Chemical Geology 469 (2017) 176–184

Contents lists available at ScienceDirect

Chemical Geology

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

Factors constraining the geographic distribution of earthquake geochemical and fluid-related precursors

Giovanni Martinelli [a,*], Andrea Dadomo [b]

[a] ARPAE Environmental Protection Agency of Emilia Romagna Region, Via Amendola 2, 42100 Reggio Emilia, Italy
[b] GEOINVEST Srl, Via della Conciliazione 45/A, 29122 Piacenza, Italy

ARTICLE INFO

Article history:
Received 29 July 2016
Received in revised form 5 January 2017
Accepted 8 January 2017
Available online 16 January 2017

Keywords:
Earthquake precursor
Earthquake prediction
Geochemical anomaly
Tectonic pumping
Natural strainmeter

ABSTRACT

Earthquake precursors are elusive, and this elusiveness has hampered earthquake prediction. In this paper, the available catalogues of historical and contemporary geochemical and fluid-related precursors of earthquakes are considered.

The locations of recording sites are mapped and compared with data concerning volcanic locations, heat flows, crustal velocities and the depth of seismic events. Possible relations among the considered geophysical parameters and the occurrence of fluid-related earthquake precursors are discussed. Only some geological and geophysical conditions may allow for the occurrence of fluid-related earthquake precursory phenomena. As a consequence, the geophysical models utilized to explain the occurrence of earthquake precursors should be updated. Furthermore, only some areas of the world are deemed suitable for earthquake fluid-related precursor monitoring.

1. Introduction

Possible precursory non-seismometric earthquake phenomena have attracted the attention of researchers for many centuries. These phenomena have been registered in historical records and considered in research oriented towards earthquake prediction experiments (Howell, 1986; Martinelli, 2000). During pioneering research carried out in the period of 1800–1950, single parameters or clusters of parameters deemed responsible for observed precursory phenomena were identified. During the 1960s, research projects into earthquake precursors started in Japan, China, the former USSR and the USA. Contrasting results were obtained, and after 1985, new more comprehensive multiparametric experiments were launched in Turkey (Berkhemer et al., 1990; Yuce and Ugurluoglu, 2003), the USA (Bakun and Lindh, 1985), Japan (Uyeda, 2013), the former Soviet Union (Sidorin, 2003), China (Zhang et al., 2013), Iceland (Stefánsson, 2011), Taiwan (Walia et al., 2009; Chen et al., 2015), etc. As a consequence, in the past few decades, many possible earthquake precursors have been utilized in research to describe and understand the physical and chemical processes occurring in the Earth's crust in the phases preceding earthquakes. A portion of the considered parameters are related to underground fluids. Fluid parameters are still widely studied in this kind of research owing to their physical and chemical peculiarities. For instance, groundwater is incompressible; thus, it may act as a natural strainmeter when an aquifer is confined (Bodvarsson, 1970; Roeloffs, 1988; Yaltirak et al., 2005; Yuce et al., 2010). The chemical composition of the groundwaters may provide interesting information about fluid movements in the crust. Gases may provide information about deep fluid migration processes towards the earth's surface (e.g. Thomas, 1988). Such information is not detectable by means of other geophysical parameters. As a consequence, underground fluid monitoring has been carried out jointly with other geophysical parameters. The idea to simultaneously monitor a variety of parameters, including deep originated fluids, was first put forward by Galitzin in 1911 (Zarkov, 1986) following publications by Michele Stefano De Rossi (De Rossi, 1879; De Rossi, 1884), and the complete works of Boris Borisovich Galitzin were published in 1960 (Galitzin, 1960; in pages 426–427 of vol.2 some recommendations about geofluid monitoring are published; an excerpt is shown in Fig. S.3 in the Supplementary material). This idea became predominant in almost all modern research projects on earthquake precursors. In particular, researchers involved in modern research projects consider that dynamic of deep fluids can be influenced by crustal deformative processes. Hence, geochemical and hydrogeologic data are compared with data related to crustal deformation, such as GPS data, seismicity, and satellite data. Fluid-related possible precursory phenomena are not always detectable (Kumpel, 1992). Many earthquakes occur in areas where underground fluids are inaccessible. In other cases, manual or automatic monitoring systems fail because no anomalous signal is recorded prior to the earthquakes. Thus, fluid-related precursors are elusive, as are many other possible earthquake precursors, and currently cannot predict earthquakes (e.g., Jordan et al., 2011). Sometimes possible

* Corresponding author.
E-mail address: giovanni.martinelli15@gmail.com (G. Martinelli).

http://dx.doi.org/10.1016/j.chemgeo.2017.01.006

fluid-related precursory signals are very clear, and researchers have tried to replicate the experience in other places; however, the results are rarely convincing. The purpose of the present work is to identify the possible existence of constraint factors capable of limiting the natural possibilities to generate eventual fluid-related precursory signals. The possibility of generating possible fluid-related precursory signals could depend on the geological context and the local geophysical conditions (e.g., Rigo, 2010). A review of possible favourable and unfavourable geophysical conditions has been carried out.

2. Catalogues of precursory signals

The need to understand when and where possible precursory phenomena have occurred has obliged contemporary researchers to compile catalogues containing metadata of previous publications (e.g., Cicerone et al., 2009). Catalogues of historical precursory phenomena are still very rare because historical seismologists usually pay attention to parameters related to the intensity and to the localization of the studied earthquakes. Historical seismologists usually study or review historical records about earthquakes of the past. In this way, catalogues of historical earthquakes have been compiled for the whole world (e.g., Albini et al., 2014 and references therein). Catalogues of the environmental effects of contemporary earthquakes usually report data about geofluids (e.g., Serva et al., 2011 and references therein), but, in general, information about possible earthquake precursors in historical seismic events are few and far between. Martinelli (1997) published a preliminary catalogue of possible precursory phenomena that occurred in Italy in the period of 1117–1980. This catalogue was recently reviewed and is available in the Supplementary material. Other catalogues considering recent earthquakes and related precursory phenomena have been compiled by different authors. In particular, Hauksson (1981) reviewed all the available radon precursory anomalies throughout the world published in the period of 1971–1981. Friedmann (1985) reviewed all available radon precursory anomalies published in the period of 1969–1982. Toutain and Baubron (1999) reviewed the gaseous anomalies published in the period of 1980–1995. Kissin and Grinevsky (1990) reviewed the available anomalies in water level data in the period of 1948–1980. Hartmann and Levy (2005) reviewed gaseous and water-related anomalies published in the period of 1978–1997. Cicerone et al. (2009) reviewed the geochemical, hydrogeological and geophysical anomalies that occurred in the period of 1948–2001. Ghosh et al. (2009) reviewed radon data recorded in many parts of the world in the period of 1983–2002. Petraki et al. (2015) reviewed radon data recorded all around the world in the period of 1966–2014. Woith (2015) reviewed radon data recorded all round the world in the period of 1967–2014. All the above-mentioned authors directly or indirectly recognized that crustal deformative processes (see also Bernard, 2001; Wang and Manga, 2010) are responsible for observed anomalies in geofluids; thus, further catalogues of geophysical precursors related to crustal deformations could be useful for understanding fluid anomalies recorded before earthquakes. Roeloffs (2006) reviewed precursory deformative anomalies published in the period of 1979–2004, whereas Cicerone et al. (2009) reviewed, among other things, precursory ground deformation anomalies published in the period of 1974–1999.

3. Maps of locations where precursors were detected

3.1. A catalogue and a map of historical earthquake precursors of Italy

The catalogue of non-seismometric precursory phenomena of Italy (Table S.1 in Supplementary material) considers all physico-chemical variations in geofluids that occurred in Italy in concomitance with earthquakes, according to Bonito (1691), De Rossi (1879), Mercalli (1883), Baratta (1901) and Boschi et al. (1995), in the period of 1117–1980. Approximately 400 earthquakes were considered, but only a few were really preceded by significant anomalies in geofluids. In particular, geochemical and geophysical anomalies were detected in the Island of Ischia (southern Italy) before the 1881 and 1883 earthquakes (Mercalli, 1883; De Rossi, 1884; Boschi et al., 1995; Molin et al., 2003). In 1883, the level of the sea water significantly lowered some days before the mainshock; thus, a possible crustal deformation phenomenon (uplift) was observed (De Rossi, 1884; see also Carlino, 2012). Fig. 1 is a map that includes all locations in Italy where geofluids were upset by earthquakes during historical times and locations where precursory anomalies in geofluids were detected jointly with ground deformations. The close relationship among fluid-related phenomena and crustal deformation processes has led to the need to map all the fluid-related precursory phenomena and all precursory deformative processes reviewed by the aforementioned authors in present research.

3.2. A catalogue and a map of contemporary earthquake precursors of the world

All the catalogues of publications considered by Hauksson (1981), Friedmann (1985), Toutain and Baubron (1999), Kissin and Grinevsky (1990), Hartmann and Levy (2005), Roeloffs (2006), Ghosh et al. (2009), Cicerone et al. (2009), Petraki et al. (2015), and Woith (2015) were reviewed and merged. All duplicates were removed and a catalogue. Available references about groundwater level changes, temperature changes, geochemical variations in gas emissions and ground deformations were obtained (Table S.2 in Supplementary material). Data on the locations where precursory phenomena were observed were obtained by reviewing the publications listed in Table S.2 (Supplementary material). A map including all the considered locations is shown in Fig. 2.

4. Geophysical common characteristics of monitoring sites where precursory signals were recorded

A significant number of monitoring sites where precursory phenomena were observed are located in areas where a relatively high heat flow was measured. These areas are characterized by intense deep fluid circulation, which also influences the mechanical characteristics of the lithospere (Ranalli and Rybach, 2005). A map including heat flow values (Goutorbe et al., 2011), Holocenic and Pleistocenic active volcanoes (Siebert et al., 2010 and references therein) and locations where precursors were observed is shown in Fig. 3.

Meanwhile, a significant number of precursory crustal deformation phenomena were detected at the boundaries of tectonic plates; thus, a map is shown in Fig. 4 to better display the strain velocity values of tectonic motion compiled by Kreemer et al. (2003) (see also Kreemer et al., 2014). In particular, the 2nd invariant parameter calculated by Kreemer et al. (2003) appears relatively high in some tectonically active areas simultaneously affected by high heat flow values. Ranalli and Murphy (1987) and Ranalli and Rybach (2005) found that various kinds of crust are possible. The mechanical behaviour of a lithosperic body is controlled by the nature of the stress regime (tensional or compressional), the strain rate, the petrological composition of the lithospheric rocks, the temperature profile and the pore fluid pressure. Crustal mechanical characteristics imply rheological stratifications. In particular, the brittle/ductile transition is shallower in areas characterized by high heat flow values. Chen and Molnar (1983) found that in regions affected by high geothermal anomalies, the maximum focal depths are shallow and most of the seismicity occurs within the first 15 km.

To describe shallower seismicity, the most updated and reviewed worldwide catalogue of instrumental seismicity compiled by the International Seismological Centre (Storchak et al., 2013) was considered. The determination of earthquakes' hypocentral depth can sometimes be a critical parameter (Bondar et al., 2015). Hence, for the sake of simplicity, all earthquakes characterized by $M \geq 4.95$ that occurred within a depth of 20 km are mapped in Fig. 5 and compared to the heat