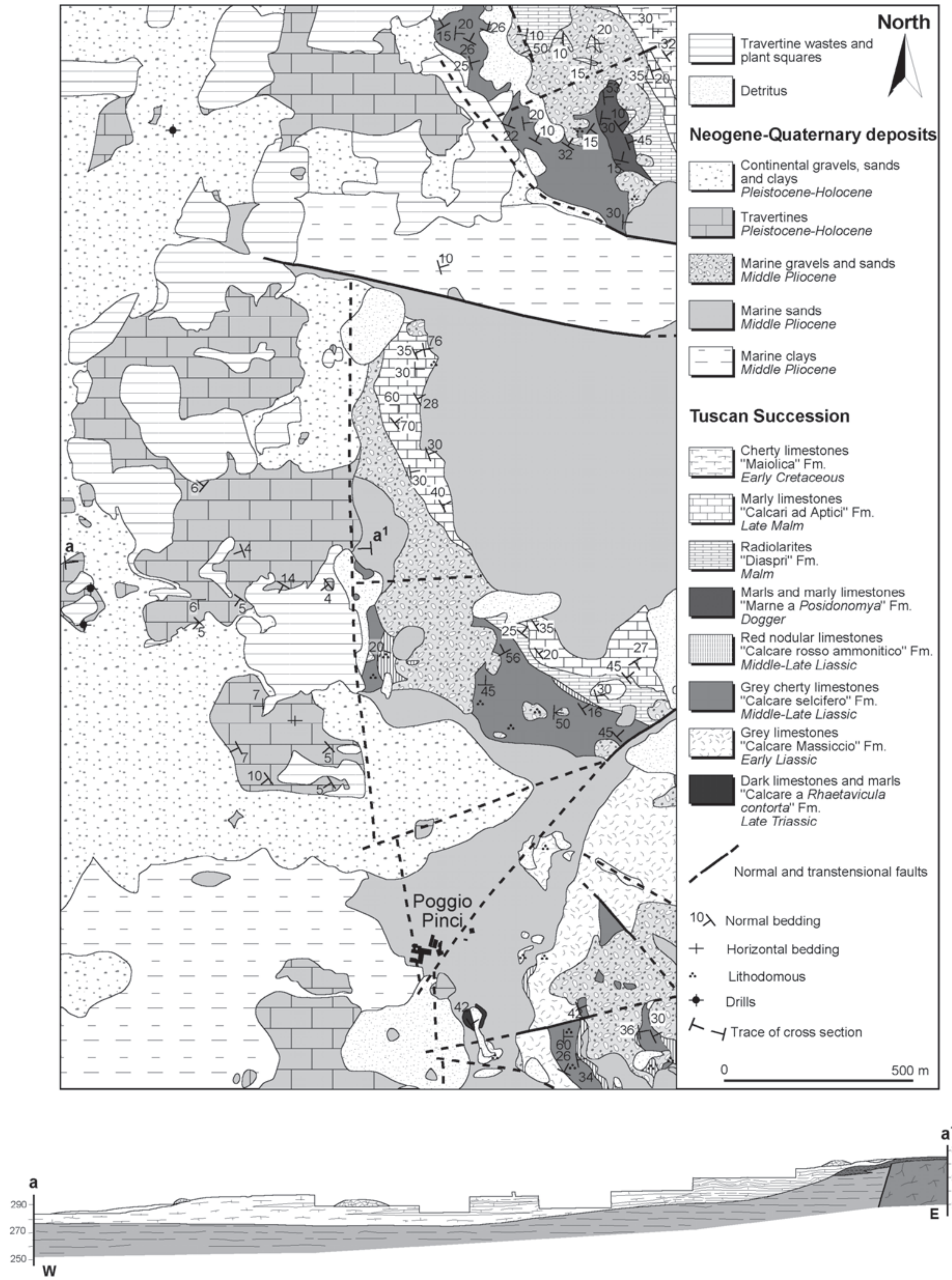

Fig. 6. Detailed geological sketch-map of the travertine deposits cropping out south of Serre di Rapolano, corresponding to the black rectangle shown in figure 2. (From Brogi et al. 1999, redrawn).

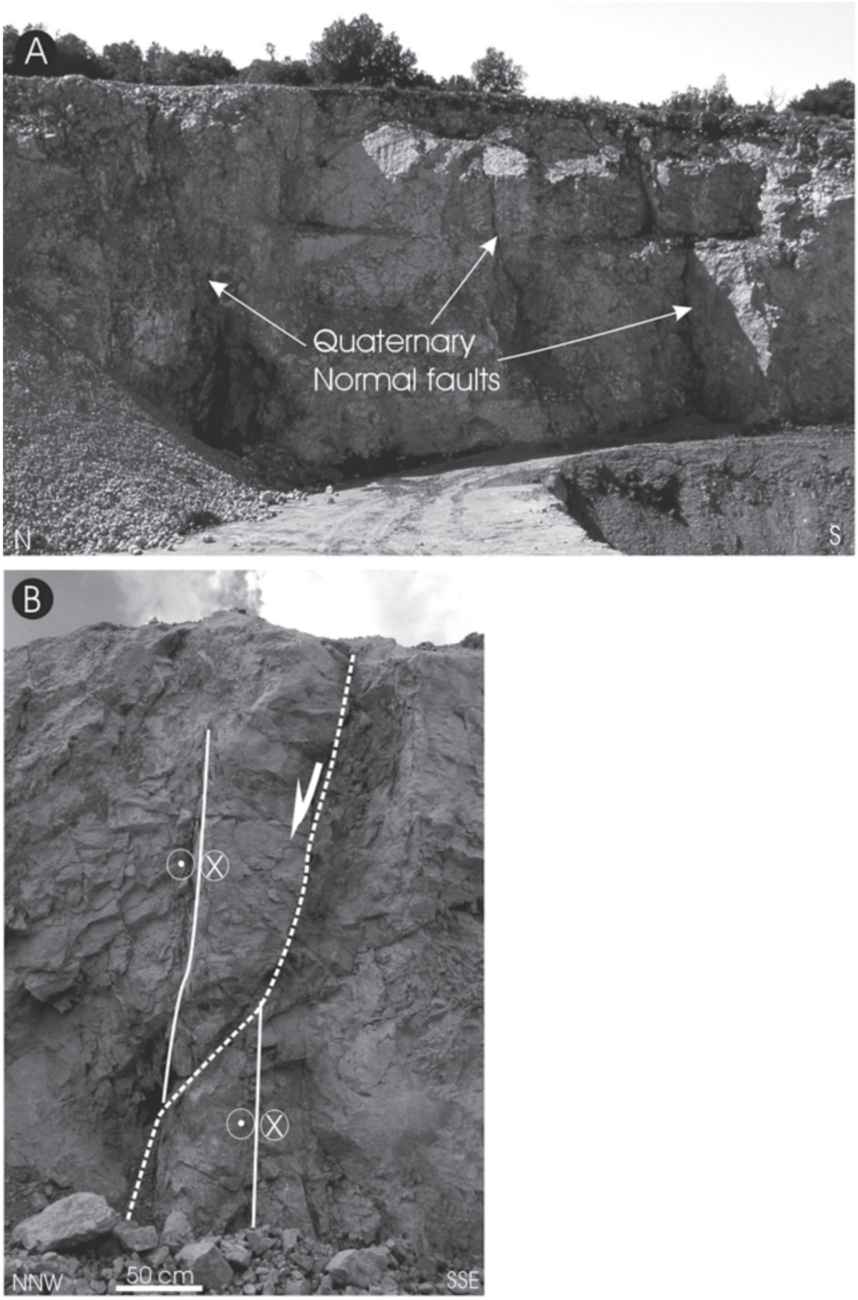

Fig. 7. SW-NE striking normal faults belonging to the second fault population. A) Sub-vertical normal faults affecting the "Calcare Massiccio" Fm. in the "S. Alberto" quarry; B) Sub-vertical normal fault affecting the "Calcare Massiccio" Fm. in the "Madonnino dei Monti" quarry, displacing a left-hand strike-slip fault belonging to the first fault population.

and Aquè & Brogi (2002). On the whole, the pre-Neogene rocks and the Neogene–Quaternary sediments were involved in brittle deformation consisting of normal and transtensional faults, Pliocene to Quaternary in age. These faults are characterised by two main populations: the first one is composed of NNW–SSE and SW–NE striking normal and transtensional faults, while the second is mainly composed of SW–NE oriented normal faults (tables 1,2,3 and 4). The structural analysis has mainly been carried out in some quarries where Mesozoic carbonate rocks of the Tuscan succession are exposed (Fig. 5). The broad exposures highlighted the relationships between the two fault populations mainly inferred by the superimposition of kinematic indicators, such as slickensides, calcite fibre growth and fracture systems associated with the fault zones (e.g. Hancock 1985; Petit 1987).

First fault population.

These faults are characterised by dip-slip (pitch ranging from 60° to 90°) and strike-slip (pitch ranging from 5° to 30°) striations, corresponding to normal and dextral or sinistral strike- to oblique-slip kinematics, respectively (tables 1, 2, 3 and 4).

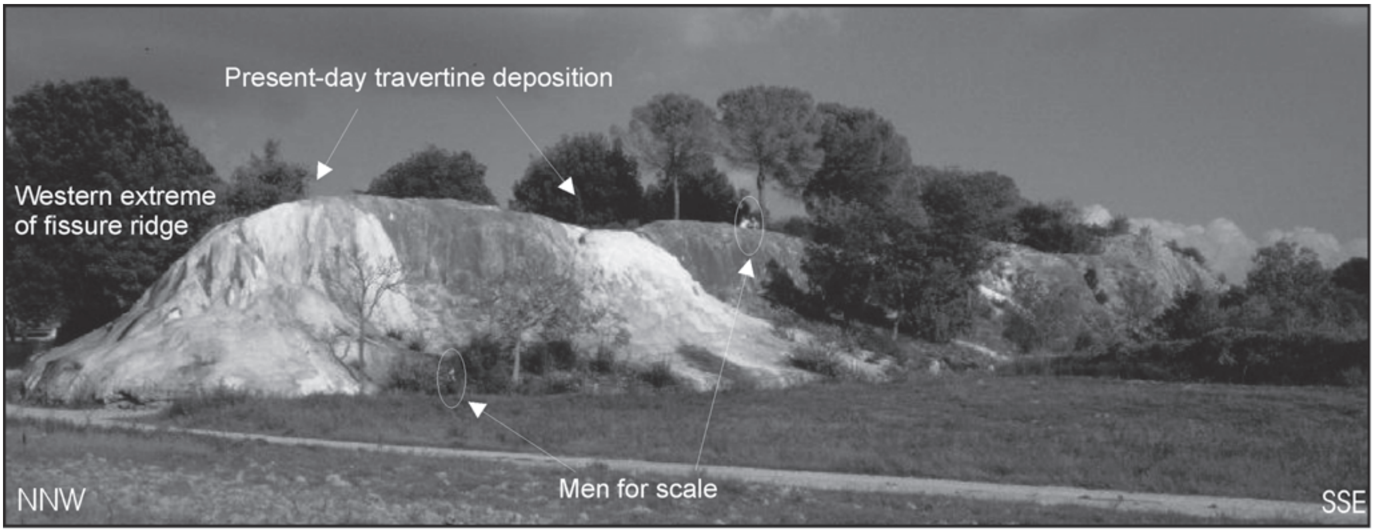

Fig. 8. Fissure-ridge cropping out in the "Terme di S. Giovanni" (Rapolano Terme). This structure, W–E striking, is related to a normal fault of the second fault population. It is around 200 m long and 15 m thick. At the top of the ridge a continuous fissure, up to 30 cm wide, occurs. Thermal springs are located along the fissure and their capacity is up to 5 litres per minute.

These faults are the most evident brittle structures of the Rapolano area. A main regional NNW–SSE normal fault occurs in the study area. This is the Rapolano Fault which locally separates the Pliocene marine sediments infilling the Siena Pliocene Basin from the Triassic–Cretaceous formations of the Tuscan succession (Figs. 2 and 5). The Rapolano Fault can be traced in the field for about 10 km (Brogi et al. 1999) and it is characterised by along-strike different offset: around 1000 metres in the northern part and around 600 metres in the southern part (Costantini et al. 1982). Localized along the trace of this major fault are Pleistocene–Holocene travertine deposits and present-day thermal springs. The Rapolano Fault is locally buried by Middle Pliocene sandy marine deposits and Pleistocene continental clayey-sandy-gravelly and carbonatic (travertine) deposits (Fig. 6). Minor faults are associated with the Rapolano Fault. Some of these are SW–NE striking and show vertical or oblique slickensides (pitch ranging from 5° to 30°) and calcite fibre growth (strike- and oblique-slip with right- and left-lateral kinematics). These latter have been considered as transfer faults (Gibbs 1984) associated with the development of the Pliocene Siena Basin (Liotta 1991). In fact, such faults were also buried by Middle Pliocene marine deposits, attesting to the end of their tectonic activity by this time (Fig. 6).

Second fault population.

These faults are characterised by dominantly dip-slip displacements (pitch ranging from 70° to 90°) kinematic indicators showing vertical or subvertical displacements (normal faults) (tables 1, 2, 3 and 4). These faults show kinematic indicators superimposed on those related to the first population of faults, suggesting more recent tectonic activity (Fig. 7). The same relationship between the two fault populations is highlighted by map-scale analysis. In fact, the second population normal faults displace both the Rapolano Fault and the Middle Pliocene marine deposits that bury it (Fig. 6).

Normal faults and travertines relationships

Travertines and thermal springs occurring in the Rapolano Terme area are mainly aligned along the Rapolano Fault, but they are preferentially located at the intersection points with the SW-NE striking normal faults of the second population (Fig. 2). In fact, the most important travertine outcrops are located where the Rapolano Fault was displaced by the youngest normal fault systems. Other travertines occur away from the trace of the Rapolano Fault but, in any case, their occurrence corresponds to the intersection points between the NNW–SSE oriented faults belonging to the first fault population and the SW–NE oriented faults of the second fault population. In other cases, present-day thermal springs and related travertines are associated with the SW–NE oriented faults of the second population. This is the case with the SW–NE travertine fissure ridge occurring in the "Terme di S. Giovanni" area (1 km SW of Rapolano) (Fig. 8). This ridge, 200 m long and W–E oriented, is associated with a normal fault displacing, at the surface, the Middle Pliocene marine deposits (Brogi et al. 1999). Travertine deposition (Guo & Riding 1992, 1994, 1996, 1998) occurs at the western and eastern margins of the ridge. At the top of the ridge a continuous fissure occurs, corresponding to the fault trace, and active thermal springs are aligned along the fissure mainly at the western and eastern extremities of the ridge (Fig. 9).

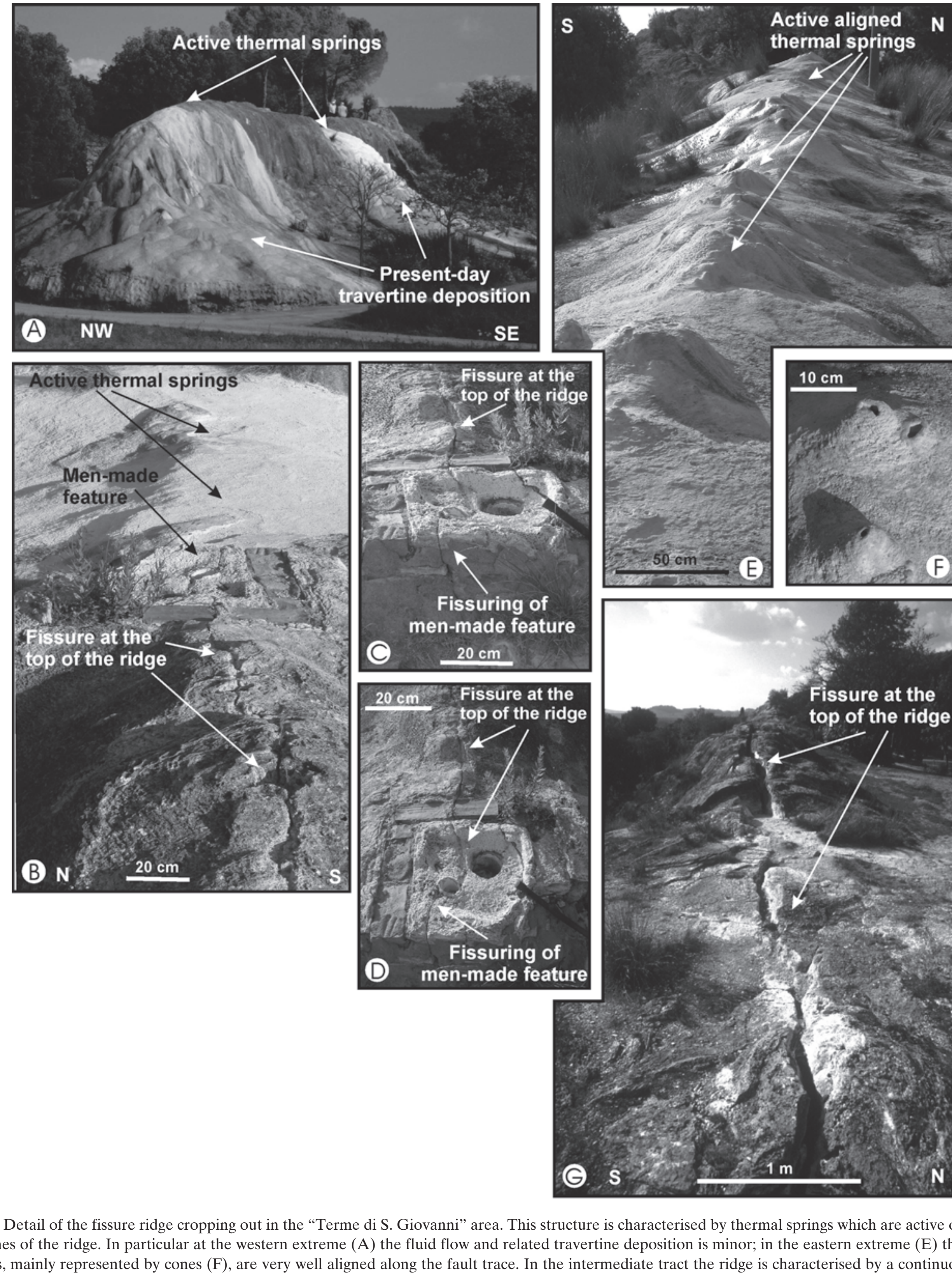

Fig. 9. Detail of the fissure ridge cropping out in the "Terme di S. Giovanni" area. This structure is characterised by thermal springs which are active only at the extremes of the ridge. In particular at the western extreme (A) the fluid flow and related travertine deposition is minor; in the eastern extreme (E) the thermal springs, mainly represented by cones (F), are very well aligned along the fault trace. In the intermediate tract the ridge is characterised by a continuous fissure along which gas vents occur (G). The present-day opening of the fissure is attested by fissuring of a man-made feature located at the top of the ridge in proximity to its western extreme (B). The structure, composed of some bricks and one block of travertine, is an old (built in 1960) base for a street-lamp, and is involved in the fissuring (C and D).

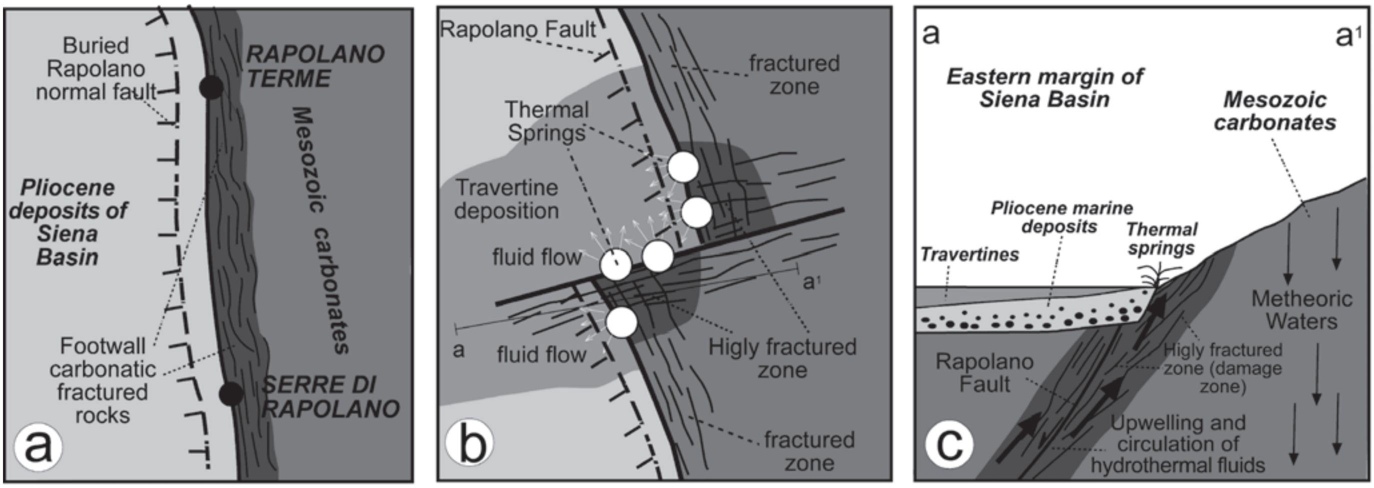

Fig. 10. Sketch showing the geometrical relationships between the faults related to the two different fault populations, and the interaction between fault geometry, damage zones, and fluid circulation and upwelling. As documented in the Rapolano Terme area, travertines and present-day thermal springs are located where the NNW–SSE striking Early–Middle Pliocene normal faults are displaced by SW–NE striking Pleistocene normal faults, or along the latter faults (e.g. the "Terme di S. Giovanni" fissure ridge). In this hypothesis the hydrothermal fluid upwelling is associated with the intense damage zones developed in the Mesozoic carbonatic rocks cropping out in the Rapolano Terme area, mainly occurring where Pleistocene normal faults crossed or were superimposed on Pliocene normal and/or transtensional faults.

Discussion

The present-day thermal springs and travertines occurring in the Rapolano Terme area have mainly been related, by some authors, to the Pleistocene activity of the Rapolano Fault (Hancock et al. 1999), because both the thermal springs and the Pleistocene–Holocene travertines are aligned along this regional structure, NNW-SSE striking. The Pleistocene age of the Rapolano Fault is not supported by any evidence highlighted through this new structural study. In fact, tectono-stratigraphical relationships of the Pliocene–Quaternary deposits and the kinematics of the faults revealed an articulated tectonic evolution of the extensional structures during the Pliocene and Pleistocene. Two contrasting factors characterise the Rapolano Fault: (a) this normal fault was buried by Middle Pliocene marine sandy and gravelly deposits and by Pleistocene–Holocene continental sediments; (b) present-day thermal springs and Pleistocene–Holocene travertines occur along the Rapolano Fault. On the basis of point (a), the age of the Rapolano Fault cannot be younger than Middle Pliocene, but on the basis of point (b) age and location of thermal springs and travertines suggest a Pleistocene–Holocene activity for the Rapolano Fault. This study can contribute to solve this apparently complicated picture. In fact, the Rapolano Fault belongs to the oldest fault population, which can be ascribed to the Early–Middle Pliocene, as attested to by tectono-stratigraphical relationships (Fig. 3). This fault was coeval with the development of the Siena Basin. The hydrothermal activity occurred (Pleistocene–Holocene) and occurs (at the present-day) where the Rapolano Fault, or associated faults, were cut by the faults of the second population, and along these latter. This evidence suggests that the hydrothermal fluid circulation and upwelling has been related to the sub-vertical damage zones associated with the SW–NE striking normal faults of the second population, and reactivation of some older faults. In particular, the emergence of hydrothermal fluids has been favoured by the intense damage zones occurring at the intersection points between the Pleistocene SW–NE striking faults and the Rapolano Fault (Fig. 10) and, probably, to the fact that the SW-NE striking faults were steeply dipping and, consequently, their damage zones provided deep-reaching permeable conduits to be utilised by fluid upwelling.

The Pleistocene extensional tectonics can be related to a late extensional tectonic phase taking place after the Siena Basin development. Extensional tectonics during Pleistocene times affected the easternmost Valdichiana Basin and has been demonstrated also in the study area. However, important extensional activity during the Quaternary typified some areas of southern Tuscany, as well as the Mt. Amiata region (around 50 km south of the Rapolano Terme area) and northern Latium, causing localised volcanic activity (Ferrari et al. 1996 and references therein; Peccerillo et al. 2001; Acocella & Funiciello 2002; Peccerillo 2002).

Conclusions

Early–Middle Pliocene and Quaternary extensional tectonics have been documented in the Rapolano Terme area. The Pleistocene–Holocene travertines and present-day thermal springs are related to Quaternary normal faults, mainly SW–NE striking, and reactivated Early–Middle Pliocene normal and transfer faults, associated with the development of the Siena Basin (e.g. Rapolano Fault). The circulation and upwelling of hydrothermal fluids during the Pleistocene and at the present day is mainly concentrated along the damage zones at the intersections between the Early–Middle Pliocene Rapolano Fault and the Pleistocene SW–NE striking normal faults. Hydrothermal occurrences are also documented along SW–NE Pleistocene faults.

In accordance with the authors which hypothesise that extensional tectonics affected the Northern Apennines since the Early-Middle Miocene (Jolivet et al. 1990; Bertini et al. 1991; Carmignani et al. 1994; Liotta et al. 1998), the Quaternary extensional tectonics could be attributed to a late event following the widespread Pliocene extensional activity which caused the development of the Tuscan Neogene basins, and can be related to differentiated vertical movement of the southern Tuscany continental crust which is associated with the uplift affecting the inner Northern Apennines (Bartolini et al. 1983; Pasquarè et al. 1983; Dallmayer et al. 1995; Dallmayer & Liotta 1998).

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