THÈSE

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par

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Identification et caractérisation des structures sismogènes des Apennins (Italie): Analyse conjointe (tectonique et géodésie) des déformations de la croûte terrestre à diverses échelles temporelles

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To my daughter

Viola

the best future I could ever dream

Résumé de Thèse de Paolo Marco De Martini

Identification et caractérisation des structures sismogènes des Apennins (Italie):

Analyse conjointe (tectonique et géodésie) des déformations de la croûte terrestre à diverses échelles temporelles

Les méthodes d'identification des failles actives et notamment l'évaluation de leur potentiel sismogène sont marquées par des incertitudes et par la diversité des interprétations. Des études récentes ont montré la persistance des difficultés de mise en évidence des structures actives lorsque les déformations récentes se superposent aux épisodes tectoniques anciens. Ces observations sont d'autant plus évidentes en ce qui concerne la chaîne montagneuse des Apennins d'Italie ou chaque faille active présente une vitesse de déformation ≤ 1.0 mm/an et une période moyenne de récurrence de 1 à 5 ka. Ces observations sont attestées par le caractère de faille «cachée» ou «aveugle» de plusieurs structures actives de la péninsule italienne telles que celles de Messine, Friuli, Irpinia, Val Comino, Gubbio, Colfiorito et Molise.

Les travaux qui sont présentés dans cette thèse s'attachent à traiter des problèmes des failles actives des Apennins. Ces problèmes se déclinent comme suit:

1. La déformation active dans les Apennins qui inclus les mouvements tectoniques aux abords des failles est souvent oblitérée par l'activité humaine (agriculture), le fort taux d'érosion conditionné par les effets climatiques qui conduit souvent à des interprétations erronées, et l'interférence avec les structures géologiques anciennes.

2. Les mouvements verticaux qui dominent le style tectonique des Apennins requièrent l'utilisation des profiles géodésiques (durant au moins le dernier siècle d'observation) conventionnels bien meilleurs que les mesures de géodésie spatiale lorsqu'il s'agit des mesures des composantes verticales.

3. Les études sur les failles actives et leurs implications sur l'évaluation de l'aléa sismique nécessitent l'utilisation d'une approche multidisciplinaire en géologie, géodésie et sismologie pour la caractérisation de structures sismogènes et le calcul de l'aléa et du risque sismiques.

Dans ce travail, nous traitons ces problèmes et apportons des réponses à l'aide de plusieurs cas d'étude des zones sismogènes des Apennins. Plusieurs de nos publications dans des revues internationales (de rang A) étayent nos observations, mesures et analyses (voir liste ci-dessous).

Cette thèse se compose de 7 chapitres:

- Le chapitre 1 présente les caractéristiques sismotectoniques des Apennins et leur évolution tectonique récente. Les structures tectoniques majeures des Apennins subdivisées en régions distinctes (Nord Apennins, Apennins centraux et Sud Apennins) définies par: a) la sismicité historique et instrumentale, b) le champ de contrainte actuel, et c) les failles actives identifiées. Nous utiliserons également les caractéristiques de l'aléa sismique de la péninsule italienne dans l'analyse des zones actives.

- Le chapitre 2 résume en premier lieu les méthodes utilisées et les notions fondamentales en tectonique active, sismotectonique et géodésie des zones actives. Les aspects théoriques de la déformation active (sismique) sont combinés aux principes de cycle sismique. Nous présentons également une courte introduction de la tectonique active et la géologie des tremblements de terre telle que développée durant les dernières décennies. Un exemple d'étude d'une région en Iran à fort potentiel sismique (Faille de Kahrizak) près de Téhéran (De Martini et al., 1998). D'autre part, le cas d'une étude paléosismologique dans une zone dite stable en Australie marque les limites des méthodes utilisées et la complexité des zones actives (Crone et al., 2003). Des éléments de comparaison aux failles normales des Apennins sont présentés par une étude de la faille d'Atalanti (Grèce centrale; Pantosti et al., 2004).

Cette présentation comporte également dans une deuxième partie les techniques du nivellement et l'histoire des réseaux géodésiques en Italie. Les marges d'erreur et précision sont mises en évidence afin de montrer les aspects qualitatifs de nos mesures des réseaux de nivellement centenaire des Apennins (article D'Anastasio et al., 2006). L'analyse des résultats est associée aux modèles des mouvements pré-sismiques, co-sismiques et des déplacements post-sismiques.

Une troisième partie explique par des illustrations et argumentation l'utilité de l'utilisation des réseaux géodésiques anciens combinés aux études de tectonique active et analyse de la sismicité pour mieux comprendre: i - les processus de déformation (pré-sismique, co-sismique, post-sismique et inter-sismique), et ii - les déformations à grande échelle. Une comparaison des déformations à court terme et à long terme nous permet de contraindre les caractéristiques géométriques et de comportement des failles actives des Apennins.

- Le chapitre 3 expose les évidences des déplacements pré-sismiques et asismiques le long des failles normales actives. Les mesures géodésiques à travers la zone sismique de l'Umbria-Marche lieu de la séquence sismique de 1997-98 montrent les mouvements pré-sismiques sur une rupture aveugle (De Martini & Valensise, 1999). Les évidences géodésiques des mouvements asismiques sur la faille normale de Amatrice avec l'absence de sismicité et des mouvements progressifs en surface posent le problème des failles silencieuses.

- Le chapitre 4 décrit les évidences de déplacements co-sismiques le long des failles normales par le biais des mesures géodésiques et géologiques. Les profiles de nivellement réoccupés suite à la séquence sismique de l'Umbria-Marche de 1997-98 conduisent à une meilleure détermination des paramètres de la source sismique et de la répartition des déplacements co-sismiques (De

Martini et al, 2003). La variation des taux de déformation le long des ruptures normales aveugles durant la séquence sismique et l'analyse conjointe avec modélisation des déformations de surface par le biais de l'InSAR nous a permis de mieux localiser les branches de failles (Stramondo et De Martini, 2004). Les évidences géologiques des failles actives et sismogènes sont compilées des divers travaux de paléosismologie auxquels nous avons contribué et qui montrent la relation entre les déformations à court terme et celles à long terme des Apennins (Pantosti et al., 1999).

- Le chapitre 5 traite des mesures géodésiques de la zone active de la plaine intra montagneuse du Fucino, site du séisme majeur de 1915. La répétition de ces mesures et la mise en évidence des mouvements (et la modélisation) indiquent l'apparition d'une déformation post-sismique probablement liée à des mouvements de relaxation associés à la tectonique crustale (Amoruso et al., 2005).

- Le chapitre 6 décrit les mouvements verticaux de grande longueur d'onde durant les derniers 50 et 100 ans par les données géodésiques combinés aux évidences géologiques des paléo rivages (D'Anastasio et al., 2006; Mancini et al., 2007). L'analyse conjointe des données géodésiques, géologiques-tectoniques (paléosismologie) et sismologiques permet de mieux contraindre les déformations inter-sismiques. L'étude de la déformation active à différentes fenêtres de temps et la comparaison du signal géodésique avec les caractéristiques de la déformation à long terme extraites de la géomorphologie quantitative permet une meilleure détermination du cycle sismique dans les Apennins.

- Le chapitre 7 résume les principaux résultats obtenus au cours de nos études des zones actives des Apennins. En parallèle, notre analyse de la déformation active de la péninsule italienne pose le problème d'une meilleure définition des dimensions des zones actives, leur état de contrainte tectonique, le lieu de chargement de ces contraintes et leur potentiel pour une recrudescence de l'activité sismique future. En perspective, ces cas d'étude nous permettent d'identifier et de mieux cerner les problèmes du signal géodésique pré-sismique et une évaluation réaliste de l'aléa sismique en Italie.

Abstract of the Paolo Marco De Martini Thesis

Combined geodetic and geologic analysis of crustal deformation at different time scales:

A contribution to the identification and characterization of seismogenic structures in the Apennines (Italy)

The methodologies used for the identification of the active faults and particularly for the estimation of their seismogenic potential are often characterized by uncertainties and different interpretations. Recent studies showed persistent difficulties in identifying active structures when the recent deformation superimposes on older tectonic phases. These considerations are even more evident along the Apennines mountain chain, where each active fault is characterized by slip rate ≤ 1.0 mm/yr and by average recurrence time between 1 and 5 kyr. These observations appear to be confirmed by the "hidden" or "blind" behavior shown by many active structures in Italy like those of Messina, Friuli, Irpinia, Val Comino, Gubbio, Colfiorito and Molise.

The works presented in this thesis discuss the problems related to the active faults of the Apennines. These problems are listed in the following:

4. The active deformation of the Apennines, which includes the tectonic movements along faults, is often obliterated by human activity (agriculture), high erosion rates due to climatic effects that often may be the source of wrong interpretations, and interference from older geologic structures.

5. The tectonic movements that dominate the Apennines tectonic style ask for the analysis of conventional leveling profiles (at least for the past century of observation) that are more precise with respect to measurements done by space geodesy, when the measurements refer to the vertical component of movement.

6. The study of active faults and its implication for the estimate of the seismic hazard ask for a multidisciplinary geologic, geodetic and seismologic approach for the characterization of the seismogenic sources and for the seismic hazard and risk calculation.

In this thesis, we examine the abovementioned problems and provide some answers based on many examples of studies of seismogenic zones in the Apennines. Several our articles on international journals (level A) support our observations, measurements and analyses.

This thesis is made by seven chapters:

- Chapter 1 presents the seismotectonic characteristics of the Apennines and their recent tectonic evolution. The main tectonic structures of the Apennines, subdivided in distinct zones (North-, Central- and South-Apennines), are defined by: a) historical and instrumental seismicity, b) present stress field, c) known active faults. We use also the characteristics of the seismic hazard of the Italian peninsula for the analysis of the active zones.

- Chapter 2 summarizes methodologies and principles of the active tectonics, seismotectonics and geodesy applied to active zones. The theoretical aspects of the active deformation (seismic) are presented with respect to the seismic cycle. We also present a short introduction to active tectonics and earthquake geology, as developed in the past decades. A case study of a region characterized by high seimic potential (Kahrizak Fault) in Iran, close to Teheran (De Martini et al., 1998) is shown. On the contrary, the example of a paleoseismological study of a stable zone in Australia highlights limitations of the applied methodologies and complexity of the active zones (Crone et al., 2003). The study of the Atalanti Fault (Central Greece, Pantosti et al., 2004) is shown in order to emphasize similarities with the normal faults acting in the Apennines.

  In a second part, this thesis also describes the geodetic leveling technique and the history of the Italian geodetic leveling network. We highlight also the leveling errors and precision in order to describe the quality of the measurements performed in the past century in the Apennines (D'Anastasio et al., 2006). The analysis of the results is associated to modeling of the preseismic, coseismic and postseismic deformations.

  A third part explains the need for the use of old geodetic data combined with active tectonic studies and the analysis of the seismicity pattern for a better understanding of: i – the deformational processes (preseismic, coseismic, postseismic and interseismic), and ii – the regional scale deformation. A comparison between short- and long- term deformations allows us to constrain the geometrical characteristics and the behavior of the Apennines active faults.

- Chapter 3 shows evidence for preseismic and aseismic movements along active normal faults. Repeated geodetic measurements across the seismic zone of the Umbria-Marche Apennines, locus of the 1997-98 seismic sequence, demonstrate the existence of preseismic movements along a blind seismogenic fault (De Martini & Valensise, 1999). The geodetic evidence for aseismic slip along the Amatrice normal fault, lacking recent seismicity and creeping at the surface, highlights the problem of the silent faults.

- Chapter 4 describes the evidence for coseismic movements along normal faults through geodetic and geologic data. Leveling measurements, performed soon after the Umbria-Marche 1997-98 seismic sequence, allow a better estimate of the seismic source parameters and of the distribution of the coseismic slip (De Martini et al, 2003). Change in the deformation rates of the blind normal faults activated during the seismic sequence and the conjunct analysis of the InSAR data through surface deformation modeling, allow us to better localize a minor fault splay (Stramondo and De Martini, 2004). The geologic evidence for active and seismogenic faults is derived from different paleoseismological works we took place, and demonstrates the relationship between short- and long- term deformation in the Apennines (Pantosti et al., 1999).

- Chapter 5 discusses the geodetic leveling measurements performed in the intermontane Fucino basin, locus of the large 1915 earthquake. The repeated surveys and the identification of deformation (together with a modeling approach) show the presence of postseismic deformation probably related to relaxation effects of tectonic crustal origin (Amoruso et al., 2005).

- Charter 6 presents regional scale vertical movements recorded by geodetic leveling data in the past 50-100 yr and by old geological paleoshorelines (D'Anastasio et al., 2006; Mancini et al., 2007). Conjuct analysis of geodetic, geologic-tectonic (paleoseismologic) and seismologic data allows to better constrain the interseismic deformation. The study of the active deformation at different time scales together with the comparison of the geodetic signal with the characteristics of the long-term deformation, derived from quantitative geomorphology, allow to better determine the seismic cycle in the Apennines.

- Chapter 7 summarizes the main results obtained with the works done in the active zones of the Apennines. Moreover, our analysis of the active deformation of the Italian peninsula discusses the problem of a better definition of: the dimension of the active zones, the amount of tectonic stress, the area of recharge of this stress and their potential for the recrudescence of future seismic activity. In perspective, these studies allow us to identify and to better circumscribe the problem of the preseismic geodetic signal and to provide a realistic estimate of the seismic hazard in Italy.

Contents

Introduction:

In Italy, the process of the identification of active faults and in particular the direct estimation of their seismogenic potential is still marked by uncertainties and often more than one interpretation remains open (Bosi, 1975; Scandone et al., 1992; Michetti et al., 2000). However, during the past twenty years, new models and methods have been developed to identify possible sources of large earthquakes. Approaches involving trenching of recent (Holocene) fault scarps, near-fault geomorphology and geological small-scale mapping of fault zones have been commonly used and also new efforts have been made for a better understanding of Pleistocene regional geomorphology and for the improvement of analytical modeling of large scale landscape features. Thus, exploring simultaneously different aspects and scales of the surface expression of a seismogenic fault becomes a peculiar characteristic of the active tectonic studies. Only recently in Italy a coherent, homogeneous and updatable database of possible sources for medium-large size earthquakes has been compiled at a national level (Valensise and Pantosti, 2001a, DISS Working Group, 2005, online version at http://www.ingv.it/resources/data-bases). Despite the important step ahead done with the publication of the latter database, several historical earthquakes still do not have a causative structure associated, as well as for several faults, expected to be active, the seismic behavior has not been evaluated based on direct studies.

The difficulties that appear to be still present in the identification and characterization of seismogenic faults in Italy could be explained, at least partially, by the relative youthfulness of the recentmost major change in the tectonic regime. Several groups of research (Cinque et al., 1993; Hyppolyte et al., 1994; Patacca and Scandone, 2001), working on various topics and applying different approaches, all seem to converge toward a similar result: a major change in the orientation and/or in the intensity of the stress field occurred in southern Apennines about 700 Kyr ago. Moreover, the important phase of the regional uplift still active in Calabria and southern Apennines (Westaway, 1993; Bordoni and Valensise, 1998; Amato and Cinque, 1999) as well as the peri-Thyrrenian back-arc volcanism (Barberi et al., 1994) appears to have started around 0.8 Ma ago. Finally, a similar age has been suggested for the inception of the largest normal faults in southern Italy (Pantosti et al., 1993). This evidence points out that the active tectonic regime can be considered quite recent and thus the younger active faults may not yet have developed a clear geological/geomorphological superficial expression. On the contrary, the signature left by the older tectonic structures would be still undoubtedly recognizable in the field and, if the fault would be well oriented with respect to the present stress field, it could easily reactivate sympathetically, thus appearing active in the geological record. A nice example of this problem (reactivation but also exhumation due to important lansliding and/or coseismic shaking) comes from the 1980 Irpinia earthquake epicentral area, where several investigators (Carmignani et al., 1981; Bousquet et al., 1983) reported evidence for the reactivation of several faults and lineaments previously mapped, but none of them resulted to have an active role in the 1980 earthquake (Pantosti and Valensise, 1990).

Another factor that clearly complicates the work of the geologists is the relatively low rate of seismic activity of each single fault. In fact, if we look at the historical and instrumental national seismic catalogues (it is noteworthy to mention that Italy has one of the best historical seismic record of the world, see CPTI, 1999, 2004 and Boschi et al., 2000, among many other catalogues) we can deduce that the expected maximum magnitude in Italy is about 7.0-7.4. Furthermore, in general the estimated slip rates of Italian seismogenic faults do not exceed 1.0 mm/yr and the recurrence times are in the order of 1-5 kyr (Valensise and Pantosti, 2001a; Galadini and Galli, 2000).

Finally, a third element that can contribute to the discussion on the difficulties and controversies associated with the process of relating recent faults to seismicity in Italy (for a complete overview see Valensise and Pantosti, 2001b) is represented by the style of faulting related to important earthquakes occurred in Italy in the past century. In fact, many of the seismogenic faults seismically activated resulted to be hidden or blind, and the investigation of their characteristics was possible only using an indirect approach and/or thanks to a very detailed field work (1908 Messina, Ward and Valensise, 1989, Valensise and Pantosti, 1992; 1976 Friuli, Bosi et al., 1976; 1980 Irpinia, Pantosti and Valensise, 1990, Pantosti et al., 1993; 1984 Val Comino, Westaway et al., 1989; Pace et al., 2002; 1984 Gubbio, Haessler et al., 1988; Pucci et al., 2003; 1997

Colfiorito, Basili et al., 1998, Chiaraluce et al., 2003; 2002 Molise Valensise et al., 2004; Chiarabba et al., 2005a).

What appears as a striking evidence along the Apennines is that the vertical component of movement seems to dominate both the local and large scale tectonic processes.

On the one side, looking at the kinematics of each single seismic source (older events available at http://www.seismology.harvard.edu/ and specifically for the European-Mediterranean Regional Centroid-Moment Tensors (Pondrelli et al., 2006) at http://www.ingv.it/resources/data-bases), we may notice that focal plane solutions of crustal earthquakes suggest a dominant NW-SE normal faulting style for the Apennine chain, while NE-SW shortening, mainly related to reverse faulting is highlighted eastward, toward the Adriatic sea and as south as the Gargano promontory. On the other hand, it is widely reported that regional uplift has to be considered as a first order dynamic mechanism of the main peninsular mountain range of Italy (Cinque et al., 1993; Bordoni and Valensise, 1998; Amato and Cinque, 1999; D'Agostino et al., 2001; Patacca and Scandone, 2001; Bartolini, 2003). Estimates of vertical motion are mainly derived from geological and geomorphological data, even if we have to admit that this evaluation is not always supported by well constrained data (mainly because of the difficulties encountered in absolute dating of the geological/geomorphological markers). Anyway, the available data suggest an average large scale uplift rate of about 1 mm/yr, for the Middle-Upper Pleistocene time interval (Bordoni and Valensise, 1998; D'Agostino et al., 2001, and reference therein). Unfortunately, present day geodetic estimates of the vertical component of movement are still lacking, while recent GPS solutions clearly suggest that the Apennines are characterized by NE-SW oriented active extension within the range, with horizontal rate of extension of about 2 to 5 mm/yr (Hunstad et al., 2003; Serpelloni et al., 2005).

Having in mind the discussion above, it appears important to make a new effort involving an intense use of available geodetic leveling data to provide a) a quantitative description of the short-term vertical velocity field across the Apennines, to be compared to the few available geological estimates, and b) an independent analytical evaluation of the seismic behavior of some Italian faults, activated in the past century, to be compared to the seismological and geological ones. Three main advantages pertain to the leveling data, at least in Italy, compared to other modern satellite geodetic techniques (GPS, InSAR, etc): 1) it is the only geodetic dataset that spans back in time to the past 50-100 years; 2) no comparable sampling of active regions is presently available from other geodetic networks; 3) the resolution in evaluating the vertical component of motion is of one order of magnitude higher than GPS to GPS measurements. On the other side, we should not forget that only relative motion can be precisely determined by comparative leveling data (Bomford, 1971), because of the lack of an absolute reference datum, intrinsic to this geodetic technique.

When we consider the huge amount of seismic energy released in historical and instrumental time in Italy (Boschi et al., 2000, Castello et al., 2006; both available on line at http://www.ingv.it/resources/data-bases) together with the important social and economical effects related to earthquakes, we are forced to make steps ahead to better contribute to seismic hazard estimates. The modern scientific methodology tends to answer to this need by applying a multidisciplinary approach, often characterized by a combination of data derived from geology, geodesy, seismology and modeling, to the identification and characterization of seismogenic structures [nice examples have been provided in USA (Hodgkinson et al., 1996; Barrientos et al., 1987), Algeria (Meghraoui et al., 1988; Meyr et al., 1990), France (Baroux et al., 2003; Siame et al., 2004) and Asia (Jackson and Bilham, 1994) and also in Italy for the study of the 1980 Irpinia fault (Pantosti and Valensise, 1990) and of the 1908 Messina structure (Valensise and Pantosti, 1992)].

I should also mention that I am aware of the fact that the detection of the present deformation pattern and in general all active tectonic studies worldwide often encounter main problems. Most of them could be applied to the Apennines case study but it is important to mention on the one side the intense and diffuse human activity and the high erosion rate, both quite common in tectonically active region, which tend to obliterate the subtle superficial earthquake imprints; and on the other the geologically young age of the active tectonic regime, that hardly superimposes on the deep signature left by older structures and makes the present picture more confuse.

This thesis is composed of 7 chapters, briefly presented in the following

Chapter 1 presents a brief review of the seismotectonics of the Apennines, with special emphasis on the major active tectonic elements and a comparison of these data with the available seismic hazard map.

Chapter 2 illustrates the basic idea that was the starting point for the analysis of the deformation of the Apennines at different time scales. This analyses the theoretical principles of the seismic cycle as refernce for a well balanced comparison of geodetic leveling and paleoseismological/geological data. A short introduction to active tectonics, together with some earthquake geology case studies I took part in (based on De Martini et al., 1998; Crone et al., 2003; Pantosti et al., 2004), and to geodetic leveling technique, focusing primarily on the peculiarities of the Italian first order leveling network (based on D'Anastasio et al., 2006), is also provided.

Chapter 3 is centered on aseismic slip and its meaning and discusses two intriguing geodetic dataset in central Apennines, where the detected geodetic deformation has been interpreted as pre-seismic slip (based on De Martini and Valensise, 1999) in one case and as creeping in the other.

Chapter 4 describes the evidence for coseismic slip along some of the main 1997-98 Umbria-Marche earthquake sequence seismogenic structures (maximum Mw 6.0) obtained from both geodetic leveling (based on De Martini et al., 2003) and geologic data (based on Pantosti et al., 1999) and it attempts to compare the short- and long-term deformation patterns.

Chapter 5 deals with the use of geodetic leveling data to highlight late stage movements of the postseismic relaxation process (based on Amoruso et al., 2005, Annex 1), the reference event occurred in 1915 (Mw 6.7) in central Apennines and the leveling dataset covers the 1950-2000 time interval.

Chapter 6 describes large scale vertical movements of the Apennines as shown by both geodetic leveling (based on D'Anastasio et al., 2006) and geologic data (based on Mancini et al., 2007, Annex 2); a brief discussion on the comparison between short- and long-term deformation patterns and on the interplay between high rate of regional uplift and of seismic moment release, is also presented.

Chapter 7 summarizes and discusses the main results and implications of the thesis and presents some perspectives about possible contribution to seismic hazard assessment.

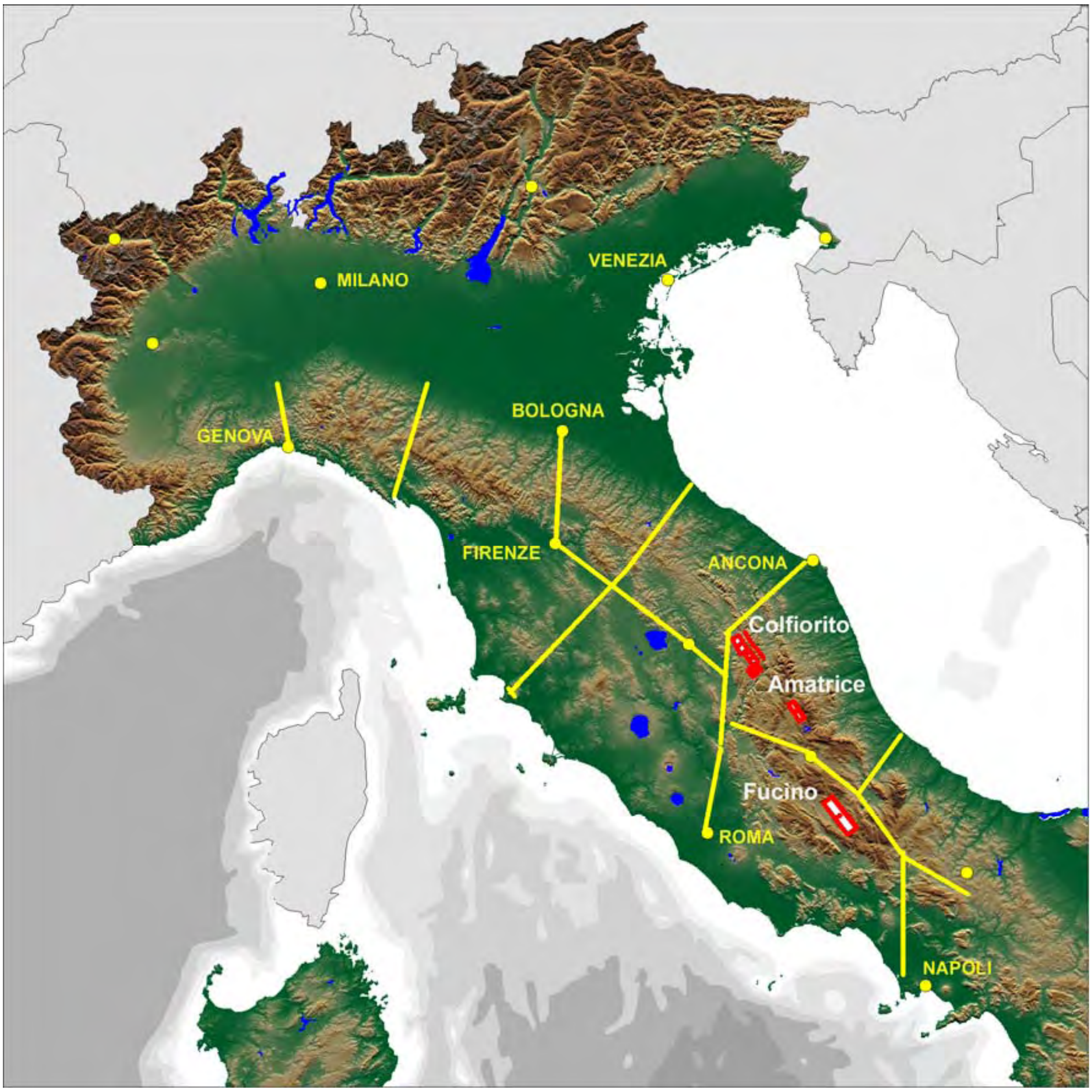

Figure A: Location of the areas under study in the Apennines (Italy): The red boxes represent the investigated active faults, while the yellow lines follow the trace of the first order leveling lines analysed and discussed in the text.

Chapter 1

Brief review of the Seismotectonics of the Apennines

Chapter 1: Brief review of the Seismotectonics of the Apennines

The Neogene-Quaternary kinematic evolution of the Central Mediterranean area, together with the tectonic structure of Italy (figure 1.1), was often described as a direct result of the Africa-Europe convergence (e.g., Dewey et al., 1973; Mazzoli and Helman, 1994). Nevertheless, the available geological and geophysical information suggests a more complex plate interaction, with an important role played by the intervening Adria microplate (Anderson and Jackson, 1987). The Apennines, with overall vergence to the E-NE, are a fold-and-thrust mountain belt overriding and accreting on the subducting Adria microplate. The Apennines are bordered to the east by a foredeep, filled up by Pliocene-Pleistocene deposits (Casnedi et al., 1981; Consiglio Nazionale delle Ricerche, 1992) and to the west by the Tyrrhenian back arc basin (Kastens et al., 1988) developed at least since middle Miocene. The late-Tertiary evolution of the Tyrrhenian-Apennines system appears linked to eastward migration during the Neogene of paired extensional (in the west) and compressional (in the east) belts. This migration, together with flexural subsidence of the Adriatic foredeep, is interpreted as response to the ‘roll-back’ of the subducting Adriatic-Ionian lithosphere (Elter et al. 1975; Malinverno & Ryan 1986; Royden, 1993; Faccenna et al. 1996; Jolivet et al. 1998). The progressive propagation of the contractional deformation toward the foreland is clearly documented by the development and evolution of a series of eastward younging foredeep basins and by the occurrence of several piggyback basins, which developed on top of the advancing allochthonous units (Patacca and Scandone, 2001). During the Quaternary, the flexural subsidence, the compressional deformation and the eastward retreat of the subduction hinge all decreased dramatically (Patacca et al. 1992; Cinque et al. 1993) and the Apennines became dominated by crustal extension and by significant regional uplift.

In the external sector of the Apennines chain, toward the Adriatic Sea, the Mesozoic-Cenozoic sequence (deformed by thrust anticlines) is overlain by prograding Quaternary deltaic sequences, with little evidence of compressional deformation after the Early Pleistocene (Bigi et al. 1997; Argnani et al. 1997, and references there in). The Quaternary evolution thus involves the final infilling and extinction of the Mio-Pliocene Adriatic foredeep (Ori et al. 1993).

In the internal sector of the Apennines chain (figure 1.1), toward the Tyrrhenian Sea, normal faulting has been active since the Upper Pliocene–Early Pleistocene (Patacca et al. 1992; Bosi & Messina 1991) and this extension is responsible for the development of several Pleistocene intermontane basins, partially filled with alluvial, fluvial and lacustrine deposits and coarse conglomerates (Cavinato & De Celles 1999).

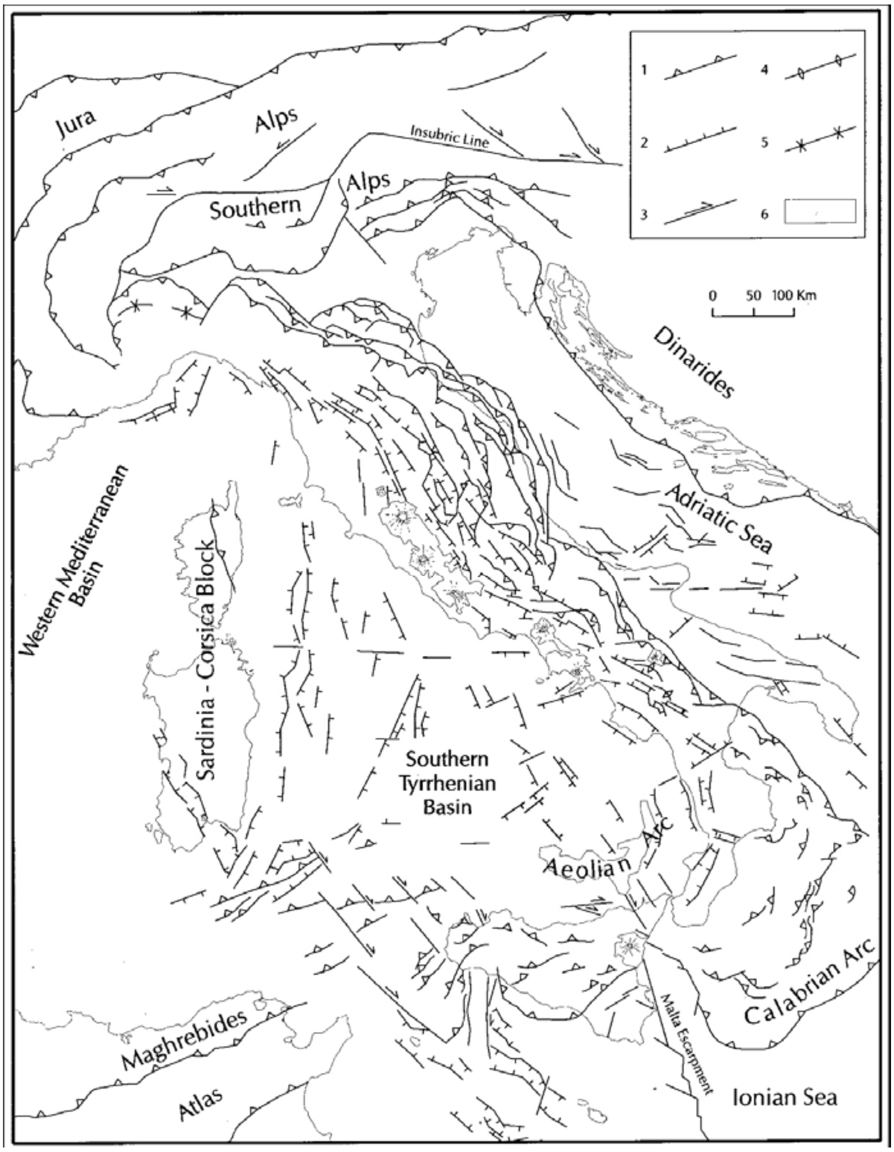

Figure 1.1. Structural sketch of Italy and surrounding regions (after Meletti et al., 2000). 1 thrusts; 2 normal faults; 3 strike-slip faults; 4 Pliocene-Quaternary anticlines; 5 Pliocene-Quaternary synclines; 6 backarc basins floored by oceanic crust.

Chapter 1.1: Distribution of active deformation

The pattern of active deformation in the Apennines is discussed based on the amount of energy released by historical and instrumental seismicity (figure 1.2) and on available focal mechanism solutions (figure 1.3), for its cinematic interpretation. At the same time, the distribution of faults that have been active in the Late Pleistocene and Holocene (figure1.4) is presented, together with the available geodetic strain rate fields (figure 1.5), obtained from GPS data.

Northern Apennines: In the Northern Apennines, looking at the historical and instrumental seismicity (figure 1.2) we may note that there are two distinct deforming bends: an external one, in front of the chain within the Po plain, and an internal one, along the intermontane basins located on the Tyrrhenian side of the chain. The moment tensors (figure 1.3) show prevailing strike-slip to thrust solutions along the outer part of the chain, with extensional focal mechanisms in the inner part. Strike-slip and thrust events in the outer part of the chain have deeper hypocentral location, often between 20 and 30 km (Pondrelli et al., 2006). Moreover, prevalent strike-slip deformation exists in the northernmost termination of the Apennines and around the buried thrusts below the Po Plain. The presence of two active bends characterized by different tectonic styles seems to be confirmed by principal horizontal strain-rate axes obtained from GPS data (figure1.5). In fact, in the northern Apennines, the Marche–Romagna region and the inner sector of the arc in northern Tuscany display clear northeast–southwest extension, while the outer sector of the chain displays weak north–south shortening (Serpelloni et al., 2005). Interestingly, the subduction is probably still active beneath the northern Apennines, where earthquakes down to 90 km of depth have been recorded (Selvaggi and Amato, 1992).

Summarizing, along the Northern Apennines, the compressional regime with Shmin directions rotating from approximately E-W in the Po Plain to NW-SE along the Adriatic coast (figure 1.6), follows the main tectonic structures of Pleistocene age, while the internal sector of the northern Apennines is undergoing NE extension, concentrated in the intermontane basins (Montone et al., 2004, and reference therein).

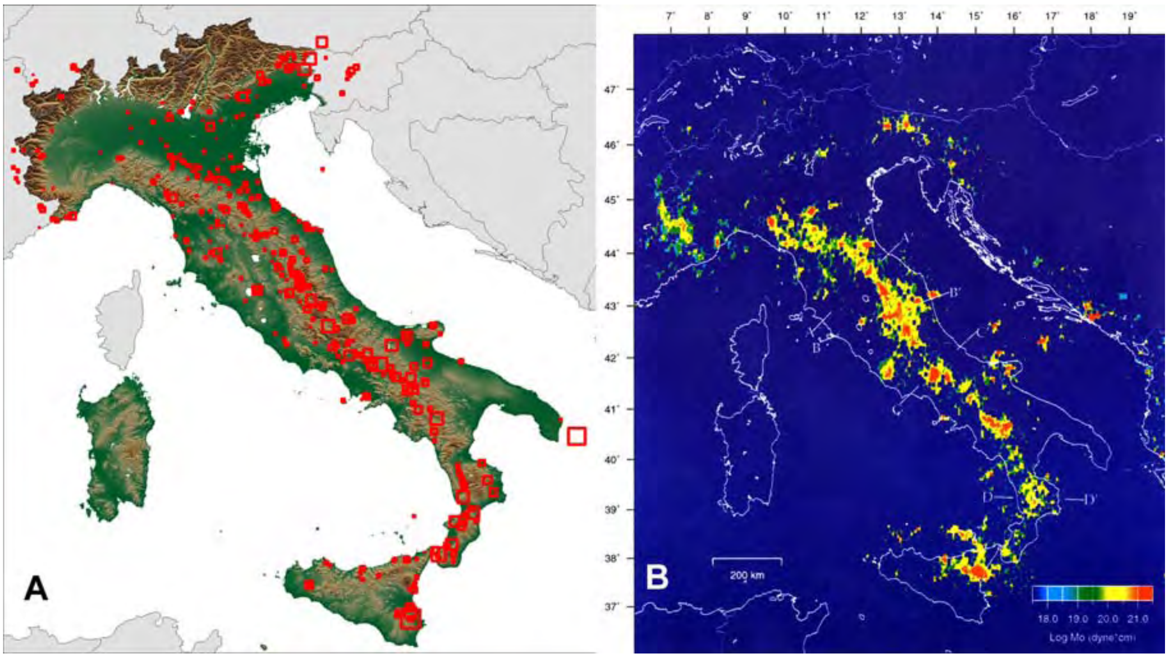

Figure 1.2: A) Italian historical seismicity (after Boschi et al., 2000); B) Instrumental (1983 to 1996) seismic moment release distribution map (after Selvaggi et al., 1997).

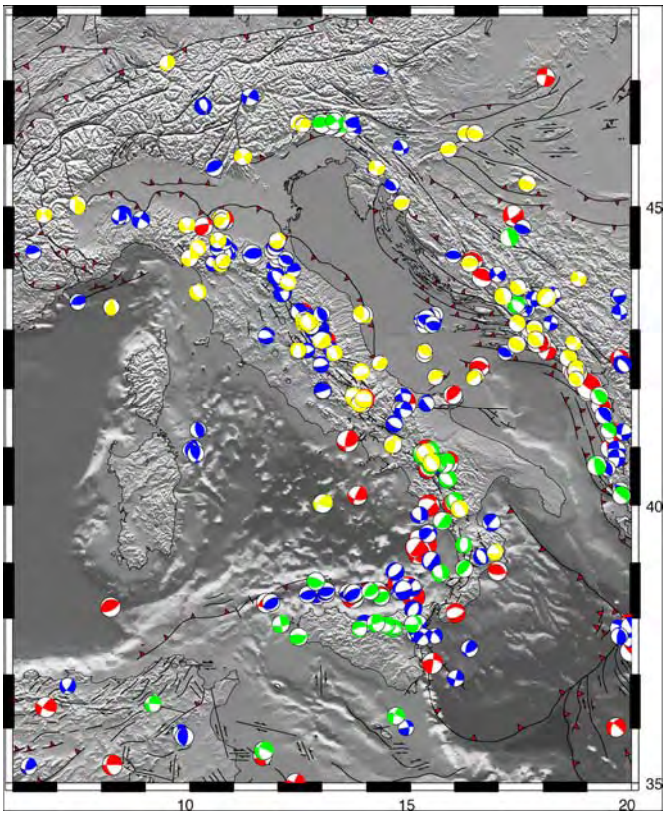

Figure 1.3: Italian CMT dataset (1976 to present), (after Pondrelli et al., 2006). Colours refer to different catalogs (e.g. Harvard CMT solutions are in red).

Figure 1.4: Map of the Italian seismogenic sources (after DISS Working Group, 2005).

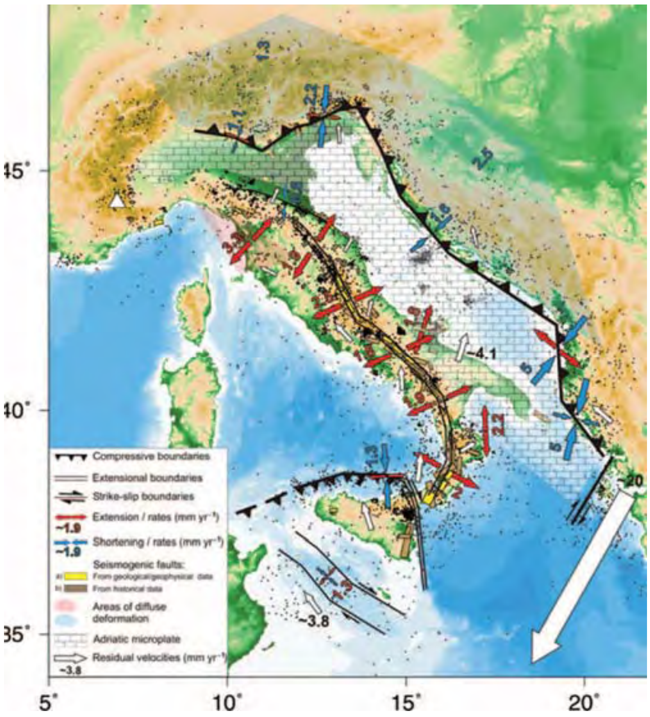

Figure 1.5: Principal horizontal strain-rate axes (after Serpelloni et al., 2005). Note that the white triangle shows the position of the Adria/Eurasia relative rotation pole.

Central Apennines: In general, historical and instrumental seismicity concentrate along a narrow belt whose width varies along the length of the Apennines. However, in the central Apennines the largest earthquakes (figure 1.2) and the faults active in Late Pleistocene and Holocene time (figure 1.4) seem to be distributed over a broader width of at least 50-60 km. The increase in width of the actively deforming belt in the central Apennines is also associated with an increase in average elevation and the across-strike width of the Apennine topographic belt itself (D’Agostino et al., 2001). From a cinematic point of view (figure 1.3) we can say that most of moment tensor solutions localized along the backbone of the Central Apennines chain are pure extensional with a constant NE–SW directions of the *T* axis (Pace et al., 2002; Pondrelli et al., 2006). Out of these events, some thrust moment tensors are present in the outer Central Apennines, but most of thrust focal mechanisms belong to earthquakes located in the Adriatic Sea. This trend appears confirmed by GPS estimates, suggesting ENE–WSW extension (figure 1.5), concentrated in a belt, about 80 km wide, while the Adriatic foredeep and the southern Tuscany–Latial volcanic area display negligible deformation rates (Serpelloni et al., 2005). Some authors (Galadini & Galli 2000, and references therein) suggested that the active deformation of the Central Apennines may involve at least two major sub-parallel normal fault systems. The western fault system has produced several large earthquakes in the past thousand years, while the eastern fault system shows evidence of Late-Pleistocene to Holocene activity but can not be associated with any known historical earthquakes. This apparent quiescence may be interpreted in two different ways: a) the eastern system is now inactive and that extension is taken up only by the western fault system; b) seismicity is clustered onto a single fault system with cycles whose time scale is longer than the historical or paleoseismological catalogues (D’Agostino et al., 2001).

Southern Apennines: Most of the historical and instrumental earthquakes concentrate along a narrow (30 km wide) belt straddling the crest of the Southern Apennines (figure 1.2). This trend appears in agreement with the location of the known seismogenic faults, all aligned along the crest of the chain (figure 1.4). As for the central sector of the chain, most of moment tensor solutions, localized along the axis of the Southern Apennines chain, are pure extensional (figure 1.3) with a constant NE–SW directions of the *T* axis. Strike-slip moment tensors are clustered close to the Gargano zone (locus of the major Mattinata strike slip fault system), and belong to the 2002 Molise seismic sequence. Southward, some more strike-slip moment tensors are related to the 1990 and 1991 Potenza earthquakes (Di Luccio et al., 2005) and have been interpreted as due to the reactivation of deep faults beneath Southern Apennines. This picture is not conflicting with the geodetic evidence (figure 1.5), suggesting that the Southern Apennines are extending in an ENE–WSW direction.

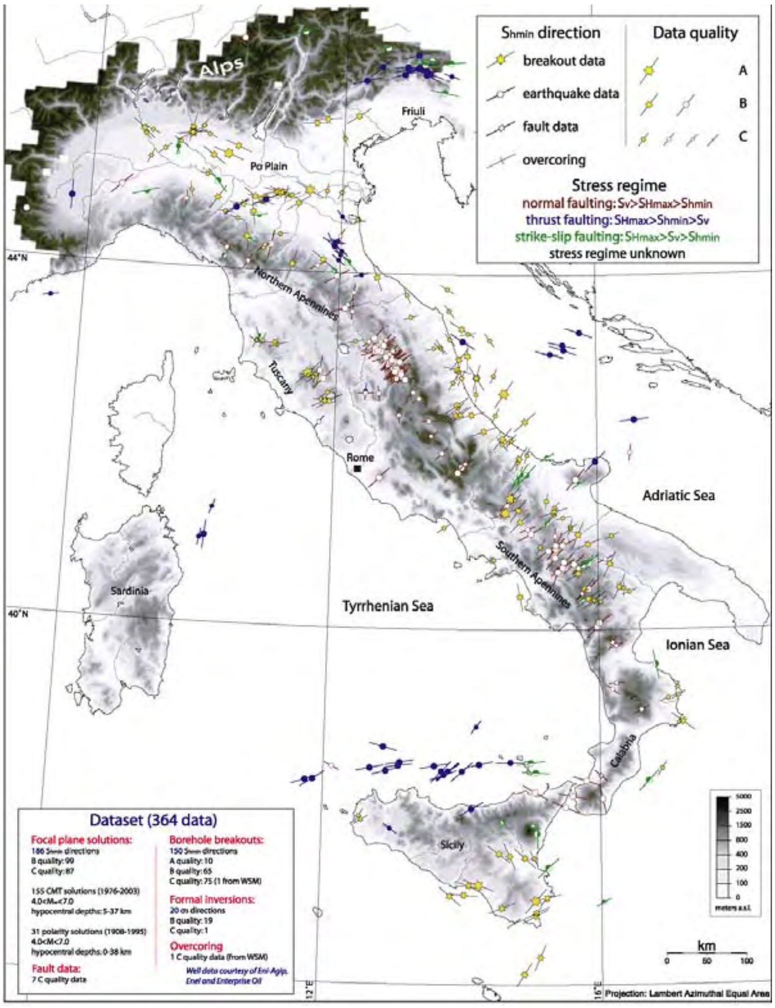

Figure 1.6: Active stress map of Italy with minimum horizontal stress orientations (after Montone et al., 2004).

Summarizing, in the Central-Southern Apennines the existence of a clear extension perpendicular to the axis of the belt is well known. The stress conditions of this sector are very well depicted by both fault plane solutions and breakouts which sample the whole seismogenic crust (figure 1.6). Faults in this area are therefore expected to rupture with normal faulting mechanisms throughout the whole belt, at least in the most active central sector. The stress data also indicate that the NE-SW direction of Shmin continues toward the foredeep, possibly in a strike-slip stress regime, (Montone et al., 2004, and reference therein).

Chapter 2

The earthquake deformation cycle

Chapter 2: The earthquake deformation cycle

This thesis is mainly focused on the comparison of geodetic leveling and paleoseismological/geological data analysed and interpreted both at a local and regional scale. In fact, in the first case looking at signal wavelength in the order of tens of km, it is possible to study the behaviour of an individual seismogenic structure, while looking at signal wavelength in the order of hundreds of km, some of the characteristics of the global process acting in the Apennines (possibly governing the ongoing seismogenetic process) may be better described. The object under study is the Central-Southern Apennine seismogenic belt, a mayor fault system, so well delineated by historical and instrumental seismicity (Boschi et al., 2000, Castello et al., 2006; both available on line together with other seismic catalogues at http://www.ingv.it/resources/data-bases).

Even if an important and fundamental contribution to the understanding of the seismic cycle comes from seismological studies, it is nowadays generally accepted that the best observational bases for physical models of the earthquake deformation cycle are the geodetic data and the geological displacement rate records. In particular, the use of geodetic leveling data, collected across and/or near major seismogenic faults activated in the last century, may shed new light on the complex deformation history of a seismic source in the proximity and during its rupture, an exceptional and relatively short time window of the seismic cycle usually investigated only by analytical and analogue approaches. Moreover, the study of the geological and paleoseismological deformation records offers the opportunity to investigate the behaviour of an individual fault segment or of complex fault zones also during several seismic cycles, thus providing a long-term picture that is undoubtedly unique.

The observation that earthquakes repeatedly rupture a given part of a fault is at the basis of the definition of the “seismic cycle" and of its subdivision into three periods, consisting of inter-seismic slip**,** co-seismic slip**,** and post-seismic slip**.** Two of these phases are illustrated by figure 2.1, namely, the period of slow accumulation of elastic strain that coincides with frictional locking of a fault between earthquakes (the interseismic phase), and the sudden rupture that is the earthquake (the coseismic phase). Inter-seismic elastic strain accumulation occurs for long-periods, until the elastic strain build-up exceeds the ability of the frictional forces that lock a fault to prevent slip. The earthquake occurs at the moment that the fault ruptures and produces not only transient vibrations of the Earth (seismic waves transmitted through the planet) but also permanent deformation in the region around the fault. It is noteworthy to mention that both of these deformational modes are related to the size and mechanism of the earthquake.

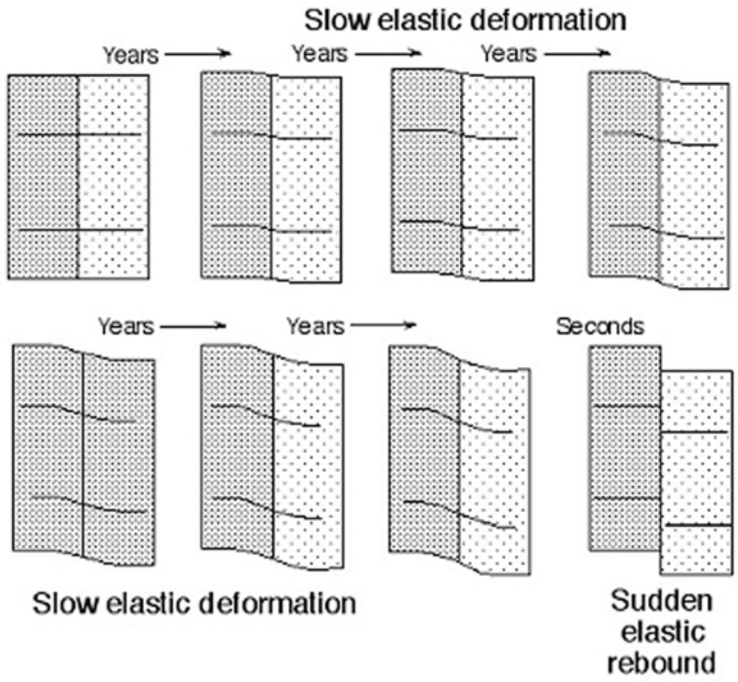

Figure 2.1. Sketch representing the interseismic and coseismic phases

The third phase of the seismic cycle corresponds to a period of minutes to years after an earthquake when the crust and fault both "adjust" to the modified state of crustal stress caused by the earthquake. During the "post-seismic" period, at least two distinct processes give rise to additional movements of the crust. One consists of additional slip, usually minor, along the fault. Some of this additional slip may be due to earthquake aftershocks on the ruptured fault. The other has been noted mainly following large events, when deeper regions of the crust flow in response to changes in crustal stress caused by the preceding earthquake.

Usually, the term inter-seismic slip refers to the strain that accumulates steadily (the red lines in figure 2.2) between the earthquakes that repeatedly rupture the fault. In general, measurements of the yearly motion of two sites that are located immediately across the fault from each other will show minor or no motion because the fault is locked between earthquakes and the crust adjacent to the fault thus cannot slip! In contrast, motion measured between two sites that are across the fault from one another, but are separated by distances of several tens of km will show that the sites move significantly relative to each other and strain accumulates in the crust closer to the fault.

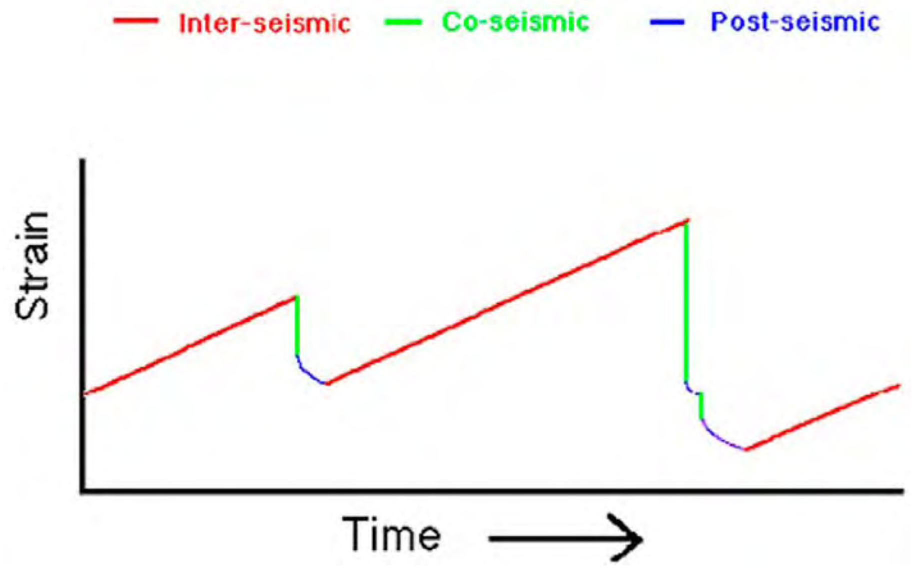

Figure 2.2: The seismic cycle. The history of strain accumulation and release along a single fault patch is shown with different colors according to the three phases described in the text.

Co-seismic slip applies to the slip that occurs at the instant of the earthquake (green lines in figure 2.2). Interestingly, measurements of co-seismic motion for sites near and far from the fault should show just the opposite pattern as exhibited for inter-seismic motion! This is due to the fact that during an earthquake, the highly strained rocks near the fault rupture, which moved little or not at all during the inter-seismic period, are allowed to slide back to a less-strained state. In contrast, sites on crust far from the rupture zone were moving steadily during the inter-seismic period and thus accumulated little or no strain.

The term post-seismic slip relates to slip that occurs in the days, months, and years after an earthquake (blue lines in figure 2.2). In fact, it has been noted that deformation is not limited to the time of the earthquake, but it continues for days, years or even decades afterwards. Several mechanisms may be responsible for this post-seismic deformation, and the dominant mechanism may change with time. Such a slip typically differs from the steady inter-seismic slip described above (although in some sense, post-seismic slip is simply a subset of inter-seismic slip). A fault that has experienced a significant rupture often continues to accommodate significant slip after the rupture. However, the post-seismic slip eventually decays back to the steady inter-seismic slip.

Three general physical models of the earthquake deformation cycle can be used to summarize the different approaches to estimate ongoing tectonic activity and its associated hazards, developed during time by the scientific community. It should be underlined that all of them are built on the assumption of a constant rate of the far-field displacement and of the strain accumulation (figure 2.3).

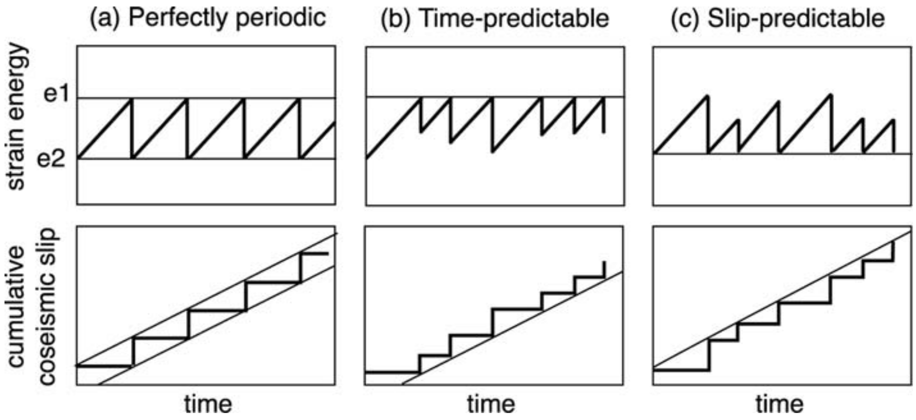

Figure 2.3: Strain release models (redrawn after Scholz, 1990).

In the perfectly “periodic model” hypothesis (Reid, 1910), earthquakes of fairly uniform slip and recurrence interval release, periodically, the elastic strain energy accumulated across completely locked faults. On this model and on examples from the San Andreas and Wasatch fault zones it is based the concept of “characteristic earthquake” (Schwartz and Coppersmith, 1984) that strongly stimulated the discussion in the past 20 years, especially within the paleoseismological community. Schwartz and Coppersmith, (1984) based their interpretation mainly on the fact that slip per event for most well documented fault segments did not seem to be significantly variable. If the faults are perfectly stable in terms of loading, segment boundaries and slip distribution this translates to periodicity. On the other hand, some researchers highlighted the fact that the inter-seismic interval and the size of earthquakes on a particular fault are not perfectly periodic and to account for this observation a "time-predictable" model was proposed (Shimazaki and Nakata, 1980). The main implication derived from this model is that the time of the next earthquake can be predicted (in a probabilistic way) based on the slip rate of the fault and on the size of the last seismic event. A variant of the latter model is the "slip-predictable" concept, able to evaluate the size of the next seismic event based on the slip rate of the fault and on the time since the last earthquake (Shimazaki and Nakata, 1980).

The discussion on physical models of the seismic cycle is complicated by the fact that strain accumulation and release can be influenced by local stress modification within the substratum due to each seismic event occurred on any tectonic structure in the area (Stein, 1999 and reference therein) and by the consideration that strain release may occur during clusters of earthquakes (Wallace, 1987). So we should take into consideration the possibility of significant interaction between adjacent seismogenic faults and of cluster of earthquakes, marked by a very high seismic strain release rate. Both these phenomena bring immediately the attention back to the timescale of observation, geodetic (100 yrs), paleoseismologic (1-10 Kyr) and geologic (100 Kyr to 1-10 Myr). A recent paper focused on the comparison of geodetic and geologic data from the Wasatch region, Utah (Friedrich et al., 2003) admitted not to succeed in distinguishing between periodic-type and cluster-type models for earthquake recurrence of crustal fault zones. Interestingly, the authors also suggest that if the "Reid-type" models are applicable, we should consider a process controlling the noteworthy variations in the strain accumulation rate at timescale of about 10 Kyr. Differently, accepting the "Wallace-type" model, the fault slip rates derived from geodesy, paleoseismology and geology should in most cases disagree. A systematic difference has been noted and investigated in the Eastern California shear zone (), where geodetically estimated rates (Gan et al., 2000; McClusky et al.,2001), obtained through elastic half-space modelling, appear to be faster than geologically estimated rates (Beanland and

Clark, 1994; Lee et al., 2001). Dixon and colleagues suggest that both slip rates changing rapidly with time and the presence of systematic errors in the geologic and/or geodetic data are unlikely, given the small difference in time scales (10 kyr vs. 20-30 yr) and the consistent results obtained for the past 3 Ma using independent geologic and geodetic studies for the Pacific-North American plate motion, respectively. The authors suggest that the discrepancy may be explained, at least in part, by a more realistic rheological model (elastic upper crust and viscoelastic lower crust-upper mantle) able to take into consideration the earthquake cycle effects.

Chapter 2.1: Active Tectonics/Earthquake Geology

Active Tectonics can be defined as “tectonic movements that are expected to occur within a future time span of concern to society” (Wallace, 1986). The evaluation of active tectonic processes is critical to many of mankind’s activities and to fully estimate ongoing tectonic activity and its associated hazards requires knowledge of the styles, patterns and rates of these processes. Many of the latter cannot be described properly only using the limited instrumental and historical records, however, most can be evaluated satisfactorily using the entire range of geologic, geophysical and geodetic techniques. The period of past behavior of tectonic movements that should be analysed have to be sufficiently long to sample adequately a particular series of events, changes in rates of events, and changes in patterns of tectonics. This period may range from days to thousands or even millions of years and thus, on one side, geodetic techniques can be used to identify and quantify very recent tectonic movements, while geology and geophysics have been already used worldwide to provide longer records.

This is probably not the right place where to make a huge summary of all the aspects related to active tectonics, on the contrary to better understand this topic it could be surely more interesting to refer to a couple of milestones as Wallace (1986) and Keller and Pinter (2002).

Earthquake geology can be considered a branch of Active Tectonics, specifically developed in the past 30 yr. for the study of medium-large earthquakes of the past, mainly on the basis of their geologic and geomorphic expression. The accurate identification and characterization of seismogenic faults can provide unique and useful medium- to long-term information for seismic hazard evaluations. At the basis of this type of studies there is the observation that sizable earthquakes produce permanent detectable deformation of the ground surface, mimicking the movement occurred at the mainshock depth. This coseismic modification of the surface creates a disequilibrium in the geologic and geomorphic processes, both at local (fault scarp, figure 2.4) and regional scale (horizontal and vertical changes in a region of several km^2 around the earthquake source). The ability of the earthquake geologists is in recognizing the deformational structures and the new erosional and sedimentary processes, taking place to restore the equilibrium, and in relating these features to a coseismic event and to the causative fault. Thus, when favorable geologic and geomorphic conditions exist, the cumulated deformation of repeated earthquakes and the record of individual events can be documented. There are no standardized techniques to identify and characterize a seismogenic structure, discriminating unambiguously the evidence of its past earthquakes. A clear understanding of this can be derived by two fundamental books that have been recently published on this subject (Yeats et al., 1997; McCalpin, 1996).

Figure 2.4: Picture of the Ovindoli-Pezza fault scarp in Abruzzi region, central Italy

In the following I would like to discuss some examples of the most common techniques used in earthquake geology and paleoseismology, for which I have a direct experience.

The first case study is based on “De Martini P.M., K. Hessami, D. Pantosti, G. D’Addezio, H. Alinaghi & M. Ghafory-Ashtiani (1998). A geologic contribution to the evaluation of the seismic potential of the Kahrizak fault (Tehran, IRAN),*Tectonophysics* , 287, 187-199”. It refers to one of the most seismically active regions of the Earth, where seismicity is the direct evidence of about 35 mm/yr (De Mets et al., 1990) continental, N-S oriented, convergence between the Arabian and the Eurasian plates. Both instrumental and historical seismicity records clearly depict the belts of active deformation in Iran and this work focuses on the Kahrizak fault, part of the southern main active fault zone of the

Tehran region. This structure has a clear geomorphic expression at the surface: a 35 km long scarp, up to 15 m high, on Holocene deposits. The investigation followed two main lines: a detailed near fault geomorphologic study for a precise identification of its geometry and sense of movement, and an approach involving trenching, to get as many as possible data on its seismic behavior. In fact, on the basis of aerial photos survey, detailed topographic profiling and field work it was possible to define length, dip and strike of the fault and to estimate both vertical and horizontal long-term rates of movement. Moreover, the trenches exposed a 30 m wide complex fault zone, composed of low- and high-angle splays showing both right-lateral and reverse slip, that deforms a strongly weathered sequence of massive clay deposits and calcrete layers. Radiometric (both C^{14} and ^{230}Th-^{234}U series), historical and archeological dating together with direct observation of evidence for instantaneous slip (i.e. paleoearthquake), made on the trenches walls, provided the evidence of the recent seismic activity of the structure. These records, coupled with the geomorphologic data collected, allowed the estimation of the following parameters: elapsed time, slip per event, slip rate, average recurrence time and maximum expected magnitude. An interesting point of discussion derives from the observation of oblique slip whereas, based on focal mechanism solutions, it was suggested (Priestley et al., 1994) that the whole region is characterized by slip partitioning.

The second case study is based on “Crone A.J., P.M. De Martini, Machette M.N., K.Okumura & J.R. Prescott (2003). Paleoseismicity of two historically quiescent faults in Australia- Implications for fault behavior in stable continental regions, *Bulletin of the Seismological Society of America*, 93 (5), 1913-1934”. It describes an attempt to perform a comprehensive paleoseismologic investigation of Quaternary faults in Australia, starting from the sole geologic information, to better understand the behavior of stable continental region faults on geologically relevant timescales. The work focuses on two historically aseismic Quaternary structures, the 30 km long, 2 to 5 m high Roopena fault scarp in South Australia, and the 30 km long, 2 to 3 m high Hyden fault scarp in Western Australia. The near fault geomorphology of both scarps is able to provide information on fault height, length and strike, highlighting the peculiar linear trend of these features, nothing about the sense of movement but the relative vertical motion across it. Trenching exposed strongly weathered Quaternary deposits, often of eolian origin, and older bedrock units, together with several fault zones characterized by a clear differentiation in the time of activity. Because of the total absence of organic material, which can be dated by radiocarbon, the work relies on luminescence techniques to estimate the age of past surface-faulting earthquakes. The estimated sense of movement of the Roopena and Hyden faults agrees with the east-northeasterly orientation of the horizontal compressive stress field in South and Western Australia (Coblentz et al., 1998). Both faults show a long-term behavior characterized by episodes of activity separated by quiescent periods. Even if the number of Quaternary earthquakes found for each fault is limited and uncertainties exist on the exact timing of these events, it should be noted that the average recurrence time within a cluster of events appears to be much shorter than the time between clusters. The mechanism and the causes governing this character are discussed together with the observation that stable continental region faults tend to reactivate very older tectonic structures.

The third case study is based on “Pantosti D**.,** P. M. De Martini, D. Papanastassiou , F. Lemeille, N. Palyvos and G. Stavrakakis (2004): Paleoseismological trenching across the Atalanti fault (Central Greece): evidence for the ancestors of the 1894 earthquake during Middle Age and Roman time, *Bull. Soc. Seism. Am*., 94 (2), 531-549”. It illustrates a paleoseismological study performed in the Lokris region, central Greece, struck by two large earthquakes that occurred a week apart, on 20 and 27 April 1894. Similarly to central-southern Apennines, normal faulting dominates this area, also known as North Evoikos Gulf, which has been recognized as one of the main active graben of central Greece, characterized by about 0.6-0.7 mm/yr of extension over the past century (Clarke et al., 1998) based on GPS data and by a subsidence rate of about 1 mm/yr (Philip, 1974). The main active tectonic feature in the area is the Atalanti fault, which appears as a typical normal fault bounding the North Evoikos Gulf to the south-west. A 30 km long fault scarp, displacing Late Pleistocene and Holocene deposits, has been identified based on contemporary reports describing the surface effects of the 1894 shocks, investigations performed in the 1970s (Lemeille, 1977), new aerial photo and field survey. An interesting characteristic is represented by the presence of one or more compound scarps paralleling the main geomorphic fault trace within tens or hundreds of meters. This peculiarity can be an advantage for the recognition of individual paleoearthquakes but, on the other hand, it decreases the possibility of finding a complete record of surface faulting. Six trenches were excavated at three different sites, selected among several favorable locations found along the central and western fault sections. By integrating paleoseismological, geological, historical and archeological data three surface faulting events (including the 1894 earthquake), were defined in the past two millenia. Estimates for average minimum slip per event and vertical slip rate are also provided.

Summarizing, from the examples shown above it appears clear that geologic studies on active structures may provide basic information on the behavior of seismogenic faults. In fact, starting from these geologic data, the following main parameters referred to the occurrence of repeated medium-large earthquakes on a single fault may be derived. Some geometrical parameters, such as total rupture length and dominant sense of movement, are usually obtained from near fault geomorphology and trenching, together with slip rate estimates on the basis of short-term (Holocene) or long-term (Late Pleistocene) deformation records. Moreover, trenching coupled with dating (historical, archeological, absolute, etc) can allow us to define the amount of coseismic slip produced by a single earthquake (slip per event), the average interval of time between earthquakes on the same fault segment (recurrence time) and the time elapsed since the last event occurred along that particular fault (elapsed time). It should be noted that all these parameters represent the unique available information on the seismic behavior of a fault for which historical and/or instrumental seismic records do not exist. For the latter reason they are commonly and widely used for modern seismic hazard assessments (SCEC/CME Collaboration, 2006).

Chapter 2.2: Geodetic leveling technique

The geodetic leveling technique is defined as the set of geodetic operational procedures to follow in order to determine the height of points on the physical earth with respect to a reference surface (Salvioni, 1951). The latter is the Earth gravitational equipotential surface, better known as geoid. This represents a hypothetical ellipsoidal surface derived from the mean level of the oceans. Thus, the height of a point is defined as its elevation, measured with the leveling technique, with respect to the mean level of the oceans at the time of the survey, commonly referred to measurements done in a specific tide gauge and arbitrarily set at zero. The zero reference is needed because the corrections due to (i) oscillations of sea-level to establish the mean value, (ii) atmospheric pressure records to correct for the pressure and wind stress effects on sea-level and (iii) reduction of mean sea-level to a standard equipotential surface, represent the major source of uncertainty in the establishment of mean sea-level and may be as high as 10 cm (Hamon and Greig, 1972).

There are three different leveling methods: the measurement of the atmospheric pressure at different points, also known as barometric leveling, the measurement of the relative zenithal distance between points, usually called trigonometric leveling, and finally the measurement of the height difference between points, well known as geometric leveling technique. Each of these methods is applied depending on the target of the work to be done. The geometric leveling is the most precise (being characterized by a precision of few mm/km) among all the other above-mentioned techniques and usually it provides the fundamental reference elevation data.

The measurement procedure consists in calculating height differences, not horizontal ones, between points on the earth surface (technically called benchmarks) by using an optical level (very similar to a theodolite but particularly efficient for strictly horizontal sights) and one or more graduated rods (figure 2.5). There are different ways to set the instruments and I will focus on the geometric leveling, which is the one used for high precision measurements in the first order leveling network. Basically a leveling line is a route made by fixed points on the ground surface, benchmarks that are 1 km apart for the first order lines. Lines are organized in closed circuits and a group of circuits may constitute a leveling network. Geometric leveling is a totally independent procedure with respect to planimetric operations and the difference in elevation between the points where the rods are set corresponds to the difference in the reading done on the rods themselves. The level is usually set at equal distance with respect to the two vertical rods (figure 2.5)

Figure 2.5: Schematic procedure used for geometric leveling: measurements of benchmarks (P1 and Pn) along a levelling line (modified after Muller, 1986)

In Italy, starting from the end of the 19th century, the Istituto Geografico Militare (IGM) is responsible for the National Geodetic Network. The fundamental elevation reference of the national net is the First Order Geodetic Leveling Network is distributed on the whole country for a total length of 5000 km in the 1950’ and now is developed for about 14000 km. There are more than 100 leveling lines that generally follow asphalt roads and train lines (Muller, 1986). This fundamental network has been measured since 1870 with high precision leveling techniques, and since 1948 following the International Geodetic Association standards defined in Oslo (Vignal, 1950). The high precision leveling standards may slightly vary state by state but since 1940 the Italian ones require (Salvioni, 1951; Muller, 1986): a) double leveling between consecutive benchmarks, b) equal number of set up for forward and backward measurements, c) circuits closure, d) instrument calibration before and after each survey, e) maximum allowed sight length of 50 m, f) independent measurements between consecutive line sectors, g) use of invar rods and rod correction.

The definition of the errors associated to leveling measurements has been subject of discussion within the scientific community since the beginning of the XX century. The main point concerns the magnitude that these errors may reach along a leveling line and the propagation law governing this process. Leveling data are affected by errors whose behavior does not follow the probabilistic law common to Gauss accidental errors (Bomford, 1971). In general, the leveling errors may be subdivided into three distinct categories: blunders, systematic and random errors (figure 2.6).

Blunders and systematic errors depend on both internal and external causes with respect to the leveling procedure, like instrumental-operational errors and atmospheric refraction or variation of the meteorological condition during the survey, respectively. Moreover, blunders and random errors may be related to man-dependent mistakes or no systematic imperfection of the instruments and during the data analysis usually can be observed, controlled and erased by the comparison between forward and backward measurements. Vice versa, systematic errors tend to accumulate with distance and topographic gradient, possibly being quite important even for short distances (Vanicek et al., 1980).

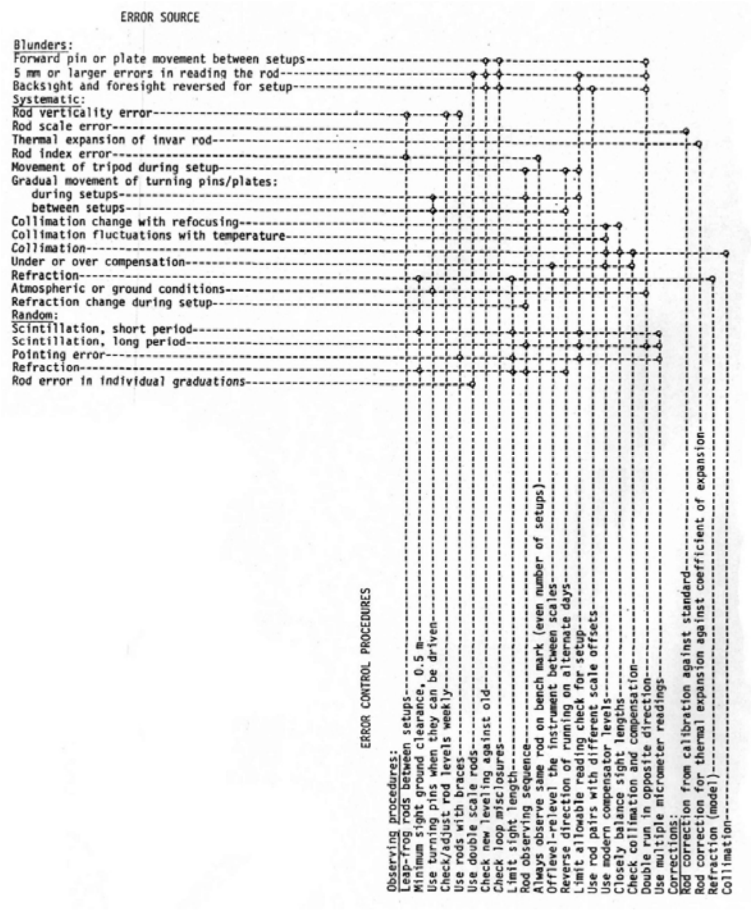

Figure 2.6: Frequent errors encountered in geodetic levelling and methods adopted to skip or at least reduce them (after Vanicek et al., 1980).

The scientific community, and particularly the geophysical one, concentrated on two major error sources: atmospheric refraction and slope-dependent errors.

They are both linked to the observation that the vertical density gradients are substantially greater than horizontal ones, being the atmospheric density dependent on pressure, temperature and humidity. The atmospheric refraction constrains the accuracy of defining the horizontal surface with precision geodetic levels to about 0.1” (Lambeck, 1988), representing a height error of 2.5×10^{-2} mm for a 50 m separation of level and stave. The refraction errors can multiply along a leveling line and become predominant over distances of 100 km and more because of: (i) systematic change in temperature during the leveling run, (ii) systematic differences in refraction between the backsights and foresights when leveling is up or down a slope. For a series of measurements along a 100 km long line, the cumulative precision amounts to about 0.1 mm/km (Lambeck, 1988), which translates to about 10 mm, while the best cumulative accuracy is about 20 mm following Bomford (1971).

Slope-dependent errors pertain to those leveling routes with grades that vary about 10%. In fact, to find an elevation-dependent error, e_{net} of 10^{-4}, a 2% grade (0.02 slope) is required to overcome the benchmark scatter and a 10% range in grade of the topography is needed to resolve a 5×10^{-5} error (Stein, 1981).

To better illustrate and describe in detail the errors discussed above and the method I used for their evaluation, I would like to bring your attention to the following article: “D'Anastasio E., P.M. De Martini, G. Selvaggi, D. Pantosti, A. Marchioni, R. Maseroli (2006): Short-term vertical velocity field in the Apennines (Italy) revealed by geodetic levelling data, *Tectonophysics* “. In particular, from page 2 to 7 there is a synthetic but organic presentation of the Italian leveling database, the method used to determine the elevation changes and the error estimation. This publication is also discussed in the following chapter 6.

In this thesis it has been decided to use the leveling terrestrial “old” geodetic method with respect to other “new” satellite geodetic techniques such as Global Positioning System (GPS), Satellite Aperture Radar (SAR), Permanent Scatter (PS), etc. for the following main reasons. 1) leveling is the only geodetic dataset regarding vertical movements that spans back in time to the past 50-100 yr; 2) no comparable sampling of active regions (about 1 benchmark per km) is presently available from GPS networks in Italy; 3) the resolution in evaluating the vertical component of motion is one order of magnitude better than GPS to GPS estimates. On the other hand, we have to take in mind not only the potential but also the main disadvantage of leveling measurements that is the lack of an absolute reference datum, given that only relative motion can be determined by comparative leveling data (Bomford, 1971).

Chapter 2.3: Why the Apennines?

At the end of this methodological chapter the reader may still have a basic question: why the proposed analysis should be done in Italy and specifically in the Apennines region? The core of the answer is related to the geographical coincidence of an excellent relatively dense geodetic leveling network 100 yr old with the occurrence, in the same time window, of several moderate to strong earthquakes characterized by a prevalent vertical component of motion. Thus, taking into account the available geodetic and geologic datasets at the national scale together with the historical and instrumental seismicity able to identify the main active structures, it appears possible to make a comparison of the seismic deformation pattern highlighted by geodetic and geologic data and an analysis of the active tectonics of the Apennines at different time scale. Main objectives of this approach are a) better understanding of the seimic deformation process and in particular of an intriguing short (100 yr long) part of the seismic cycle (preseismic, coseismic and postseimic evidences) related to faults activated during the past century, b) better definition of the Apennines large scale deformation, c) comparison of the short-and long-term datasets and consequently building of a robust estimate of the geometrical and behavioral characteristics of active faulting in the Apennines.

Chapter 2

Published articles:

D'Anastasio E., P.M. De Martini, G. Selvaggi, D. Pantosti, A. Marchioni, R. Maseroli (2006): Short-term vertical velocity field in the Apennines (Italy) revealed by geodetic levelling data, *Tectonophysics*, doi: 10.1016/j.tecto.2006.02.008

De Martini, P.M:, K. Hessami, D. Pantosti, G. D'Addezio, H. Alinaghi and M. Ghafory-Ashtiani (1998): A geologic contribution to the evaluation of the seismic potential of the Kahrizak fault (Tehran, Iran), *Tectonophysics*, 287, 187-199

Crone A.J., P.M. De Martini, Machette M.N., K.Okumura & J.R. Prescott (2003). Paleoseismicity of two historically quiescent faults in Australia- Implications for fault behavior in stable continental regions, *Bulletin of the Seismological Society of America*, 93 (5), 1913-1934

Pantosti D., P. M. De Martini, D. Papanastassiou , F. Lemeille, N. Palyvos and G. Stavrakakis (2004): Paleoseismological trenching across the Atalanti fault (Central Greece): evidence for the ancestors of the 1894 earthquake during Middle Age and Roman time, *Bulletin of the Seismological Society of America*, 94 (2), 531-549

Short-term vertical velocity field in the Apennines (Italy) revealed by geodetic levelling data

E. D'ANASTASIO, P.M. DE MARTINI, G. SELVAGGI, D. PANTOSTI, A. MARCHIONI and R. MASEROLI

Tectonophysics, 2006, Vol. 418, Pages 219-234

A geologic contribution to the evaluation of the seismic potential of the Kahrizak fault (Tehran, Iran)

P.M. DE MARTINI, K. HESSAMI, D. PANTOSTI, G. D'ADDEZIO, H. ALINAGHI, M. GHAFORYA-ASHTIANI

Tectonophysics, 1998, Vol. 287, Pages 187-199

Paleoseismicity of two historically quiescent faults in Australia: implications for fault behavior in stable continental regions

Anthony J. CRONE, Paolo M. DE MARTINI, Michael N. MACHETTE, Koji OKUMURA, and John R. PRESCOTT

Bulletin of the Seismological Society of America, 2003, Vol. 93, No. 5, Pages 1913–1934

Paleoseismological Trenching across the Atalanti Fault (Central Greece): Evidence for the Ancestors of the 1894 Earthquake during the Middle Ages and Roman Times

D. PANTOSTI, P. M. DE MARTINI, D. PAPANASTASSIOU, F. LEMEILLE, N. PALYVOS and G. STAVRAKAKIS

Bulletin of the Seismological Society of America, 2004, Vol. 94, No. 2, Pages 531–549

Chapter 3

Evidence of aseismic slip along active normal faults

Chapter 3: Evidence of aseismic slip along active normal faults

The term “aseismic slip” usually refers to movements of tectonic structures occurred without a clear correlation with seismic events. Actually a number of terms have been used to describe it: *transient slip*, *silent earthquake*, *fault-creep*, *slow slip,* etc. Generally the areas where it was observed are the plate boundaries (subduction zones and major strike-slip fault systems, mainly). Most of the latter are known to accommodate motion along relatively narrow regions of deformation, apart from those involving continental lithosphere (Molnar and Tapponnier, 1975). Furthermore, it has been recognized that fault slip in a subduction zone takes place with a source duration varying from seconds (earthquakes) to years (silent earthquakes) (Kawasaki et al., 1995; Heki et al., 1997; Burgmann et al., 1997). Clearly, understanding the ratio of fast seismic slip to slow aseismic slip is fundamentally important in assessing the danger of active faults, considering that many of the most damaging earthquakes occur within these zones. Recently observed aseismic slip events in the Cascadia, Japan and Mexico subduction zones stimulated the scientific community in discussing the role played by slow slips in the readjustment of the stress in the seismogenic zones. It was observed, both along the San Andreas Fault (Linde et al., 1996; Gao et al., 2000) and the North Anatolian Fault (Cakir et al., 2005), that aseismic slip may occur in an area adjacent to the coseismic slip area. Moreover, spatial-temporal correlation of aseismic transients and nearby seismicity in the Guerrero area (Mexico) suggests that transients may indicate a period of increased probability for nucleating a damaging subduction thrust event (Liu and Rice, 2005). To conclude this brief introduction it should be noted that most of the examples of aseismic slip events are related to plate boundaries and very little is known on active intra-plate faults. In this light, the examples presented in the following may contribute to stimulate focused studies of aseismic fault processes, based on dense leveling networks as well as on borehole strainmeters and continuous GPS studies.

Introducing the two case studies of the central Apennines I have to mention that no geological data exist on possible evidence for aseismic slip on the two faults that will be discussed in this chapter (figure 3.1). Both tectonic structures, the Colfiorito and Amatrice faults, have been recognized as important active normal faults but creeping has not been detected at the surface. Thus, the evidence comes only from geodetic leveling data of some routes belonging to the first order national network.

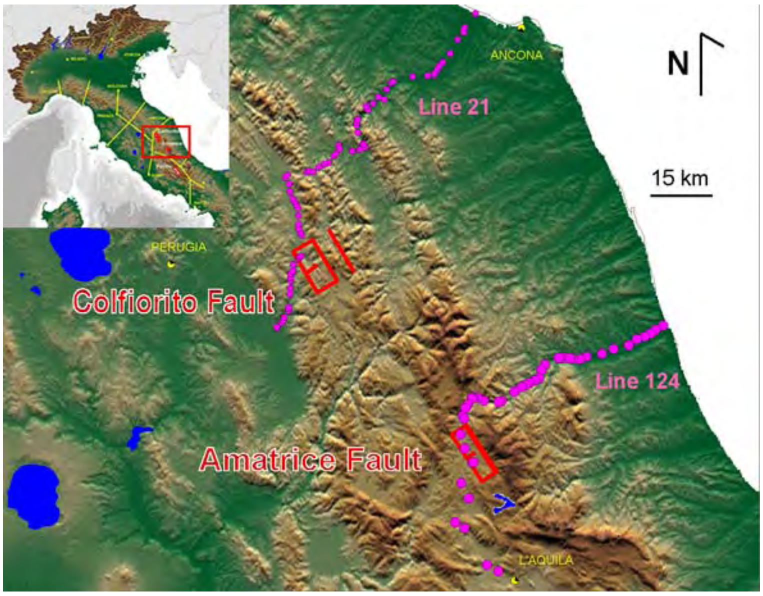

Figure 3.1. Location of the two leveling lines (purple dots), branches of the Italian first order leveling network, together with the surface projection of the two faults (in red) after Valensise and Pantosti (2001a) possibly responsible for the detected aseismic deformations.

Chapter 3.1: The Colfiorito aseismic slip case

The first case study is related to the geodetic evidence of possible pre-seismic slip on a blind seismogenic normal fault in the area of the 1997-98 Umbria-Marche sequence and it is based on “De Martini P.M. & G. Valensise (1999). Pre-seismic slip on the 26 September 1997, Umbria-Marche earthquake fault? Unexpected clues from the analysis of 1951-1992 elevation changes, *Geophysical Research Letter*, 26 (13), 1953-1956. “

The work is centered on 1951-1992 elevation changes recorded by Line 21, a first order leveling line crossing the northernmost section of the 26 September 1997 earthquake causative fault. The geodetic signal shows an amplitude of about 1/3 of the expected coseismic deformation (25 and 80 mm, respectively) and a wavelength of about 12 km. No significant earthquakes occurred in the area between 1951 and 1992 and most of the subsiding benchmarks lie on bedrock or well consolidated deposits making natural and/or induced subsidence unlikely. Therefore, the elevation changes recorded during the 41 yrs interval may be related to crustal strain of tectonic origin. Forward modeling of the geodetic signal was performed with a code developed by Ward & Valensise (1989) based on standard dislocation theory and several combinations of fault parameters were tested. The expected coseismic displacements of the 09:40, 26 September 1997 shock were compared with the 1951-1992 elevation changes and interestingly the observed subsidence was found to mimic the expected coseismic deformation pattern. Moreover, it was found that 10 cm of slip along the northernmost 5 km of the above mentioned earthquake fault could reproduce the 1951-1992 geodetic signal, implying a minimum slip-rate of 2.5 mm/yr during the time elapsed between the two geodetic surveys. This latter value is well above any estimate that could be done based on historical data (the only known predecessor possibly being the 1279 earthquake (Boschi et al, 2000) or on available paleoseismological data collected along the Apennines (Galadini and Galli, 2000; Valensise and Pantosti, 2001a; DISS Working Group, 2005).

Such a fast slip-rate may represent slip acceleration in preparation for the impending failure and it could account, at least partially, for the observed variability of the coseismic slip, characterized by a sharp drop towards the northern end of the 09:40, 26 September 1997 seismogenic fault, as suggested by several authors (Pino et al., 1999; Starmondo et al., 1999; Capuano et al., 2000). Furthermore, a couple of speculations can be done on this singular geodetic signal: a) it could be the evidence for the *stable sliding stage* (Dieterich, 1978) of the model for preseismic fault slip behavior, often equated with aseismic fault creep; b) it could imply a relatively short period of important stress changes in the focal zone, able to facilitate the occurrence of the mainshock, as suggested by *strain softening* models (Brady, 1974; Stuart, 1974, 1979; Mjachkin et al., 1975), and in this regards it can be considered as accelerated precursory slip.

Chapter 3.2: Does the Amatrice fault slip aseismically?

The second case study is related to a geodetic signal of possible tectonic origin in the area of Amatrice, central Apennines (figure 3.2).

Line 124 runs NE-SW from the city of Ascoli Piceno, located on the Adriatic coast, to the middle of the central Apennines near the city of L'Aquila.

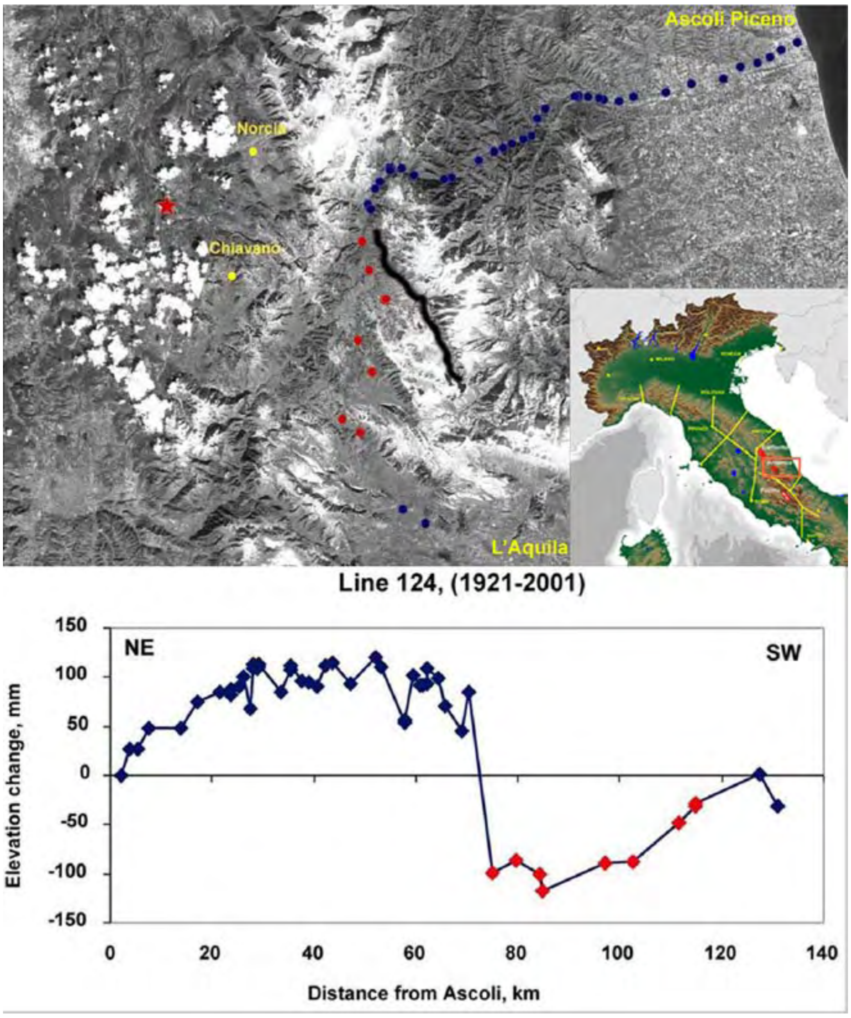

Figure 3.2. Above: Map of Line 124, a fundamental branch of the Italian first order leveling network, measured in 1921 and 2001, red dots show an anomalous behavior (INGV location of 1979 mainshock plotted as red star), the trace of the main active fault of the area (Laga Fault System (Amatrice and Campotosto faults) according to Galadini and Galli 2000) is also shown with a black line; below: the elevation changes recorded between the two geodetic surveys.

It has been surveyed two times in 1921 and 2001 by the Istituto Geografico Militare d'Italia. The wavelength (about 30 km) and magnitude (~15 cm) of the subsiding area (red benchmarks in figure 3.2) are quite important and may suggest a crustal tectonic origin. What really attracted our attention is the presence of an abrupt change in elevation between km 70 and 75 and the striking coincidence of this pronounced deformational pattern with the northernmost tip of the Amatrice fault (figures 3.2 and 3.3).

Based on the available historical and instrumental seismic records (Boschi et al., 2000, Castello et al., 2006; both available on line at http://www.ingv.it/resources/data-bases), we noticed that the area has been the locus of important earthquakes (the largest being the October 7, 1639 M~6.3 event) in the past, but that no significant seismic events occurred in the time window between the two geodetic surveys (figure 3.3).

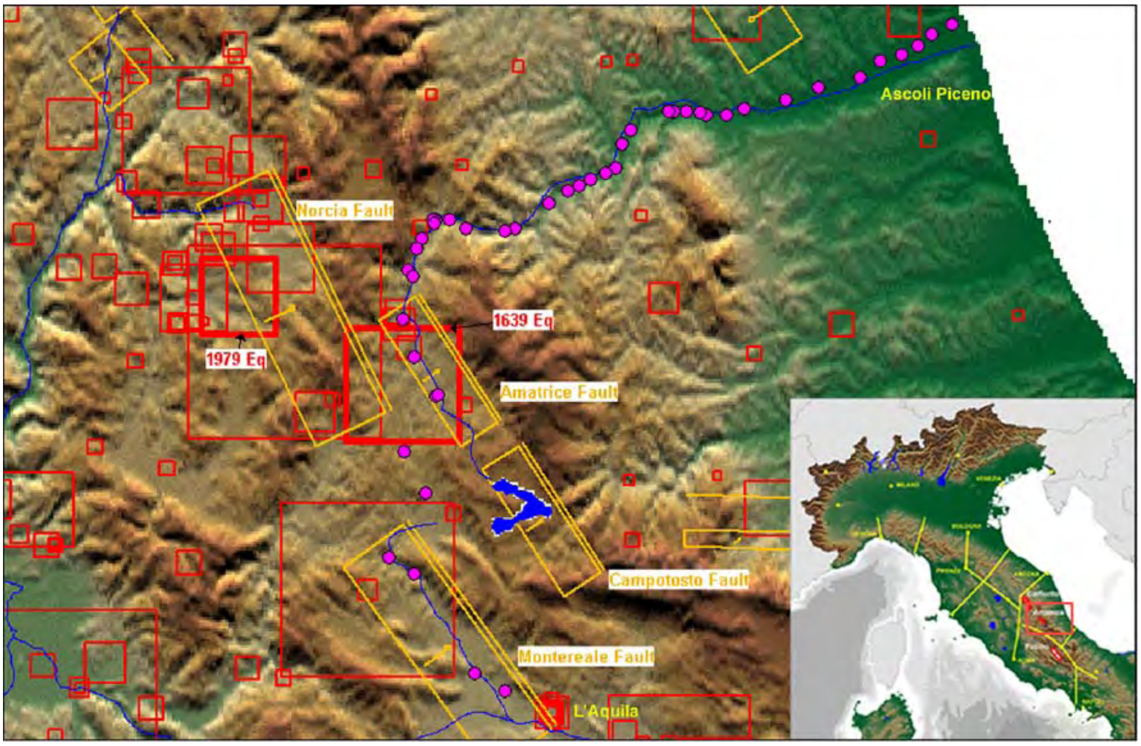

Figure 3.3. Historical (CPTI, 2004) and instrumental (Castello et al., 2006) seismicity (available on line at http://www.ingv.it/resources/data-bases) of the area crossed by Line 124 (pink dots), major seismogenic faults (DISS Working Group, 2005) are also shown (orange rectangulars).

The only exception is represented by the M~5.8 September 19, 1979 Norcia earthquake (CPTI, 2004), whose epicentre is located 15-20 km to the NW (figure 3.3), but based on the aftershocks distribution (Deshamps et al., 1984) the best candidate to have produced it appears to be the Norcia fault, a well known seismogenic structure (Calamita et al., 1994; Blumetti, 1995; Cello et al., 1997; Galli et al., 2005).

In order to exclude any obvious influence of the substratum on the shape of the geodetic signal, a detailed geological field survey was done along all the Line 124 benchmarks (figure 3.4) located between km 55 and 105 (figure 3.5). The main purposes were to describe the geological units on which the benchmarks lie and to verify the presence of active geomorphologic features, such as landslide, able to produce important local vertical movements. On the one side we found that all the surveyed benchmarks settle on the “Molasse formation” (figure 3.5), mainly composed by Upper Miocene stratified sandstone with gray marls intercalation at the bottom, locally up to 500 m thick.

Figure 3.4. Typical benchmarks of the first order leveling Line 124

On the other we verify the absence of important landslides, even if we can not exclude the contribution of small gravitational structures at the local scale.

Considering the above mentioned data, we may exclude a deformation of Line 124 due to obvious coseismic (there were no earthquakes in the area between 1921 and 2001 with enough energy to produce such elevation changes), postseismic (the most recent earthquake that can be related to the Amatrice fault being the October 7, 1639 M~6.3 event following Valensise and Pantosti, 2001a, DISS Working Group, 2005), creeping (at the surface it was never observed any clear slow movements along the trace of the Amatrice fault) and gravitational movements.

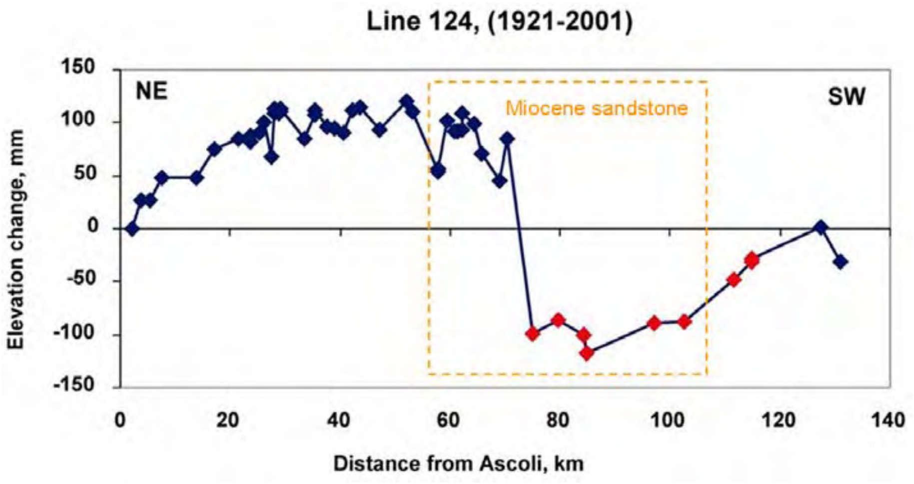

Figure 3.5. Elevation changes recorded between 1921 and 2001, the area for which a Miocene substratum has been observed in the field is also shown in orange.

At this point we may suggest that the observed elevation changes are related to aseismic movements on the Amatrice fault and we decided to adopt a procedure involving forward modeling of the observed geodetic signal in order to calculate the amount of slip needed to fit the dataset. We started our modeling approach taking into account the available information about the geometric parameters of the Amatrice fault (length 14 km, width 9.5 km, strike 150°, dip 65°, after DISS Working Group, 2005) and not having any direct data about its kinematic we decided, in accordance with all the main seismogenic structures of the area, to adopt a rake of 270°, that it’s to assume a pure normal faulting style. The calculations assume uniform slip on planar, rectangular fault embedded in an elastic half-space, and were performed with a code developed by Ward & Valensise (1989) based on standard dislocation theory.

During this preliminary approach, it was decide to vary the amount of slip only, in order to avoid a mixture of the influences of all the parameters involved in the calculations. From all the calculations done, it is clear that movement along the Amatrice fault is able to account for the abrupt change in elevation observed along Line 124 between km 70 and 75 (figure 3.2). More in detail, it was found that a slip of 25±5 cm is able to produce a reasonable good fit of the observed geodetic data (figure 3.6).

While modeling the observed geodetic dataset, we should consider that the elevation changes of all the benchmarks located east of the fault are at least partially due to regional uplift expressed as a symmetrical bulge (Bordoni and Valensise, 1998; D'Agostino et al., 2001; D'Anastasio et al., 2006) almost centered on the chain axis (see figure 3.2 and note the trend from Ascoli westwards). This introduces a further uncertainty in trying to fit the observed leveling signal and it could be properly solved only with the help of independent data able to discriminate the different contributions. Another problem that clearly shows up in figure 3.6 is related to the large dimension of the observed area of subsidence, difficult to model with the parameters proposed by DISS Working Group, 2005. Very likely, we will try to enlarge the fault width (at least from 10 to 15 km) in order to get a larger hangingwall area, probably fitting better the observed geodetic records, located at about 100 km along Line 124 (figure 3.6).

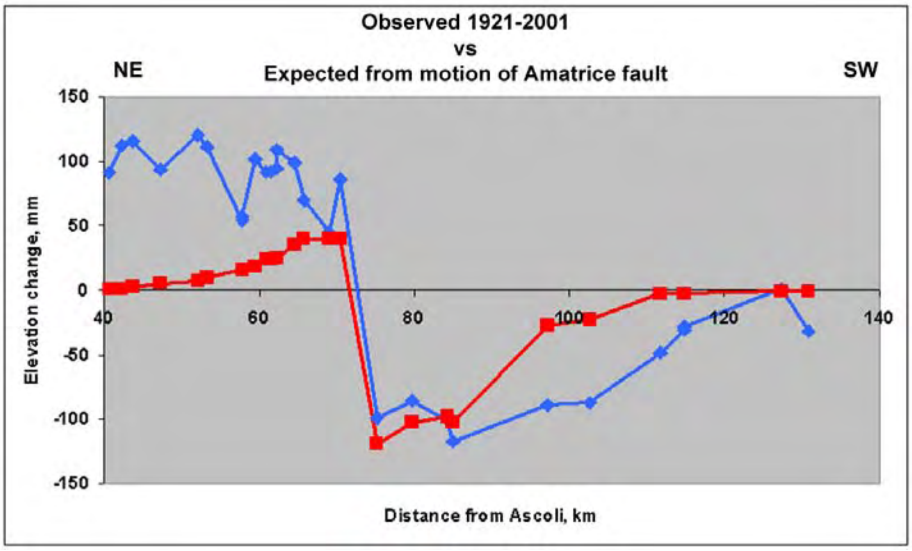

Figure 3.6. 1921-2001 elevation changes recorded by Line 124 (blue colour) and expected elevation changes associated with 25 cm slip along the Amatrice fault (red colour).

Note that, despite the fact that 25 cm is not a considerable amount in terms of coseismic movement, it implies slip at a minimum rate of 3.0±0.5 mm/yr between 1921 and 2001. Based on available geomorphological and paleoseismological data a Late Pleistocene vertical slip rate of 0.7-0.9 mm/yr is estimated (Galadini and Galli 2000), thus suggesting that such a fast short-term slip rate can hardly be considered representative of the long-term behavior of the Amatrice fault.

In conclusion, the geodetic signal observed along leveling Line 124 could be related to the activity of the Amatrice fault. This recent tectonic movement occurred in the 1921-2001 time interval and can not be related to any significant seismic event, nor to creeping or gravitational movements. Thus, a preliminary interpretation seems to suggest the occurrence of aseismic slip at a minimum rate of 3.0±0.5 mm/yr. If we take in consideration the Colfiorito example presented before, we may be tempted to interpret the Amatrice fault aseismic slip as a precursory accelerated movement before a seismic event. Since 2001 no significant earthquakes happen in the study area and thus, at present, this interpretation has no physical support but at the same time it can not be simply ruled out.

Pre-Seismic Slip on the 26 September 1997, Umbria-Marche Earthquake Fault? Unexpected Clues from the Analysis of 1951-1992 Elevation Changes

P. M. DE MARTINI, G. VALENSISE

Geophysical research letters, 1999, Vol. 26, Pages 1953-1956

Chapter 4

Evidence of co-seismic slip along active normal faults

Chapter 4: Evidence of co-seismic slip along active normal faults

This chapter deals with geodetic and geologic evidence of co-seismic slip recorded along some of the earthquake faults responsible for the 1997-98 Umbria-Marche (central Italy) seismic sequence. This sequence was characterized by seven Mw > 5 events (Amato et al., 1998; Ekström et al., 1998; Barba and Basili, 2000; Morelli et al., 2000) occurred in the upper crust between 9 and 3 km depth.

The first section of the chapter focuses on coseismic geodetic vertical elevation changes recorded in the 1997-98 epicentral area, and discusses the use of geodetic leveling data, combined with seismological information, in order to constrain earthquake source parameters and slip distribution. It is based on "De Martini P.M., N. A. Pino, G. Valensise & S. Mazza (2003): Geodetic and seismologic evidence for slip variability along a blind normal fault in the Umbria-Marche 1997-1998 earthquakes (central Italy), *Geophysical Journal International*, 155, 819-829". Moreover, a joint analysis of InSAR and leveling data is presented, trying to explain how this combined approach may help in localizing possible small coseismic fault splays. It is based on "Stramondo S. and P.M. De Martini (2004): Modeling surface displacements of the 1997 central Italy earthquakes from InSAR and leveling geodetic data, 32nd International Geological Congress, Florence, Italy, 20-28 August 2004"

The second section focuses on the coseismic geologic effects observed soon after the 1997-98 Umbria-Marche earthquakes and discusses the data obtained from field survey and exploratory paleoseismological trenching along the surface rupture produced by the October 14, 1997 Mw = 5.6 earthquake. It is based on "Pantosti D., P.M. De Martini, P. Galli, F. Galadini, P. Messina, M. Moro & A. Sposato (1999): Studi paleosismologici lungo la rottura superficiale prodotta dal terremoto del 14 Ottobre 1997 (Umbria-Marche), in *Atti del 18° Convegno del Gruppo Nazionale di Geofisica Della Terra Solida*, 13 pp., Roma 9-11 Novembre 1999".

Chapter 4.1: Coseismic geodetic vertical changes in the 1997-98 Umbria-Marche epicentral area

On 26 September 1997, two moderate-size (Mw 5.7 and 6.0, respectively at 00:33 and 09:40 GMT) but damaging earthquakes struck the Umbria-Marche Apennines near Colfiorito (central Italy), about 30 km E of Assisi and 130 km N-NE of Rome, starting an 8 month-long seismic sequence (figure 4.1). The earthquakes occurred within a ~50 km-long, roughly NW-SE trending elongated region and most of them occurred less than 9 km depth (Amato et al., 1998; Barba and Basili, 2000; Cattaneo et al., 2000; Deschamps et al., 2000). The aftershock sequence was characterized by seven upper-crustal Mw>5 earthquakes (Ekström et al., 1998; Morelli et al., 2000) and culminated with the 14 October 1997, Sellano (Mw 5.6) and the 3 April 1998, Gualdo Tadino (Mw 5.1) events, respectively located near the SE and NW ends of the rupture zone.)

Chapter 4.1.1: Leveling and seismological evidence for coseismic slip variability

As already mentioned, from September 26, 1997 to April 3, 1998 an important seismic sequence occurred along a 50 km long NW-SE elongated region of the central Apennines, between Nocera Umbra and Sellano in the Umbria-Marche regions. The northern part of this epicentral area is crossed by a fundamental route of the Italian first order leveling network (Line 21). The record of coseismic elevation changes supplied by Line 21 (surveyed in 1992 and 1998) was compared with elevation changes predicted using fault models inferred combining short-period and regional broad-band seismological data (Amato et al., 1998; Ekström et al., 1998; Pino et al., 1999; Barba & Basili, 2000; Morelli et al., 2000; Pino & Mazza, 2000). The calculations assume uniform slip on planar, rectangular faults embedded in a elastic half-space and were performed with a code developed by Ward & Valensise (1989) based on standard dislocation theory. The fault responsible for the 1997 September 26, 09:40 Mw=6.0 mainshock (F1) accounts for over 90% of the observed signal along Line 21 and only one additional fault, that responsible for the 1998 April 3, Mw=5.1 shock, produces significant elevation changes (figure 4.0).

An approach involving both uniform and variable slip, together with a grid search analysis performed by varying the fault length, width and top depth, were adopted for the abovementioned two faults. Under the assumption of slip uniformity, a significant misfit with large residuals in the central-northern section of Line 21 existed. Viceversa, by using a coseismic slip function obtained from regional broad-band seismological data for F1 (Pino et al., 1999; Pino & Mazza, 2000), the misfit reduces substantially. The best fitting fault model for F1 has a length of 14 km, width of 8 km and depth of the fault top at 3.4 km, thus it suggests the existence of a clearly blind, low-angle (~ 40°) seismogenic normal fault (figure 4.0).

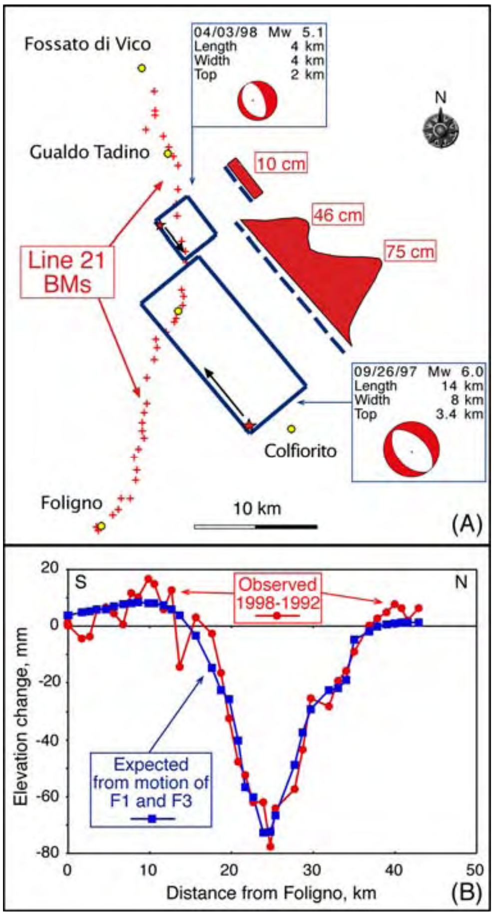

Figure 4.0. (a) Best-fitting model faults and relative maxima of variable slip distribution (modified after De Martini et al., 2003). Directivity (black arrow inside box) from Pino et al. (1999). (b) Observed elevation changes (red line) compared with the expected displacements (blue line) from motion of our best-fitting model faults (F1, F3).

With respect to other fault models derived from GPS (Hunstad et al., 1999) and SAR interferometry data (Stramondo et al., 1999; Salvi et al., 2000), our solution requires a longer and deeper fault, in good agreement with the results obtained from the analysis of strong motion data (Capuano et al., 2000) and from the re-leveling of a 4 km long aqueduct located in the central part of the epicentral area running perpendicular to the 1997 September 26, 09:40 Mw=6.0 causative fault (Basili & Meghraoui, 2001).

The variable distribution of coseismic slip adopted in this work exhibits two maxima (75 and 46 cm centered at 4 and 10 km from the southeastern edge of the fault, respectively) that could be interpreted as evidence for major asperities, in accordance with the distribution of aftershocks (Barba & Basili, 2000) showing a larger density of seismic release outside and around the two main slip patches. Moreover, the asymmetry in the distribution of coseismic slip could be at least partially justified by the 10 cm pre-seismic slip documented along the northern portion of the fault plane by De Martini and Valensise (1999).

Chapter 4.1.2: Joint analysis of InSAR and leveling data

A strategy involving combined analysis of InSAR (differential interferogram after Stramondo et al., 1999) and leveling data (elevation changes after De Martini et al., 2003) was adopted in order to identify and model peculiarities of the coseismic deformation pattern such as unexpected uplifted sectors in the fault hanging wall (De Martini et al., 2003) or minor fault splays as already suggested by Basili and Meghraoui, (2001).

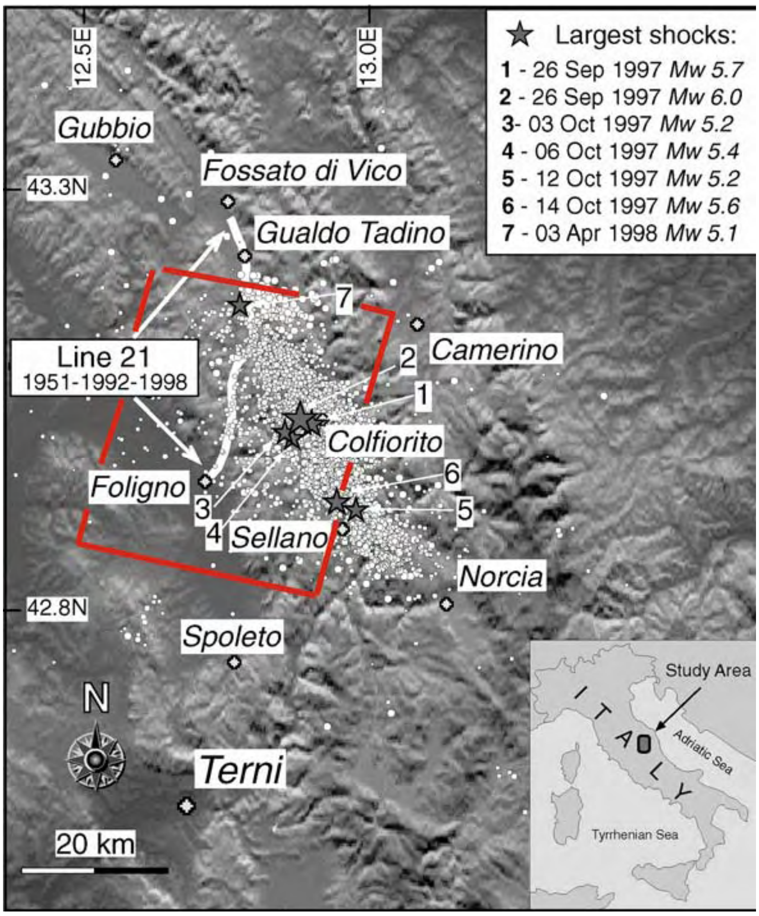

Figure 4.1. Seismicity distribution of the Sept. 1997-April 1998 central Italy seismic sequence. Stars locate the mainshocks; white line indicates first order leveling Line 21; red quadrilateral locates the pre and post-seismic ERS1-ERS2 InSAR images covering the 1997-1998 epicentral area.

Because of leveling data location with respect to seismicity distribution (figure 4.1) and rupture directivity of major shocks (Pino et al., 1999) we concentrate on the 26 Sept 09:40 event only. The two datasets reinforce each other being the leveling data located in the northern part of the differential interferogram, where InSAR signal (the interferometric fringes) obtained from the satellite images are less clear and tend to dissolve (Stramondo et al., 1999).

As starting point we use two different fault models available from the study of InSAR (after Lundgren and Stramondo, 2002) and leveling (after De Martini et al., 2003) data. We have to mention that the fault model (length 18 km, width 10 km, top 0 km) derived from the inversion of InSAR data includes the earthquake sources of both 26 September mainshocks, while the best fitting fault model (length 14 km, width 8 km, top 3 km), derived from leveling data forward modeling, refers to the 26 September 09:40 event only. A branch cut algorithm has been used for InSAR phase unwrapping (Goldstein et al., 1988) (figure 4.2 A). The solution propagates from a point in the most coherent area close to the center of the image. Thus we start to "clean" the original InSAR unwrapped phase by subtracting the contribution of the first important shock (26 September 00:33 event) occurred in the study area in order to obtain an InSAR modified image (figure 4.2 B) related to the 26 September 09:40 event only.The coseismic deformation to be subtracted has been obtained by modeling the southern part of the Lundgren and Stramondo (2002) fault model, expected to be related to the first mainshock (figure 4.3 A). Forward modeling is performed with a code developed by Ward & Valensise (1989) based on standard dislocation theory.

Finally the synthetic deformation derived from the leveling fault model has been calculated (figure 4.3 B) in order to definitely "clean" the unwrapped interferogram from any major coseismic contribution (figure 4.4). The decision to use the leveling derived fault model is based on the fact that: a) the residuals obtained from the comparison of the expected and observed (InSAR interferogram) coseismic deformation fields are smaller even with respect to those obtained using the InSAR inversion fault model and b) it represents an independent dataset with respect to the satellite data. We were expecting an image dominated by sparse noise and characterized by large areas with similar behavior. Interestingly, we noticed that northeast of Annifo village (see red dashed square in the northern sector of figure 4.4) there is an area where a rounded sector of positive residuals faces another one dominated by negative residuals; interestingly the separation between the opposite fields appears anomalously sharp.

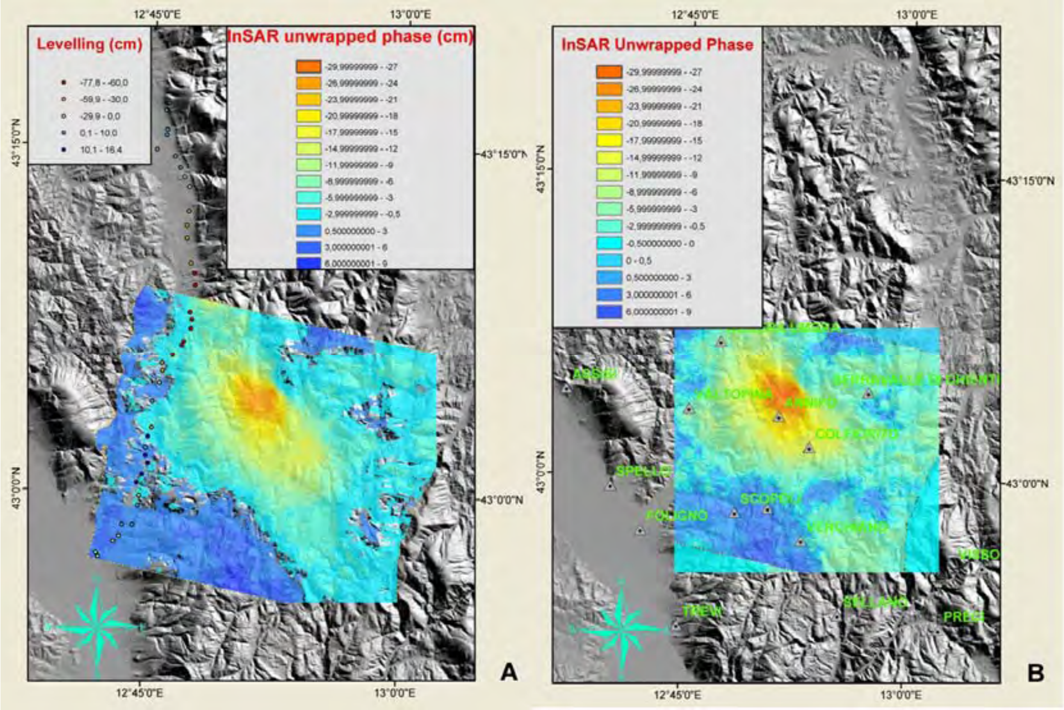

Figure 4.2. A) Original InSAR unwrapped phase and leveling benchmarks, please note that the transparent zones are stable (no movement) and that a large uplifted area is visible in the SW sector; B) modified InSAR unwrapped phase related to the 26 Sept 09:40 earthquake only.

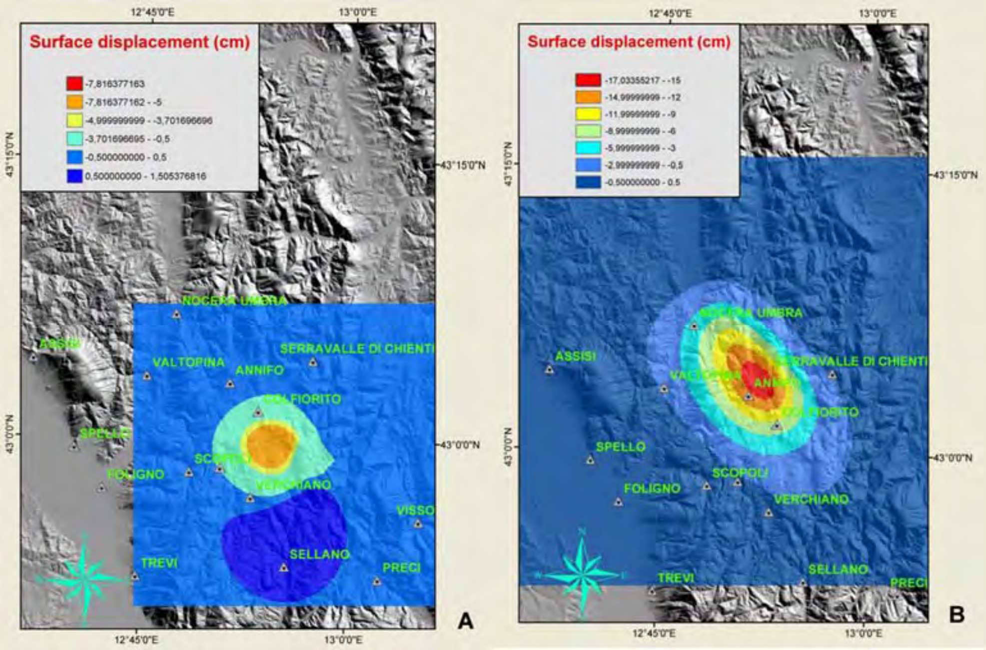

Figure 4.3. A) Coseismic deformation of the 26 Sept 00:33 event; B) Coseismic deformation of the 26 Sept 09:40 event

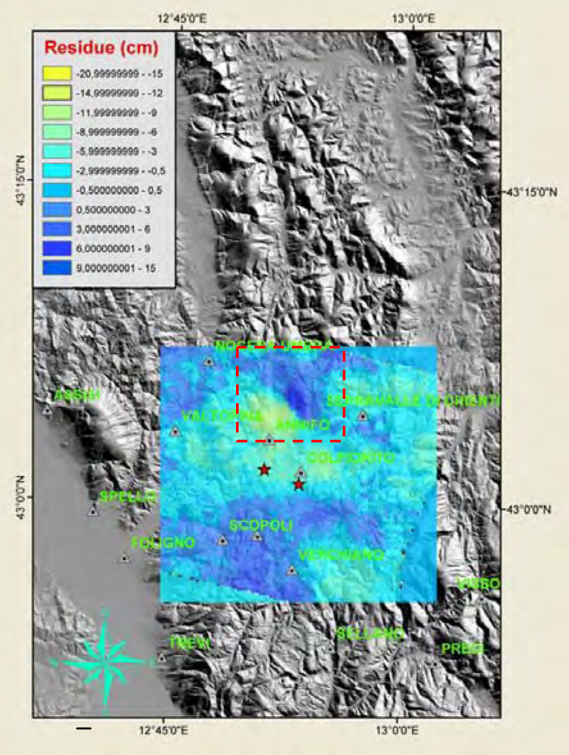

Figure 4.4. Modified InSAR unwrapped phase obtained by subtracting the coseismic deformation of both 26 September mainshocks. Please note the peculiar "coseismic-like" pattern of the area within the red dashed square, where positive and negative residuals define two circular areas.

The distinctive pattern highlighted in figure 4.4 looks like a coseismic signal related to a small (4-5 km long) fault splay possibly activated on 26 September 09:40. To better describe this feature three displacement profiles were traced across it (figure 4.5) and a significant elevation change (up to 30 cm) over a length of about 4 km showed up. A similar figure has been already presented by Basili and Meghraoui (2001) for an area located a few km to the south, and interpreted as evidence for upward branching of a minor but steep fault splay. In fact, elevation changes recorded by an old aqueduct in the Colfiorito plain, leveled before and after the 26 September 1997 earthquakes show a general similarity with the profiles of figure 4.5, even if the deformation of the aqueduct appears distributed over a smaller distance (1 to 1.5 km).

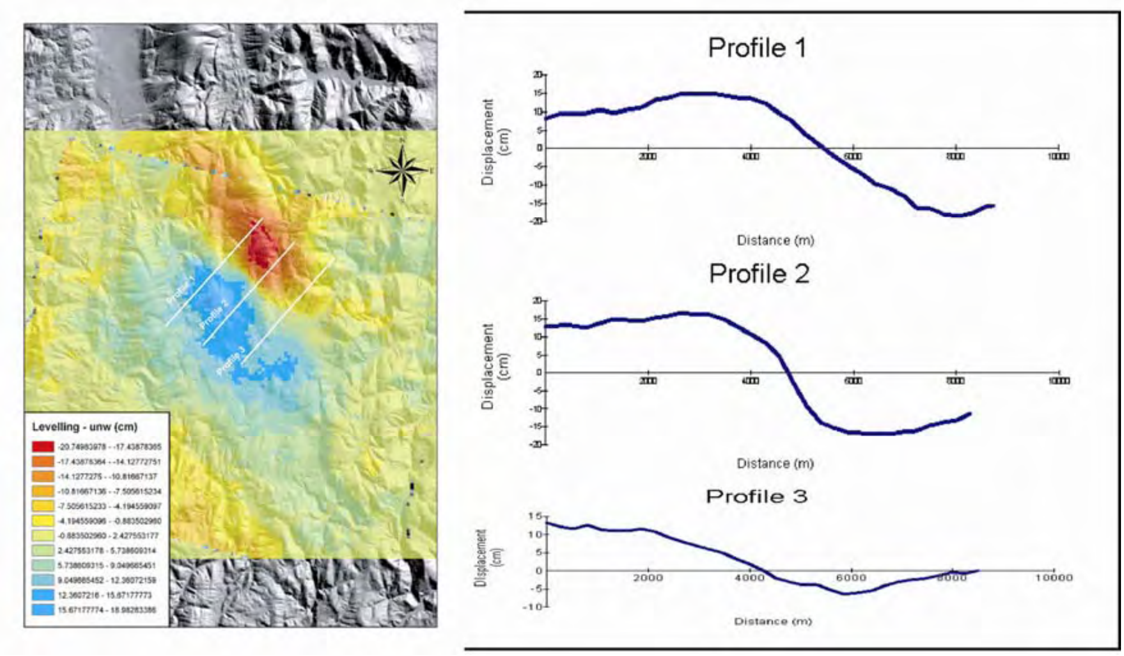

Figure 4.5. Left) Zoom-in of the area marked with a red dashed square in figure 4.4, trace of profiles 1, 2 and 3 is also shown; right) profiles 1, 2 and 3 derived from the InSAR unwrapped phase shown on the left. The maximum vertical separation of the "uplifted" and "subsided" areas appears to be about 30 cm over a length of a few km.

In conclusion, the elevation changes observed in figures 4.4 and 4.5 could be interpreted as the result of tectonic (coseismic) deformation quite similar to those published by Basili and Meghraoui (2001). A splay from the main fault, responsible for the 26 September 1997, 09:40 earthquake, may have ruptured the upper 4-5 km resulting in the deformation pattern shown in figure 4.5, obtained by subtracting the coseismic contribution of the 26 September mainshocks to the original InSAR image. The next step will be the modeling of this signal and possibly the conjunct interpretation of the Basili and Meghraoui (2001) model in order to better define the 3D geometry of the supposed fault splay. At the same time it will be probably interesting to work on the "anomalous" uplift visible in the SW epicentral sector both on the leveling profile (De Martini et al., 2003) and on the InSAR unwrapped phase (figure 4.2 A).

Chapter 4.2: Paleoseismological analysis of the October 14th 1997 surface ruptures (central Italy)

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Abstract. During the Autumn 1997 a seismic sequence struck the Umbria region in central Italy with three main shocks. The third in size of these shocks occurred on October 14th 1997 (Mw=5.6) and hit the Sellano area. It produced a double set of surface ruptures between the Mevale and Renaro villages, for a total length of 1.7 km, and near Rasenna village, where the main trace was 0.4 km long. Interestingly the NNW-SSE trending ruptures affected both the bedrock and the recent colluvium/alluvium deposits showing a maximum vertical offset of 15 cm. No clear linkage with the topography or active tectonic structure previously mapped were found. The discussion on the tectonic meaning of these surface ruptures is still going, even if instrumental data such as focal mechanism, hypocentral depth and aftershocks distribution appear to be in agreement with the location and the geometry of these features. We opened two explorative trenches across the Mevale-Renaro ruptures. Trench 1 was located just south of Renaro village and showed a colluvial/alluvial sequence up to 3 m thick lying on weathered tertiary bedrock (Scaglia Cinerea formation). Below a gentle flexure at the surface we could observe a V shaped zone of strong disturbance produced by the 1997 earthquake and by at least an older event of deformation. Trench 2 was dug where the vertical offset was maximum and exposed mainly the Scaglia Cinerea formation under 1 m thick sequence of poorly developed colluvium deposits. In coincidence with the surface ruptures, still visible at this site, a well defined fault zone affects the whole section that appears strongly sheared and embricated. Evidence for a pre-1997 event of deformation is represented by an abrupt increment of the offset of unit 3a with respect to the surface, along with a scarp derived deposit (colluvial wedge unit 2). Size and geometry of the deformation produced by this pre-1997 event is comparable to the 1997 ruptures, suggesting a similarity

between the two events. Radiocarbon ages of samples collected in the trenches are used to constrain the age of the event as more recent than 170 BC. The information we collected in the trenches suggest that at least one moderate size paleoevent occurred in the past 2000 years and that the 1997 earthquake could be considered as the maximum expected magnitude for this source. Unfortunately the absence of an upper limit for the timing of the penultimate event does not allow precise correlation to any of the historical earthquakes felt in the Sellano area.

Introduction. The 1997 Umbria-Marche earthquakes (figure 4.6) produced surface ruptures for which the tectonic or gravitational origin, together with all the possible intermediate interpretations, is still a matter of debate (Galli et al., 1997; Basili et al., 1998; Cello et al., 1998; Cinti et al., 1999; Galli & Galadini, 1999; Barba e Basili, 2000; Vittori et al., 2000). The surface ruptures produced by the two 26 September mainshocks occurred along some NW and NNW striking normal faults, previously interpreted as active faults (Cello et al., 1997; 1998). As discussed by many authors, the latter ruptures are discontinuous, localized at the contact of the Mesozoic calcareous formations with the Quaternary slope deposits; individually none of them exceeds 300 m in length, showing an average vertical offset of 2-4 cm with a maximum value of 21 cm. Cello et al. (1998) infer a total length of 6 km by linking all the ruptures each other.

On the contrary, the 14 October event surface ruptures did not run along previously detected tectonic lineaments and could be subdivided in two different sets: the first between Mevale and Renaro villages and the second one around the Rasenna village (figure 4.7). The ruptures appear discontinuously on the ground and are characterized by an average NNW strike and by maximum vertical offset of about 15 cm. By linking all the contiguous portions, the surface ruptures between Mevale and Renaro villages may be traced for a total length of about 1.7 km (figure 4.7). Close to Rasenna village the main rupture is about 0.4 km long and other smaller fractures of the ground have been observed for a total distance of about 3 km (Galli et al., 1997).

Taking into account the moderate magnitude of the mainshocks (and consequently of the small amount of the observed surface ruptures) together with the low-angle geometry of the causative faults, “anomalous” for a normal fault, as suggested by focal mechanism solutions (Ekstrom et al., 1999; Morelli et al., 2000), by pre-seismic and coseismic elevation changes (De Martini & Valensise, 1999; De Martini et al., 2000) and by InSAR interferogram (Salvi et al., 2000), the debate on the tectonic meaning of these ruptures probably will remain an open question.

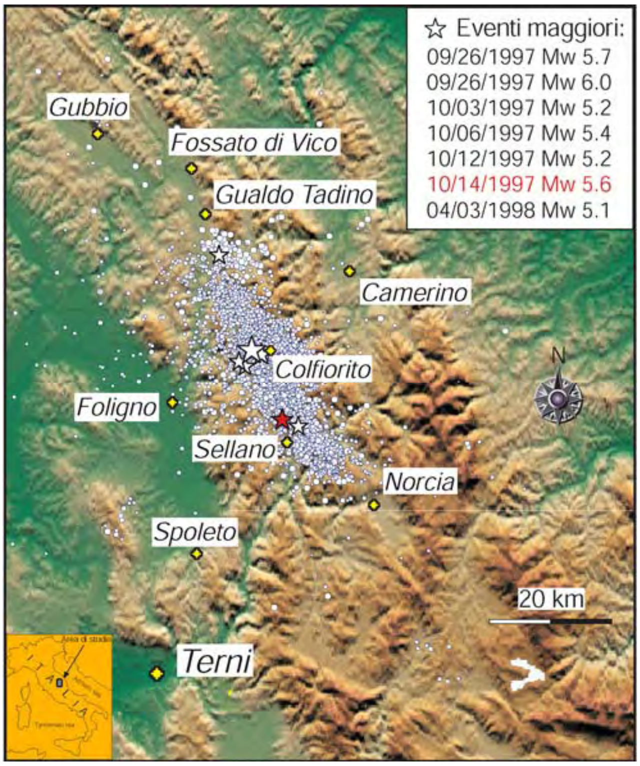

Figure 4.6. Seismicity distribution of the Colfiorito sequence from September 1997 to April 1998 (after Boschi et al., 1998). Note that the aftershoks tend to distribute along the Apennine chain axis and include several earthquakes (marked by stars) characterized by medium-high energy (after Ekstrom et al., 1999; Morelli et al., 2000). The red star locates the epicentre of the event responsible of the surface ruptures investigated in this work.

The present work does not want to add a new interpretation on this subject, but aim to investigate the long-term seismic behaviour of the sources responsible of the 1997 seismic sequence, in order to understand the frequency of moderate size earthquake in this sector of central Apennines. To reach this goal, the most effective approach is undoubtedly to dig exploratory trenches across the 1997 seismic surface ruptures looking for evidence of paleo surface breaks. The question about the direct or indirect/gravitational meaning of these ruptures can be initially overcome assuming that, apart from their intrinsic origin, a previous earthquake would have produced similar features at the same sites. Obviously, the initial assumption will be discussed and re-evaluated based on the obtained results.

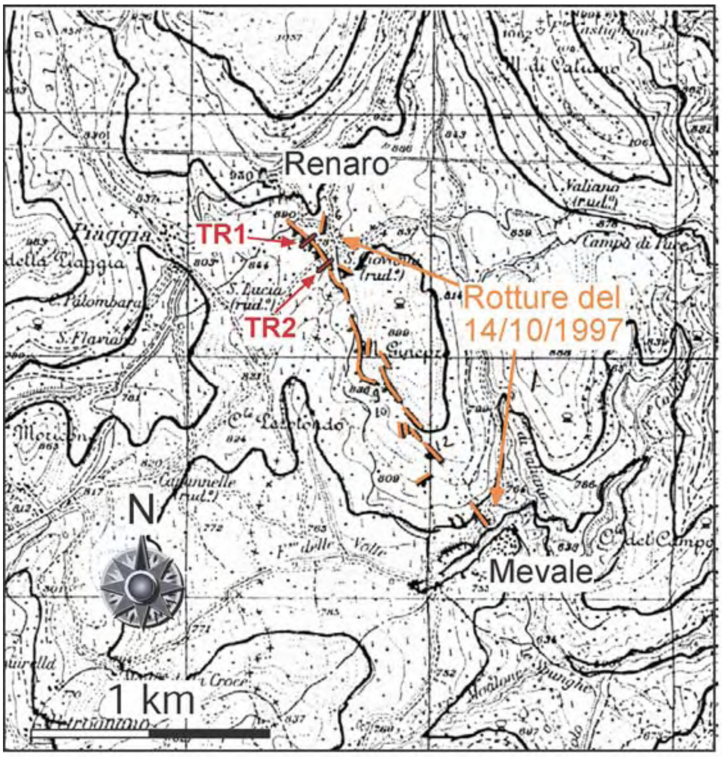

Figure 4.7. Simplified trace (orange) of the ruptures produced by the 14 October 1997 earthquake between the Renaro and Mevale villages and location of the two exploratory trenches (modified after Basili et al., 1998). Note how these ruptures striking NNW-SSE are not influenced by the local morphology and the absence of clear morphological evidence.

Exploratory trenches were already opened in 1998 and 1999 along the fault bounding the Colfiorito basin (at La Pintura locality and close to the basin threshold) by two different research groups (Meghraoui, pers. com.; Micarelli, pers.com.). In both trenching campaigns, digging was performed across morphological features probably related to repeated movement of the fault but not across the 1997 ruptures. On the contrary, the 14 October 1997 Sellano ruptures crosscut colluvia and alluvial deposits and thus can be investigated through paleoseismological excavations. In this work, we present preliminary results of two trenches dug across the ruptures occurred between the Renaro and Mevale villages (figure 4.7).

The trenches. The excavations were done at two sites selected on the basis of the potentiality to find the geological record of paleoevents of deformation. Trench 1 is localized in a small E-W oriented valley at the foothill of the Renaro village (figure 4.7). At this site, the 1997 surface ruptures showed an almost null vertical offset, disappearing few tens of meters northward. The irregular saw-blade like trend of these ruptures was suggestive of a not negligible horizontal component of movement, similarly to the left horizontal component of the ruptures visible on the dirt road of the nearby Dominjianni property (figure 4.8). Agricultural activity performed after the 1997 Autumn completely obliterated the coseismic traces, still visible south of the asphalt road only.

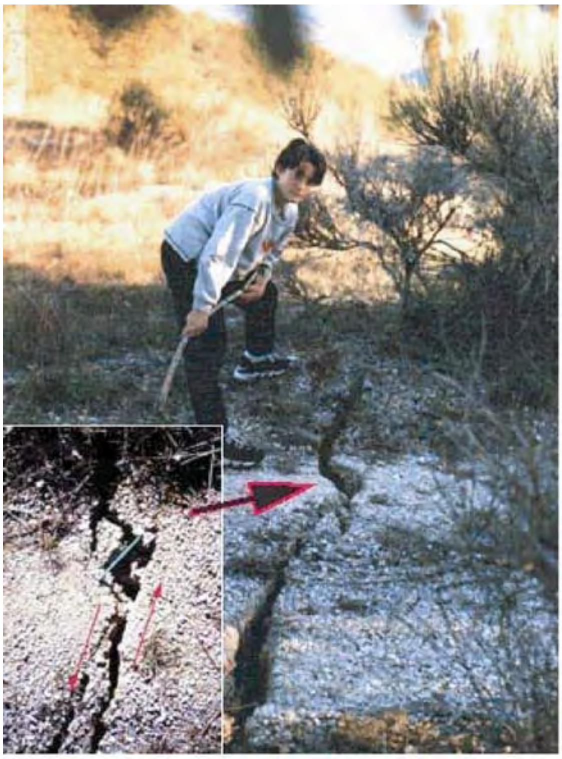

Figure 4.8. The 14 October 1997 rupture on the dirt road that takes to the Dominjianni house (courtesy of the Dominjianni family) and detail showing the presence of a left-horizontal component of movement.

Trench 1 site was selected because, despite the small magnitude of the 1997 surface ruptures, these crosscut recent alluvial deposits related to a small seasonal drainage, nowadays canalized in order to facilitate the agricultural activity.

Trench 2 was dug where the 1997 surface rupture showed the maximum vertical offset, close to 15 cm, about 100 m from the asphalt road (figures 4.7 and 4.9). At this site the coseismic rupture is well preserved and it affects a 20-30 cm thick soil developed on a colluvial coverage, lying on Tertiary basement (Scaglia Cinerea formation) locally outcropping nearby. Note that, as usually it occurs with loose sediments characterized by fine matrix, susceptible to volumetric changes depending on the water content, at this site the rupture width changes with time because of the seasonal humidity or dryness.

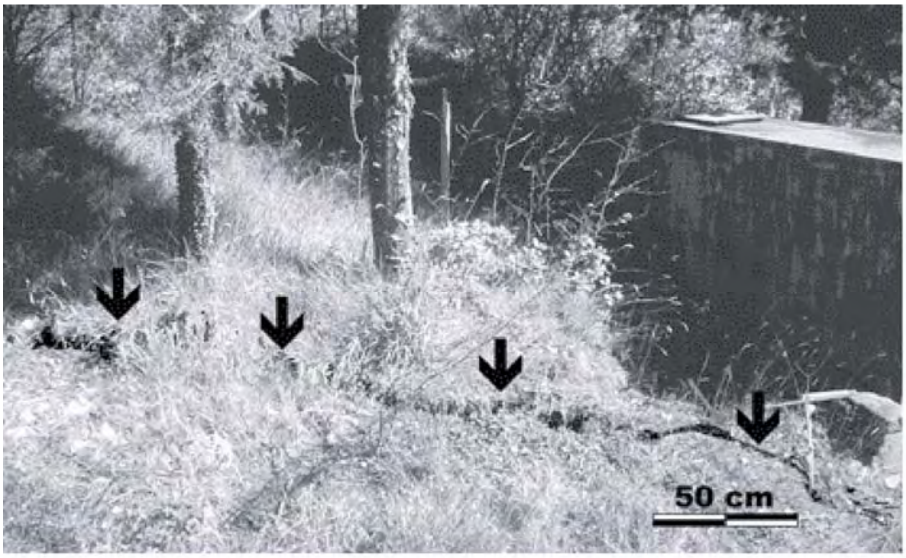

Figure 4.9. South of Dominjianni house the coseismic rupture exhibits the observed maximum vertical offset (about 15 cm), Trench 2 was dug few meters to the right of this picture.

Trench 1. Trench 1 walls exposed an alluvial and colluvial sequence up to 3 m thick above the regolitic horizon of the Scaglia Cinerea formation (unit 6 in figure 4.10). In detail, an organic paleosol partially colluviated (unit 5) up to 50 cm thick rests on the Scaglia Cinerea formation. This paleosol is covered by about 40-70 cm of silty massive deposits with few clasts (units 3 and 4) and by a stratified sequence of silt and coarse sand layers (unit 2). The sequence ends with about 40 cm of plowed horizon (unit 1 in figures 4.10 and 4.11). Even if the 1997 ruptures were completely obliterated on the ground, the detailed reconstruction of the topographic profile traced on the trench walls shows a wide inflection exactly where the ruptures occurred (figure 4.10). This slope change could represent the flexure, modified and back-shifted by agricultural activity, that occurred together with the coseismic ruptures and was not identified at the time of the earthquake because the lack of excavations and detailed topographic profiles. At depth, just below this flexure, the 1997 ruptures are still visible as subvertical discontinuous thin fractures (m 3-4 in figure 4.10). In the area enclosed within these fractures, the deposits are heavily disturbed, barely cemented or completely loose and it is not possible to recognize their stratified structure.

Another fracture zone, separating perturbed and undisturbed deposits, is well visible about 1 m west of the previous one (m 4-5 in figure 4.10). This second one is characterized by an eastward dip and by clearly structure-less deposits but cemented, differently from the loose sediments characterizing the nearby eastern fracture zone.

Altogether, these two fracture zones delineate a V-shaped sector internally totally disturbed, while externally the structure of the more recent deposits (units 2 and 3) appears preserved. Lower deposits (units 4, 5 and 6) do not show clear evidence of fracturing or dislocation, probably thanks to their more plastic behaviour. Nevertheless, in the few places where the Scaglia Cinerea formation (unit 6) is not completely altered, in coincidence of the fracture zone an increment of the bedding dip occurs, thus suggesting a buried flexure. Moreover, in the organic paleosol layer, thickening and several geometrical irregularities occur in correspondence with the disturbed zone. Eastward of the main fracture zone (m 2-3 in figure 4.10) both the paleosol (unit 5) and the massive silt layer (unit 4) appear displaced by about 10 cm. This deformation is not clear in the Scaglia Cinerea formation below and it appears completely sealed by younger units.

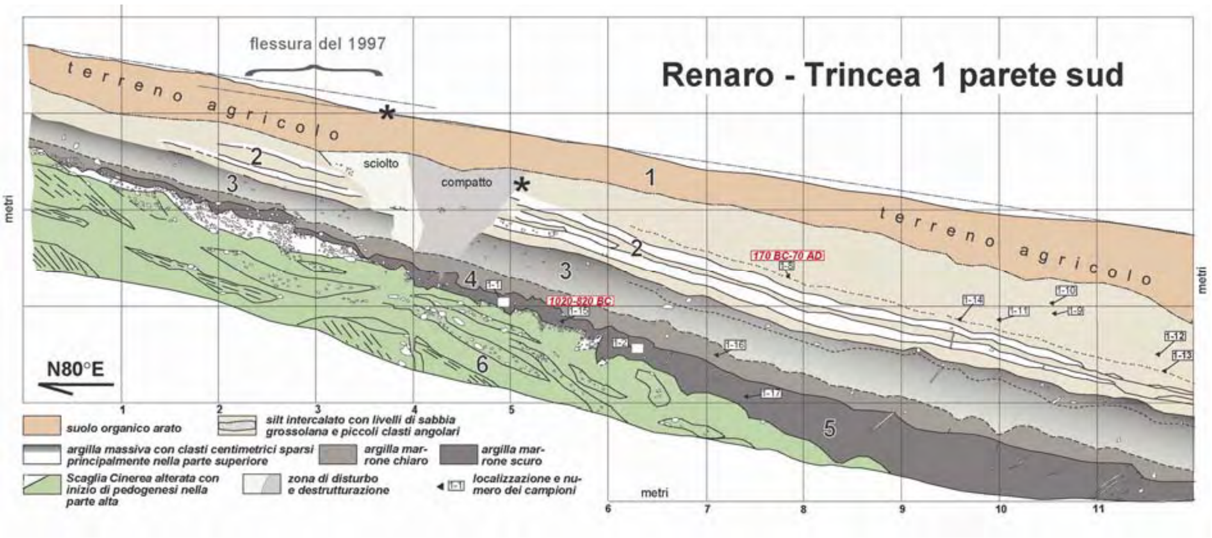

Figure 4.10. Trench 1 south wall, log simplified from a detailed work done at scale 1:20. Big black numbers refer to units cited in the text. Small black triangles represent charcoal samples. Astericks mark event horizons.

Figure 4.11. Picture of Trench 1 south wall, the two red arrows delimitate the main fracture zone internally totally disrupted in terms of sedimentary structures.

Preliminary datings of charcoal samples collected within unit 5 (MEV1-15) and at the top of the stratified unit 2 (MEV1-8) gave dendrocronogically calibrated ages of 1020-820 BC and 170 BC-70 AD, respectively (black small triangles in figure 4.10). Thus, the colluvial and alluvial sequence from units 5 to unit 2 deposited in a time window bracketed between 650 and 1100 years.

Trench 2. Trench 2 walls (figure 4.12) exposed mainly the Tertiary Scaglia Cinerea formation (unit 6 in figure 4.12) and colluvial deposits (units 2 and 3) directly derived from unit 6, with exception for some clasts. The uppermost 20-30 cm is made by the present soil and appears bioturbated. The 1997 ruptures, still well visible at the surface, connect at depth with a well defined deformation zone (figure 4.12). The latter is composed by a main fault plane that bifurcates at the surface and by many minor faults and fractures. Both the Scaglia Cinerea formation and colluvia are drag and re-oriented close to the fault zone. In the lower part of the trench, where the fault plane is single, putting in contact different horizons of the Scaglia Cinerea formation, some striae are visible testifying a dominant normal dip slip movement with a small left lateral component. The 14 October 1997 earthquake produced a vertical deformation mainly along the westernmost fault plane and only a minor activation of the easternmost one (figure 4.12). The intense de-structuralization together with magnitude and geometry of the observed deformation suggest that other events, apart from the 1997 one, contributed to the trench walls tectonization.

Evidence for a previous deformational event is represented by the double amount of dislocation of the colluvial unit 3a, visible along the westernmost fault plane, with respect to the 1997 dislocation observable at the ground surface. The presence of a colluvial wedge (unit 2), probably derived by the erosion of a paleoscarp very similar in magnitude and geometry to the 1997 one, seems to reinforce this hypothesis. Unfortunately, the lack of a good quality stratigraphy across the fault zone prevents us from extending back in the past the identification of paleoevents.

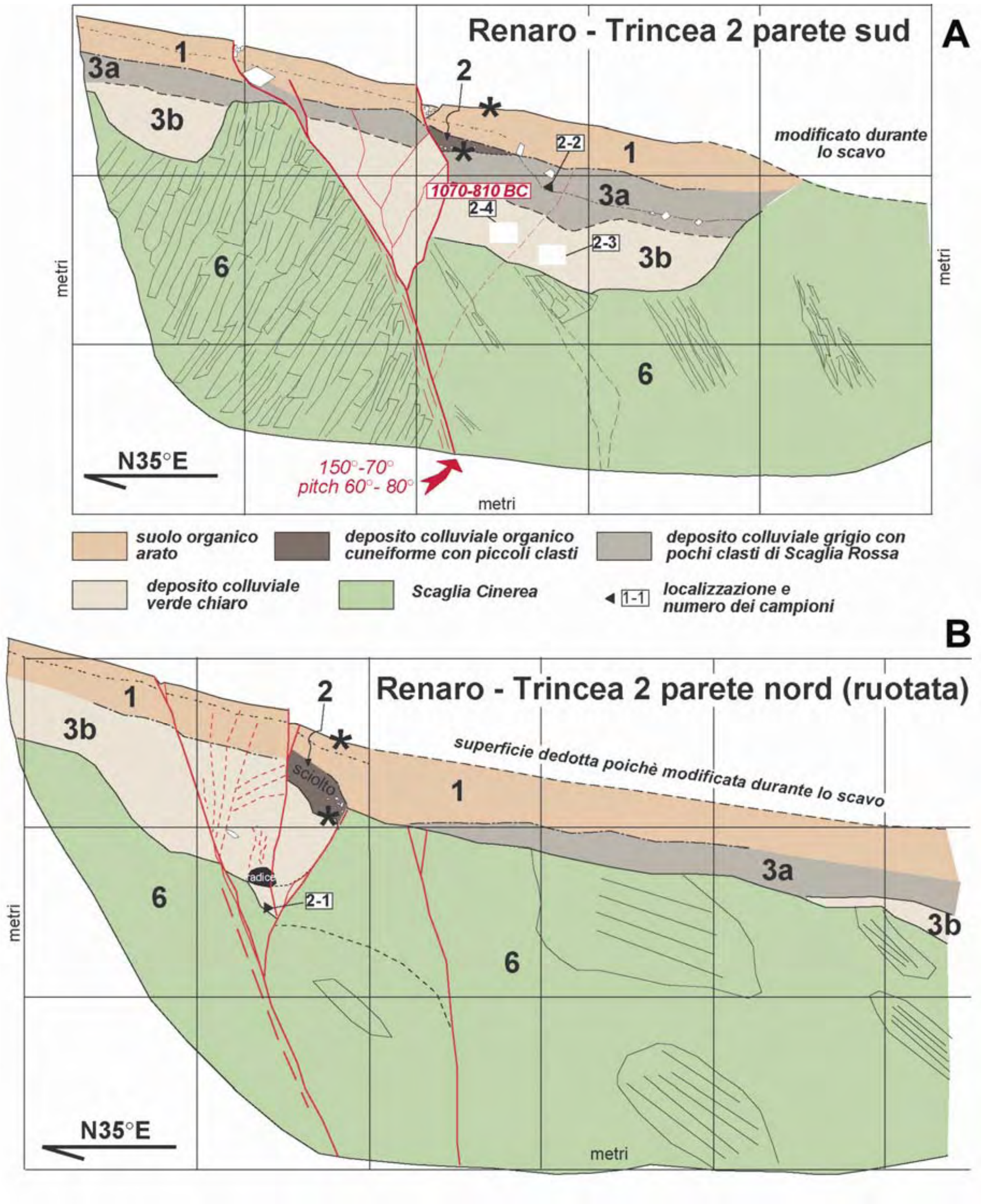

Figure 4.12. Trench 2 walls, logs simplified from a detailed work done at scale 1:20. A) South wall, B) North wall (flipped). Big black numbers refer to units cited in the text. Small black triangles represent charcoal samples, white boxes are bulk samples. Astericks mark event horizons.

Preliminary dating of the organic portion of the colluvial unit 3b (MEV2-4 in figure 4.12a) gave dendrocronogically calibrated age of 1070-810 BC. This age is in good agreement with those of Trench 1, demonstrating that the colluvial/alluvial sedimentation, very probably related to climatic factors, started in this area about 3000 years ago. The lack of datable charcoal pieces and the closeness of the colluvium unit 2 to the ground surface (presently an open system with the atmosphere) prevent us from further detailing the age of the exposed deposits.

Discussion. The study of Trench 2 shows evidence for multiple events and in particular it allows the discrimination of an event prior to the 1997 earthquake, it occurred before the deposition of unit 2 (figure 4.12) and thus it is certainly younger than 1070 BC. Differently, the interpretation of Trench 1 is not univocal, but it suggests that deformations similar to those occurred in 1997 were produced at least once after the sedimentation of the clearly stratified part of unit 2 (figure 4.10) and possibly many times before. This hypothesis is based on the observation that structureless deposits close to the 1997 deformation zone are loose and clearly fractured while those close to the westward contiguous zone of deformation appear similarly structureless but well cemented, suggesting that since their deformation a certain amount of time occurred during which the water circulation and the weight of the sediments themselves produced new compaction of these deposits. The age of the presumed penultimate event in trench 1 should be at least younger than the sedimentation of the stratified part of unit 2 that seems clearly disturbed. Taking into account the position of sample MEV1-8, the penultimate event age should be younger than 170 BC-70 AD. Thus, assuming that the recognized penultimate event in the two trenches is coeval, it would be younger than 170 BC and obviously older than 1997. Considering the stratigraphic position of sample MEV1-8 in trench 1 (figure 4.10) and assuming little reworking, we may conclude that the paleoevent is close to the older part of the interval 170 BC-1997.

Assuming that the studied deformations are essentially coseismic, hypothesis supported by the deformational pattern observed in the trenches, and apart from their primary or secondary relationship with the seismogenic structure (that is directly related or not necessarily related to the fault plane rupture at depth), these can be used as evidence of paleoseismicity. The study of effects at the surface induced by earthquakes, different from the typical fault scarp, like secondary fractures, landslides, liquefaction, inundations is often used in paleoseismology (McCalpin, 1996). For example, some trenches were dug across secondary ruptures produced by the 1994 Northridge earthquake (M 6.7, California) and showed the existence of older ruptures similar in magnitude and geometry to those occurred in 1994 (Hecker et al., 1995; Rymer et al., 1995). The only limitation in using secondary effects to built the seismic history of a single source is that these could have been produced at the same site by the activation of different seismogenic structures or that, vice versa, because of special conditions (change of the sediment thickness and/or of the water content, different coseismic rupture propagation, etc) these could not occur. Anyway, even considering the uncertainties associated to this approach, these studies represent an important source of information on shaking recurrence at a site.

Because of the agreement of different research groups and local inhabitants on the fact that the ruptures studied in the present work were produced only by the 14 October event, we may exclude, in first approximation, that these could form because of the activation of the 26 September 1997 causative faults. Moreover, local people and farmers working for long in this area agree in excluding that similar phenomenon occurred in the past 50-60 years. Thus, we may exclude that the seismogenic structures responsible for the Valnerina 1979 and Gubbio 1984 earthquakes had any influence on the formation of these ruptures. Therefore, the source responsible for the studied ruptures should be local and it likely includes the 14 October 1997 causative fault.

Looking at the historical seismic catalogues (Boschi et al., 1998; Camassi and Stucchi, 1998) it appears that the earthquakes that could hev been generated in the past by the same structure activated in 1997 (14 October), as single source or in association with others, are those of 1328, 1703 (14 January), 1791, 1838 (14 February) and 1898 (25 August). As from the interpretation of the trenches the deformational event prior to 1997 one occurred after 170 BC, any among the historical earthquakes mentioned above could be the candidate. Further uncertainty in the correlation with the historical data comes from the fact that the time interval properly recorded by the historical seismic catalogues hardly includes the first millennium AD.

Conclusions. The trenches dug across the surface ruptures produced by the 14 October 1997 demonstrated that these ruptures are related to the activity of a fault showing limited morphological evidence and that other ruptures occurred in the past with similar characteristics both in term of magnitude and geometry. All this suggest that the seismogenic structure responsible for the 14 October earthquake exhibits a repeated activity and that the most recent event could represent the “characteristic earthquake” or maximum expected earthquake. In fact, if the same structure would have produced larger magnitude earthquakes in the past 3000 years (unit 3b in figure 4.12 and unit 5 in figure 4.10) for example breaking the surface during a big earthquake of magnitude close to 7 in association with the faults responsible for the 26 September 1997 mainshocks, we should observe much larger dislocation in the trenches. For stratigraphic reason the Scaglia Cinerea formation offset are not measurable directly, even if the lack of a clear morphological expression of the structure may suggest limited cumulated dislocation or, vice versa, important but balanced by strong erosional processes. In this second option, the deformation rate would be balanced or overcome by erosion, fact that is more probable when the fault movement occurs by small successive steps (moderate earthquakes).

Preliminary datings performed on charcoals and on the organic part of a colluvium suggest that the penultimate event is younger than 170 BC.

The lack of an upper limit to constrain better the age of the penultimate event related to the 14 October 1997 seismogenic structure, the moderate magnitude of the events recognized and the impossibility to compare the paleoseismological results with the historical data for the first millennium, all prevent a more detailed reconstruction of the seismic history of this structure. Anyway, with the available data we can identify at least two moderate earthquakes (including the 1997 one) in the past 2000 years.

References

Amato A. et al., 1999: La sequenza sismica di Umbria-Marche del 1997-1998. Riassunti estesi delle comunicazioni al 18° Convegno Nazionale GNGTS, 189. GNGTS – Atti del 18° Convegno Nazionale / 10.07

Barba S. e Basili R., 2000: Analysis of seismological and geological observations for moderate-size earthquakes: the Colfiorito fault system (Central Apennines, Italy), *Geophys. J. Int.*, 141, 241-252.

Basili R, Bosi C., Bosi V., Galadini F., Galli P., Meghraoui M., Messina P., Moro M. e Sposato A., 1998: The Colfiorito earthquake sequence of September-October 1997. Surface breaks and seismotectonic implications for the central Apennines (Italy), *Journal of Earthquake Engineering*, 102(2), pp. 291-302.

Boschi E., Guidoboni E., Ferrari G. e Valensise G., 1998: I terremoti dell'Appennino Umbro-Marchigiano. Publ. Istituto Nazionale di Geofisica e Storia Geofisica Ambiente, pp. 266, Editrice Compositori, Bologna 1998.

Camassi R. and Stucchi M., 1998: NT4.1, a parametric catalogue of damaging earthquakes in the Italian area (versione NT4.1.1), Gruppo Nazionale per la Difesa dai Terremoti, pp 66, Milano (http://emidius.itim.mi.cnr.it/NT/home.html).

Cello G., Mazzoli S., Tondi E. e Turco E., 1997: Active tectonics in the central Apennines and possible implications for seismic hazard analysis in peninsular Italy, *Tectonophysics*, 272, pp. 43-68.

Cello G., Deiana G., Mangano P., Mazzoli S., Tondi E., Ferreli L., Maschio L., Michetti A. M., Serva L. e Vittori E., 1998: Evidence for surface faulting during the September 26, 1997, Colfiorito (Central Italy) earthquakes, *Journal of Earthquake Engineering*, 102(2), 303-324.

Cinti F.R., Cucci L., Marra F. e Montone P., 1999: The 1997 Umbria-Marche (Italy) earthquake sequence: relationship between ground deformation and seismogenic structure, *Geophys. Res. Lett.* 26(7), pp. 895-898.

De Martini, P.M., e Valensise G., 1999: Pre-seismic slip on the 26 September 1997, Umbria-Marche earthquake fault? Unexpected clues from the analysis of 1951-1992 elevation changes, *Geophys. Res. Lett.* , 26(13), pp. 1953-1956.

De Martini P.M., Pino N.A., V alensise G. e Mazza S., 2000: An unusual pattern of faulting in the Central Apennines (Italy): geodetic and seismologic evidence for pre- and co-seismic slip along a low angle, blind normal fault and implications for active faulting studies, *Proceedings of the Hokudan International Symposium and School on Active Faulting*, pp. 69-73, Hokudan (Japan, Gennaio 2000).

Ekstrom G., Morelli A., Boschi E. e A.M. Dziewonski; 1998: Moment tensor analysis of the central Italy earthquake sequence of September-October 1997, *Geophys. Res. Lett*., 25, pp. 1971-1974.

Galli P., Bosi V., Galadini F., Meghraoui M., Messina P., Basili R., Moro M. e Sposato A., 1997: Fratturazione superficiale connessa ai terremoti umbro-marchigiani del settembre-ottobre 1997, *Il Quaternario,* 10(2), pp. 255-262.

Galli P. e Galadini F., 1999: Seismotectonic framework of the 1997-98 Umbria-Marche (Central Italy) earthquakes, *Seismological Research Letters*, 70(4), pp. 404-414.

Hecker S., Ponti D. J., Garvin C.D., e Hamilton J.C.,1995: Characteristics and origin of ground deformation produced in Granada Hills and Mission Hills during the January 17, 1994 Northridge, California, earthquake, in Woods M.C. and Seiple W.R. (Eds.): *The Northridge, California Earthquake of 17 January 1994*, California Dept. of Conservation, Division of Mines and Geology special publ 116, pp. 111-131.

McCalpin J. (1996). Paleoseismology, Accademic Press Ldt., pp. 588, London.

Morelli, A., Ekström, G. e M. Olivieri, 2000: Source properties of the 1997-98 Central Italy earthquake sequence from inversion of long-period and broad-band seismograms, *J. of Seism.*, *in stampa*.

Rymer M.J., Fumal T.E., Schwartz D.P., Powers T.J., and Cinti F.R., 1995: Distribution and Recurrence of the Surface Fractures in Potrero Canyon associated with the 1994 Northridge, California, earthquake, in Woods M.C. and Seiple W.R. (Eds.): *The Northridge, California Earthquake of 17 January 1994*, California Dept. of Conservation, Division of Mines and Geology special publ 116, pp. 133-146.

Salvi S., Stramondo S., Cocco M., Tesauro M., Hunstad I. e altri nove autori, 2000: Modeling of coseismic displacements resulting from SAR interferometry and GPS measurements during the 1997 Umbria-Marche seismic sequence, *J. of Seismology*, *in press*.

Stuiver, M., and P. J. Reimer, 1993: Extended 14C database and revised CALIB radiocarbon calibration program (version 3.0.3A), *Radiocarbon, 35*, pp. 215-230.

Vittori, E., Deiana, G., Esposito, E., Ferreli, L. e altri sette autori; 2000: Ground effects and surface faulting in the September-October 1997 Umbria-Marche (Central Italy) seismic sequence, *J. of Geodynamics*, 29, pp. 535-564.

Abstract title

MODELLING SURFACE DISPLACEMENTS OF THE 1997 CENTRAL ITALY EARTHQUAKES FROM INSAR AND LEVELLING GEODETIC DATA

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Keywords

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Abstract

On 26 September 1997, two moderate size (M_W 5.7 and 6.0, respectively at 00:33 and 09:40 GMT) earthquakes occurred in the Umbria-Marche Apennines near Colfiorito (central Italy), and started a 6 month-long seismic sequence. In this work we focus on the record of coseismic surface deformation supplied by traditional (levelling) and space (InSAR) geodesy. These two tecniques have been selected because provided a remarkably well constrained vertical component of the motion, even if the magnitude of the earthquakes was modest. This seismic sequence has been the first example of the use, in Italy, of SAR Interferometry (InSAR) technique for surface movements detection. Pre- and post-seismic ERS1-2 data have been processed to extract the phase component of the radar signal and compare them. The resulting co-seismic interferograms show the centimetric surficial evidences of the fault slip at depth. SAR data available are from both ascending and descending orbits. In particular the September 26th – October 12th and September 7th –September 26th interferograms show the contribution to the displacement field of the two mainshocks of September 26th, even if the first one should also contain the cumulative deformation at the surface from minor events (October 3rd and 6th). The epicentral area is crossed by a fundamental branch of the Italian first order

levelling network. In this work we analyse in detail only the first (southernmost) section of this route, identified as Line 21 and measured in 1992 and 1998, which trends almost N-S between Foligno and Fossato di Vico. The line carries a record of coseismic elevation changes associated mainly with the causative fault of the 26 September 1997, 09:40 mainshock (M_W 6.0). Being the two datasets particularly efficient in different zones of the epicentral area, we decided to combine the datasets to derive a unique source model of the abovementioned mainshock. We employed both a standard uniform slip approach and a strategy involving spatial variability of slip. The final goal of our approach is to address the following question: may a combination of levelling and InSAR geodetic data help constraining more strongly the fault location, geometry, its down-dip extent and its dip?

Presentation mode

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G16.02 - Seismicity and Active tectonics

Geodetic and seismologic evidence for slip variability along a blind normal fault in the Umbria-Marche 1997–1998 earthquakes (central Italy)

Paolo Marco DE MARTINI, Nicola Alessandro PINO, Gianluca VALENSISE and Salvatore MAZZA

Geophysical journal international, 2003, Vol. 155, Pages 819-829

(The definitive version is available at www.blackwell-synergy.com**)**

Chapter 5

Evidence of post-seismic slip along active normal faults

Chapter 5: Evidence of post-seismic slip along active normal faults

Among many factors/sources that may change the surface of the earth there are those produced by a strong earthquake. In the previous chapters we have discussed evidence for preseismic and coseismic surface deformation; here we discuss the postseismic one. Post-seismic movements usually happen because of elastic crust relaxation due to the accumulation of stress in the lithosphere-asthenosphere after a significant seismic event. In fact, apart from the coseismic deformation, strong earthquakes are able to induce significant movements below the elastic portion of the lithosphere due to restauration of the equilibrium. The geometry, magnitude and timing of the postseismic movements strongly depend on the rheology and structure of the lithosphere-asthenosphere stratification (Pollitz et al., 1992).

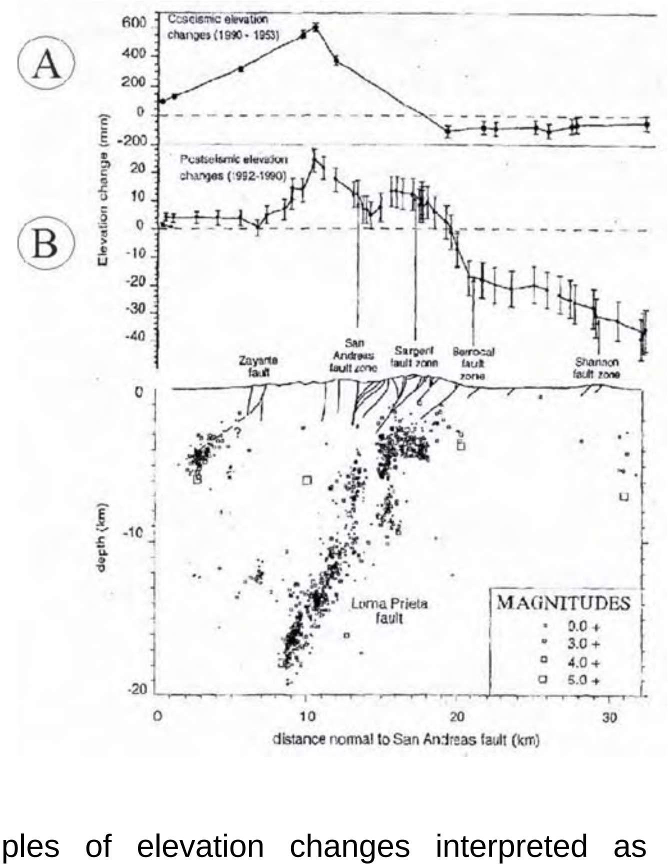

Figure 5.1. Examples of elevation changes interpreted as coseismic (A) and postseismic (B) deformations related to the 1989 loma Prieta earthquake (after Burgman et al., 1997). Note the significant magnitude difference of the detected signals.

In the literature there are some examples (figure 5.1) describing how leveling data were interpreted following the abovementioned mechanism (Pollitz et al., 1992;

Bürgmann et al., 1997; Nishimura & Thatcher, 2003; Dalla Via et al., 2003, Riva et al., 2007 and reference therein). Direct modeling and best-fit seeking based on leveling data surveyed at least two times after a strong event can provide new information about the properties, behavior, and stratification of the lithosphere (Nishimura & Thatcher, 2003 among many others), and possibly also further constraints for the seismogenic source responsible for the studied earthquake (Bürgmann et al., 1997 among many others).

Chapter 5.1: Postseismic deformation along the Fucino fault

In this chapter, the geodetic evidence for postseismic relaxation detected by five high precision leveling lines located in the area of the 1915 Fucino earthquake (central Italy) are presented. Specifically, we discuss how the use of geodetic leveling data may highlight particular late stage movements (occurred between 35 and 85 years after the causative event) of the postseismic relaxation process. More details and specifications on the procedure adopted are in the publication “Amoruso, A., L. Crescentini, E. D’Anastasio, P.M. De Martini, (2005): Clues of postseismic relaxation for the 1915 Fucino earthquake (central Italy) from modeling of leveling data, *Geophysical Research Letter*, 32, L22307, doi: 10.1029/2005GL024139” available in Annex 1.

The 1915 Fucino earthquake (Ms=6.9) was one of the largest and most destructive events in Italy during the past century. The epicentral area is centered in the Abruzzi region (Central Italy), where a long historical record of large earthquakes is available (CPTI, 1999 and Boschi et al., 2000, among many other catalogues). Seismotectonic studies on this region, based on instrumental seismicity (focal mechanism solutions of major events and stress analysis of background seismicity), borehole break-out studies, geological and paleoseismological investigations, suggest NE-SW oriented active extension. The 1915 earthquake fault produced detectable surface ruptures for about 20 km along NW-SE striking SW-dipping structures (Oddone, 1915; Galadini and Galli, 1999 and references therein). Coseismic geodetic data recorded in the epicentral area have been inverted in the past (Amoruso et al. 1998 and references therein), indicating a source fault dipping at moderate angle toward SW and a normal focal mechanism, with a minor left-lateral component.

Five high precision leveling lines, located in a wide sector north and east of the Fucino plain and forming a "T-shape" net (figure 5.2), were measured in 1950 and 1997-2000 by the IGM (Istituto Geografico Militare). The total length is about 400 km with a mean benchmark density higher than 0.5 bm/km.

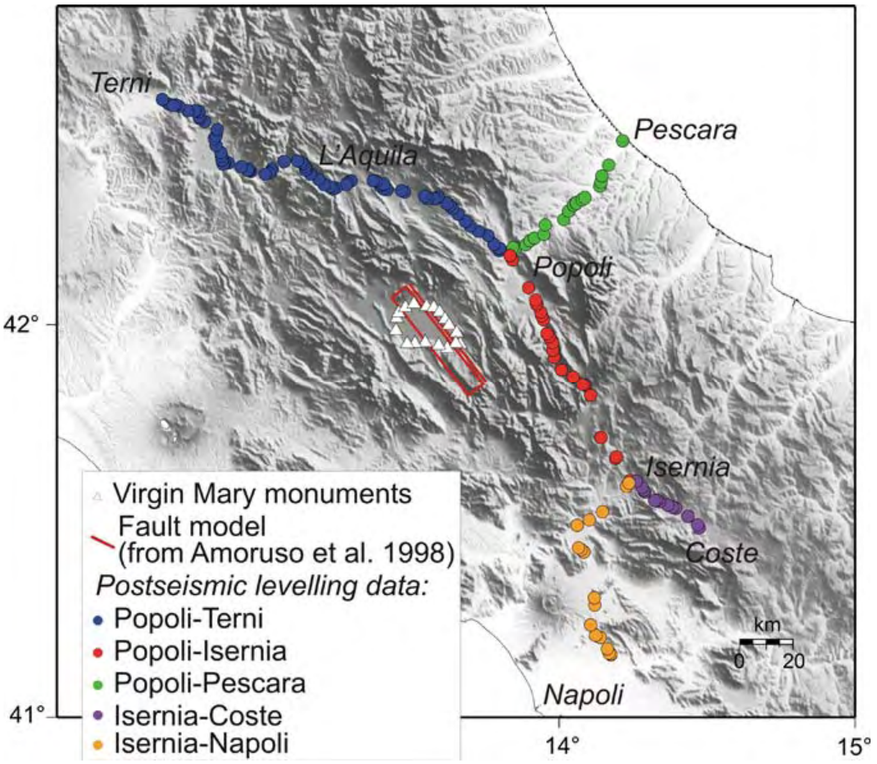

Figure 5.2. Map of the five high precision leveling lines located around the epicentral area of the 1915 Avezzano earthquake (Ms = 6.9). All the lines were measured in 1950’ and 2000’. Red rectangular represents the surface projection of the modeled fault after Amoruso et al., 1998.

The relative elevation changes recorded during this time interval show maximum values between 7 and 12 cm with a signal wavelength of 40-70 km (figure 5.3, upper profile). The observed elevation changes stand significantly above the calculated total error of 1.13 mm $(L)^{1/2}$ km. Coseismic contribution should be negligible since no significant earthquake has been recorded in the investigated area in the time elapsed between the first and second surveys (Boschi et al., 2000; Castelllo et al., 2006). A sharp gradient has been noticed north-east of the earthquake epicenter, where we observe peculiar elevation changes along a 40 km long section of the leveling line. The observed elevation changes in the Fucino earthquake area (figure 5.3, upper profile) seem to comprise both regional tectonic deformation and post-seismic relaxation. The former and the latter effects are expected to dominate along sections of the leveling lines which are about perpendicular and parallel to the Apennines respectively. Since we compare measurements performed in 1950 and 1997-2000, relaxation effects should refer to a late stage of the process.

We have used Pollitz (1997) code for computing gravitational-viscoelastic postseismic relaxation on a layered spherical Earth. Different Earth models, characterized by different thicknesses and viscosities of crustal layers and of the upper mantle, have been considered. Even if S/N ratio of expected post-seismic effects is not high, comparison between predictions and observations allows constraining regional crustal structure.

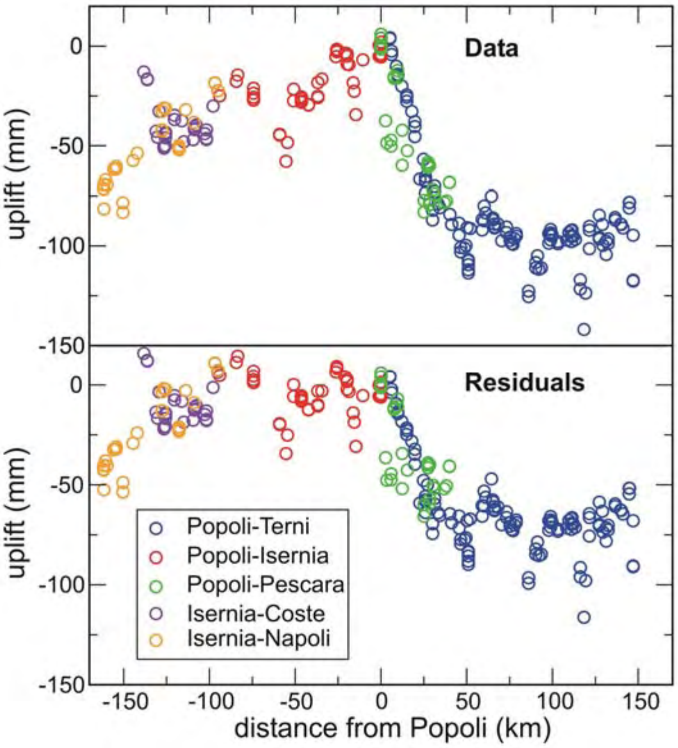

Figure 5.3. Above, the elevation changes, referred to the nodal benchmark of Popoli (km 0 of the profile), show maximum values between 7 and 12 cm, with a signal wavelength of 40-70 km. Residuals of the computed postseismic benchmark elevation changes (using the code of Pollitz, 1997) are shown in the lower profile.

Best fit misfits exhibit lower values when we introduce a transition zone, with a viscosity value that is an order of magnitude higher than that of the lower crust. Best fitting residual plot (figure 5.3, lower profile) was obtained setting the following thickness values: upper crust lower boundary at 10 km, transition zone lower boundary at 20 km, mantle upper boundary at 30 km. Upper crust thickness is in agreement with the seismogenic layer thickness calculated by the cut-off of instrumental seismicity (Chiarabba et al., 2005b). Note that the residual profile (figure 5.3, lower profile) is about flat for benchmarks along the Apennines and decreases aside the Apennines, showing a quasi-symmetric shape toward the Adriatic Sea and the Tyrrhenian Sea. This feature could be interpreted as evidence for the existence of a significant regional uplift (about 1 mm/yr) bulge shaped, in agreement with geodetic (D'Anastasio et al., 2006) and geologic (Galadini et al., 2003) estimates.

Summarizing, relaxation effects, referring to a late stage of the postseismic process, account for about 30% of the observed geodetic signal (figure 5.3). The remaining 70% of the signal (a significant elevation change between the Adriatic coast and the Apennine axis) is more likely due to regional uplift process. Unfortunately, neither the best fitting model postseismic deformation (figure 5.4) nor the regional uplift contribution can satisfactory explain the sharp gradient observed along the 40 km-long section of the leveling line north-east of Popoli.

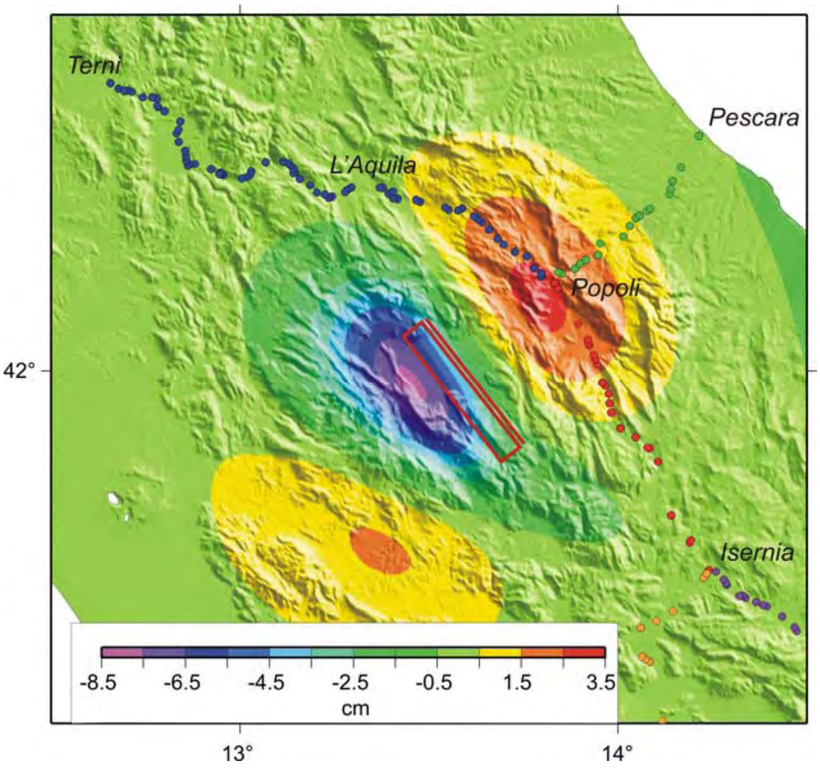

Figure 5.4. Postseismic deformation by inverting elevation changes observed between 1950 and 2000 along the leveling lines around the epicentral area of the 1915 Avezzano earthquake.

Chapter 6

Large scale vertical movements of the Apennines

Chapter 6: Large scale vertical movements of the Apennines

The identification and quantification of the deformation occurring on the earth surface can provide important information on the tectonic processes of seismically active regions. On the one side, the characterization of crustal movements in these areas is fundamental to identify and define the areas experiencing strong deformation that potentially may be the locus of strong earthquake. On the other, there are some regions where the crustal deformation occurs without seismic events and it is governed by plate convergence along a subduction zone. For example in Himalaya the interseismic deformation detected by leveling data was modeled with a giant blind thrust fault able to accommodate the Indian and Asian plates convergence (Jackson & Bilham, 1994) and similar approach was used for the central Cascadia subduction zone (Williams & McCaffrey, 2001). Following these models, the aseismic deformation at the surface is related to the stress of the subduction zone and of the ductile asthenosphere transferred at the bottom of the elastic lithosphere (Vergne et al., 2001).

This chapter deals with geodetic and geologic evidence of large scale movements of the tectonically active Apennines chain. The main scope is to study the regional uplift of this region at different time scales. In fact recent works, mainly geologically based, demonstrated that in the past 1 Myr the Apennines experienced significant movements, mainly vertical (Cinque et al., 1993; Bordoni & Valensise, 1998; D’Agostino et al., 2001). Apart from the geological data, the historical geodetic leveling database available in Italy is the only tool that we may try to use to observe vertical movements over a time window of about 50-100 years-long. Nowadays, among all the geodetic techniques, geodetic leveling allows an accurate determination of the vertical component related to crustal deformation (Bomford, 1971) thus providing an independent geophysical contribution to Active Tectonic studies. Surely, in the near future this technique will be substituted by modern space geodesy but for regions characterized by slow vertical crustal movements this will be probably the best approach still for a long time.

The first section of this chapter discusses leveling data from the past 50-100 yrs and their use to estimate the Apennines regional uplift, its magnitude and wavelength. Details and thoughtful discussion are in the paper “D'Anastasio E., P.M. De Martini, G. Selvaggi, D. Pantosti, A. Marchioni, R. Maseroli (2006): Short-term vertical velocity field in the Apennines (Italy) revealed by geodetic levelling data, *Tectonophysics*, doi: 10.1016/j.tecto.2006.02.008", already included in chapter 2 of this thesis.

The second section of this chapter discusses the geologic evidence for large scale vertical movements along the Apennines on the basis of new data for the central part of the chain, based on "Mancini, M., E. D'Anastasio, M. Barbieri, P.M. De Martini (2007): Geomorphological, paleontological and 87Sr/86Sr isotope analyses of Early Pleistocene paleoshorelines to define the uplift of Central Apennines (Italy), *Quaternary Research*, 67, 487-501, doi:10.1016/j.yqres.2007.01.005" available in Annex 2.

Chapter 6.1: Large scale geodetic vertical elevation changes of the Apennines

The analysis of geodetic data of the first order leveling network of the Istituto Geografico Militare d'Italia (IGM) allows estimating the vertical movements occurred in Italy between at least two measurement campaigns performed during the past 100 years. The adjusted heights of benchmarks belonging to 65 leveling lines were collected and studied, among them only those crossing the Apennines have been selected. The geodetic sections (leveling line sub-units) that, in the time interval comprised between two measurements campaigns, were clearly affected by coseismic, volcanic and anthropic signals, characterized by magnitude and/or geometry evidently not compatible with large wavelength signal, have not been considered further.

The selected lines, for a total length of about 1600 km, comprise an observational time interval of about 50 years (1950-2000), with a benchmark density of 0.3 bm/km. Taking into account that the absolute heights of the leveling benchmarks is related to tide gouge measurements, and that these are affected by significant uncertainty (about 10 cm), the elevation changes of the present work are calculated, referred to a special benchmark (usually the nodal one) of the studied transect (one or more leveling lines). Being the first order leveling surveys not homogenous in time, a conjunct analysis of the entire IGM network is not possible. Anyway, it is possible to subdivide the whole geodetic network into sectors measured within a few years and to study each single sector, fixing only one reference benchmark (as in the case of a single line). Usually, leveling data are affected by different errors due to instrumental errors or external factors. In order to control the quality of the data the IGM follows strict international standards properly set for the first order leveling lines. Nevertheless, the systematic error propagation along a leveling route is one of the main problems related to the use of such data. A comprehensive discussion on the errors associated to leveling data can be found in D’Anastasio et al., 2006, in chapter 2.

An interesting signal, characterized by a wavelength of regional meaning (> 50 km), well above the error associated to the data, shows up for four among six of the analysed transects. The calculated vertical movements show sectors with maximum relative elevation change rates comprised between 1.0 and 3.0 mm/yr and vary along the Apennines chain axis. Moreover, the analysis of the lines running along the Apennines strike, on its internal part, shows a strong elevation change gradient in correspondence with the Abruzzi region. A comparison of these data with those published by Arca and Beretta (1985) for the 1890-1950 time interval suggests that shape and magnitude of the vertical velocity field were almost constant during the past century.

The shape of relative elevation changes in northern Apennines shows maximum values of 1.5-3.0 mm/yr, concentrated east-northeast of the drainage divide and well correlated with the area where important active compression is going on (Pondrelli et al., 2004).

Transects across the central Apennines exhibit less pronounced geodetic signal. In fact, the elevation change profiles are characterized by a nearly homogeneous pattern with maximum vertical rates of 1.0-1.5 mm/yr and a few sectors marked by high gradients.

Differently from what observed in northern Apennines, the southernmost transect, traced at the boundary between central and southern Apennines, presents maximum relative rates of 2.0-2.5 mm/yr located on the central part of the belt. Unfortunately, the lack of more lines crossing the southern Apennines prevents a more detailed and robust discussion. Nevertheless, the observed geodetic bulge appears to be in agreement with the uplift determined from geological data in southern Apennines (Bordoni and Valensise, 1998) and coincides with the area of maximum extension rate, measured by space geodesy (Hunstad et al., 2003; Serpelloni et al., 2005).

Chapter 6.2: Large scale geologic vertical movements of the Apennines

The main problem that can be encountered in using geological and geomorphological data is the need for an accurate knowledge of the elevation, shape and age of the selected markers at the time of their formation. All these data are crucial for calculating the vertical deformation rates associated. It is well known that the Apennines are a mountain chain resulting from the African and Eurasian plates convergence, started in Miocene time and still active. This process occurred together with a progressive east-northeastward migration, parallel to the Apennines axis, of two tectonic styles, compression to the east and extension to the west. The development of a retro-arc basin in the Tyrrenian sea, the Adriatic fore-deep flexure and the progressive rejuvenation of the Neogene fore-deep basins are all interpreted as the result of Adriatic and Ionic subducting lithosphere roll-back process (Malinverno & Ryan, 1986; Faccenna et al., 1996; Patacca & Scandone, 2001). During the Quaternary a drastic change of the tectonic regime occurred, superimposing an important crustal extension (characterized by significant vertical movements) on those areas previously dominated by compressional tectonic (Cinque et al., 1993; D’Agostino et al., 2001; Patacca & Scandone, 2001).

Different hypotheses exist on the inception time of the regional uplift of the chain, but most of them converge to a period within the Lower-Middle Pleistocene. Based on geomorphological studies, some authors (Dramis, 1992; Amato & Cinque, 1999) suggest that the uplift rate was not constant, but started quite slowly and increased with time especially during the Middle Pleistocene. Other researchers (Patacca & Scandone, 2001) set the uplift inception period at about 700-500 kyr ago, suggesting also that this large scale phenomenon contributed substantially to the present Apennines topography (D’Agostino et al., 2001).

Geological records testifying the geodynamical change occurred during the Quaternary are of different kind and cover diverse time intervals. The development of Pliocene-Pleistocene marine formations, trasgressively covering the Meso-Cenozoic platform and basin (overthrusted since Miocene time), indicates an important change with respect to the compressional phase (Ambrosetti et al., 1987). During the Quaternary, both the Plio-Pleistocene marine boundary along the Adriatic coast (Bigi et al., 1992) and the Lower Pleistocene deposits filling the Bradanic fore-deep (Cinque et al., 1993) were basculated toward east-northeast. This tilting, coupled with the present hydrographical network pattern, characterized by SW-NE parallel and almost straight river courses, suggest the presence of a Quaternary large scale uplift, acting more efficiently on the internal part of the Apennine chain with respect to the external Adriatic zone.

More in detail, a huge amount of sediments derived from the erosion of the Apennines during the Quaternary fills the northern Tyrrhenian Sea (Bartolini et al., 1996; Zattin et al., 2000), and the high erosional rates derived from these studies have been interpreted as evidence for significant coeval regional uplift (Zattin et al., 2000).

In the central Apennines, the presence of deep fluvial incisions and the development of intra-mountain basins, filled by a large thickness of continental deposits, testify clear relief rejuvenation due to lowering of the base level during the Plio-Pleistocene (D’Agostino et al., 2001). Moreover, there is a notable literature on probably marine paleosurfaces, uplifted at different heights (Demangeot, 1965; Galadini et al., 2003, and reference therein). Finally, the southern Apennines present the more numerous and best preserved indications for the occurrence of differential large scale uplift of the chain: the Irsina conglomerates (about 700 kyr old) are clearly eastward tilted (Cinque et al., 1993); different erosive marine (?) paleosurfaces dated at about 1.5 Myr (Amato & Cinque, 1999) and marine terraces (Cosentino & Gliozzi, 1988; Bordoni & Valensise, 1998) belonging to the 5e isotopic stage (about 125 kyr old) show different heights along the chain, suggesting maximum uplift rates in correspondence with the Apennines axis.

All these elements substantiate the occurrence of significant regional uplift along the Apennine chain, at least during the Quaternary. The interaction between erosional, depositional and tectonic processes made possible the differential uplift (even in the order of several hundreds of meters) of geologic and geomorphologic markers, formed in a coastal environment or by interaction with local base level.

In this sense it should be considered the following contribution, showing a multidisciplinary study of an old 100 km long paleoshoreline along the Tyrrhenian coast. This morphological element was recognized and analyzed by many authors (Ambrosetti et al., 1987; Girotti & Piccardi, 1994) but none of them was able neither to provide an age constraint more precise than Plio-Pleistocene age nor to evaluate in terms of regional uplift the height difference of about 260 m showed by the paleoshoreline.

Along the middle Valley of the Tiber River the eastern border of the Chiani-Tevere Formation (CTF) (Mancini & Cavinato, 2005) is characterised by several palaeo-shorelines, which highlight the on-lapping termination of the CFT neritic deposits above the Meso-Cenozoic carbonatic and terrigenous substratum (Girotti & Piccardi, 1994). These palaeo-shorelines extend in the NNW-SSE direction for more than 100 km along the western margin of the Amerini, Narni, Sabini, Lucretili and Cornicolani Mountains. The uppermost palaeoshoreline was studied by means of an interdisciplinary approach - geologic, paleontologic and isotopic – in order to determine both its geographic/stratigraphic setting and its age (figure 6.1). The CTF, Late Gelasian-Santernian in age, aggraded the Paglia-Tevere Graben in concomitance with the basin subsidence (Patacca et al., 1992; Barberi et al., 1994; Mancini & Cavinato, 2005). As the eustatic sea level oscillations within the basin, presumably 40 kyr spaced, are considered less prominent than the basin subsidence (Girotti & Mancini, 2003), the highest palaeo-shoreline represents the most recent sea level highstand in that area.

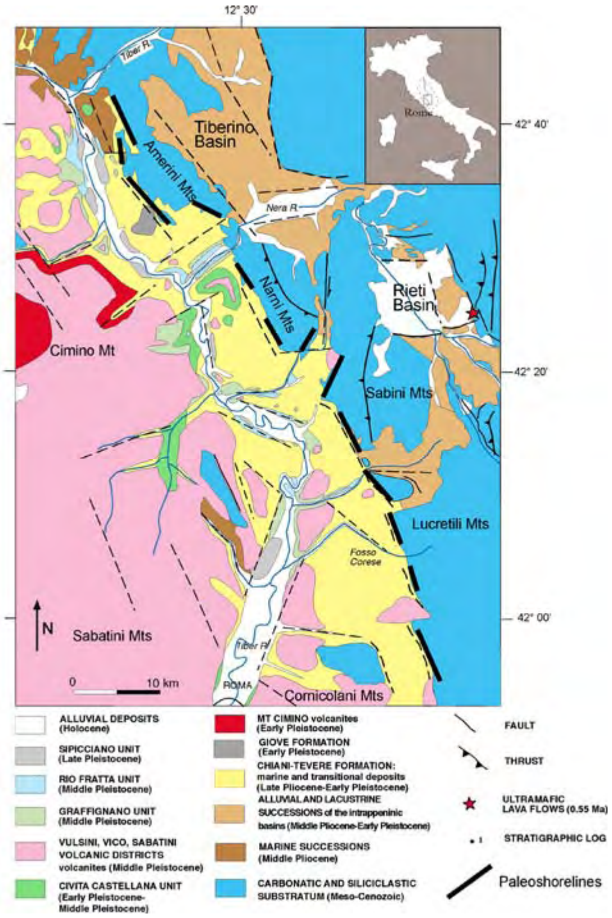

Figure 6.1. Geological synthetic map of the Middle Valley of the Tiber river.

This shoreline was detected and mapped through detailed geologic and stratigraphic surveys and facies analyses, which led to the recognition of nearshore deposits, cliff breccias, alignements of *Lithophaga* borings, together with morphological features such as fossil abrasion notches and wave-cut platforms (figure 6.2). The uppermost palaeoshoreline altitude gently decreases almost regularly in the NNW-SSE direction from 480 to 220 m a.s.l., apart from few local irregularities (± 75 m in elevation) due to Early-Middle Pleistocene reactivation of well-documented tectonic elements such as the Sabina and Tenaglie faults (Alfonsi et al., 1991; Girotti & Piccardi, 1994).

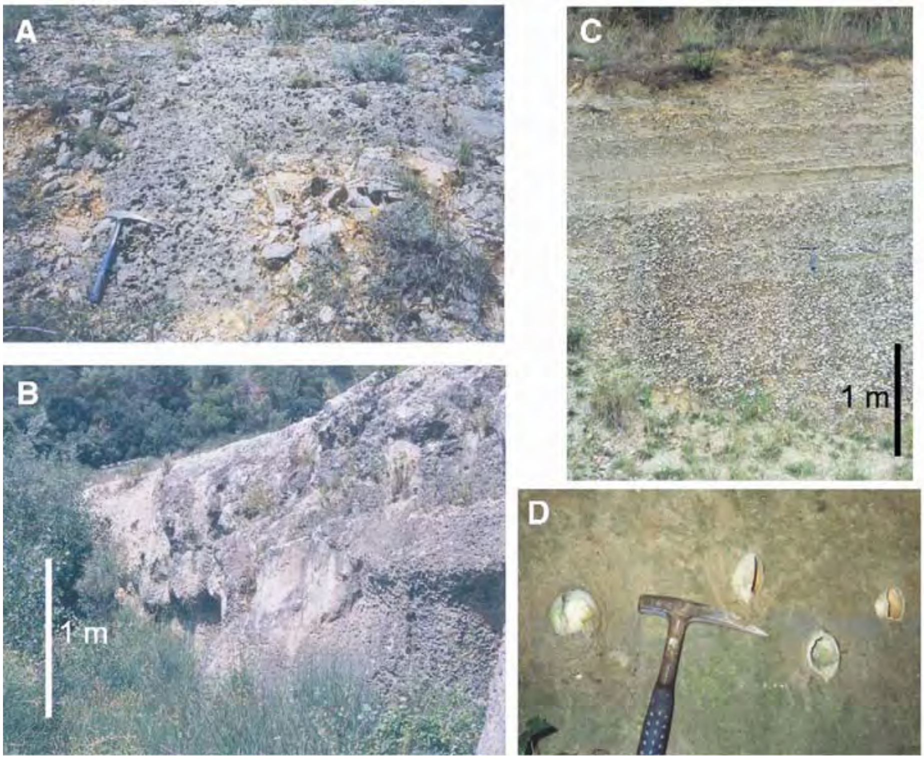

Figure 6.2. Geomorphic, sedimentary and paleobiologic markers of the Santernian paleoshorelines. A) wave cut platform, note the lithodomous borings; B) tidal notch; C) beachface clinostartified gravel; D) transition offshore-shoreface mollusks in living position, some of them were sampled for isotopic analysis.

A preliminary estimate of the palaeoshoreline age is obtained through litho- and bio-stratigraphic correlations; indeed, its nearest deposits bear typical Santernian markers: *Bulimina etnea*, *Globigerina* aff. *G. calida calida* and *G. calabra*. Moreover, measurements of the $^{87}Sr/^{86}Sr$ ratio were conducted for chrono-stratigraphic purposes on shell fragments of corals and molluscs sampled from the uppermost beds of the CTF in several sites close to the palaeo-shoreline. The resultant numerical values range between 0.70907 and 0.70910, which correspond to 1.90-1.34 Ma.

The important variation in altitude of this Santernian shoreline, more than 260 m between Montecchio and Palombara Sabina, would suggest a relevant differential uplift from North to South. Considering the altitudinal setting and the age of the shoreline, a minimum uplift rate, averaged for the past 1.6-1.5 Ma, may be estimated in this region. The northernmost sector shows an uplift rate of about 0.34±0.03 mm/yr, while the southern one would have uplifted at a lower rate of 0.17±0.03 mm/yr (figure 6.3). Thus, considering that a differential uplift paralleling the Central Apennines seems to be unfavorable (based on marine terraces heights distribution, the Tyrrhenian coast remained stable at least for the last 125 kyr, with exception of the Latium Volcanic Districts) and no clear evidence exist about a major volcanic control on the paleoshoreline altitudinal trend, it has been decided to investigate the existence of symmetrically warped shape of the Apennines uplift, as recently hypothesized for the southern Apennines (Bordoni and Valensise, 1998). Interestingly, it can be noted that the altimetric position of the studied paleoshoreline decreases as the distance with respect to the mean Apennine chain axis increases (figure 6.3). This negative correspondence seems to increase the possibility of a quasi-cilindric bulge shaped regional uplift also for the central Apennines.

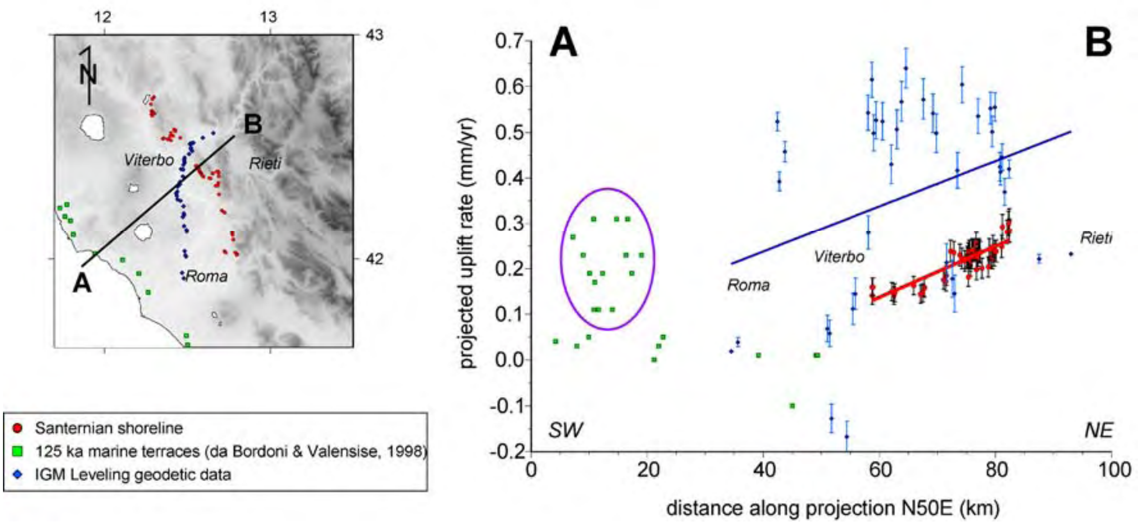

Figure 6.3.Left, map showing the geological and geodetic data compared for uplift rate estimates along the A-B transect; right, projected uplift rate estimates, symbols color as in the map to the left.

Finally, these results were compared against the current vertical movements given by original leveling data available in the study area. In fact, it is noteworthy that a geodetic line, which belongs to the IGM first order leveling network, intersects the Santernian shoreline near Narni. From the analysis of geodetic data, collected in the time window 1951-1997, it is possible to obtain relative benchmarks elevation changes and to derive their averaged rates. A preliminary comparison between short-term uplift rate, geodetically derived, and long-term uplift rate, obtained from the present study on the Santernian shoreline, shows that: a) they both exhibit higher velocity in the northeastern sector; b) their numerical values are of the same magnitude (figure 6.3).

Summarizing, new Sr isotope analyses and biostratigraphic data set the age of the studied paleoshoreline in the range 1.65–1.50 Ma. This geomorphological feature, which slowly decreases in the NNW–SSE direction from 480 to 220 m a.s.l., is isochronous all over its 100-km-long outcrop. Corresponding uplift rates are in the range of 0.34–0.17±0.03 mm/yr and a similar trend along this chain sector is recorded by geodetic leveling data. The uplift of the Tiber Valley is considered to be regional as no relevant effects of volcanism are recorded from the uppermost paleoshoreline nor from Late Quaternary marine terraces along the Tyrrhenian coastline. Moreover, a symmetrically warped shape of the regional uplift is suggested from the decreasing trend of uplift rates in the NE–SW direction, orthogonal to the mean axis of the Apennines

More details and specifications on the procedure adopted are in the publication “Mancini, M., E. D'Anastasio, M. Barbieri, P.M. De Martini (2007): Geomorphological, paleontological and 87Sr/86Sr isotope analyses of Early Pleistocene paleoshorelines to define the uplift of Central Apennines (Italy), *Quaternary Research*, 67, 487-501, doi:10.1016/j.yqres.2007.01.005” available in Annex 2.

Chapter 7

Conclusions and Perspectives

Chapter 7: Conclusions and Perspectives

This chapter consists of three parts. The first section is devoted to the presentation of the results obtained on individual seismogenic faults of the Apennines from geodetic and geologic analyses performed at local scale. The second part focuses on the short- and long-term geodetic and geologic vertical velocity field across the Apennines, observed at regional scale. Finally, the third part is about the possible contribution of all these studies to the seismic hazard assessment, considering the new data collected in terms of seismic behavior of some Italian faults and the possible definition of the zones where the stress tends to concentrate.

Chapter 7.1: The contribution of geodetic and geologic studies at local scale for the identification and characterization of active faults of the Apennines.

In this thesis an important effort was devoted to provide an independent analytical evaluation of the seismic behavior of some Italian faults. It involved an intense use of available geodetic leveling data. Three different phases of the seismic cycle were investigated: preseismic (chapter 3) for the Colfiorito (26-09-1997, Mw=6 earthquake) and Amatrice faults, coseismic (chapter 4) for the Colfiorito (26-09-1997 Mw=6 earthquake) and Sellano (14-10-1997, Mw=5.6 earthquake) faults and postseismic (chapter 5) for the Fucino fault, responsible for the Ms=6.9, 1915 earthquake).

The results obtained looking at the aseismic deformation recorded by leveling data crossing the Colfiorito and Amatrice faults both imply an unusual fast slip along these faults (a minimum slip rate of 2-3 mm/yr was calculated). Note that this latter value is at least three times larger than any estimate that could be done based on available historical (Boschi et al, 2000) and paleoseismological data collected along the Apennines (Galadini and Galli, 2000; Valensise and Pantosti, 2001a; DISS Working Group, 2005). In the case of the 26 September 1997 earthquake fault, such slip was interpreted as pre-seismic slip, suggesting slip acceleration in preparation for the impending rupture. In fact, the 10 cm preseismic slip documented in this work (figure 7.1) justifies, at least partially, the coseismic slip deficit observed along the northern portion of the 26 September 1997 causative fault by independent seismological (Pino and Mazza, 2000), InSar (Salvi et al., 2000) and strong motion data (Capuano et al., 2000). For the Amatrice fault a similar interpretation can be proposed but, lacking the relative seismic event, it simply remains a working hypothesis.

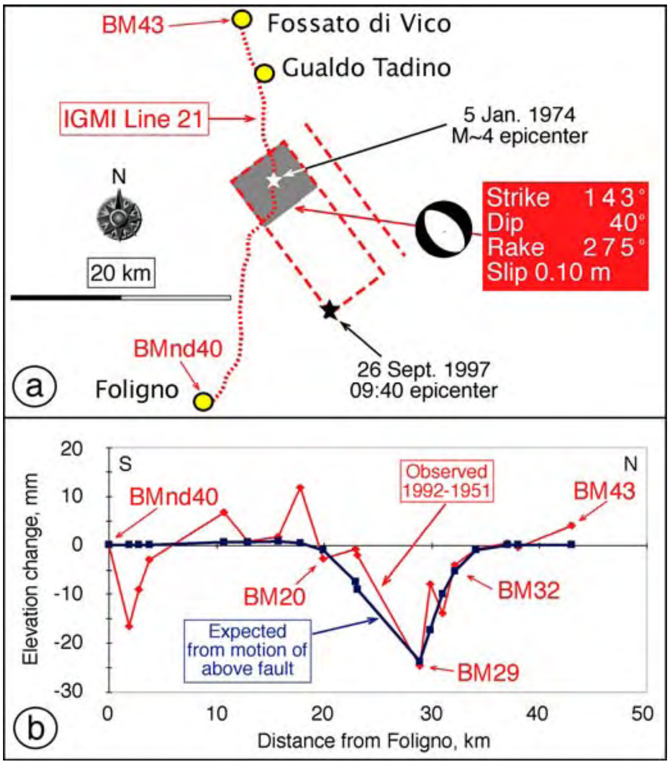

Figure 7.1: (a) Northern portion of the 09:40 shock fault (in gray), which may have experienced 10 cm of slip between 1951 and 1992. (b) 1951-1992 elevation changes (red line) and expected elevation changes associated with slip along the 5 km fault shown above (blue line) (modified after De Martini and Valensise, 1999).

The coseismic deformation is discussed in this thesis through different approaches involving both leveling and geological data, plus a preliminary InSAR-Leveling data combined analysis. The main results, obtained by working on the leveling data, contribute to the definition of the geometry of the 26 September 1997 09:40 Mw=6.0 earthquake causative fault and of the coseismic slip variability. The smallest misfit values (rms) are observed for a fault width in the range 7–8 km and for a minimum faulting depth of 2.8–4.0 km. The fit improves substantially for a fault length ≥14 km, suggesting that the rupture must have crossed Line 21 (figure 7.2). Further tests showed that the fit is quickly degraded by even small changes in fault strike and dip, which alter the relative position of the uplift and subsidence maxima seen in the data. Moreover, these tests verified that the assumption of coseismic slip uniformity for the 26 September 1997 09:40 Mw=6.0 earthquake fault is inadequate to reproduce the observed geodetic signal and that the problem is independent of fault geometry and cannot be solved simply by adjusting fault strike and dip. The variable slip pattern, adopted in the work, exhibits two maxima of 75 and 46 cm, respectively, centered at 4 and 10 km from the southeastern edge of the fault (figure 7.2). This slip pattern suggests the presence of a major and stronger asperity in the central–southern portion of the rupture, which might result from a strong rheological heterogeneity along the fault plane.

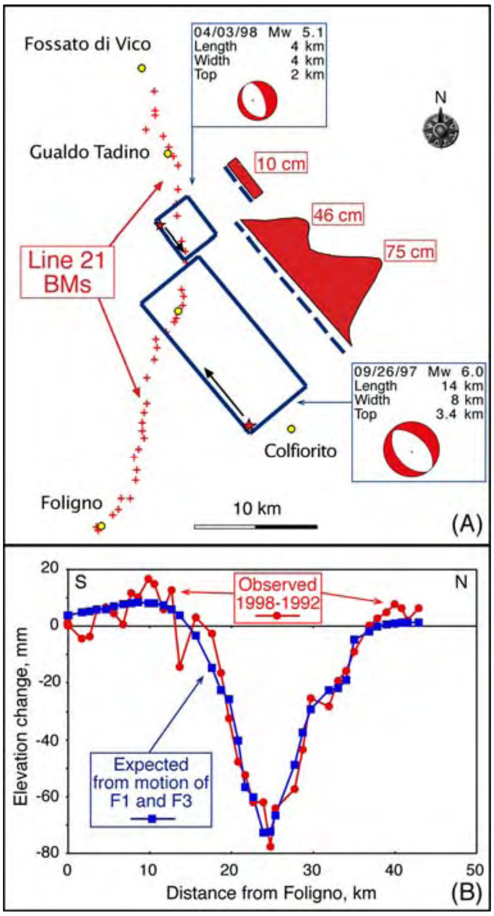

Figure 7.2: (a) Best-fitting model faults and relative maxima of variable slip distribution (modified after De Martini et al., 2003). Directivity (black arrow inside box) from Pino et al. (1999). (b) Observed elevation changes (red line) compared with the expected displacements (blue line) from motion of our best-fitting model faults (F1, F3).

Interestingly, the preliminary results of the combined analysis of InSAR and leveling data, comprising the 1997 Umbria-Marche mainshocks deformation pattern, suggest the possible presence of a small (4-5 km long) fault splay. A similar figure has been already presented by Basili and Meghraoui (2001) for an area located few km to the south, and interpreted as evidence for branching upward of a minor but steep fault splay. Obviously these preliminary results need further investigation and possibly exploratory paleoseismological trenches in the two investigated areas in order to try to detect the geodetically observed surface deformation.

From the geological point of view, the analyses of the trenches dug across the surface ruptures produced by the 14 October 1997 demonstrated that these ruptures are related to the activity of a fault and that other ruptures occurred in the past with similar characteristics both in term of magnitude and geometry. In this sense, the 14 October 1997 Mw=5.6 earthquake could represent the “characteristic earthquake” or maximum expected event for this seismogenic fault. The available data allow the identification of at least two moderate earthquakes (including the 1997 one) in the past 2000 years.

Finally, post-seismic deformation case is based on the elevation changes observed between 1950 and 2000 along the leveling lines around the epicentral area of the 1915 Avezzano earthquake. Relaxation effects refer to an exceptionally late stage of the process, accounting for about 30% of the observed geodetic signal (Amoruso et al., 2005). Results indicate that: upper crust thickness in this region is about 10 km, in agreement with the rupture geometry (Amoruso et al., 1998); the existence of a transition zone (as suggested by Aoudia et al., 2003, for the Umbria region) is confirmed; the total crustal thickness is larger than about 25 km. The remaining 70% of the signal (a significant elevation change between the Adriatic coast and the Apennine axis) is more likely due to regional uplift process.

Chapter 7.2: The contribution of geodetic and geologic studies to the identification and characterization of large scale vertical movements of the Apennines.

Another important part of this thesis is the study of the regional uplift of the Apennines at different time scales (using geodetic leveling data for the 10^2 yr time interval and the geological markers for the 10^4-10^6 yr time interval). The final aim is the characterization of crustal movements, in this seismically active region, in order to identify and delimitate the areas experiencing strong deformation that potentially may be the locus of strong earthquakes.

The short-term vertical velocity field for the past 50 years along and across the Apennines was studied from the geodetic point of view. The resulting elevation changes are above the random and systematic error propagation. Maximum relative elevation change rates, referred to an arbitrary fixed point, are comprised between 1.0 and 3.0 mm/a, are characterized by wavelengths up to 100 km, and vary along the chain axis (figure 3.3). The comparison of these results with those published by Arca and Beretta (1985), which provided a map of vertical movements in northern Apennines for the 1890–1950 time interval, shows a similar uplift shape and similar maximum relative elevation changes for each transect. Thus, the vertical velocity field appears to be nearly constant at least during the past century and it is likely related to regional scale tectonic movements. A comparison between the position of the highest geodetic rates with the location of instrumental seismicity does not show a clear positive correlation (figure 7.3), while a moderate agreement can be found when compared with the main seismogenic structures and the topography, especially in the southern Apennines.

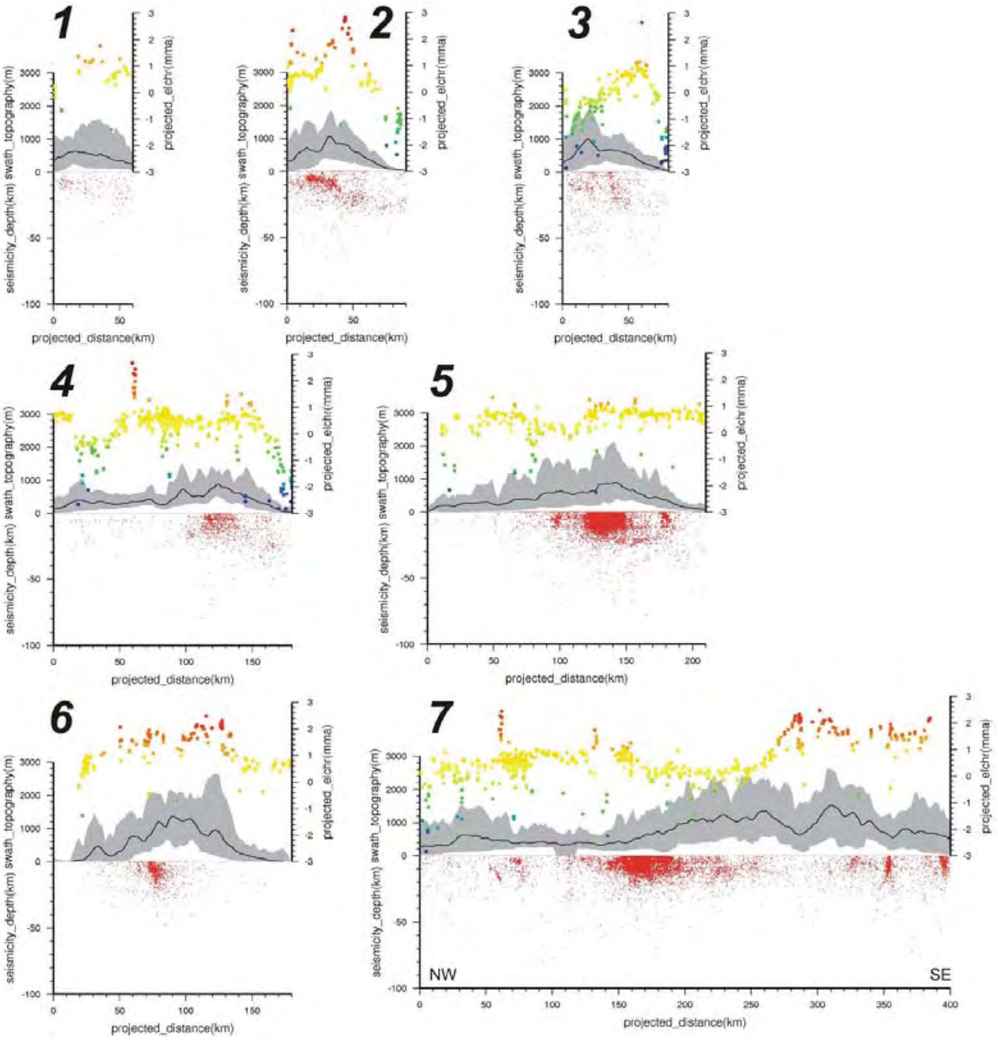

Figure 7.3: Leveling data cross sections (all oriented SW-NE, except for n. 7) against seismicity (Castello et al., 2006) and topography (swath topographic profiles, with maximum, minimum and mean topography calculated on 30 km wide boxes), (modified after De Martini et al., 2007)

Moreover some new geomorphological and paleontological data, together with Sr isotope analyses, were collected in a large area along the Tyrrhenian side of the Central Apennines on a series of old geomorphological markers (paleoshorelines). The obtained results, together with biostratigraphic data, constrain the age of the youngest paleoshorelines to 1.65–1.50 Ma. The uppermost and youngest palaeoshoreline altitude gently decreases almost regularly in the NNW-SSE direction from 480 to 220 m a.s.l.. These paleoshorelines are thus considered almost isochronous, yielding an uplift rate of 0.34 to 0.17 ±0.03 mm/yr decreasing from N to S. Shape, length and continuity of the 100-km-long observed movements indicate that the studied markers have a regional importance and were interpreted as the result of the Quaternary uplift of the Central Apennines. Interestingly a comparison of these results against the present vertical movements given by original nearby leveling data shows similar signal trends and magnitude, suggesting that the large scale uplift process acting in the Central Apennines may have a steady-state behavior.

Chapter 7.3: Results implication and prospect for future studies

The results shown in this thesis clearly highlighted the strong potentiality of the geodetic leveling data at the local scale for the identification and characterization of some active faults of the Apennines. Important constraints on the geometrical parameters and on the variability of the slip for the 26 September 1997 Mw=6 earthquake were derived from leveling data, providing an additional estimate independent from the seismologic/geologic/GPS/InSAR information. The awareness of this potentiality is not completely new, because since the beginning of the modern tectonic geodesy, it was clear that leveling data provide the directions to identify the coseismic surface deformation related to large earthquakes (Reilinger and Brown, 1981). Moreover, this thesis demonstrated that it is possible to detect not only the coseismic changes but also crustal deformations occurring in proximity (before/after) of a medium-large (M <7) earthquake (chapters 3 and 5). The estimated crustal deformation occurring before and after a seismic event may have important implications for earthquake prediction (Sikes et al., 1999) and for the definition of the rheology and structure of the lithosphere-asthenosphere stratification (Pollitz et al., 1992). In fact, it is generally accepted that the contribution of transient aseismic slip in stress accumulation and relief, in fault interactions and in earthquake nucleation is still inadequately understood.

Even if I am aware of the fact that, in the near future, this “old” technique will be substituted by modern space geodesy, for regions characterized by slow crustal movements (the Apennines but also the Pyrenees, central Greece or the Rhine graben, in Europe) it probably remains the best approach. In fact, it could be really interesting to install dedicated short (20-30 km long) leveling loops around and across some of the main seismogenic structures of the Apennines. In this way it could be possible to reduce significantly the expenses and time, commonly needed to built and re-measure frequently (2-3 times every 10 yr) regular first order leveling circuits (usually longer than 150 km), considering that, at present, these aspects represent the main disadvantage of the leveling technique.

At the regional scale, the work done in this thesis represents the first attempt to provide a quantitative description of the short-term vertical velocity field across the Apennine chain using a network of first order leveling lines. The importance of this result is related to the fact that, at present, only the large scale horizontal component of movement was estimated for the Apennines from geodetic data (Hunstad et al., 2003; Serpelloni et al., 2005, and reference therein). In fact, it should be noted that available estimates of vertical motion are mainly derived from geological or geomorphological data. The comparison of the results obtained from leveling and geological data is not simple, mainly because of the lack of well defined geological markers at the regional scale. Moreover, it is generally thought that a comparison of data separated by several orders of magnitude is not possible, not even for large scale process. This thesis it was demonstrated that some similarity exists between the abovementioned datasets, at least along the western flank of the central Apennines, but I should admit that the leveling data quality is not good. Even if the work is still in progress, I want to show an example (figure 7.4) from the southern Apennines that is the only section of the chain where it is possible to have reliable and widespread geological data (De Martini et al., 2007). A preliminary comparison of the geodetic data with the available geological information seems to suggest that the large scale uplift process acting in the Southern Apennines may have a steady-state behavior.

All these new data on location, geometry and behavior of active faults in the Apennines, together with the constraints obtained from regional scale studies, could be transferred into modern seismic hazard analysis and may contribute to the development of new deterministic approaches to the defense against the seismic risk.

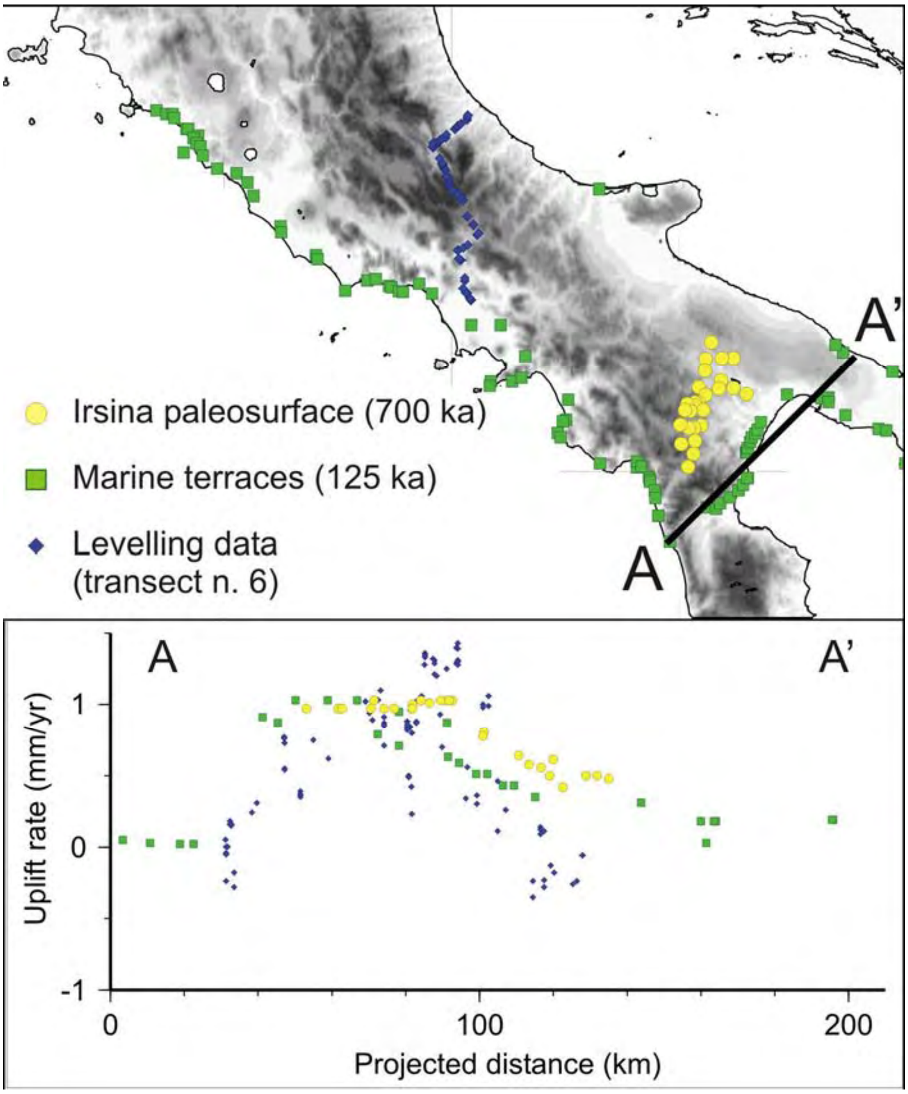

Figure 7.4: Comparison between profile n. 6 from figure 7.3 (50 years record, blue diamonds), and geological data in Southern Apennines, covering a time span of 125 ka (MIS 5e terrace, green squares) and about 0.7-0.8 Ma (Irsina paleosurface, yellow dots), (after De Martini et al., 2007).

Annex 1

Amoruso, A., L. Crescentini, E. D’Anastasio, P.M. De Martini, (2005): Clues of postseismic relaxation for the 1915 Fucino earthquake (central Italy) from modeling of leveling data, *Geophysical Research Letter*, 32, L22307, doi: 10.1029/2005GL024139

Clues of postseismic relaxation for the 1915 Fucino earthquake (central Italy) from modeling of leveling data

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Geophysical research letters, 2005, Vol. 32, L22307

Pages 183-186 :

Annex 2

Mancini, M., E. D'Anastasio, M. Barbieri, P.M. De Martini (2007): Geomorphological, paleontological and 87Sr/86Sr isotope analyses of Early Pleistocene paleoshorelines to define the uplift of Central Apennines (Italy), *Quaternary Research*, 67, 487-501, doi:10.1016/j.yqres.2007.01.005

Geomorphological, paleontological and 87Sr/86Sr isotope analyses of early Pleistocene paleoshorelines to define the uplift of Central Apennines (Italy)

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References

Alfonsi, L., Funiciello, R., Mattei, M., Girotti, O., Maiorani, A., Martinez, M.P., Trudu, C., Turi, B., 1991. Structural and geochemical features of the Sabina strike-slip fault (Central Apennines). Bollettino della Società Geologica Italiana 110, 217–230.

Amato, A. *et al.,* 1998. The 1997 Umbria-Marche, Central Italy, earthquake sequence: a first look to main shocks and aftershocks, *Geophys. Res. Lett.,* XXV, **15,** 2861–2864.

Amato, A., Cinque, A., 1999. Erosional landsurfaces of the Campano-Lucano Apennines (S. Italy): genesis, evolution, and tectonic implications. Tectonophysics 315, 251–267.

Ambrosetti, P., Carboni, M.G., Conti, M.A., Esu, D., Girotti, O., La Monica, G.B., Landini, B., Parisi, G., 1987. Il Pliocene ed il Pleistocene inferiore del Bacino del Fiume Tevere nell'Umbria meridionale. Geografia Fisica e Dinamica Quaternaria 10, 10–33.

Amoruso, A., Crescentini, L., D'Anastasio, E., De Martini, P.M., 2005. Clues of postseismic relaxation for the 1915 Fucino earthquake (central Italy) from modeling of leveling data. Geophys. Res. Lett. 32, L22307. doi:10.1029/2005GL024139.

Amoruso, A., L. Crescentini, and R. Scarpa 1998. Inversion of source parameters from near- and far-field observations: An application to the 1915 Fucino earthquakes, central Apennines, Italy, J. Geophys. Res., 103, 29,989–29,999.

Anderson, H. J., and Jackson, J. (1987), Active Tectonics of the Adriatic Region, Geophys. J. R. Astron. Soc. 91, 937–983.

Aoudia, A., A. Borghi, R. Riva, R. Barzaghi, B. A. C. Ambrousius, R. Sabadini, L. L. A. Vermeersen, and G. F. Panza 2003. Postseismic deformation following the 1997 Umbria-Marche (Italy) moderate normal faulting earthquakes, Geophys. Res. Lett. 30(7), 1390, doi:10.1029/2002GL016339.

Arca, S., Beretta, G.P., 1985. Prima sintesi geodetico—geologica sui movimenti verticali del suolo nell'Italia Settentrionale (1897–1957). Boll. Geod. Sci. Affini 2, 125–156 (anno XI.IV).

Argnani, A., Bernini, M., Di Dio, G.M., Papani, G. & Rogledi, S., 1997. Stratigraphic record of crustal-scale tectonics in the Quaternary of the Northern Apennines (Italy), Il Quaternario, 10, 595–602.

Barba, S. & Basili, R., 2000. Analysis of seismological and geological observations for moderate-size earthquakes: the Colfiorito Fault System (Central Apennines, Italy), *Geophys. J. Int.,* **141,** 241–252.

Barberi, F., Buonasorte, G., Cioni, R., Fiordalisi, A., Foresi, L., Iaccarino, S., Laurenzi, M.A., Sbrana, A., Vernia, L., Villa, I.M., 1994. Plio-Pleistocene geological evolution of the geothermal area of Tuscany and Latium. Memorie Descrittive della Carta Geologica d'Italia 49, 77–134.

Baroux, E., Pino, N.A.; Valensise, G. Scotti, O. Cushing, M.E., 2003. Source parameters of the 11 June 1909, Lambesc (Provence, southeastern France) earthquake; a reappraisal based on macroseismic, seismological, and geodetic observations, Journal of Geophysical Research, vol.108, no.B9, 23 pp.

Barrientos S.E., Stein R.S., Ward S.N. 1987. Comparison of the 1959 Hebgen Lake, Montana and the 1983 Borah Peak, Idaho, earthquake from geodetic observations, Bull. of Seism. Soc. of Am., vol 77, n.3, p. 784-808

Bartolini C., Caputo R., and Pieri M., 1996. Pliocene-Quaternary sedimentation in the Northern Apennine foredeep and related denudation, Geol. Mag., 133, n.3, p. 255-273

Bartolini, C., 2003. Uplift and erosion: driving processes and resulting landforms. Editor Quaternary International 101–102, 280.

Basili R, Bosi C., Bosi V., Galadini F., Galli P., Meghraoui M., Messina P., Moro M. e Sposato A., 1998: The Colfiorito earthquake sequence of September-October 1997. Surface breaks and seismotectonic implications for the central Apennines (Italy), *Journal of Earthquake Engineering*, 102(2), pp. 291-302.

Basili, R. & Meghraoui, M., 2001. Coseismic and postseismic displacements related with the 1997 earthquake sequence in Umbria-Marche (central Italy), *Geophys. Res. Lett.,* XXVIII, **14,** 2695–2698.

Beanland, S. and Clark, M. M., 1994. The Owens Valley fault zone, eastern California, and surface faulting associated with the 1872 earthquake, U. S. Geological Survey Bulletin, Report: B 1982, 29 pp., 4 sheets.

Bigi, G., Cosentino, D., Parotto, M., Sartori, R. & Scandone, P., 1992. Structural Model of Italy. Scale 1:500,000, Quad. Ric. Sci., 114.

Bigi, S., Cantalamessa, G., Centamore, E., Didaskalou, P., Micarelli, A., Nisio, S., Pennesi, T. & Potetti, M., 1997. The Periadriatic basin (Marche-Abruzzi sector, central Italy) during the Plio–Pleistocene, Giorn. Geol., 59, 245–259.

Blumetti, A.M., 1995. Neotectonic investigations and evidence of paleoseismicity in the epicentral area of the January-February 1703, central Italy, earthquakes, Special Publication - Association of Engineering Geologists, vol.6, pp.83-100.

Bomford, G., 1971. Geodesy. Oxford University Press, New York. 731 pp.

Bordoni, P., Valensise, G., 1998. Deformation of the 125 ka marine terrace in Italy: tectonic implications. In: Stewart, I.S., Vita-Finzi, C. (Eds.), “Coastal Tectonics”. Special Publication-Geological Society of London, vol. 146, pp. 71–110.

Boschi E., Guidoboni E., Ferrari G. e Valensise G., 1998: I terremoti dell'Appennino Umbro-Marchigiano. Publ. Istituto Nazionale di Geofisica e Storia Geofisica Ambiente, pp. 266, Editrice Compositori, Bologna 1998.

Boschi, E., Guidoboni, E., Ferrari, G., Mariotti, D., Valensise, G. & Gasperini, P., 2000. Catalogue of strong Italian earthquakes from 461 BC to 1997, *Ann. Geofis.,* **43**(4), 607–868, with Database on CD-ROM.

Bosi, C. & Messina, P., 1991. Ipotesi di correlazione fra successioni morfo-litostratigrafiche plio-pleistoceniche nell'Appennino lazialeabruzzese, Studi Geologici Camerti, Special Volume CROP, 11, 257–263.

Bosi, C. 1975. Preliminary observations on probably active faults in the central Apennines, Bollettino della Societa Geologica Italiana, vol.94, 4, pp.827-859.

Bosi, C., Camponeschi, B., and Giglio, G., 1976. Signs of possible movement along faults as a result of the May 6, 1976 Friuli earthquake, Bollettino della Societa Geologica Italiana, vol.95, 3-4, pp.803-830.

Bousquet, J. C., G. Gars, G. Lanzafame and H. Philip, 1983. Ruptures de surface d'origine gravitationelle lors du seisme de l'Irpinia 23/11/1980; Italie Meridionale, Geol. Appl. Idrogeol., 18, 427-435

Brady, B.T., 1974. Theory of earthquakes, Part I: a scale independent theory of rock failure, Pure and Appl. Geophys., 112, 701-715.

Burgmann, R., M. G. Kogan, V. E. Levin, C. H. Scholz, R. W. King, and G. M. Steblov, 1997. Rapid aseismic moment release following the 5 December, 1997 Kronotsky, Kamchatka, earthquake, Geophys. Res. Letters, 28, 1331– 1334.

Cakir, Z., A.M. Akoglu, S. Belabbes, S. Ergintav and M. Meghraoui, 2005. Creeping along the Ismetpasa section of the North Anatolian fault (Western Turkey): rate and extent from InSAR, Earth and Planetary Science Letters, 238, 225-234.

Calamita, F.; Cello, G.; Deiana, G.; Paltrinieri, W., 1994. Structural styles, chronology rates of deformation, and time-space relationships in the Umbria-Marche thrust system (central Apennines, Italy), Tectonics, vol.13, no.4, pp.873-881.

Camassi R. and Stucchi M., 1998. NT4.1, a parametric catalogue of damaging earthquakes in the Italian area (versione NT4.1.1), Gruppo Nazionale per la Difesa dai Terremoti, pp 66, Milano (http://emidius.itim.mi.cnr.it/NT/home.html).

Capuano, P., Zollo, A., Emolo, A., Marcucci, S.&Milana, G., 2000. Rupture mechanism and source parameters of Umbria-Marche mainshocks from strong motion data, *J. Seismol.,* **4,** 463–478.

Carmignani, L., G. Cello, A. Cerrina Feroni, R. Funiciello, O. Kalin, M. Mecchieri, E. Patacca, G. Plesi, F. Salvini, P. Scandone, L. Tortorici and E. Turco, 1981. Analisi del campo di fratturazione superficiale indotta dal terremoto Campano-Lucano del 23/11/1980, Rend. Soc. Geol. It., 4, 451-465

Casnedi, R., U. Crescenti, C. D'amato, F. Mostardini, and U. Rossi 1981, Il Plio-Pleistocene del sottosuolo molisano, Geol. Romana, 20, 1 – 42.

Castello B., Selvaggi G., Chiarabba C., Amato A., 2006. CSI Catalogo della sismicità italiana 1981-2002, versione 1.1. INGV-CNT, Roma.

Cattaneo, M. *et al.,* 2000. The 1997 Umbria-Marche (Italy) earthquake sequence: analysis of the data recorded by the local and temporary networks, *J. Seismol.,* **4,** 401–414.

Cavinato, G.P., De Celles, P., 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., Deiana G., Mangano P., Mazzoli S., Tondi E., Ferreli L., Maschio L., Michetti A. M., Serva L. e Vittori E., 1998: Evidence for surface faulting during the September 26, 1997, Colfiorito (Central Italy) earthquakes, *Journal of Earthquake Engineering*, 102(2), 303-324.

Cello, G., Mazzoli, S., Tondi, E. & Turco, E., 1997. Active tectonics in the central Apennines and possible implications for seismic hazard analysis in peninsular Italy, *Tectonophysics,* **272,** 43–68.

Chiarabba et al., 2005a. Mainshocks and aftershocks of the 2002 molise seismic sequence, southern Italy, J. Seismol., 9, 487-494

Chiarabba, C., Jovane, L., Di Stefano, R., 2005b. A new view of Italian seismicity using 20 years of instrumental recording recordings. Tectonophysics 395, 251–268. doi:10.1016/j.tecto.2004.09.013.

Chiaraluce, L., W. L. Ellsworth, C. Chiarabba and M. Cocco, 2003. Imaging the complexity of an active normal fault system: The 1997 Colfiorito (central Italy) case study, J. Geophys. Res., 108, B6, 2294, 10.1029/2002JB002166

Cinque, A., Patacca, E., Scandone, P., Tozzi, M., 1993. Quaternary kinematic evolution of the Southern Apennines. Relationships between surface geological features and deep lithospheric structures. Annali di Geofisica 36, 249–260.

Cinti, F.R., Cucci, L., Marra, F. & Montone, P., 1999. The 1997 Umbria-Marche (Italy) earthquake sequence: relationship between ground deformation and seismogenic structure, *Geophys. Res. Lett.,* XXVI, **7,** 895–898.

Clarke, P. J., R. R. Davies, P. C. England, B. Parsons, H. Billiris, D. Paradissis, G. Veis, P. A. Cross, P. H. Denys, V. Ashkenazi, R. Bingley, H.-G. Kahle, M.-V. Muller, and P. Briole 1998. Crustal strain in central Greece from repeated GPS measurements in the interval 1989–1997, *Geophys. J. Int.* **135,** 195–214.

Coblentz, D. D., S. Zhou, R. R. Hillis, R. M. Richardson, and M. Sandiford 1998. Topography, boundary forces, and the Indo-Australian intraplate stress field, *J. Geophys. Res.* **103,** 919–931.

Consiglio Nazionale delle Ricerche (1992), Structural model of Italy and gravity map, scale 1:500,000, Progetto Finalizzato Geodin, vol. 3, Quad. Ric. Sci., 114.

Cosentino, D., Gliozzi, E., 1988. Considerazioni sulle velocità di sollevamento dei depositi eutirreniani dell'Italia meridionale e della Sicilia. Memorie della Società Geologica Italiana 41, 653–665.

CPTI Working Group, 1999. Catalogo Parametrico dei Terremoti Italiani. ING, GNDT, SGA, SSN, Bologna, pp. 92 (1999).

CPTI Working Group, 2004. Catalogo Parametrico dei Terremoti Italiani, version 2004 (CPTI04), INGV, Bologna.

Crone A.J., P.M. De Martini, Machette M.N., K.Okumura & J.R. Prescott 2003. Paleoseismicity of two historically quiescent faults in Australia- Implications for fault behavior in stable continental regions, Bulletin of the Seismological Society of America, 93 (5), 1913-1934.

D'Agostino, N., Jackson, J.A., Dramis, F., Funiciello, R., 2001. Interactions between mantle upwelling, drainage evolution and active normal faulting: an example from the central Apennines (Italy). Geophysical Journal International 147, 475–497.

Dalla Via G., De Natale G., Troie C., Pingue F., Obrizzo F., Riva R., Saladini R. 2003. First evidence of post-seismic deformation in the central Mediterranean: crustal viscoelastic relaxation in the area of the 1980 Irpinia earthquake (Southern Italy), Geoph. J. Int., n. 154, F9-F14.

D'Anastasio, E., 2004. Analisi e integrazione di dati geodetici ed elementi geologici per la definizione del campo di deformazione verticale a breve e lungo termine in Appennino (Italia). Ph.D. dissertation in Geophysics, XVI cycle, Dipartimento di Fisica, Università degli Studi di Bologna, 189 pp., Bologna.

D'Anastasio, E., De Martini, P.M., Selvaggi, G., Pantosti, D., Marchioni, A., Maseroli, R., 2006. Short-term vertical velocity field in the Apennines (Italy) revealed by geodetic levelling data. Tectonophysics 418, 219–234.

De Martini P.M., K. Hessami, D. Pantosti, G. D’Addezio, H. Alinaghi & M. Ghafory-Ashtiani 1998. A geologic contribution to the evaluation of the seismic potential of the Kahrizak fault (Tehran, IRAN),Tectonophysics , 287, 187-199.

De Martini P.M., Meghraoui M., Pantosti D., D'Anastasio E., 2007. Conjunct Geodetic and Geologic analysis of the Apennines active deformation (Italy), IUGG XXIV General Assembly, 2-13 July, Perugia, Italy, abstract book.

De Martini P.M., Pino N.A., V alensise G. e Mazza S., 2000: An unusual pattern of faulting in the Central Apennines (Italy): geodetic and seismologic evidence for pre- and co-seismic slip along a low angle, blind normal fault and implications for active faulting studies, *Proceedings of the Hokudan International Symposium and School on Active Faulting*, pp. 69-73, Hokudan (Japan, Gennaio 2000).

De Martini, P.M., e Valensise G., 1999: Pre-seismic slip on the 26 September 1997, Umbria-Marche earthquake fault? Unexpected clues from the analysis of 1951-1992 elevation changes, *Geophys. Res. Lett.* , 26(13), pp. 1953-1956.

De Martini, P.M., Pino, N.A., Valensise, G., Mazza, S., 2003. Geodetic and seismologic evidence for pre and co-seismic slip along a lowangle, blind normal fault, and implications for active faulting studies. Geoph. J. Int. 55 (3), 819–829 (December).

De Mets, C., Gordon, R.G., Argus, D.F., Stein, S., 1990. Current plate motions. Geophys. J. Int. 101, 425-478.

Demangeot J., 1965. Geomorphologie des Abruzzes Adriatiques, Centre Recherche et Documentation Cartographiques Memories et Documents, Numero hors. Serie, Paris, pp. 1-403

Deschamps, A. *et al.,* 2000. Spatio-temporal distribution of seismic activity during the Umbria-Marche crisis, 1997, *J. Seismol.,* **4,** 377–386.

Deschamps, A., Iannacone, G. & Scarpa, R., 1984. The Umbrian earthquake (Italy) of 19 September 1979, *Ann. Geophysicae,* **2,** 29–36.

Dewey, J. F., Pitman, W. C., Ryan, W. B. F., and Bonnin, J. 1973, Plate Tectonics and the E6olution of the Alpine System, Bull. Geol. Soc. Am. 84, 3137–3180.

Di Luccio, F., Piscini, A., Pino, N.A., Ventura, G., 2005. Reactivation of deep faults beneath Southern Apennines: evidence from the 1990-1991 Potenza seismic sequences. Terra Nova 17 (6), 586–590. doi:10.1111/j.1365–3121.2005.00653.x.

Dieterich, J.H., 1978. Preseismic fault slip and earthquake prediction, J. Geophys. Res., 83, 3940-3948.

DISS Working Group, 2005. Database of individual seismogenic sources (version 3.0.2): a compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas, available at http://www.ingv.it/resources/data-bases

Dixon, T. H; Norabuena, E; Hotaling, L, 2003. Paleoseismology and Global Positioning System; earthquake-cycle effects and geodetic versus geologic fault slip rates in the Eastern California shear zone, Geology, vol.31, no.1, pp.55-58.

Dramis, F., 1992. Il ruolo dei sollevamenti tettonici a largo raggio nella genesi del rilievo appenninico, *Studi Geologici Camerti,* Vol. Spec. 1992/1, 9–15.

Ekstrom G., Morelli A., Boschi E. e A.M. Dziewonski; 1998: Moment tensor analysis of the central Italy earthquake sequence of September-October 1997, *Geophys. Res. Lett*., 25, pp. 1971-1974.

Elter, P., Giglia, G., Tongiorgi, M. & Trevisan, L., 1975. Tensional and compressional areas in the recent (Tortonian to present) evolution of North Apennines, Boll. Geof. teor. Appl., 17, 3–18.

Faccenna, C., Davy, P., Brun, J.P., Funiciello, R., Giardini, D., Mattei, M. & Nalpas, T., 1996. The dynamic of backarc basins: an experimental approach to the opening of the Tyrrhenian Sea, Geophys. J. Int., 126, 781–795.

Friedrich, A.M., B.P. Wernicke, N.A. Niemi, R.A. Bennett and J.L. Davis, 2003. Comparison of geodetic and geologic data from the Wasatch region, Utah, and implications for the spectral character of earth deformation at periods of 10 to 10 million years, J. of Geoph. Res., vol. 108, B4, 2199, doi: 10.1029/2001JB000682.

Galadini, F., Galli, P., 2000. Active tectonics in the Central Apennines (Italy)—Input data for seismic hazard assessment. Natural Hazards 22, 225–270.

Galadini, F., Messina, P., Giaccio, B., Sposato, A., 2003. Early uplift history of the Abruzzi Apennines (central Italy): available geomorphological constraints. Quaternary International 101–102, 125–135.

Galli P., Bosi V., Galadini F., Meghraoui M., Messina P., Basili R., Moro M. e Sposato A., 1997. Fratturazione superficiale connessa ai terremoti umbro-marchigiani del settembre-ottobre 1997, *Il Quaternario,* 10(2), pp. 255-262.

Galli, P. & Galadini, F., 1999. Seismotectonic framework of the 1997–1998 Umbria-Marche (Central Italy) earthquakes, *Seism. Res. Lett.,* **70,** 417–427.

Galli, P., F. Galadini and F. Calzoni, 2005. Surface faulting in Norcia (central Italy): a “paleoseismological perspective”, Tectonophysics, 403, 117-130.

Gan, W.; Svarc, J L; Savage, J C; Prescott, W H, 2000. Strain accumulation across the eastern California shear zone at latitude 36 degrees 30'N, Journal of Geophysical Research, vol.105, no.B7, pp.16,229-16,236.

Gao, S. S., P. G. Sliver, and T. Linde, 2000. Analysis of deformation data at Parkefield, California: detection of long-term strain transient, J. Geophys. Res., 105, 2955– 2967

Girotti, O., Mancini, M., 2003. Plio-Pleistocene stratigraphy and relations between marine and non-marine successions in the Middle Valley of the Tiber River (Latium, Umbria). Il Quaternario 16 (1 Bis), 89–106.

Girotti, O., Piccardi, E., 1994. Linee di riva del Pleistocene inferiore sul versante sinistro della media Valle del Fiume Tevere. Il Quaternario 7, 525–536.

Goldstein, R. M., Zebker, H. A. and Werner, C. L., 1988. Satellite Radar Interferometry - Two-Dimensional Phase Unwrapping, *Radio Science*, 23 (4), 713-720.

Haessler, H., R. Gaulon, L. Rivera, R. Console, M. Frogneux, G. Gasparini, L. Martel, G. Patau, M. Siciliano and A. Cisternas, 1988. The Perugia (Italy) earthquake of 29 April 1984: a microearthquake survey, Bull. Seismol. Soc. Am., 78, 1,948-1,964.

Hamon, B V, and Greig, M A, 1972. Mean Sea Level in Relation to Geodetic Land Leveling around Australia, Journal of Geophysical Research, vol.77, no.36, pp.7157-7162.

Hecker S., Ponti D. J., Garvin C.D., e Hamilton J.C.,1995: Characteristics and origin of ground deformation produced in Granada Hills and Mission Hills during the January 17, 1994 Northridge, California, earthquake, in Woods M.C. and Seiple W.R. (Eds.): *The Northridge, California Earthquake of 17 January 1994*, California Dept. of Conservation, Division of Mines and Geology special publ 116, pp. 111-131.

Heki, K., S. Miyazaki, and H. Tsuji, 1997. Silent fault slip following an interpolate thrust earthquake at the Japan Trench, Nature, 386, 595– 598.

Hippolyte, J.C., Angelier, J., Roure, F., 1994. A major geodynamic change revealed by Quaternary stress patterns in the Southern Apennines (Italy). Tectonophysics 230, 199–210.

Hodgkinson K.M., Stein R.S., Marshall G.A. 1996. Geometry of the 1954 Fairview Peak-Dixie Valley earthquake sequence from a joint inversion of leveling and triangulation data, J. of Geoph. Res., vol. 101, n. B11, p. 25,437-25,457

Hunstad, I., Anzidei, M., Cocco, M., Baldi, P., Galvani, A. & Pesci, A., 1999. Modelling coseismic displacements during the 1997 Umbria-Marche earthquake (central Italy), *Geophys. J. Int.,* **139,** 283–295.

Hunstad, I., Selvaggi, G., D'Agostino, N., England, P., Clarke, P., Pierozzi, M., 2003. Geodetic strain in peninsular Italy between 1875 and 2001. Geophys. Res. Lett. 30 (4), 1181. doi:10.1029/2002GL016447.

Jackson, M., Bilham, R., 1994. Constraints on Himalayan deformation inferred from vertical velocity fields in Nepal and Tibet. J. Geophys. Res. 99 (B7), 13,897–13,912.

Jolivet, L., et al., 1998. Midcrustal shear zones in postorogenic extension: the Northern Tyrrhenian Sea case, J. geophys. Res., 88, 12 123–12 160.

Kastens, K., et al. 1988, ODP Leg 107 in the Tyrrhenian Sea: Insights into passive margin and back-arc basin evolution, Geol. Soc. Am. Bull., 100, 1140 – 1156.

Kawasaki, I., Y. Asai, Y. Tamura, T. Sagiya, N. Mikami, Y. Okada, M. Sakata, and M. Kasahara, 1995. The 1992 Sanriku-oki, Japan, ultra-slow earthquake, J. Phy. Earth, 43, 105–116.

Keller, E. A.; and Pinter, N., 2002. Active tectonics; earthquakes, uplift, and landscape, Prentice Hall, Upper Saddle River, NJ, United States (USA), pp. 362.

Lajoie, K.R., 1986. Coastal tectonics. In: Wallace, R. (Ed.), Active Tectonics. National Academy Press, Washington, pp. 95–124.

Lambeck, K., 1988. Geophysical Geodesy; the slow deformation of the Earth, Oxford Univ. Press, New York, NY, United States (USA), pp. 718.

Lee, J., Spencer, J.; and Owen, L., 2001. Holocene slip rates along the Owens Valley fault, California; implications for the recent evolution of the Eastern California shear zone, Geology, vol.29, no.9, pp.819-822.

Lemeille, F. 1977. Etudes ne´otectoniques en Gre`ce centrale nord-orientale (Eube´e centrale, Attique, Be´otie, Locride) et dans les Sporades du Nord (ıˆle de Skiros), in *The`se de Troisie`me Cycle*, Universite´ Paris XI, Centre Orsay, 173 pp. (in French).

Lewis, J. D., N. A. Daetwyler, J. A. Bunting, and J. S. Moncrieff (1981). The Cadoux earthquake, 2 June 1979, *Geol. Surv. West. Aust. Rept. 11.*

Linde, A. T., M. T. Gladwin, M. J. S. Johnston, R. L. Gwyther, and R. G. Bilham, 1996. A slow earthquake sequence on the San Andreas fault, Nature, 383, 65–68

Liu, Y. and J.R. Rice, 2005. Aseismic slip transients emerge spontaneously in three-dimensional rate and state modeling of subduction earthquake sequences, J. Geophys. Res., 110, doi: 10.1029/2004JB003424.

Lundgren, P. and S. Stramondo, 2002. Slip distribution of the 1997 Umbria-Marche earthquake sequence; joint inversion of GPS and synthetic aperture radar interferometry data, Journal of Geophysical Research, vol.107, no.B11, 9 pp.

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

Mancini, M. & Cavinato, G.P., 2005. The Middle Valley of the Tiber River, central Italy: Plio-Pleistocene fluvial and coastal sedimentation, extensional tectonics and volcanism. In: Blum, M.D., Marriott, S., Leclair, S. (Eds.), Fluvial Sedimentology VII. IAS Spec. Publ., vol. 35, pp. 373–396.

Mancini, M., E. D'Anastasio, M. Barbieri, P.M. De Martini 2007. Geomorphological, paleontological and 87Sr/86Sr isotope analyses of Early Pleistocene paleoshorelines to define the uplift of Central Apennines (Italy), Quaternary Research, 67, 487-501, doi:10.1016/j.yqres.2007.01.005.

Mazzoli, S.,& Helman, M. 1994. Neogene Patterns of Relati6e Plate Motions for Africa-Europe: Some Implications for Recent Central Mediterranean Tectonics, Geol. Rundsch. 83, 464–468.

McCalpin J. 1996. Paleoseismology, Accademic Press Ldt., pp. 588, London.

McCalpin, J.P., 1996. Paleoseismology, International Geophysics Series, vol.62, 588 pp.

McClusky, S C; Bjornstad, S C; Hager, B H; King, R W; Meade, B J; Miller, M M; Monastero, F C; Souter, B J, 2001. Present day kinematics of the eastern California shear zone from a geodetically constrained block model, Geophysical Research Letters, vol.28, no.17, pp.3369-3372.

Meghraoui, M; Philip, H; Albarede, F; Cisternas, A, 1988. Trench investigations through the trace of the 1980 El Asnam thrust fault; evidence for paleoseismicity, Bulletin of the Seismological Society of America, vol.78, no.2, pp.979-999

Meletti, C., Patacca, E. & Scandone, P., 2000. Construction of a seismotectonic model: the case of Italy, *Pure appl. Geophys.*, **157,** 11–35.

Meyr, B; Meghraoui, M., Tapponnier, P; Shunmin, G; Hongfa, X; Zhitai, C; Shuahua, C, 1990. Comparaison morphologique des escarpements de failles normales et inverses synchrones du tremblement de terre d'El Asnam, Algerie (10 octobre 1980). Morphologic comparison of coeval normal and reverse fault scarps of the El Asnam, Algeria, October 10, 1980 earthquake, Comptes Rendus de l'Academie des Sciences, Serie 2, vol.310, no.2, pp.139-146

Michetti A.M., Serva L. and Vittori E. coord. 2000: ITHACA. Italy Hazard from Capable Faulting. A database of active capable faults of the Italian onshore territory. ANPA, CD-ROM.

Mjachkin, V.I., W.F. Brace, G.A. Sobolev and J.H. Dieterich, 1975. Two models for earthquake forerunners, Pageoph., 113, 169-181.

Molnar, P. And P. Tapponnier, 1975. Cenozioc tectonics of Asia; effects of a continental collision, Science, 189, 419-426

Montone, P., Amato, A. & Pondrelli, S., 1999. Active stress map of Italy, Journal of Geophysical Research*,* **104,** 25 595–25 610.

Montone, P., Mariucci, M.T., Pondrelli, S., Amato, A., 2004. An improved stress map for Italy and surrounding regions (Central Mediterranean). J. Geophys. Res. 109, 10410. doi:10.1029/2003JB002703.

Morelli, A., Ekstr¨om, G. & Olivieri, M., 2000. Source properties of the 1997–98 Central Italy earthquake sequence from inversion of long-period and broad-band seismograms, *J. Seismol.,* **4,** 365–375.

Muller, G., 1986. Appunti di Livellazione. Collezione dei Testi Didattici dell'Istituto Geografico Militare. 92 pp.

Nishimura T., and Thatcher W., 2003. Rheology of the lithosphere as inferred from postseismic uplift following the 1959 Hebgen Lake earthquake, J. of Geoph. Res., vol. 108, n. B8, 2389-2401.

Oddone, E., 1915. Gli elementi fisici del grande terremoto marsicano-fucense del 13 gennaio 1915, Boll. Soc. Sism. It., 19, 71-291

Ori, G.G., Serafini, G., Visentini, G., Lucchi, F.R., Casnedi, R., Colalongo, M.L. & Mosna, S., 1993. Depositional history of the Pliocene-Pleistocene Adriatic foredeep (Central Italy) from surface and subsurface data, in Generation, accumulation and production of Europe's hydrocarbon III, pp. 233–258, ed. Specer, A.M., Spec. Publ., Eur. Ass. Petr. Geosc., 3.

Pace, B., P. Boncio and G. Lavecchia, 2002. The 1984 Abruzzo earthquake (Italy): an example of seismogenic process controlled by interaction between differently oriented synkinematic faults, Tectonophysics, 350, 237-254.

Pantosti D., P. M. De Martini, D. Papanastassiou , F. Lemeille, N. Palyvos and G. Stavrakakis 2004. Paleoseismological trenching across the Atalanti fault (Central Greece): evidence for the ancestors of the 1894 earthquake during Middle Age and Roman time, Bull. Soc. Seism. Am., 94 (2), 531-549.

Pantosti D., P.M. De Martini, P. Galli, F. Galadini, P. Messina, M. Moro & A. Sposato 1999. Studi paleosismologici lungo la rottura superficiale prodotta dal terremoto del 14 Ottobre 1997 (Umbria-Marche), in *Atti del 18° Convegno del Gruppo Nazionale di Geofisica Della Terra Solida*, 13 pp., Roma 9-11 Novembre 1999, in italian.

Pantosti, D., and Valensise, G., 1990. Faulting mechanism and complexity of the November 23, 1980, Campania-Lucania earthquake, inferred from surface observations, Journal of Geophysical Research, vol.95, no.B10, pp.15,319-15,341.

Pantosti, D.; Schwartz, D.; Valensise, G., 1993. Paleoseismology along the 1980 surface rupture of the Irpinia Fault; implications for earthquake recurrence in the Southern Apennines, Italy, Journal of Geophysical Research, vol.98, no.B4, pp.6561-6577.

Patacca, E., Sartori, R., Scandone, P., 1992. Tyrrhenian Basin and Apenninic Arcs: kinematics relations since Late Tortonian time. Memorie della Società Geologica Italiana 45, 425–451.

Patacca, E., Scandone, P., 2001. Late thrust propagation and sedimentary response in the thrust–belt–foredeep system of the Southern Apennines (Pliocene–Pleistocene). In: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an orogen: the Apennines and adjacent Mediterranean basins. Kluwer Academic Publishers, pp. 401–440.

Philip, H. 1974. Etude ne´otectonique des rivages ege´ens en Locride et en Eube´e nord-occidentale (Gre`ce), in *The`se de Troisie`me Cycle*, Academie de Montpellier, Universite´ des Sciences et Techniques du Languedoc, 103 pp. (in French).

Pino, N.A. & Mazza, S., 2000. The Umbria-Marche (central Italy) earthquakes: relation between rupture directivity and sequence evolution for the *Mw* > 5 shocks, *J. Seismol.,* **4,** 451–461.

Pino, N.A., Mazza, S. & Boschi, E., 1999. Rupture directivity of the major shocks in the 1997 Umbria-Marche (Central Italy) sequence from regional broadband waveforms, *Geophys. Res. Lett.,* XXVI, **14,** 2101–2104.

Pollitz F.F., Sacks I.S., Selwyn I. 1992. Modeling of postseismic relaxation following the great 1857 earthquake, Southern California Bull. Seism. Soc. Of America, vol. 82, n. 1, p. 454-480

Pollitz, F. F. (2003), VISCO1D v. 2 program package, U.S. Geol. Surv., Menlo Park, Calif. (http://quake.wr.usgs.gov/research/deformation/modeling/papers/2003/fred/)

Pollitz, F. F. 1997. Gravitational-viscoelastic postseismic relaxation on a layered spherical Earth, J. Geophys. Res., 102, 17,921– 17,941.

Pondrelli, S., Morelli, A., Ekstrom, G., 2004. European–Mediterranean Regional Centroid Moment Tensor catalog: solutions for years 2001 and 2002. Phys. Earth Planet. Inter. 145, 127–147. doi:10.1016/j.pepi.2004.03.008.

Pondrelli, S., S. Salimbeni, G. Ekström, A. Morelli, P. Gasperini and G. Vannucci, 2006. The Italian CMT dataset from 1977 to the present, Phys. Earth Planet. Int., doi:10.1016/j.pepi.2006.07.008, 159/3-4, pp. 286-303,

Priestley, K., Baker, C., Jackson, J.A., 1994. Implications of earthquake focal mechanism data for the active tectonics of the south Caspian Basin and surrounding regions. Geophys. J. Int. 118, 111-141.

Pucci, S., P. M. De Martini, D. Pantosti and G. Valensise, 2003. Geomorphology of the Gubbio Basin (Central Italy): understanding the active tectonics and earthquake potential, Ann. Geophys.-Italy, 46, 5, 837-864

Reid, H.F., 1910. On mass-movements in tectonic earthquakes. The California earthquake of April 18, 1906. Report of the state earthquake investigation commission: Carnegie Institute of Washington, D.C.

Reilinger, R., & Brown, L., 1981. Neotectonic deformation, nearsurface movements and systematic errors in U.S. relevelling measurements: implications for earthquake prediction. In: Simpson, D.W., Richards, P.G. (Eds.), Earthquake Prediction: An International Review, Maurice Ewing Ser., vol. 4, pp. 422–440. AGU.

Riva, R., E M; Borghi, A; Aoudia, A; Barzaghi, R; Sabadini, R; Panza, G F, 2007. Viscoelastic relaxation and long-lasting after-slip following the 1997 Umbria-Marche (central Italy) earthquakes, Geophysical Journal International, vol.169, no.2, pp.534-546.

Royden, L.H., 1993. Evolution of retreating subduction boundaries formed during continental collision, Tectonics, 12, 629–638.

Rymer M.J., Fumal T.E., Schwartz D.P., Powers T.J., and Cinti F.R., 1995. Distribution and Recurrence of the Surface Fractures in Potrero Canyon associated with the 1994 Northridge, California, earthquake, in Woods M.C. and Seiple W.R. (Eds.): *The Northridge, California Earthquake of 17 January 1994*, California Dept. of Conservation, Division of Mines and Geology special publ 116, pp. 133-146.

Salvi, S. *et al.,* 2000. Modeling coseismic displacements resulting from SAR interferometry and GPS measurements during the 1997 Umbria-Marche seismic sequence, *J. Seismol.,* **4,** 479–499.

Salvioni, G., 1951. Manuale di Livellazione. Collezione dei Testi Tecnici dell'Istituto Geografico Militare, Firenze. .

Salvioni, G., 1953. Primo contributo sulla comparazione dei risultati fra la nuova rete altimetrica fondamentale e la vecchia livellazione di precisione. Boll. Geod. Sci. Affini XII (I), 87–97.

Salvioni, G., 1957. I movimenti del suolo nell'Italia centrosettentrionale, dati preliminari dedotti dalla comparazione di livellazioni. Boll. Geod. Sci. Affini XVI (3), 325–366.

Scandone, P., et al., 1992. Struttura geologica, evoluzione cinematica e schema sismotettonico della penisola italiana. CNR-GNDT 1990 Congress, Vol. I, pp. 119-135.

SCEC/CME Collaboration, Maechling, P., et al., 2006. Using the *SCEC* computational platforms for seismic hazard analysis research, Scientific Investigations Report, Report: SIR 2006-5201, pp.10.

Scholz, C.H., 1990. The mechanics of earthquakes and faulting, Cambridge Univ. Press, Cambridge, United Kingdom, pp. 439

Schwartz, D, and K. Coppersmith, 1984. Fault behavior and characteristic earthquakes: examples from the Wasatch and the San Andreas fault zones, Journal of Geophysical Research, 89, B7, 5681-5698.

Selvaggi, G. & Amato, A., 1992. Subcrustal earthquakes in the Northern Apennines (Italy): evidence for a still active subduction?, *Geophys. Res. Lett.*, **19**(21), 114–127.

Selvaggi, G., B. Castello, R. Azzara, 1997. Spatial distribution of scalar seismic moment release in Italy (1983-1996): seismotectonics implications for the Apennines, Annali di Geofisica, vol. 40, 1565-1578.

Selvaggi, G., Chiarabba, C., 1995. Seismicity and P-wave velocity image of the Southern Tyrrhenian subduction zone. Geophysical Journal International 121, 818–826.

Serpelloni, E., Anzidei, M., Baldi, P., Casula, G., Galvani, A., 2005. Crustal velocity and strain-rate fields in Italy and surrounding regions: new results from the analysis of permanent and non-permanent GPS networks. Geophys. J. Int. 161, 861–880. doi:10.1111/j.1365-246X.2005.02618.x.

Shimazaki, K., and T. Nakata, 1980. Time-predictable recurrence model for large earthquakes, Geophys. Res. Lett., 7, 279–282

Siame et al., 2004. Local erosion rates versus active tectonics; cosmic ray exposure modelling in Provence (south-east France), Earth and Planetary Science Letters, vol.220, no.3-4, pp.345-364

Stein, R.S., 1981. Discrimination of tectonic displacement from slopedependent errors in geodetic leveling from southern California, 1953–1979, in *Earthquake Prediction: an International Review,* Vol. 4, pp. 441–456, eds Simpson, D.W. & Richards, P.G., Maurice Ewing Ser. American Geophysical Union.

Stein, R.S., 1999. The role of stress transfer in earthquake occurrence, Nature, vol.402, no.6762, pp.605-609.

Stramondo, S. *et al.,* 1999. The September 26, 1997 Colfiorito, Italy, earthquakes: modeled surface coseismic displacement from SAR interferometry and GPS, *Geophys. Res. Lett.,* XXVI, **7,** 883–886.

Stuart, W.D., 1974. Diffusionless dilantancy model for earthquake precursors, Geophys. Res. Lett., 1261-1264.

Stuart, W.D., 1979. Aging and strain softening model for episodic faulting, Tectonophysics, 52, 613-626.

Stuiver, M., and P. J. Reimer, 1993: Extended 14C database and revised CALIB radiocarbon calibration program (version 3.0.3A), *Radiocarbon, 35*, pp. 215-230.

Stuiver, M., P. J. Reimer, and T. F. Braziunas (1998b). High-precision radiocarbon age calibration for terrestrial and marine samples, *Radiocarbon* **40,** 1127–1151.

Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, G. S. Burr, K. A. Hughen, B. Kromer, F. G. McCormac, J. van der Plicht, and M. Spurk (1998a). INTCAL98 Radiocarbon age calibration 24,000–0 cal BP, *Radiocarbon* **40,** 1041–1083.

Sykes, L.R., B.E. Shaw and C.H. Scholz 1999. Re-thinking earthquake prediction, Pure Appl. Geophys., 155, 207-232.

Valensise, G. & Pantosti, D., (eds), 2001a. Database of potential sources for earthquakes larger than M 5.5 in Italy, *Ann. Geofis.,* **44**(4), Suppl., 183 pp. plus database on CD-ROM.

Valensise, G. & Pantosti, D., 1992. A 125 kyr-long geological record of seismic source repeatability: the Messina Straits (southern Italy) and the 1908 earthquake (*Ms* 7 1/2), *Terra Nova*, **4,** 472–483.

Valensise, G.& Pantosti, D., 2001b. The investigation of potential earthquake sources in peninsular Italy: a review, *J. Seismol.,* **5,** 287–306.

Valensise, G., D. Pantosti and R. Basili, 2004. Seismology and Tectonic Setting of the 2002 Molise, Italy, Earthquake, Earthquake Spectra, 20, S1, 23-37.

Vanicek P., Castle R.O., Balazs E.I. 1980. Geodetic leveling and its application, Rew. of Geoph. and Space Phys., vol. 18, n.2, p. 505-524.

Vanneste, K., M. Meghraoui, and T. Camelbeeck (1999). Late Quaternary earthquake-related soft-sediment deformation along the Belgian portion of the Feldbiss fault, lower Rhine graben system, *Tectonophysics* **309,** 57–79.

Vannoli, P., Basili, R., Valensise, G., 2004. New geomorphic evidence for anticlinal growth driven by blind-thrust faulting along the northern Marche coastal belt (central Italy). Journal of Seismology 8 (3), 297–312.

Vergne J., Cattin R., and Avouac J.P. 2001. On the use of dislocations to model interseismic strain and stress build-up at intracontinental thrust faults, Geophys. J. Int., 147, p. 155-162.

Vignal, J., 1936. Evaluation de la precision d'une methode de nivellement. Bull. Geod. 49, 1–159.

Vignal, J., 1950. Comptes rendus des séances de travail de la Secion II. Nivellments, de l'Assocation Internationale de Géodésie à l'Assemblée Générale d'Oslo (Aout 1948). Bull. Géod. 18, 401–565.

Vittori, E., et al.; 2000. Ground effects and surface faulting in the September-October 1997 Umbria-Marche (Central Italy) seismic sequence, *J. of Geodynamics*, 29, pp. 535-564.

Wallace, R. E., 1986. Active tectonics, Studies in geophysics, Natl. Acad. Press, Washington, D.C., United States (USA), pp 266.

Wallace, R. E., 1987. Grouping and migration of surface faulting and variation in slip rates on faults in the Great Basin province, Bull. Seismol. Soc. Am., 77, 868– 877.

Ward, S.N. & Valensise, G., 1989. Fault parameters and slip distribution of the 1915, Avezzano, Italy earthquake derived from geodetic observations, *Bull. seism. Soc. Am.,* **79,** 690–710.

Wells, D. L., and K. J. Coppersmith (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seism. Soc. Am.* **84,** 974–1002.

Westaway, R., 1993. Quaternary uplift of Southern Italy. Journal of Geophysical Research 97, 15437–15464.

Westaway, R., R. Gawthorpe and Tozzi M., 1989. Seismological and field observations of the 1984 Lazio-Abruzzo earthquakes: implications for the active tectonics of Italy. Geophysical Journal, 98, 489-514

Williams C.A., and McCaffrey R. 2001. Stress rates in the central Cascadia subduction zone inferred from an elastic plate model, Geophys. Res. Lett., 28, n.10, p. 2125-2128.

Yeats, R. S.; Sieh, K.; Allen, C. R, 1997. The geology of earthquakes, Oxford University Press, New York, NY, United States (USA), pp. 568.

Zattin M., Landuzzi A., Picotti V., and Zuffa G.G., 2000. Discriminating between tectonic and sedimentary burial foredeep succession, Northern Apennines J. Geol. Soc., London, 157, p. 629-633.