Earth and Planetary Science Letters 304 (2011) 389–398

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Geochemical evidence for and characterization of CO_2 rich gas sources in the epicentral area of the Abruzzo 2009 earthquakes

G. Chiodini [a], S. Caliro [a], C. Cardellini [b,*], F. Frondini [b], S. Inguaggiato [c], F. Matteucci [b]

[a] INGV, Sezione di Napoli, Osservatorio Vesuviano, via Diocleziano 328, 80124 Napoli, Italy
[b] Dipartimento di Scienze della Terra, Università di Perugia, Piazza dell'Università, 06123 Perugia, Italy
[c] INGV, Sezione di Palermo, Via Ugo La Malfa 153, 90146 Palermo, Italy

ARTICLE INFO

Article history:
Received 29 October 2010
Received in revised form 3 February 2011
Accepted 7 February 2011
Available online 17 March 2011

Editor: R.W. Carlson

Keywords:
carbon dioxide
Abruzzo earthquakes
carbon isotopes
helium isotopes
Earth degassing
groundwater

ABSTRACT

We describe the results of a detailed hydrogeochemical campaign on the groundwater circulating in two regional aquifers located in the area of the Abruzzo 2009 earthquakes. The influx of deeply derived CO_2 rich gases into the two aquifers is highlighted by the ^{13}C isotopic composition of dissolved carbon species. The source of the gas is roughly localised beneath the epicentral area of the earthquakes where the presence of sources of fluids under high pressure is suggested by seismological investigations. The carbon isotopic-mass balance of the aquifers indicates that the amount of the deep CO_2 dissolved and transported by the groundwaters is ~530 t/day. The chemical and isotopic composition of the gas entering the aquifers, named Abruzzo gas, has been derived by comparing the data measured in the springs with the results of a gas–water–rock reaction model, that simulates the evolution of the chemical and isotopic composition of groundwater affected by the input of a deeply-derived CO_2 rich gas phase. The composition of Abruzzo gas is compared to that of 40 large gas emissions located in central Italy. The gas becomes progressively richer in radiogenic elements (^4He and ^{40}Ar) and in N_2, from the volcanic complexes in the west to the Apennines in the east. The Abruzzo gas, in agreement with its location, well matches the composition of the gases emitted in the pre-Apennine region. These geochemical features, consistent with the structural setting of the region, indicate increasing residence times of the gas in the crust moving from west to east. In particular we suggest that the strong increase in radiogenic crustal gases reflects the occurrence of deep traps where the gas is stored at high pressures for a long time and that such high pressure gas pockets play a major role in the generation of Apennine earthquakes.

1. Introduction

The influx of fluids into fault zones and high fluid pressure facilitate fault movement and earthquake nucleation (e.g., Cox, 1995; Rice, 1992; Sibson, 2000). This general consideration well applies to the Apennines. Here geological investigations suggested the primary role of fluids on the past movement of exhumed faults (Collettini et al., 2008) and seismological studies highlighted the role of fluids in recent seismic crises. In particular, according to Miller et al. (2004), the aftershocks of the Colfiorito1997 seismic sequence, in Northern Apennine, were driven by a high CO_2 pressure at depth.

Eleven years after the 1997 Colfiorito earthquakes, the Apennines were affected by another strong seismic sequence, here after called Abruzzo earthquakes, located about 100 km to the south. The crisis started in October 2008 and culminated on April 6th 2009 (Fig. 1), when a Mw 6.3 earthquake devastated the town of L'Aquila and the surrounding villages of the Abruzzi Region (Italy), causing 300 deaths and leaving 60,000 people homeless (Chiarabba et al., 2009). The aftershocks continued until the autumn 2009.

The possibility that, similar to the Colfiorito crisis, the Abruzzo earthquakes were also generated by high fluid pressure at depth was proposed by Di Luccio et al. (2010). Based on Vp/Vs ratio and its evolution with time, they recognised a first phase of increased pore fluid pressure from October 2008 to the date of the main earthquakes on April 6th 2009. This process occurred along the NW–SE fault planes associated with the main earthquake and was followed by a second phase of pore pressure diffusion, due to the upward migration of fluids, which controlled the temporal and spatial evolution of the aftershocks (Di Luccio et al., 2010). A key role in the fault failure process played by fluids has been also inferred by Lucente et al. (2010), based on seismological observations of the foreshock sequence preceding the April 6th 2009 earthquake. Furthermore, based on a new analysis technique, termed focal mechanism tomography, Terakawa et al. (2010) identified three large-scale pockets of high fluid pressure (up to 50 MPa above hydrostatic pressure) at the hypocentral depths of 7–10 km which may have had a major role in the generation of the Abruzzo earthquakes.

* Corresponding author. Tel.: +39 0755852698; fax: +39 0755852603.
E-mail address: geochem@unipg.it (C. Cardellini).

0012-821X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2011.02.016

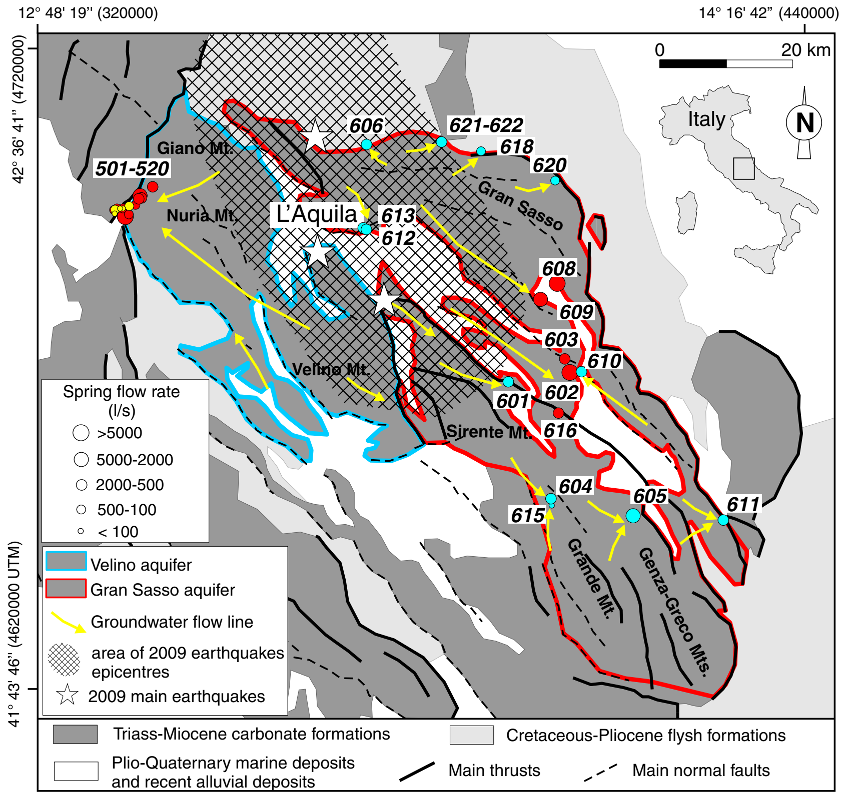

Fig. 1. Schematic geological map (modified after Boni et al., 1986) with the location of the studied aquifers, sampled groundwaters, and the Abruzzo earthquakes (ISIDE, 2009). Groups A, B and C groundwaters refer to the chemical and isotopic classification (see Section 4.1).

The fluids involved in the process are mainly CO_2-rich gases supplied by a large deep source existing in central Italy, suggested by numerous CO_2 rich gas emissions mainly located in the Tyrrhenian region and by the large amounts of deeply derived CO_2 dissolved by groundwater of the regional aquifers of the Apennines (Chiodini et al., 2000, 2004). Frezzotti et al. (2009) hypothesised that melting of sediments and/or of continental crust of the subducted Adriatic–Ionian slab at great depth (130 km) may represent a regional CO_2 source. In particular the melting of carbonate lithologies would generate small fractions of carbonate-rich melts characterised by low density and viscosity. The subsequent upwelling in the mantle of these carbonate-rich melts to depths less than 60–70 km, would induce the massive outgassing of CO_2 observed at the Earth surface (Frezzotti et al., 2009).

While the occurrence in the peri-Tyrrhenian sector of central Italy of a CO_2 source at mantle depth and of CO_2 contributions from thermo-metamorphic processes at crustal depth, are largely accepted (e.g., Chiodini et al., 2000, 2004, 2007; Italiano et al., 2008; Minissale et al., 1997; Minissale, 2004), the origin of the CO_2 rich fluids found in the eastern sector of central Italy (i.e., in the pre-Apennine–Apennine belt) is still a matter of debate. In particular, recent works proposed a pure crustal origin for the CO_2 release over seismic zones of central Italy (Heinicke et al., 2006; Italiano et al., 2008), of Friuli (northern Italy, Italiano et al., 2009) and Calabria (southern Italy, Italiano et al., 2010), suggesting, for the first two cases, a possible mechano-chemical production of CO_2 by faults movement.

With the goal of investigating the possible presence of a deep CO_2 source active in the epicentral area of the Abruzzo earthquakes we performed a detailed hydrogeochemical study on the aquifers of the area. The analysis includes major solutes, dissolved gases and the isotopic composition of water, dissolved carbon and helium. In order to characterise the deep gas source, the chemical and isotopic compositions of the major gas emissions of central Italy have been also considered.

We will show clear evidence for input into the aquifers of large amounts of deep gases whose composition, constrained by the analytical data and by geochemical modelling. are similar to the compositions of gas emitted, 100 km north, by the deep pressurised reservoirs which were thought to be involved in the Colfiorito 1997 seismic sequence.

2. Geological and hydrogeological settings

Two of the largest aquifers of central Italy are considered in this study (Fig. 1): the first, hereafter called Gran Sasso Aquifer, includes the Gran Sasso, Monte Sirente, Monte Genzana and Monte Grande massifs (outcropping area of 2164 km^2, Boni et al., 1986), the second, called Velino Aquifer, includes the Monte Velino, Monte Nuria and Monte Giano massifs (outcropping area of 1016 Km^2, Boni et al., 1986). The aquifers consist of Meso-Cenozoic carbonate formations (limestones and dolostones) of platform (Lathium–Abruzzi platform) and of platform-to-basin transitional domains.

The thick carbonate sequences of Gran Sasso aquifer are imbricated eastward onto Neogene flysch deposits and dislocated by recent normal NW–SE fault systems. These carbonate structures, which, due to fractures and karst are highly permeable, are bound by low permeability deposits (Boni et al., 1986; Salvati, 2002; Fig. 1). Only a small portion of the infiltrating water recharges small springs located at high altitudes, while the majority recharges the regional aquifer, feeding moderate springs at relatively high altitudes (800–1300 m a.s.l.) and large basal springs, located at low-altitudes (200–500 m a.s.l.) at the border of the carbonate ridges (Barbieri et al., 2005; Boni et al., 1986). The Gran Sasso aquifer feds also two large flow rate water discharges at high elevation (960 m a.s.l.), which are the water drainage of the Gran Sasso motorway tunnel.

The Velino aquifer consists of carbonate formations of the northernmost part of the Lathium–Abruzzi platform sequences. The