In search of evidence of deep fluid discharges and pore pressure evolution in the crust to explain the seismicity style of the Umbria-Marche 1997-1998 seismic sequence (Central Italy)

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Abstract
Starting soon after the first main-shocks of the long seismic sequence which has occurred along the Umbria-Marche boundary since September 1997, fluid geochemistry surveying was accomplished (around 200 samples) over the epicentre area as a whole, collecting information on hydrological variations too. The collected experimental data allowed to discuss the spatial and temporal evolution of the circulating fluids, either in the chemistry or in the dynamic paths, during the different stages of the seismic sequence. All the geo-structural, seismological and fluid geochemistry information gathered in this sector of the Central Apennines are discussed together in an attempt to speculate about the possible role and evolution of pore-pressure at depth up to surface within the seismogenic process recalling the «Fault Valve Activity Model», the «Coseismic Strain Model», the «frictional heating-frictional stress coupling model» and the «Dilatancy Model». This overview may also explain the geochemical and hydrological experimentally observed anomalies, in occurrence of the seismic sequence. The seismic style of the long sequence is revised in terms of pore-pressure regime down to seismogenic depth (2-10 km), within the poly-phase Evaporite Triassic Basement (ETB) and the Paleozoic Crystalline Basement (PCB), corresponding to the horizons of transient dehydration reactions: process triggered and enhanced during the seismogenic process, involving further fluid overpressure, and consequently further seismicity (chain effect). All the recalled processes and models may explain fluid remobilization and over-pressuring in the upper crust starting soon after the main-shocks, along relict low angle planes (close Apennine and anti-Apennine fault segments), rendering the Umbria-Marche boundary a «transiently weakened frictional instability zone», for a period spanning more than one year.

Key words *fluid geochemistry/seismicity – pore-pressure field – Umbria-Marche 1997-1998 – seismic sequence*

1. Introduction

The nature of the world-wide observed relations between earthquakes, faults and terrestrial fluids on a geological scale (Irwin and Barnes, 1980; Gold and Soter, 1985; Sibson, 1998) remains poorly defined to date. Direct observational data which are required to specify the chemical composition and the physical and thermodynamic status of fluids within the current stress field are lacking.

The geochemical monitoring carried out since 1990 by the Istituto Nazionale di Geofisica (ING) over different Italian seismic regions (Dall'Aglio *et al.*, 1995; Quattrocchi and Calcara, 1998) has the main purpose to add knowledge on the relations between fluid geochemistry and seismicity (*i.e.*, King, 1986; Thomas, 1988; Tsunogai and Wakita, 1995; Igarashi and Wakita, 1995; Igarashi *et al.*, 1995; Nishizawa *et al.*,

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1998; Toutain and Baubron, 1999), as an indirect method to understand the pore-pressure field during the earthquake cycles, thus trying to overcome the lack of the above-mentioned observational data. The main concept that justifies such studies was also outlined recently (Toutain and Baubron, 1999), exploiting the observational methods either in soil-gases or in groundwater. To date, groundwater dissolved gases monitoring has proved a more powerful tool with respect to soil gases monitoring when the study is addressed to the knowledge of the relations between fluids and seismicity as well as earthquake precursors, despite the huge evidence of preferential soil degassing throughout active faults.

Starting soon after the September 26, 1997 main-shocks, which occurred over the Umbria-Marche boundary (Colfiorito area), fluid geochemistry surveying and hydrogeological information collection was accomplished both in the frame of the «Geochemical Seismic Zonation» EC funded program (Lombardi *et al.*, 1999) and in the frame of an ING multidisciplinary task force (Boschi and Cocco, 1997). Areal groundwater sampling was performed (around 200 samples, throughout a NW-SE belt, comprising Gualdo Tadino - Norcia - Foligno - Assisi polygon) and at the same time discrete temporal monitoring was accomplished in a few strategic groundwater sites (Bagni di Triponzo, Rasiglia and S. Vittore springs).

The multidisciplinary study revealed this seismic sequence as the most energetic and destructive to have occurred in Italy since the 1980 Irpinia earthquake ($M_w = 6.9$). Starting with an $M_l = 4.7$ fore-shock on September 3, 1997 it lasted more than one year, with around twenty shocks with $M_w > 4.0$, among which five with $M_w > 5.5$, and with up to 9000 triggered events.

Both seismological and ground deformation-geological data collected soon after the strongest shocks have not definitely established where and whether the main-shocks ruptured the surface. In this critical situation ($M < 6.0$), the engaged fluids geochemistry methods have had the specific aim to help in revealing the seismogenic structure, considering the «activated» fault zone as a possible seat of the maximum distribution belt of geochemical and hydrological anomalies at surface (*i.e.*, drop in water level, gushing of CO_2 and H_2S flame smoothing from ground, explosive sounds, brontides, sulphureous smell, vigorous bubbling from wells, see also Gold and Soter, 1985; Muir-Wood and King, 1993; Roberts *et al.*, 1996).

Post seismic fluid discharge in the vicinity of the rupture segment is an expected consequence either of the «Fault Valve Activity» behaviour (Sibson *et al.*, 1975; Sibson, 1981, 1990, 1998) or of crustal fluids redistribution foreseen by the «Coseismic Strain Model» (Muir-Wood and King, 1993; Nur, 1995). These phenomena may be observed at the surface and can give indirect evidence of the style and origin of the seismogenic process, *i.e.* as a consequence of the deep pore-pressure field.

A great deal of evidence has recently emerged pointing out the importance of the pore pressure field in fault zones (Byerlee, 1990; Blanpied *et al.*, 1991, 1992; Fournier *et al.*, 1991; Nur and Walder, 1992a,b; Axen, 1992; Chester *et al.*, 1993; Miller *et al.*, 1996; Scholz, 1998); perhaps, one of the most important current questions regarding the mechanics of active faults and earthquake triggering is the role of pore pressure, *i.e.* groundwater dynamics and chemistry evolution during faulting episodes. Especially important is the possibility that enhanced pore pressure may be responsible for the low shear stress for fault slip, aftershocks occurrence (Nur and Booker, 1972; Linde *et al.*, 1994), and multiple main-shocks over an «activated» area (Sibson, 1996), as verified during the discussed long seismic sequence.

A few selected crustal processes possibly involved within the seismogenic layer, made up of the Evaporitic Triassic Basement (ETB) and of the Paleozoic Crystalline Basement (PCB), have been revised and discussed in an attempt to explain the geochemical and hydrogeological observed anomalies and the seismicity style of the sequence.

2. Seismo-tectonics and pore-pressure field of the Umbria-Marche boundary seat of the 1997-1998 seismic sequence

2.1. *Geo-structural data settings*

The Umbria-Marche boundary belt from Gualdo Tadino to Norcia towns is comprised inside the Central Apennines Fault System

(CAFS), that is defined as a band of deformation (Cello *et al.*, 1997) overprinting ancient structures of the folded and thrusted Apennine Belt (Calamita *et al.*, 1994; Lavecchia *et al.*, 1994). Surface features of the belt consist in thrust-related roughly asymmetric folds, NW-SE to N-S trending. The cover has been detached from the underlying basement, however involved in the deformation. In the hypothesis of Cello *et al.* (1997), the shallow fault zone fragmentation infers the existence of a deep N-S left-lateral strike-slip motion shear zone along the CAFS, despite the rare seismological and neotectonic evidence. The folds are often bordered westward by high vertical displacement faults, that cut the back-limb of regional thrust-related anticlines, interpreted as «gravity faults» and not as «tectonic faults». As regards the candidate seismogenic faults, the authors have generally agree in hypothesizing low angle faults, that are superimposed on pre-existing compressive structures (Gregori, 1990; Brozzetti and Lavecchia, 1994; Cello *et al.*, 1997).

2.2 *Seismological data settings*

The CAFS is characterized by diffuse seismicity distributed along a NNW-SSE trend, inferring a NW-SE compression and a NE-SW extension (*T*-axis): the seismogenic structures have been inferred to be mainly trans-tensional to the normal fault, NW-SE oriented and secondly left lateral to strike-slip, N-S trending fault segments (Deschamps *et al.*, 1984; Haessler *et al.*, 1988; CNR, 1980; Cello *et al.*, 1998).

To date, the Seismic Hazard Assessment (SHA) hypotheses (Console *et al.*, 1986; Haessler *et al.*, 1988; Menichetti and Minelli, 1991; Lavecchia *et al.*, 1994; Di Giovambattista and Tyupkin, 1999) have been established on instrumental seismicity, historical earthquakes as well as on evidence of recent faulting activity along the CAFS, testified by faulted Pliocene-Holocene continental deposits.

It must be noted that the 1997-1998 seismic sequence is located along a «seismic gap» belt in the frame of the CAFS, inferred reworking either historical or instrumental seismicity (Di Giovanbattista and Tyupkin, 1999; Boschi and Cocco, 1997 and references herein).

The strongest historical earthquakes in the studied area (Boschi *et al.*, 1997) were related to the 1703 destructive seismic sequence (Cello *et al.*, 1998), with a maximum felt MCS intensity of X and multiple main-shocks (more segments activated). In the same area the 1730 earthquake occurred (12/5, IX MCS). Other devastating earthquakes occurred in 1328 around Preci and Norcia (X MCS) and in 1279 near Serravalle di Chienti - Nocera Umbra (X MCS). The 1751 earthquake (27/7, X MCS) took place along a NW-SE belt, east of Gubbio town.

The strongest seismic sequence recorded instrumentally, before the 1997-1998 one, was the September 19, 1979 Norcia earthquake (CNR, 1980; Deschamps *et al.*, 1984; Brozzetti and Lavecchia, 1994), with $M_s = 5.9$ and maximum MCS intensity of IX degree, destroying a small area south of Norcia. It revealed a NNW-SSE trending *P*-axis of the focal mechanism (oblique-slip rather than pure extensive faulting) of the 10 km-wide seismogenic structure.

Noteworthy information on the seismogenic behaviour along the CAFS came from the 1997-1998 seismic sequence which started in September 1997.

On September 26, 1997, at 00:33 UTC (02:33 local time) the Colfiorito area was struck by a strong earthquake ($M_w = 5.7$, about 8 km deep), soon followed by a second stronger main-shock at 09:40 UTC (11:40 local time), with $M_w = 6.0$ (Ekström *et al.*, 1998; Amato *et al.*, 1998). These earthquakes caused noteworthy damage, loss of human lives and very wide macroseismic effects throughout Central Italy (Boschi and Cocco, 1997 and references herein).

A long sequence of earthquakes, seven of which with magnitude between 5 and 6, followed these two main-shocks, with the focal mechanisms revealing normal faulting with NE-SW *T*-axis, consistently with the neotectonic evidence throughout this sector of the CAFS. Normal faults with low angle ($\sim 40^{\circ}$), dipping southwestward and confined in the upper 10 km of the crust, have been inferred from seismological data as seismogenic structures. These «detachment extension planes» (see also in Reynolds and Lister, 1987; Axen, 1992), suggested they might have reactivated Pliocenic thrust planes (see also in Cello *et al.*, 1997). The seismogenic belt consists of a 40 km wide NW-SE elongated fault zone, in which different fault segments have been activated during the sequence. These appeared to be laterally offset (Amato *et al.*, 1998; Stramondo *et al.*, 1999; Salvi *et al.*, 1999): the Sellano segment (14/10/1997, 15:23 UTS, $M_w = 5.6$) exhibited a quite different location and strike, 15 km southeast of the former seismogenic structures, with a strong directivity toward southeast of the aftershocks. Recent results (Chiaraluce *et al.*, 1999) highlighted different T-axes for the area of Sellano (14/10/1997 event), trending in an Apenninic direction (N10°W), but further work is needed to confirm these hypotheses.

The seismological evidence inferred a still present gap of strong seismicity ($M > 5.5$ events) throughout the Rasiglia-Verchiano area, located between the two main still activated fault zones: Colfiorito-Gualdo Tadino and Sellano-Norcia, respectively. The Rasiglia-Verchiano area deserves special interest also as regards the neotectonics (Cencetti, 1993), as a consequence of to the presence of a transverse anti-Apenninic structure, likely acting as a barrier for propagating the rupture.

As a consequence of the complexity of the described seismic sequence, it is not yet clear if the seismogenic structures have been able to produce properly tectonic ground deformation at surface (Galli *et al.*, 1997; Vittori *et al.*, 1998; Cinti *et al.*, 1999; Stramondo *et al.*, 1999; Salvi *et al.*, 1999). In this region, the two main neotectonic NW-SE normal faults have been recognized just inside the Colfiorito Basin and at a few kilometers southwest of it (Cello *et al.*, 1997). A possible correlation between the inferred CMT plane solutions (Ekström *et al.*, 1998) and the ground-deformation data analysis have been recognized.

On the other hand, the ground surface deformation, the reconstruction of the possible projection at surface of the seismogenic structure (by aftershocks distribution, moment tensor calculation, dip propagation choice, etc.), and the SAR Interferometry coupled with GPS data (Stramondo *et al.*, 1999; Salvi *et al.*, 1999) inferred that the rupture-faults stopped before reaching the surface, although probably very close to it.

2.3. *Hydrogeological data settings*

From the hydrogeological point of view, the CAFS and in particular the Gualdo Radino - Norcia - Spoleto - Assisi polygon, may be divided in three litho-hydrogeological typologies (Giaquinto *et al.*, 1991):

i) The recharge areas, outcropping throughout the limestone massifs of the Umbro-Marchigiana Nappe; the underlying ETB involves a groundwater evolution towards a $CaSO_4$-NaCl chemistry. These hydrogeological formations, with pervious and karstic behaviour, prevail along the Umbria-Marche boundary as a whole and in some internal anticlines (*i.e.*, Subasio, Gubbio).

In the above-mentioned area two main hydrogeological structures (fig. 1) can be distinguished (Boni *et al.*, 1986; Giaquinto *et al.*, 1991), corresponding to distinct «recharge areas»: the Valnerina System to the east and the North-Eastern Umbria System (NEUS, in the following text and figures), as a carbonate belt, which spans over 700 km^2, delimited by the Valnerina Line southeastward, while eastward it is limited by the regional boundaries; westward the structure is bounded by a clear NW-SE extensive line between Spoleto and Foligno, that became a simple stratigraphic limit northward.

Moreover from the hydrogeological point of view it is possible to distinguish:

ii) The semi-impervious areas, where the Cenozoic sedimentary cover prevails, made up of the marly-arenaceous rocks (Marnoso Arenacea formation), overlying the Mesozoic carbonate rocks; this formation is almost impermeable and give rise to artesian aquifers at depth.

iii) The Tiberina Valley continental basin: it was seat of a wide lake during the Pleistocene age, before the refilling of clayey and silty deposits; this sector of the studied area exibits very heterogeneous hydrogeological properties, often with the role of impervious cover.

The epicentral area falls almost entirely inside the NEUS hydrogeological structure (fig. 1). The NEUS massif is completely filled by groundwater up to a high topographic elevation, with draining network lines oriented both eastward and westward (the main springs are *i.e.*, Argentina - 1000-1500 l/s; ENEL - near Sellano; Fonti del Clitunno - 1200-1700 l/s -

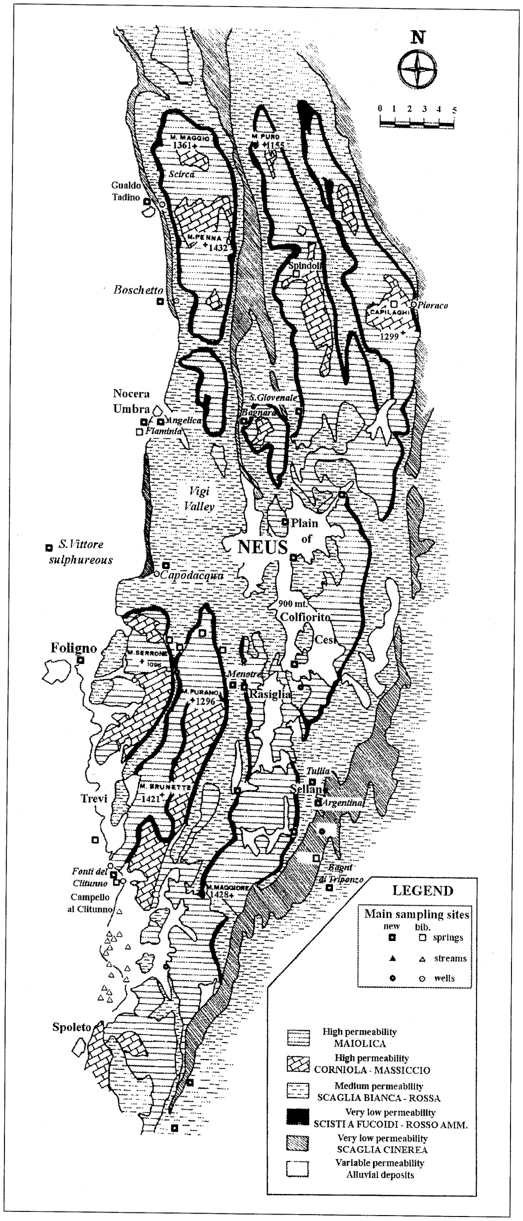

Fig. 1. Hydrogeological map of the area affected by the Umbria-Marche boundary 1997-1998 seismic sequence. NEUS = North Eastern Umbria System, that is the shallow main aquifer affected by the fault-segments activated during the sequence; the main sampled springs location is reported (modified after Giaquinto *et al.*, 1991).

with a slight SO_4 anomaly; Rasiglia-Menotre - around 700 l/s plus the river-bed flow 900 l/s; Capodacqua, San Giovenale and Boschetto - 150, 300, 300 l/s respectively).

The Colfiorito Basin – inside which the main surface rupture hints have been suspected – represents a draining endoreic closed basin (Gregori, 1990), whose high topographic boundaries are good recharge areas.

Apart from the Bagni di Triponzo thermal-sulphureous spring, located around 10 km southeast of Sellano, there are no hydrogeological hints of deeper geothermal reservoirs, within the NEUS area.

2.4. *Hydrogeochemical data settings*

Throughout the Central Apennines as a whole the hydrogeological, geochemical and isotopic data obtained to date (*i.e.*, Chiodini *et al.*, 1982; Governa *et al.*, 1989; Quattrocchi *et al.*, 1997) distinguish two different circuits: one which is epidermic and with fast circulation through the Mesozoic carbonate massifs, possibly fractured and karstic, and another which is progressively deeper (or mixed with different proportions) within ETB or below. The latest is characterized by thermally and chemically anomalous groundwater. The $\delta^{34}S$ and $\delta^{13}C$ values in the dissolved species reflect the complexity of the redox reactions and the CO_2 enrichment within ETB thermal reservoirs, by reaction such as

$$SO_4^{=} + CH_3COO^{-} = 2\ HCO_3^{-} + HS^{-}.$$

Studies on the de-carbonation of siliceous dolomites inferred that part of the CO_2 is produced by the reaction

$$5\ \text{Dol.} + 8\ \text{Qtz} + H_2O = 1\ \text{trem} + 3\ \text{calc} + 7\ CO_2$$

multiple sources may be due to CO_2 produced by oxidation of organic matter in the rock during metamorphism, with a very clear $\delta^{13}C$ signature (Kreulen, 1980).

In general the deep CO_2 may be enriched in ^{13}C for the high temperature isotope exchange within the basement, but to date, no signature of this enrichment has been found in the studied area ($\delta^{13}C$ data provided by the GSZ EC program, G.M. Zuppi, personal communication, see also in Quattrocchi *et al.*, 1999). A deep isotopically and chemically uniform flow was recognized, corresponding to the «base» groundwater (with more far recharge area), usually over-saturated in calcite, while the shallower flow may be seasonally variable in the stable isotopic composition and under-saturated in Calcite.

The groundwater chemistry of the Umbria region aquifers is characterized mainly (95%) by earth-alkaline bicarbonate waters (Chiodini *et al.*, 1982; Quattrocchi *et al.*, 1997), with few exceptions of alkaline-chlorine and calcium sulfate waters. The Marche region is affected by more apparent Na-Cl circuits, connected to the Adriatic domain compressive front belt, with «lifting and squeezing» of relatively deep salt waters and brines (Nanni and Zuppi, 1986), related to tectonic thrust lines, as well as with $CaSO_4$ chemistry throughout the Messinian shallow deposits. At the Umbria-Marche border two main groups of shallow groundwater can be distinguished (Giaquinto *et al.*, 1991; Quattrocchi *et al.*, 1997): the first, with salinity less than 10 meq/L, that circulate mainly within the Umbro-Marchigiana Nappe formations (*i.e.*, Angelica and Flaminia springs in Nocera Umbra, Boschetto, Giovenale, Acqua Tullia, Scirca) and the second, with salinity spanning from 10 and 25 meq/L, that circulate within the marly-sandstone rocks (Miocene to Pleistocene deposits).

Sodium-bicarbonate groundwater may be found in peculiar conditions, as observed at the newly gushed S.Vittore sulphurous spring (see below).

Mixing solutions between Ca-bicarbonate and Ca-sulfate waters developed where leaching of the ETB is appreciable (*i.e.*, Rasiglia, Fonti del Clitunno springs). The isolated Ca-SO_4 Bagni di Triponzo thermal spring deserves special attention (see also in Quattrocchi *et al.*, 1999), because of water-rock interaction within ETB is more pronounced.

3. Experimental data: fluid geochemistry evolution during the seismic sequence

3.1. *Areal surveying*

The experimental data have been entirely collected by both the ING fluid geochemistry surveys and hydrogeological effects information collection, spanning from September 1997 to December 1998, during the seismic sequence period as a whole (first data partially discussed in Quattrocchi *et al.*, 1997 and EC program GSZ deliverables).

The area taken into consideration (around 200 samples) spanned in a NW-SE direction from Gualdo Tadino to Norcia-Preci, analysing physico-chemical parameters, dissolved gases in groundwater (^{222}Rn, CO_2, H_2S, NH_3 Ar, N_2, O_2, CH_4, CO_2), major elements, few selected minor and trace elements (Fe, Li, B, As, Sr, SiO_2), as well as isotopic ratios ($^3He/^4He$, $^{87}Sr/^{86}Sr$, $\delta^{13}C$, δD, $\delta^{18}O$, $\delta^{37}Cl$), significant from the seismotectonic point of view. The most apparent hydrogeological anomalies, which occurred at the main springs, have been partially reported (Quattrocchi *et al.*, 1997, 1999).

Three significant springs (Bagni di Triponzo, Rasiglia and S.Vittore) were selected to accomplish a discrete geochemical monitoring on weekly basis before and on a monthly basis afterwards, as regards all the above-mentioned parameters. Field and laboratory analytical methods are described in Quattrocchi *et al.* (1999).

In an attempt to summarise the most important results useful for the subsequent discussion, we can point out a few out-comings. Starting soon after the first main shock of 26/09/97, throughout the epicentral area we generally found groundwater that may be divided into two families:

i) Shallow circulation - cold groundwater, with bicarbonate chemistry and electrical conductivity from 200 to 700 μS/cm.

ii) Mineralised groundwater, often sulphurous, either cold (Scanzano di Foligno - Pontecentesimo - S. Vittore area) or warm, with Ca-SO_4 chemistry (*i.e.* Bagni di Triponzo spring, 30°C). The chloride groundwater is absent throughout the epicentral area, testifying the shallow circulation as a whole, and the almost total lack of leaching of terrigenous-clayey formations within the area.

Very low dissolved gases content (with composition near to the equilibrium with atmosphere) as well as a low radon content was found (fig. 2), although the few discovered exceptions may gain a noteworthy tectonic significance: the Rasiglia, S.Vittore and Bagni di Triponzo springs, that were therefore selected for a discrete temporal monitoring, on a weekly basis before and on a monthly basis afterwards.

In particular, the map of radon concentration in groundwater (fig. 2) and a few available data on radon in soil gases (unpublished data within the GSZ EC program deliverables, Lombardi *et al.*, 1999) give an evaluation of both the possible escape pathways for endogenous gases, in occurrence of the seismic sequence and the most probable new enhanced fracturing and permeability patterns generated during the ongoing seismic activity. In this map the most apparent gas gushing episodes have been reported too, all verified in occurrence of the 26/07/97 and 14/10/97 main shocks; among these, the most important was that reported in the Rasiglia - Verchiano - Costa area, mainly in the S. Martino - Col Pasquale sector, where soils gas radon values are maximum (up to 190 Bq/L).

This main radon anomaly is located along a NE-SW direction (anti-Apenninic), just following a geomorphological and hydrogeological boundary between the northern sector (Colfiorito-Nocera Umbra) and the southern sector of the seismic sequence (Sellano-Val Nerina).

This main radon anomaly may be explained by two hypotheses:

– A structural model (Acocella *et al.*, 1997) that assumes the existence of two seismogenic belts, as Apenninic fault segments along the two above-mentioned sectors, separated by an offset area. It was recognised to be very important from the neotectonic point of view (Cencetti, 1993), acting as tectonic barrier between the two main segments. This «tectonic decoupling», therefore, is characterised by higher secondary permeability, due to an enhanced fracturing field up to the surface. The crossing point of faults with different orientation may generate slight convective circulation of fluids, further enhanced by the seismic sequence, as testified by the highest radon and temperature values just after the first main-shocks, at the Rasiglia spring (figs. 2, 3 and 4). Radon and temperature have long been considered a pathfinder (*i.e.* Rn used as «flow meter» or «velocity meter» of a hydrothermal cell) of this kind of processes (King, 1986, Thomas, 1988; Toutain and Baubron, 1999 and references herein).

– An hydrogeological-structural model, supported by experimental data (Giaquinto *et al.*, 1991) that assumes the existence of the confluence of a huge mass of groundwater, pertaining to the NEUS hydrogeological body, just at the Rasiglia-Menotre springs (highest radon values): the NEUS sector of the Colfiorito Basin has been discriminated as the primary seat of the geological effects at surface of the coseismic faulting-slip at depth (Cinti *et al.*, 1999). Therefore in this recharge area the enhanced permeability and fracturing field affected the final radon content at the spring, because of the upraised radon release from the rock matrix, also from shallow crustal strata. This hydrogeological explanation may sustain the hydrogeological scheme of this sector of Central Italy as supposed by previous authors (Giaquinto *et al.*, 1991 and references herein).

Alternatively both the hypotheses together (structural and hydrogeological) may explain the observed anomalies within the Rasiglia-Verchiano area (mainly radon, but also: dissolved gases, salinity, thermal effects, geothermal tracers), with respect to the geochemical background of the studied area, mostly during the coseismic phase of the most energetic shocks of the sequence.

The redox potential values distribution (fig. 3) is very powerful to testify that the groundwater was affected on a regional scale by slightly deeper input in occurrence of the main-shocks, inferred by the lowest redox values recorded soon after the first main-shocks for the sampled sites as a whole. Moreover the map exhibits a NW-SE anomalous Eh belt, corresponding to the projection at the surface of the activated faulted segments (Cinti *et al.*, 1999). The redox potential anomalies have been found well correlated with the hydrological and turbidity variations observed during the sequence.

3.2. *Temporal monitoring during the seismic sequence*

S. Vittore spring – The S. Vittore sulphurous spring (figs. 1, 2, 3 and 4) appeared gushing out on 26/09/1997 at 08:00 local time, just after the first main-shock (00:33 GMT) and before the

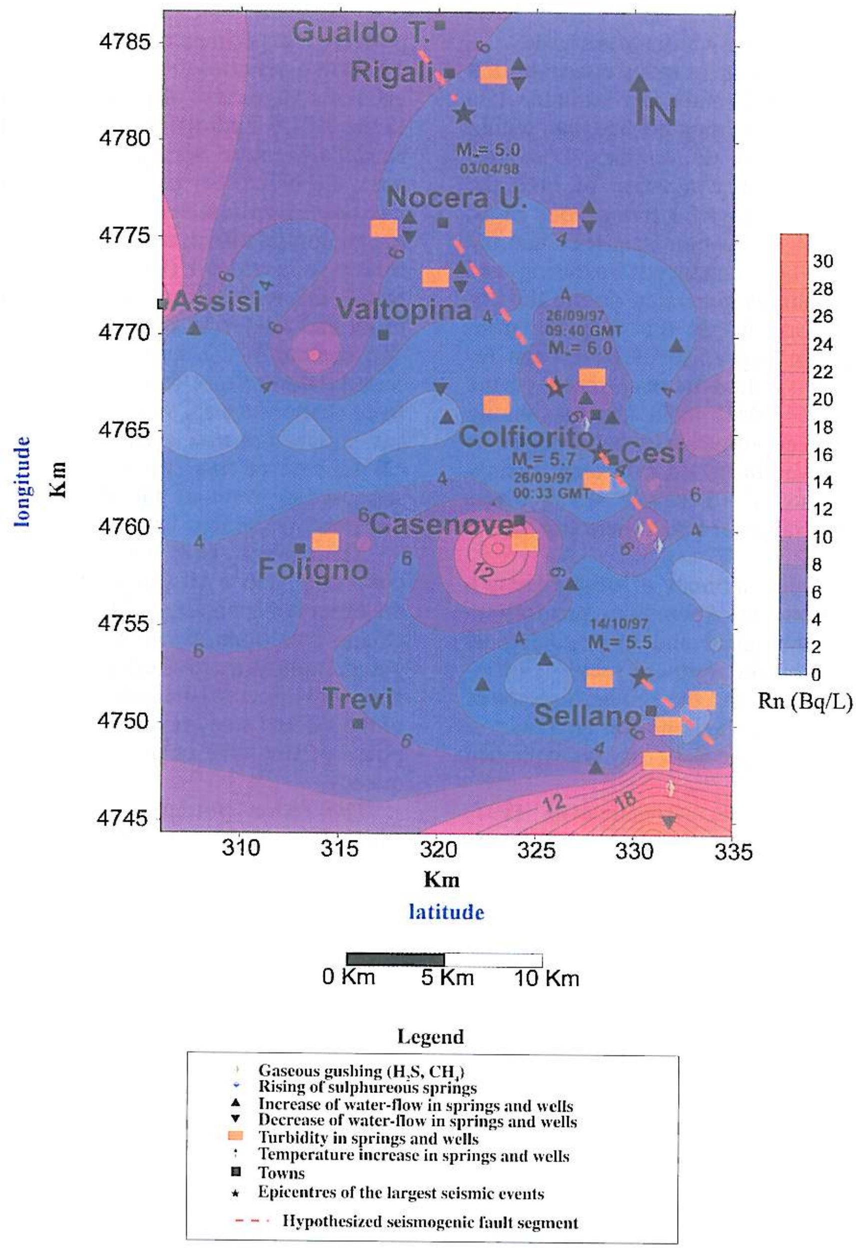

Fig. 2. Map of the hydrogeochemical and hydrological anomalies and groundwater ^{222}Rn content, verified soon after the first main-shocks on 26/09/1997, soon after the 14/10/1997 Sellano earthquake and soon after the Gualdo Tadino-Nocera Umbria seismic reactivation (April-June 1998). The hypothesized seismogenic fault segments traces come from seismological and ground deformation studies (Amato *et al.*, 1998; Cinti *et al.*, 1999; Stramondo *et al.*, 1999; Salvi *et al.*, 1999).

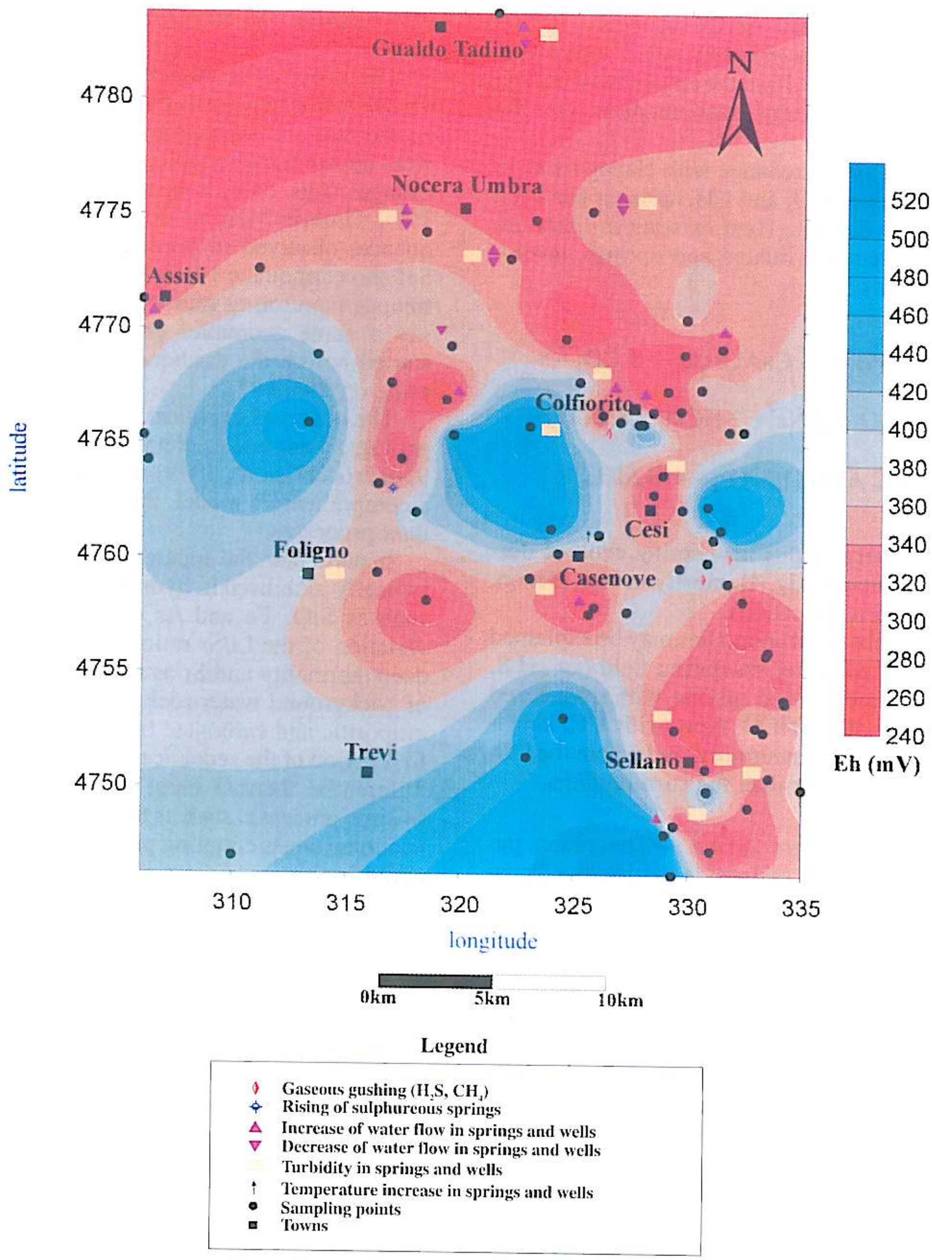

Fig. 3. Map of the hydrogeochemical and hydrological anomalies and the groundwater redox potential values, verified soon after the first main-shocks on 26/09/1997, soon after the 14/10/1997 Sellano earthquake and soon after the Gualdo Tadino-Nocera Umbria seismic reactivation (April-June1998): two positive peaks are relative to the Bagni di Triponzo and S. Vittore springs (the latter gushed out 3 h before the 26/09/97, 9:40 GMT event), exhibiting apparent anomalies associated with the earthquakes (fig. 4). A NW-SE Eh anomalous belt is evident from Sellano to Nocera Umbra, following the activated fault segments direction.

strongest earthquake of the sequence (09:40 GMT), testifying noteworthy stress-strain variations on aquifers within the epicentral area (see the explanation of this phenomena in the discussion).

Here cationic exchange with clayey rocks in the presence of CO_2 and CH_4 uprising has been inferred by our data (first existing in literature about this tectonic related new spring), involving reactions like

$$2\ NaAlSi_3O_8 + CaAl_2Si_2O_8 + 3\ CO_2\uparrow +$$

$$+ 13\ H_2O = 2\ Na^+ + 2\ HCO_3^- + CaCO_3 +$$

$$+ 2\ Al_2Si_2O_5(OH)_4 + 4\ H_4SiO_4.$$

The chemistry of this new spring evolved during the sequence (fig. 4), mostly in H_2S, Radon, Eh, Cl, and main cations.

All the observed anomalies may be explained in terms of enhanced fracturing field (*i.e.*, H_2S, Rn, Eh) and enhanced mixing with a squeezed out aquifer of Ca-HCO_3 type, with a Cl signature, a pH close to neutrality, and where the CO_2 is relatively higher than the surroundings.

Rasiglia-Menotre spring – The radon parameter temporal trend inside the discussed positive areal anomaly of Rasiglia follows apparently the seismic sequence as a whole, with positive peaks corresponding to the 26/09/97 shocks and of the paroxysmal seismicity re-activation at the end of March 1998 (Gualdo Tadino area, including a 50 km deep moderately strong earthquake). The electrical conductivity exhibits an increasing trend (from 350 to 700 μS/cm) at the end of 3 months from the onset of the sequence, and in occurrence of the end of March 1998 seismicity re-activation, whereas geochemical anomalies are less apparent during the Sellano earthquake period. Probably these radon observed anomalies are to be related to episodes of enhanced convection, the radon being a stress intensity factor for the local crack system at the intersection of different direction lineaments (see also the review of Toutain and Baubron, 1999) as explained above.

3.3. *Bagni di Triponzo spring*

The deepest circulation aquifer throughout the epicentral area is rising at the Bagni di Triponzo thermal and sulphurous spring, that underwent apparent hydrogeologial and geochemical changes (figs. 5a,b) in occurrence of the 1997-1998 Umbria-Marche boundary seismic sequence, observed in particular soon after the Sellano earthquake 14/10/1997. Lacking a continuous monitoring station, it is not possible to say if some anomalies observed on 15/10/97 started before the earthquake (preceding sampling on 29/09/97).

The observed chemical, isotopic and hydrogeological anomalies, detailed in another paper (Quattrocchi *et al.*, 1999) may be explained by a comprehensive model, that foresees concomitant processes.

In particular, the apparent spikes of elements typically mobilised in hydrothermal conditions, such as SiO_2, Fe and As (figs. 5a,b), and the variation of the Li/Sr ratio (Li as pathfinder of deep thermality and Sr as minor element tracer of background water-rock interaction with the evaporitic and carbonate basement), during the first period of the sequence, may be the effect of differential thermal input linked to sharp co-seismic processes such as the frictional heating-frictional stress coupling process (see below for definition).

Alternatively enhanced water-rock interaction processes, or mixing processes with hotter fluids at depth may bring in solution these elements as a response to episodic Fault Valve Activity processes.

The Li/Sr ratio returned to normal values only three months after the Sellano earthquake, testifying the modification as a whole within the deep reservoir associated with the seismogenic segment.

During the coseismic and immediately post-seismic phases of the Sellano earthquake and in occurrence of the two main-shocks of Gualdo Tadino and Verchiano, we set forth the hypothesis of a variation of the water-rock interaction processes as a whole between the $CaSO_4$ thermal reservoir and both the shallow meteoric waters and the Cl-rich alkaline component (pH ~ 8.0, see also pH data of Heinicke *et al.*

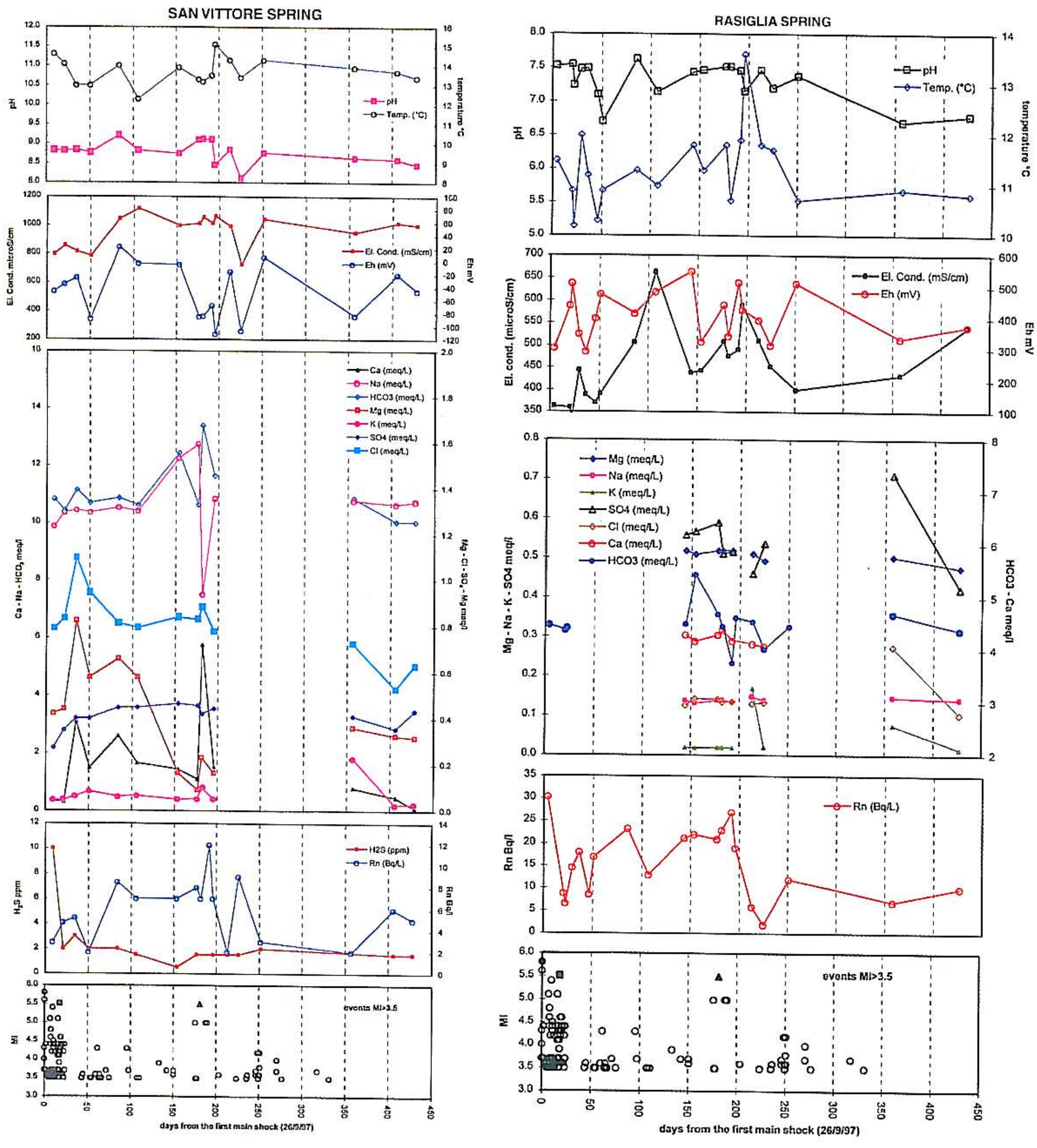

Fig. 4. Temporal trends of the geochemical parameters analyzed at the Rasiglia spring (main drainage collector of the Colfiorito Plain, within the NEUS hydrogeological system) and at the S. Vittore sulphurous spring, as discussed in the text. The seismicity trend (M_l = local magnitude) shows the 26/09/97 strongest shock (full circle), the 14/10/97 Sellano main-shock (full square), the Gualdo Tadino seismic reactivation at the end of March, 1998 (full triangle).

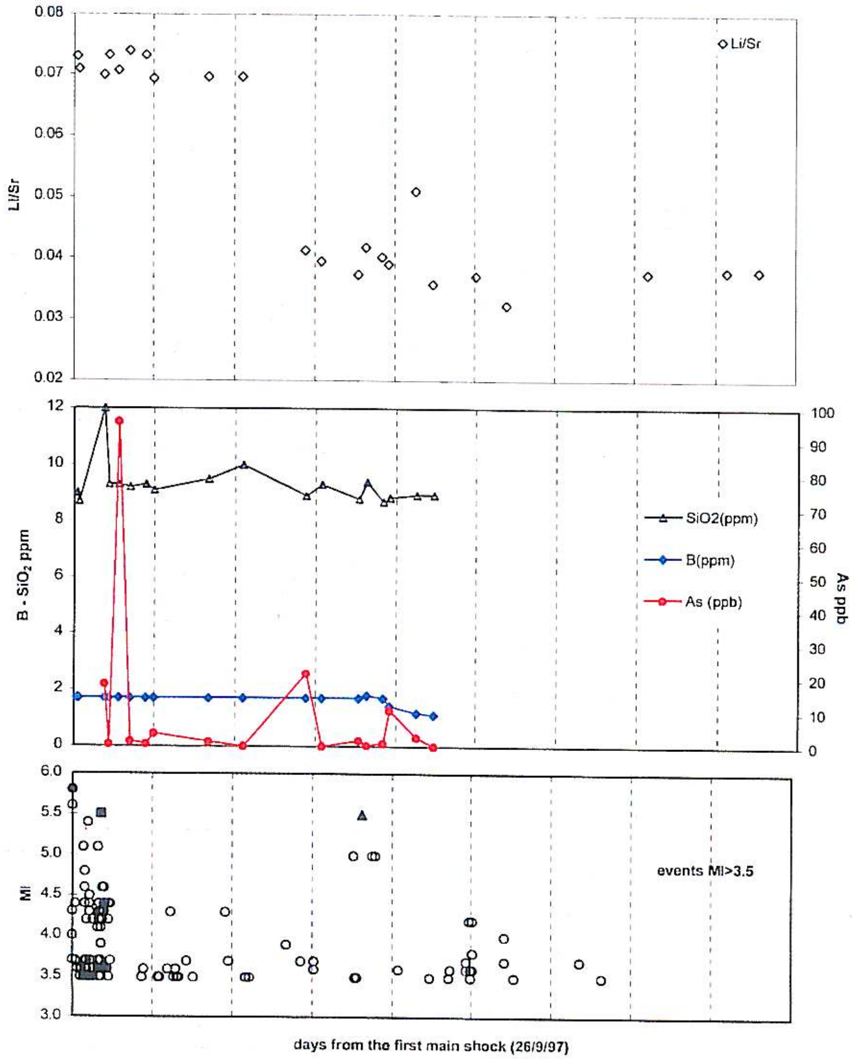

Fig. 5a. Temporal trends of the geochemical parameters analyzed at the Bagni di Triponzo sulphurous and thermal spring, as discussed in the text: a few trace elements. The seismicity trend (M_l = local magnitude) shows the 26/09/97 strongest shock (full circle), the 14/10/97 Sellano main-shock (full square), the Gualdo Tadino seismic reactivation at the end of March, 1998 (full triangle).

1999) from deeper strata. It has been pointed out by the apparent variations in SO_4, and Ca, as well as in the calculated saturation indexes of the sulphate phases (figs. 5a,b). The differential mixing calculated by the Phreeqc1.3 code, between chloride groundwater, related to the deeper PCB and shallower end-members are discussed in detail in another paper (Quattrocchi *et al.*, 1999). Generally it was more apparent in the period of the re-activated seismic sequence with the main-shocks of the Gualdo Tadino area.

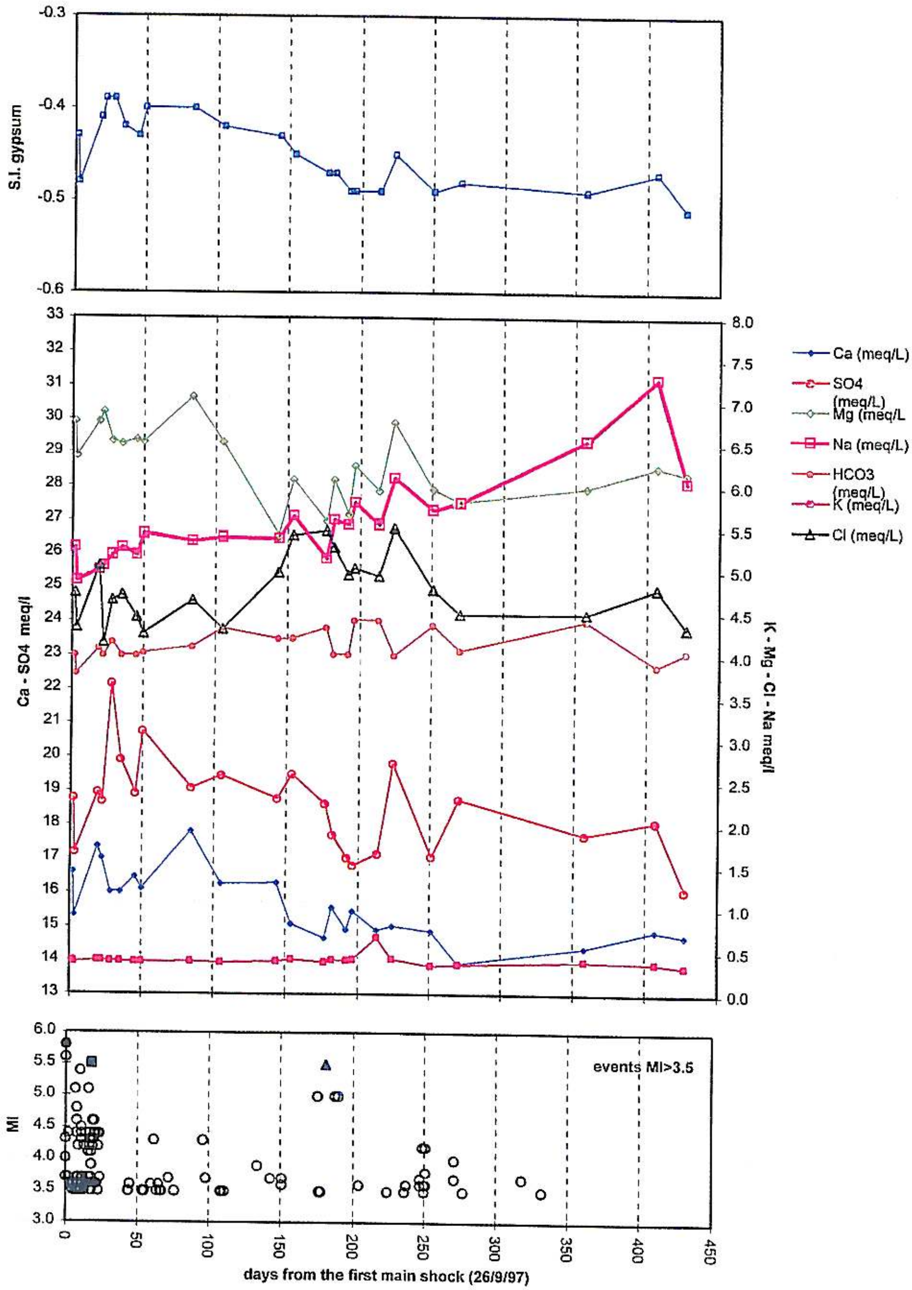

Fig. 5b. Temporal trends of the geochemical parameters analyzed at the Bagni di Triponzo sulphurous and thermal spring, as discussed in the text: major elements. The seismicity trend (M_l = local magnitude) shows the 26/09/97 strongest shock (full circle), the 14/10/97 Sellano main-shock (full square), the Gualdo Tadino seismic reactivation at the end of March, 1998 (full triangle).

The response of some of the geochemical variations was observed at the surface only two months after the main shocks: this datum establishes important information to reconstruct the reservoir ascending flux rate and possibly the deep fluid valve mechanism rate at depth, in occurrence of the main earthquakes. This delay may be attributed to the time necessary for the modified fluids (by deeper mixing and enhanced water-rock interaction) to reach the surface from depths closer to the seismic source, where the geochemical and dynamical effects of the Fault Valve Activity processes are hypothesised to be maximum.

Hints of deep fluid upwelling from the PCB domain, *i.e.* due to Fault Valve Activity, may be inferred from the continuously uprising trend of geochemical parameters such as Na, NH_4, CH_4, starting from the 26/09/97 main-shocks. While the Na trend may be readily attributed to the PCB improved leaching, the other two parameters may also have an organic-biogenic origin (*i.e.* a deep hydrocarbon reservoir), considering also the negative $\delta^{13}C$ measured (GSE EC program unpublished data, Lombardi *et al.*, 1999) for almost all of the Bagni di Triponzo spring samples during the same period.

Moreover, during the coseismic and immediately post-seismic phases of the Sellano earthquake and of the two main-shocks of Gualdo Tadino at the end of March 1998, we put forward the hypothesis of a variation of the fracture field up to the surface around the Bagni di Triponzo spring, testified by a noteworthy change in $^3He/^4He$ and $^4He/^{20}Ne$ detailed in another paper (Quattrocchi *et al.*, 1999). These concomitant variations suggested, with all probability, an input of shallow meteoric groundwater with prevailing atmospheric He ($R/R_a = 1.0$) to the typically crustal background component of the thermal groundwater ($R/R_a = 0.01 - 0.03$; see also Hooker *et al.*, 1985).

At the same time, the dissolved radon gas has had a more random behaviour, although the values tend to remain constant at the end of the seismic sequence. Also the highest H_2S values may be referred to the Gualdo Tadino earthquakes. Other dissolved gases composition confirms the circulation inside the crustal strata as a whole, without apparent source modification during the sequence (*i.e.* fluid remobilization remained in the crustal strata).

In conclusion, all the geochemical and hydrogeological spatial and temporal anomalies and trends observed during the seismic sequence may be explained by a very enhanced fracture field up to the surface down to crustal strata (anomalies in Rn, He, SO_4, Cl, etc…), excluding mantle or magmatic origin input and minimising the input of reducing and acidic gases (CO_2, H_2S, CH_4 etc..) from depth, as happened in other earthquakes. It implies seismogenic faults that are not deep enough to reach sub-crustal strata. The enhanced thermality signature is not to be disregarded, to speculate on the role of fluids in the seismogenic processes (see below).

4. Discussion

4.1. *The development of episodic fluid overpressure triggered during the sequence*

The discussion will focus on possible porepressure uprising mechanisms, explaining coseismic geochemical anomalies at the surface and the seismic style at depth, *i.e.* a long seismic sequence of moderate magnitude earthquakes.

In particular, the fluid geochemistry experimental data and the newly gathered information on the hydrogeological effects of seismicity may be very useful to understand the role of fluids within the seismogenic long-period process. This information may be considered one of the few available experimental tools to speculate on deep pore pressure field and deep water-rock interaction processes linked to the ongoing seismicity.

Also seismological arguments suggest to follow this kind of approach (Chiaraluce *et al.*, 1999), involving the role of fluids to explain the seismic sources and style of the sequence.

Considerations on failure criteria suggest that frictional instability, with consequent faulting or other macroseismic brittle failures may be induced either by an increase in τ (deviatoric stress) due to elastic strain accumulation, or by a decrease in σ_n (overburden pressure) by an increase in P_p, (pore pressure), causing a reduction of effective normal stress across potential slip planes. This simple concept has been reworked in recent decades to date, progressively enhancing the importance of pore pressure in earthquake generation (Scholz, 1998).

The level of fluid pressure at a depth z in the Earth's crust is conveniently defined in terms of pore-fluid factor λ (fig. 6; Sibson, 1990, 1996; Bradshaw and Zoback, 1988; Axen, 1992)

$$\lambda = P_p / \sigma_v = P_p / (\rho_r g z)$$

where σ_v is the vertical stress, ρ_r is the average rock density, g is the gravitational acceleration and z is the depth. Effective overburden pressure and fluid pressure may then be written respectively

$$\sigma_v' = (\sigma_v - P_p) = \rho_r g z\,(1 - \lambda_v),\ P_p = \rho_f g z.$$

This is true at shallow depths, where the fractures are commonly interconnected and the water table is at or near the Earth's surface, here $\lambda_v = \rho_f / \rho_r \sim 0.4$ where ρ_f is the fluid density and the gradient is said to be hydrostatic (fig. 6). The transition up to $\lambda \rightarrow 1$ (lithostatic conditions) marks the limit of downward convective flow of meteoric waters, testified at surface by *e.g.*, temperature and radon groundwater anomalies, as mentioned above.

On the other hand, without permeability barriers («critical surfaces» in Gold and Soter, 1985; «pressure seals» in Bredehoeft and Hanshaw, 1968; Parry and Bruhn, 1990; Brantley *et al.*, 1990, Fournier, 1991; Blanpied *et al.*, 1992; or «sink regions» in the model of Etheridge *et al.*, 1984) it is not likely that P_f exceeds P_h to depth of at least 10 km, persisting as an aqueous solution (Nur and Walder, 1992a).

The near hydrostatic condition may be easily inferred for the Umbro-Marchigiana Nappe formations down to the ETB layer, while below this layer boundary (variable from 1 to 4 km) and within the PCB, the conditions may became supra-hydrostatic with local $\lambda_v \sim 0.9$, over the depth range of 2 to 5 km (fig. 6) as a consequence of the lowering in permeability of the poly-phase basement rocks.

Transition towards supra-hydrostatic fluid pressures has been noted at depths exceeding a few kilometers in many sedimentary basins and in areas of active deformations (*i.e.* Alps, Apennines, Pyrenees).

Here we wish to understand how the development of a long period of episodic supra-hydrostatic conditions is possible within the peculiar geo-structural settings of the Umbria-Marche boundary, and if it is really possible and reliable to record this process at surface *i.e.* by geochemical and hydrogeological methods.

High Conductivity Layers (HCL) within the crust have been widely studied in recent decades (Shankland and Ander, 1983; Jones and Nur, 1984; Frost and Bucher, 1994) and various models have been proposed, involving the permanent and pervasive presence of free water within the crust. The problem with this interpretation is that the maintenance of high pore pressure for geologically significant periods requires adequate permeability around 10^{-16} darcy. Frost and Bucher (1994) stressed the fact that fluid cannot be stored long in the lower crust for both mechanical reasons and because at temperatures above *ca* 250 °C, reaction rates are so fast that fluids must be rapidly consumed by retrograde hydration reactions, to reach a dry condition. Also the fluids produced in tecto-thermal processes are removed from the crust «very rapidly» (Lasaga, 1984), by retrogression reactions like

$$7\ FeSiO_2 + SiO_2 + H_2O = Fe_7SiO_8O_{22}(OH)_2$$

$$\text{Pyroxene} + \text{Quartz} + \text{fluid} = \text{Amphibole}.$$

These reactions have a rate of about eight orders of magnitude faster at 300 °C compared to the rates at surface temperature.

Therefore, to maintain a wet crust, fluids must be continuously supplied. Alternatively fluid sources are likely to occur episodically, transiently «pumped» in a discontinuous way, *i.e.* during energetic faulting, passing through usually sealed barriers, like normally isolated over-pressurised fluid pockets. Infiltration of pressurised fluids into the crust under regional or local stress field is possible, perhaps initially along existing discontinuities (*i.e.* detachment low-angles planes, as in fig. 6), enhancing fault zone instability, but fluid source is always necessary (meteoric, mantle degassing, metamorphic devolatilization, evolution of igneous fluids, etc.).

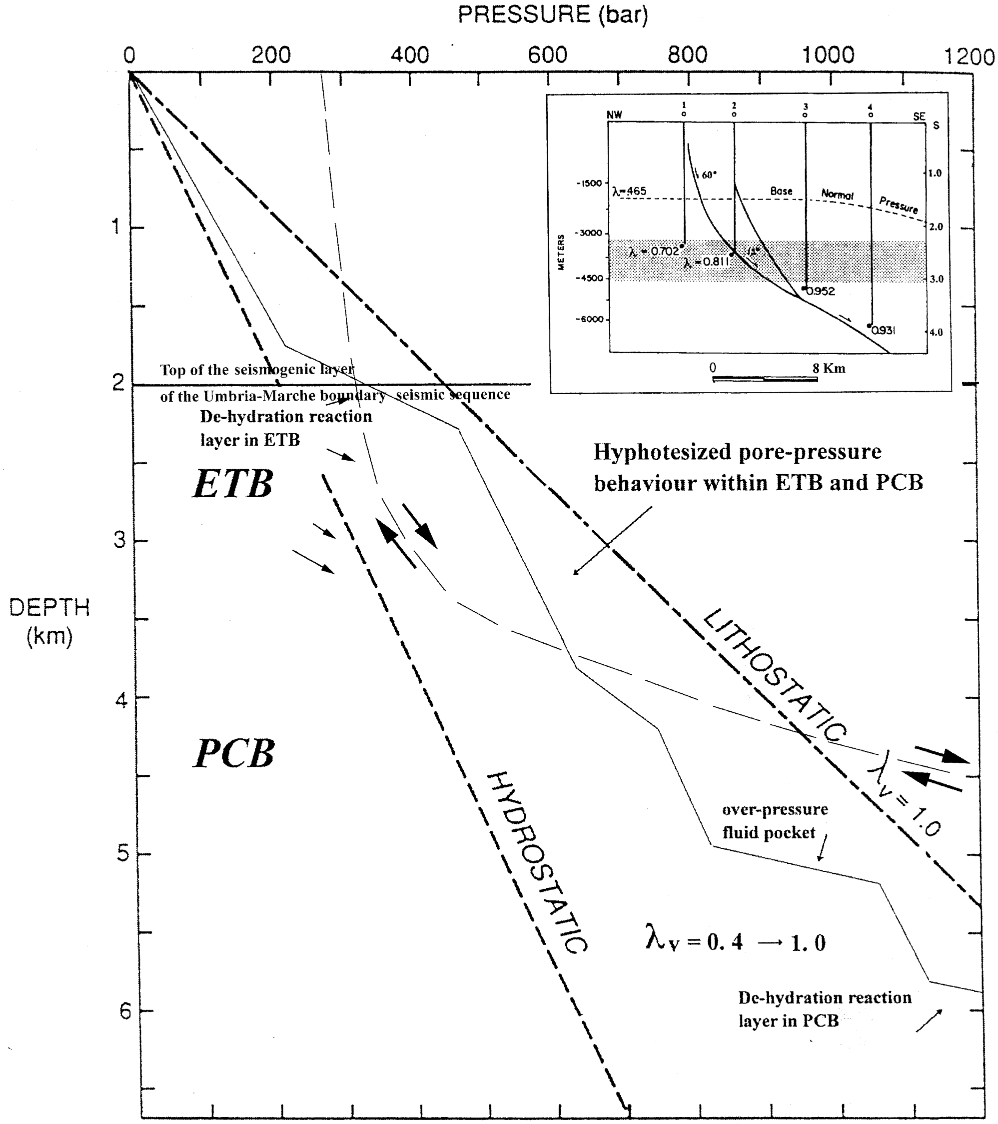

Fig. 6. Depth-fluid pressure diagram (modified after Sibson, 1990), reporting the hydrostatic and lithostatic pore-pressure gradient respectively. The segmented curve inside the two gradients is hypothesized for the Umbria-Marche boundary seismogenic layer (no experimental data exist), in similarity with the fluid pressure measurement performed by Sibson (1990), within the poly-phase sedimentary basement. Changes in slope toward the lithostatic condition $\lambda \rightarrow 1.0$ correspond to fluid over-pressured pockets. We hypothesise similar conditions as revealed by the schematic cross section (small square figure, modified after Bradshaw and Zoback, 1988), interpreting a seismic profile observed in the Gulf Coast (U.S.A.). Here a listric fault system, showing fault dip, flattening with a zone of smectite-illite transition diagenesis with high fluid overpressure (stipped region). Flattening (decreasing of dip with depth) of listric normal faults (as inferred in the discussed sequence, see Amato *et al.*, 1998) has been explained by stress refraction (rotation of maximum principal stress) away from vertical with depth.

The sources are normally buried: after progressive burial of fluid saturated rocks, like compaction (Sleep and Blanpied, 1992; Chester *et al.*,1993; Segall and Rice, 1995), fault healing (Marone, 1998), tectonic loading, progressive metamorphic dehydration and other regional methamorphism processes (Etheridge *et al.*, 1984), fluid overpressures are created. They involve frictional instability, noteworthy affecting the seismic cycles: earthquakes occurred as a function of both P_p and τ cycles (Nur and Booker, 1972). Tomography studies of the source area in occurrence of earthquakes may be required (Zhao *et al.*, 1996).

Either mobile or sealed high-pressure fluids will have substantial rheological effects, especially in poly-phase rocks (ETB, PCB, underlying the Central Apennines), while these effects can be relative within a higher permeability – «monophase» carbonatic basement like the Apulian Platform Basement (APB), underlying the Southern Apennines, differentiating the seismicity style as a whole.

Here the most prograde metamorphic reactions, especially those involving de-volatilization, are relatively rapid and the overall reaction rate is controlled by mass or heat transport rate, for the reaction

$$\text{Calcite} + \text{Quartz} = \text{Wollastonite} + CO_2\uparrow$$

that is typical (Fyfe *et al.*, 1978) of carbonate regional metamorphism as well as of limestone «contact metamorphism», as expected under the Southern Apennines. In this situation a CO_2 steady-state flow from depth is established, with rare fluid overpressure, yet the bulk rock permeability remains relatively high.

This difference may explain the different seismogenic styles among the two Apenninic domains, with moderate magnitude long sequence and strongest-isolated events respectively, as testified by the seismic catalogue itself (Boschi *et al.*, 1997); however this hypothesis must be deepened by reworking the existing geophysical data and models (*i.e.* Dragoni *et al.*, 1996). In the conditions of Central Apennines with respect the southern ones, we may hypothesise more «weakened» fault belts (Sleep and Blanpied, 1992; Chester *et al.*, 1993; Walder and Nur, 1984), *i.e.* the CAFS belt.

Any form of Fault Valve Activity, leading to fluids discharge, also has important implications for any regularity/cyclicality of earthquake recurrence and/or aftershock style, because a post failure drop in fluid pressure must cause an increase in the frictional resistance of the fault, before self-sealing occurs again and fluid pressure starts to re-accumulate, given the potential magnitude of fluid pressure cycling.

Moreover, in the *P-T* thermodynamic field of the de-hydration reactions, such as of gypsum-anhydrite (MacDonald, 1953), any stress drop may involve the transition curve of the phase boundary passing from a positive to a negative derivative, resulting towards the dehydrate phase field spreading, with consequent water release in the rock matrix and finally strength drop.

Even though the rate of tectonic stress accumulation may be constant, the rate of fluid pressure re-accumulation, *P-T* field thermodynamic transitions and strength reduction may vary greatly from one cycle to the next, depending upon a range of variables, such as transient post-seismic *T-P* regime, previous fluid loss, permeability, rate of hydrothermal self-sealing within the rupture zone, thermodynamic and phase equilibrium conditions, etc. Nothing is known about it along the Italian candidate seismogenic fault segments, but we stress the discussed seismic sequence has been a consequence of very narrow fluid overpressuring cycles mainly driven by the thermodynamic laws in a wetted polyphasic crust, the deviatoric stress after the mainshocks remaining almost constant (despite the stress/strain redistribution along adjacent segments).

If pressure seals and critical thermodynamic conditions along adjacent segments are widespread, a large portion of the Earth's crust may be in a state of incipient failure, without giving a single strong main-shock, but a lot of mainshocks along a fault segments population, as happened during the Umbria-Marche boundary seismic sequence.

Moreover, ancient compressive regime structures like thrust ($\sigma_v = \sigma_3$), occurring in the Central Apennines, in spite of the current prevalent extensive regime, may also permit a high degree of relict fluid overpressure beneath a given depth

($\lambda_v \geq 1$), allowing detachment low-angle sliding to occur (Reynolds and Lister, 1987; Bradshaw and Zoback, 1988), during the narrow pore-pressure rising cycles. Failure episodes on these low-angle fault and consequent seismicity recall deep Fault-Valve Activity (Sibson, 1981, 1990, 1998; Sibson *et al.*, 1975; Keller and Loaiciga, 1993), where transient post-seismic rupture permeability promotes upward fluid discharge up to the surface, possibly giving rise to the slight geochemical/hydrogeological anomalies observed.

Anticlines typically may reach $\lambda_v \sim 0.9$ at depth 3-5 km, involving – if «opened» – an extreme fault valve behaviour, with large post-seismic discharge (Muir-Wood and King, 1993; Martinelli and Albarello, 1997) near the surface ruptures (*i.e.* during historical earthquakes throughout the Western Transverse Ranges with $\sim 10^7$ m^3 of groundwater over a period of 2 months).

Despite the evidence of episodic huge fluid discharges soon after earthquakes, generally the signatures at surface of deep Fault Valve Activity are very slight, mostly in extensive regime, as we observed for the Umbria-Marche boundary seismic sequence.

Different inter-seismic behaviour of fluid bearing structures in extensive fault zones, classified by using different segment configuration (*i.e.* bend, termination, branch, cross-faulting, offset), is well summarised by Bruhn *et al.* (1990), in which the offset situation (*i.e.* anti-Apenninic transverse segments among Apenninic rupture segments as occurred in the discussed sequence) may play a critical role in local fluids accumulation and in the inter-seismic time dependence: instability within the transverse barriers reaches larger values because of more distributed and dishomogeneous deformations as compared to the segments (poly-oriented fracture planes, involving disoriented focal planes, see also Chiaraluce *et al.*, 1999). «Barriers» and «asperities» fluid driven models (*i.e.* Pennington *et al.*, 1986) may be recalled to explain multiple moderate magnitude earthquake generation in brief periods of time, if the Earth crust conditions are wet or if at least a stratification of fluid-dominated fluid-absent domains also exists at great depth (Touret, 1994).

It is however always necessary to find other local-transient fluid overpressure generating mechanisms during the seismic sequence.

In each domain, local-transient fluid overpressure generating processes may be enhanced by its peculiar crustal conditions, *i.e.* phase separation processes at depth in volcanically quiescent regions during extensive episodes (see Fournier, 1987; Quattrocchi and Calcara, 1998).

In the present hypothesis, further than the above-mentioned large-scale processes, some other specific local-scale mechanisms (*i.e.* slip source) of fluid overpressure generation may be implicated in the coseismic and immediately post-seismic main-shock phases, at the seismogenic depth of the Umbria-Marche seismic sequence.

The transient and local fluid overpressure generation is hypothesised mainly due to the frictional heating-frictional stress coupled processes and the mineral dehydration processes within the fault core, as the best candidate occurring in the Umbria-Marche seismogenic belt.

Also in this hypothesis, wet conditions, mainly along relict thrust low-angle planes, are hypothesised within the ETB and PCB layers, falling up to the green-shists metamorphic grade (maximum 10-15 km depth and temperature around 200-350 °C) throughout the whole observed seismogenic layer inferred mainly comprised between 5 and 8 km (Amato *et al.*, 1998). Further constraints may be added knowing the geothermal gradient, the heat flow density, the degree of hydration (producing softer rheology) and other crustal conditions (*i.e.* Dragoni *et al.*, 1996).

Both the ETB and PCB layers at those depths are the seat of anhydre-hydrate mineral phase boundaries, with noteworthy thermo-mechanical and rheological consequences.

We recall briefly that expansion of pore fluid overpressure caused by coseismic frictional heating might have an important effect on frictional resistance and temperature during earthquakes (Lachenbruch, 1980; Mase and Smith, 1985).

When confined water is heated, the fluid pressure increases rapidly ($\geq$ 10 bars/°C), causing a sharp transient reduction in effective normal stress and dynamic friction on the fault surface. The main variables which influence the temperature transient rise – frictional heat process – and the fluid pressure transient rise – frictional stress process – are the width of the shear zone and the conductive transport for the former and the pore dilatation and the rate of Darcian transport for the latter. Each process depends upon event duration (*i.e.* earthquake, aseismic creep), particle velocity, dynamic friction and permeability.

The frictional heat process is followed by a frictional stress process, if wet condition is present, as a consequence of the rapid increase in fluid pressure due to thermal expansion.

The differential equation for fluid pressure variation as a consequence of thermal variation is (Lachenbruch, 1980)

$$\partial P/\partial t = 1/\beta\ [\gamma\ (\partial\Theta/\partial t) - D] - \alpha_P\ (\partial^2 P\ /\ \partial x^2)$$

where β is the coefficient of compressibility (4.50×10^{-5}/bar), γ is the coefficient of thermal expansion of pore fluid (6.75×10^{-4}/°C), $\partial\Theta/\partial t$ is the temperature rise, D is the pore dilatational strain rate, α_P is the Darcian diffusivity corresponding to thermal diffusivity ($\alpha_\Theta = K/\rho c$, $\approx 0.007 - 0.012$ cm^2/s, in the 5-10 km deep fault zones).

The theoretical development of these differential equations is detailed coupling source term in temperature equations with pressure equations.

Roberts *et al.* (1996) developed the same kind of equations to simulate the long-term effects of upward fluid expulsion and associated transport along fluid overpressured faults, after an «opening event» (*i.e.* slip event).

Finally, thermal expansion of the fluid during an earthquake may cause a homogeneous episodic expansion of the pore volume, the opening of micro-cracks, or – for $P_p > \sigma_3$ condition – the formation of macro-cracks in a lot of slip events.

It is clear that if the frictional stress is to be produced by heating during the earthquake process, three conditions are necessary: i) friction must cause an appreciable temperature rise; ii) the temperature rise must cause an appreciable increase in fluid pressure, and iii) the increase in fluid pressure, must cause an appreciable reduction of friction; failure of any of these conditions is sufficient to «decouple» frictional resistance from frictional heating.

In general, it has been inferred from the theoretical model that, in the presence of fluids at seismogenic depth, the thermal transport «decoupling» is quite impossible for earthquake events ($\approx M > 4.5$), but not, of course, for creep events.

If otherwise this chain-process takes place, it can trigger a large number of aftershocks in a seismogenic fluid-rich crust layer where a mainshock occurred.

Another possible co-existent mechanism in which transient pore pressure uprising may occur at the observed seismogenic depth (2-8 km) within ETB and PCB, is the dehydration of hydrate mineral at the phase boundary in the observed P-T field.

Raleigh (1977) was among the first to show that a transient-local increase in pore pressure might be caused by the dehydration of clay minerals in fault gauge during an earthquake.

Abnormally high fluid pressure has been encountered in drilling evaporites inter-bedded with salt and clay, of which the ETB is made up, although the same behaviour is expected below the ETB layer, *i.e.* in the ancient metamorphosed basement (PCB).

As recalled, low-angle (dip < 30°-40°) normal faults accommodate much extension of the continental crust. The close association of overpressured evaporites (or shales) and flattening (decreasing of dip with depth) of listric normal faults (Axen, 1992) have been explained by stress refraction (rotation of maximum principal stress) away from vertical with depth (fig. 6), as a consequence of change in viscosity – pore pressure, explained mainly by the Smectite-Illite transition zone (Bradshaw and Zoback, 1988), possible either in ETB and PCB layers.

In triaxial compression tests at 2-5 kbars pressure, Heard and Rubey (1966) first observed a tenfold strength decrease in sealed poly-crystalline gypsum samples, if the temperature was increased from 100 to 150 °C and above. This marked strength decrease is interpreted as being due to the dehydration of gypsum following the reaction

$$CaSO_4 \cdot H_2O = CaSO_4 + H_2O$$
$$(\Delta H_r = 4 \times 10^{-3}\ \text{cal})$$

with a consequent rise in pore pressure to a value of the confining overburden pressure (Heard and Rubey, 1966; Hanshaw and Bredehoeft, 1968; Bredehoeft and Hanshaw, 1968).

Similar behaviour would almost certainly be expected when other hydrous minerals (zeolites, micas, amphiboles, montmorillonite, etc.) are heated through their respective dehydration temperatures, as in sedimentary layers under metamorphism, within ETB and PCB. They are rich in hydrous minerals other than gypsum, which phase transitions would then have expected at other temperatures and depths, always comprised within the observed seismogenic layer.

If most of the observed hypocentres have been located within the PCB, the MgO - Al_2O_5 - SiO_2 - H_2O system phase transition reactions may be invoked to explain the same strength drop transient mechanism, as for the gypsum dehydration process.

The following reactions involve the dehydration of serpentine between 1 and 5 Kb (around 3-15 km), in a range of 300-600 °C, corresponding to the observed seismogenic layer

$$\text{5 Serpentine} \rightarrow \text{6 Forsterite} + \text{Talc} + 9\ H_2O_{\text{vapour}}$$

$$\text{Serpentine} + \text{brucite} \rightarrow \text{2 Forsterite} + 3\ H_2O_{\text{vapour}}$$

$$\text{Al Serpentine} + \text{2 Brucite} \rightarrow \text{3 Forsterite} + \\ + \text{Spinel} + \text{2 Quartz} + 6\ H_2O_{\text{vapour}}$$

$$\text{3 Serpentine} + \text{5 Anorthite} \rightarrow \text{Actinolite} + \\ + \text{Epidote} + \text{2 Almandine} + \text{2 Quartz} + 5\ H_2O_{\text{vapour}}$$

It may be useful to recall that at conditions of 3.5 Kbar (*i.e.* 10 km) and temperature of 325 °C, 3 moles of released H_2O from silicate minerals would have a volume of 58 cm^3, thus giving a total solid plus vapour volume increase of 11%: if this added volume of water vapour cannot readily escape, its pressure will rise until it is equal to or slightly greater than the overburden pressure ($\lambda \rightarrow 1.0$ condition).

All the mentioned dehydration reactions will run to completion, in a local volume, within the time order of magnitude of days-months-years, depending upon overburden temperature (Nishiyama, 1989), likely to be highly episodic on a local scale, leaving most of rock dry, most of the time.

If we consider (fig. 7) a range of possible geothermal gradients, between 36 and 22 °C/km (for the Umbria-Marche border seismogenic layer is expected around 30 °C/km), as the strain rate decrease (*i.e.* as a consequence of stress drops after strong events), the strength transition region progressively migrates up to the geothermal gradient, towards the surface, until it coincides with the calculated phase-boundary transition curves (C_1 and C_2, in fig. 7, from MacDonald, 1953). When it occurs, with a delay function of the strain rate decrease, the condition $\lambda \rightarrow 1.0$ is reached and sliding occurs, also in low deviatoric stress condition, involving a long sequence style of seismicity.

All these discussed processes deserve special attention to understand the seismogenic processes origin and style, different for each Apennine domain.

At this point it should be necessary to discuss how all the processes hypothesized at depth may be observed also at the surface, *i.e.* by fluid geochemistry methods, and if not, why.

Soon after the main-shocks, slight evidence, but not absent, of the deep pore pressure uprising was recorded by the geophysical and geochemical task force on field (Boschi and Cocco, 1997).

Why so slight?

After the conclusion of an earthquake or other slip events the heat source vanishes sharply and the temperature and pressure excess within the deep shear zone, due to the previously described processes, decays as a result of upward transport of heat and fluids. This latter effect should be especially marked with normal faults, like those activated within the Umbria focal zone, where σ_3 is horizontal and the cracks may lie in vertical planes (perpendicular to least compressive stress). On the other hand, the generally lower differential stresses associated with normal faulting may reduce the extent of dilatancy for moderate earthquakes ($6.5 > M > 5$), like those of the Umbria-Marche seismic sequence.

Otherwise the possibility to reach the surface for this heat and mass strongly depends on the permeability of the overburden rocks above the seismogenic layer.

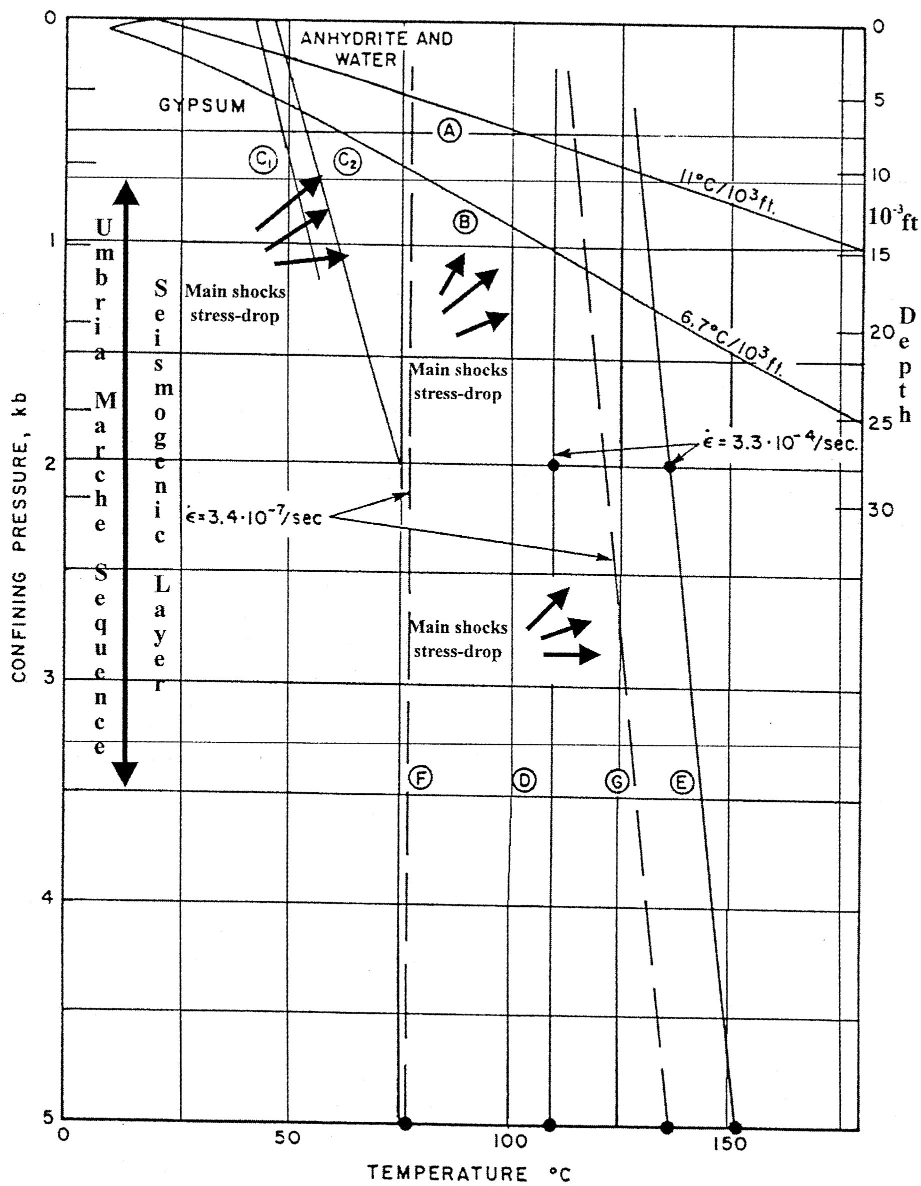

Fig. 7. Confining pressure *versus* temperature with a range of geothermal gradient curves spanning from 22 (B) to 36 (A) °C/km, typical of crustal environments. Curve C_1 is an extrapolation of MacDonald's (1953) calculated gypsum-anhydrite boundary; C_2 is the Zen's calculated gypsum-anhydrite boundary. Curves D and E represent the beginning and completion of the transitional strength at 3.3 10^{-4} /s strain-rate, while the curves F and G exhibit the similar strength transition for slow regional strain rate of 3.4 10^{-7}/s. The seismogenic layer of the Umbria-Marche 1997-1998 seismic sequence is also shown together with the possible transient dehydration phase transition episodes (schematic arrows) due to coseismic sharp P-T variation processes, see the text for the discussion (modified from Heard and Rubey, 1966).

Fault can play a passive role in the emplacement of hydrothermal deposits, acting either as permeable conduits for ascending fluids, or in some cases (more ancient-quiescent faults) as impermeable barriers for migrating fluids, depending upon the overburden permeability gradients. We stress the role of seismic faulting in playing a key role in the intermittent transport of hydrothermal fluids and mineral phases oversaturation evolution as pointed out by the saturation indexes at the Bagni di Triponzo spring (Quattrocchi *et al.*, 1999, and see also Dall'Aglio *et al.*, 1995, for the M_l = 5.4, 1990 Syracuse earthquake).

The seismic pumping process, as part of the Fault Valve Activity mechanism, depends both on the ability of faults to behave as impermeable seals through the inter-seismic period, and to form highly permeable channel-ways for fluid flow immediately post-failure. The resulting upward discharge of fluid along the fault from the over-pressured zone may continue until the entire hydraulic gradient reverts to hydrostatic or the fault reseals, also by repeated cycles (Fyfe *et al.*, 1978; Etheridge *et al.*, 1984; Kerrich, 1986; Parry and Bruhn, 1990; Brantley *et al.*, 1990).

In unfavorable conditions (mostly normal faulting), as encountered in the region of the discussed sequence, the fault-valve mechanism gives rise occasionally to slight post-seismic discharges at the surface, from the source region of over-pressured fluids. If they are sub-crustal (fluids originating even at the mantle depth, may be episodically «pumped» to the surface of the Earth throughout the different geo-pressured domains) it may be inferred from $^3He/^4He$ temporal trends, as discussed.

Therefore the relatively slight, but not absent, geochemical signature of fluids redistribution within the crust observed in occurrence of the Umbria-Marche border seismic sequence, may be explained as a consequence of multiple factors:

i) Moderate magnitude events during the sequence, involving both less strain-related fluid-dynamics and less pronounced fault-valve behaviour.

ii) Normal faulting, in which fluid squeezing and seismic pumping related discharges up to surface are uncommon.

iii) Lack in the epicentral area of steady-state deep fluid out-welling sites (*i.e.* thermal springs, gas venting, etc., excluding the Bagni di Triponzo spring, which circulation is not so deep, see before), because of the hiding by shallow huge-flow aquifers.

iv) Possible presence of permeability barriers within ETB, separating the deep fluid source and the shallow aquifers under monitoring.

4.2. *Model fitting with the variations of the groundwater level in the main aquifers*

The 26/09/97 main shocks involved major hydrodynamic variations (turbidity and flow capacity, fig. 2) mainly within the NEUS sector of Nocera Umbra-Colfiorito, at the huge-flow springs called Nocera Umbra (Polla Flaminia and Polla Angelica), Bagnara, Capodacqua, Rio, Boschetto, Rasiglia-Menotre and Pratarelle-Colfiorito, while in occurrence of the 14/10/97 earthquake (Sellano-Preci area), the Bagni di Triponzo spring exhibited an apparent lowering of the piezometric level (around 4 m) observed since the 15/10/97 and lasting 5 months (restored conditions observed on 15/04/98). At the same time, an uprising in the flow capacity of around 10% at the Argentina spring near Sellano, starting one day before the Sellano 14/10 main shock was observed.

The interpretation of these observed anomalies may be accomplished remembering that patterns of the hydrogeological changes that follow moderate-strong magnitude earthquakes has been found to be dependent on the style of faulting, rather than simply on the size of the earthquakes, showing the most significant response accompanying normal faults (Muir-Wood and King, 1993). In this case excess flow along down-wall fault segment area and drying up at the lateral boundary of the «activated» fault segment (26/09/98 and 14/10/98 main-shocks) may be verified, as in the case of the Baranello normal-faulting earthquake of July 26, 1805 (Muir-Wood and King, 1993), which exhibited a similar geographical extent of hydrogeological response of the discussed seismic sequence.

Such hydrological earthquake related phenomena are short-lived and have the effect of redistributing the discharge budget, with flow excess and deficit compensating one another over a period of days and weeks, after the main-shock, as observed during the Umbria seismic sequence (around two-three days).

Therefore, the experimental evidence associated with the main shocks is explained by the Coseismic Strain Model, where the strain induced hydrological effects to normal faulting reflect the coseismic deformation field, calculated using a boundary element program in which dislocation elements are introduced into an elastic medium (Muir-Wood and King, 1993).

On the other hand in the Dilatancy Model (see Sibson *et al.*, 1995) the coseismic pore-pressure drop level is explained in the frame of the seismic cycle, as strictly linked to the post seismic pore-pressure field propagation from seismogenic depth; in this case the localisation of the sites where the static level increased/decreased does not fit with the latter model.

In any case, locally, the problem may be conceived as one/dimensional non-steady flow. The basic equations which govern the flow of fluid in a porous medium have been discussed by a number of authors, starting from Jacob (1950).

Restoring time to initial conditions depends mostly upon aquifer permeability and depth.

We observed in concomitance with the Umbria-Marche sequence main shocks, that generally the water table level returned to its initial conditions (after a brief opposite sign compensation) one-two days after the main-shock, corresponding to the decay of the excess head. We can state that in the case of the shallow main aquifer springs within the NEUS system, the restoring time of the water level, following the normal faulting strain field, was of the order of magnitude of days, as a consequence of lack of connection with deep strata and the permeability being relatively high.

Otherwise, in the case of the sulphurous thermal spring of Bagni di Triponzo, characterised by deeper and slower circulation within the relatively impermeable ETB strata, it is hypothesised that the longer observed restoring time (seven months, since 14/10/97 to around 15/04/98) was a consequence of minor permeability, as well as of deeper source of hydrological change. In fact, as stressed also by Muir-Wood and King (1993), the characteristics of deep source hydrological changes that accompany earthquakes are their extended duration (commonly several months) and the absence of any short-term compensatory adjustment in the hydrological field, once the pre-seismic hydrogeological regime has been restored.

A deep source for excess water flow is unambiguous when the water emerges at a temperature or geochemistry different from the background or in equilibrium with crustal rocks at depth, but this was not so apparent in case of Bagni di Triponzo spring post-seismic temporal trends (see before and in Quattrocchi *et al.*, 1999), despite the noteworthy variations observed in the saturation indexes and other geochemical parameters.

The available observational data, relative to the sequence, did not establish beyond doubt whether the coseismic and pre-seismic water table variations have some direct link with fluid overpressure processes ongoing at depth: the continuous monitoring of the piezometric level on a regional scale in seismogenic areas is strongly requested to understand seismic cycles and seismic sources and fluid evolution.

The distribution of hydrological and geochemical anomalies on occasion of this seismic sequence, suggests for the future to monitor shallow aquifer springs located in the vicinity of deeper fluid steady-state input.

5. Conclusions

Overlooking the fluid geochemistry spatial and temporal data as a whole, it is possible to infer that the geochemical and hydrological apparent variations observed are related to the different stages of the Umbria-Marche boundary seismic sequence. The most powerful geochemical seismotectonic pathfinder parameters (*i.e.* changing in specific phases of the seismic cycles) have been revealed: Rn, SO_4, Cl, SiO_2, As, NH_4, He and other dissolved gases (H_2S, CO_2, CH_4), redox potential, pH, and a few isotopic ratios (He, C). These parameters deserve special attention for discrete and continuous monitoring addressed to earthquake surveillance and to deepen the knowledge of relation between fluids and seismic cycles.

In conclusion, all the spatial and temporal anomalies observed during the seismic sequence may be explained by a noteworthy enhanced fracture field up to the surface down to the crustal strata excluding mantle or magmatic origin input and minimising the input of volcanic reducing and acidic gases, as happened in other earthquakes, inferring here seismogenic faults are not deep enough to reach sub-crustal strata and seismic faults occur without CO_2 degassing.

In general the Sellano-Triponzo fault system is characterised by helium enrichment typically of crustal origin, with apparent chemical and isotopic variations in occurrence with main shocks.

Coseismic Strain Model has been advised to better account for the observed anomalous hydrological phenomena accompanying the main-shocks.

On the other hand, our data allow speculation on the possible processes wich occurred to enhance the pore pressure from seismogenic depth up to the surface.

Assembling the fluid geochemistry, seismological and geo-structural data available, as well as reworking a few models explaining the relationships between pore pressure evolution beneath this sector of Central Apennines, the seismicity style, *i.e.* a more than one year long seismic sequence, with moderate-strong magnitude events may be explained.

It may be inferred that the Umbria-Marche boundary fault zone (as sector of the CAFZ) became a transiently weakened frictional instability zone, as a consequence of fluid overpressure evolution at seismogenic depth, involving the coefficient of friction became unusually and transiently low, and frictional instability episodically high along a population of adjacent Apenninic fault segments.

Starting from the initial failure condition (main-shocks), driven by the ongoing extensive regional stress field, it follows the triggering of a chain-effect process, creating episodes of fluid overpressure development, for the entire duration of the 1997-1998 seismic sequence. We set forth the hypothesis that the main-shocks have had the critical role to enhance: the Fault Valve Activity at depth along ancient low-angle detachment planes, as the main process of post-seismic fluid redistribution within the upper crust, the dehydration phase transition reactions within ETB and PCB layers and the frictional heating-frictional stress coupling transient processes, involving further and closer fluid overpressure episodes.

These processes triggered frequent moderate magnitude events, other than expected by a normal aftershocks coda, mostly along Apenninic faulted segments separated by anti-Apenninic barriers, finally resulting in a long moderate magnitude seismic sequence, spanning from one segment to another.

The complex dynamic and static relationship between frictional slip, porosity and pore pressure inside a poly-phase basement (*i.e.* ETB and PCB) are to be deepened, also to understand different seismicity styles in each seismogenic domain, *i.e.* Southern Apennines (Apulian Platform Basement, APB domain), with respect Central Apennines (ETB-PCB domain). One open problem, in fact, is the understanding of the different seismogenic styles between Central and Southern Apennines: the first mainly with long moderate magnitude sequences, the latter with strongest events, with fewer aftershock. A possible explanation is the unlikely possibility to develop at seismogenic depth fluid over-pressures within the Southern Apennine basement, as a consequence of a minor percentage of hydrate minerals, as hypothesised for the APB. This is both poorer in minerals subject to dehydration processes, and more permeable, avoiding strong pore pressure development at depth, but allowing *e.g.*, a CO_2 steady-state flux from carbonate thermo-metamorphic reactions.

Otherwise throughout the Central Apennines, between 2 and 5 Kb (seismogenic layer, within ETB or PCB) episodic thermodynamically driven dehydration processes involving overpressures have been strongly hypothesised during the sequence. Here a slight strain rate (*i.e.* driven by· regional stresses) may have resulted in enormous changes in mechanical properties of rocks, up to frequent sliding and finally to a long seismic sequence, the duration of which probably depends on the number of pressure seals, fluids inter-communication paths, presence of permeability-tectonic barriers, *i.e.* anti-Apenninic segments.

One of the best indirect observational methods to help the understanding of the above processes is the geochemical and hydrogeological temporal monitoring, possibly continuous, in seismogenic areas and the study of the deep physico-chemical and thermodynamic conditions in the *P-T* field, *i.e.* by a drilling task project and *P-T* field experiments (also with simulated drained and undrained conditions in occurrence of failure).

Interdisciplinary work must be devoted to verifying the transient motion of fluids along faults, during seismic sequences and in the frame of earthquake prediction experiments.

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