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RADON, CARBON DIOXIDE AND FAULT DISPLACEMENTS IN CENTRAL EUROPE RELATED TO THE TŌHOKU EARTHQUAKE

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Tectonic instability may be measured directly using extensometers installed across active faults or it may be indicated by anomalous natural gas concentrations in the vicinity of active faults. This paper presents the results of fault displacement monitoring at two sites in the Bohemian Massif and Western Carpathians. These data have been supplemented by radon monitoring in the Mladeč Caves and by carbon dioxide monitoring in the Zbrašov Aragonite Caves. A significant period of tectonic instability is indicated by changes in the fault displacement trends and by anomalous radon and carbon dioxide concentrations. This was recorded around the time of the catastrophic $M_W = 9.0$ Tōhoku Earthquake, which hit eastern Japan on 11 March 2011. It is tentatively suggested that the Tōhoku Earthquake in the Pacific Ocean and the unusual geodynamic activity recorded in the Bohemian Massif and Western Carpathians both reflect contemporaneous global tectonic changes.

INTRODUCTION

It is possible to measure tectonic instability directly using extensometers installed across active faults(1, 2). However, in the absence of direct measurements, instability can also be inferred from anomalous concentrations of radon or carbon dioxide in the vicinity of active faults. Many studies have shown that high concentrations of these gases relate closely to geodynamic phenomena such as earthquakes(3) or the body tides of the Earth(4). These relationships exist because the geodynamic phenomena lead to a fundamental change in the volume of the rock mass and such volumetric changes enable greater amounts of gas to emanate towards the ground surface. However, perhaps surprisingly, few studies have been able to show a convincing relationship between directly measured fault displacements and anomalous radon or carbon dioxide concentrations. In recent years, a number of natural laboratories have been established across central Europe to record both active fault displacements and a range of natural gases including ^{222}Rn and CO_2(5).

This study aims to further constrain the relationship between directly recorded fault displacements and significant anomalies in radon and carbon dioxide concentrations. The two study sites are situated in the broad contact zone between the Bohemian Massif and Western Carpathians (Figure 1). The Bohemian Massif represents the easternmost part of the European Platform, while the Western Carpathians comprises part of the Alpine-Carpathian Orogenic Belt. The contact between the two units is represented by an accretionary prism whose evolution took place from the Palaeogene to the Neogene. The fault displacement monitoring is supplemented by ^{222}Rn monitoring in the Mladeč Caves and by CO_2 monitoring in the Zbrašov Aragonite Caves. The Mladeč Caves are located in the foreland of the Western Carpathians, near the town of Olomouc, at the southern edge of the regionally significant Hornomoravský úval Fault Zone. The Zbrašov Aragonite Caves are located at the contact between the Bohemian Massif and Western Carpathians, near the town of Teplice, in the Devonian limestones of the Hranice Karst.

BACKGROUND

^{222}Rn originates from the radioactive decay of ^{226}Ra in the ^{228}U decay series(6). The atoms are dissolved and transported towards the ground surface with diffusion normally taking place along preferential pathways such as faults(7, 8). The rate of diffusion along a fault may be influenced by a number of factors including its propensity to move and the character of the fault infill. In the Bohemian Massif and Western Carpathians cave radon concentrations are known to change significantly at times of increased tectonic instability(5). However, in this region, the mass activity of the radon parent element, ^{226}Ra, is generally low for carbonate and clastic lithologies. For example, it is 20–60 Bq kg^{-1} for carbonate lithologies and 3–20 Bq kg^{-1} for clastic lithologies in show caves in the Czech Republic. Despite this, the caves are often associated with high radon concentrations, sometimes as much as tens of thousands of Bq m^{-3}. The high concentrations accumulate despite very low emanation coefficients, which vary from 0.0 to 0.1, and

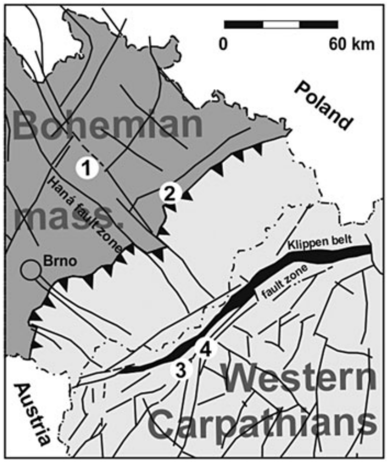

Figure 1. The location of the fault displacement monitoring sites in the contact zone between the Western Carpathians and Bohemian Massif. 1, Mladeč Caves; 2, Zbrašov Aragonite Caves; 3, Čachtická Cave; 4, Beckovská Cave.

reflect the low cave ventilation coefficient (c. 0.1 h^{-1}). It is also known that gases emanating from faults are commonly characterised by relatively high concentrations of carbon dioxide[9, 10]. This often, although by no means exclusively, originates from degassing of the mantle and, therefore, the rate of diffusion is also influenced by the same factors as those that are applicable for radon. Many CO_2-rich springs are associated with major zones of seismicity including some that have been found in association with rifting continental platforms[11].

METHODS

The active fault displacements at both sites are recorded using a type of 3D extensometer called a TM-71[12]. These are installed in caves because the faults in such settings are largely shielded from diurnal or seasonal climatic effects[13]. The relative displacements are recorded with a precision of better than ± 0.007 mm, while the angular rotations are recorded with a precision of better than ± 0.00016 rad[14]. In the Mladeč Caves, the radon concentrations are recorded using a radon monitor Radim 3A, while the temperature and atmospheric pressure are recorded using an Ejkelkamp Baro-Diver. The Radim 3A has been placed in a plastic box with an anhydrous calcium chloride desiccant that does not adsorb radon and, therefore, it is not necessary to correct the results for humidity[5]. In the Zbrašov Aragonite Caves, the carbon dioxide concentrations, temperature and atmospheric pressure are recorded using a Gascard-II Infrared Gas Sensor. The statistical processing of continually monitored radon and carbon dioxide concentrations has been made for the period from September 2010–2011.

RESULTS

Mladeč Caves

The Mladeč Caves are equipped with two TM-71s, a RADIM 3A and an Ejkelkamp Baro-Diver. During the past 4 y of monitoring, it has not been possible to characterise significant fault displacement trends at this site. In contrast, however, processing of the radon dataset has provided important results. Initial attempts to process the measured radon concentrations in order to find diurnal variations proved unsuccessful. In view of this fact, the data were divided into a training dataset and a testing dataset. The training dataset comprised a total of 553 values measured prior to the Tōhoku Earthquake on 11 March 2011 (all values were measured prior to 14 January 2011). This dataset was used to generate a suitable statistical model of the radon time line. The software Statgraphics Centurion XVI compared five different forecasting models and, for each model, five tests were run on the residuals to determine whether the model was adequate for the data. The selected model, the Simple exponential model, passed four tests and had the smallest mean absolute percentage error. In the model the parameter alpha equals 0.7248, the mean absolute deviation equals 73.78 Bq m^{-3} and the mean absolute percentage error equals 2.28 %. Figure 2 presents the annual record of radon concentrations measured at the Mladeč Caves and the absolute percentage error of the Simple exponential model calculated using the formula: ((measured value − forecast values)/measured value). It shows clear anomalies in the cave radon concentrations shortly before the catastrophic $M_W = 9.0$ Tōhoku Earthquake.

Zbrašov Aragonite Caves

The Zbrašov Aragonite Caves, located 57 km east–southeast of the Mladeč Caves, is equipped with four TM-71s and a Gascard-II Infrared Gas Sensor. Three of the TM-71s were installed in 2006, with a fourth added in 2011, while the Gascard-II was installed in 2007. During early 2011, enormous concentrations of carbon dioxide were recorded (Figure 3). The CO_2 concentrations dropped from ~7 % on the 23 February to 0.4–0.6 % on the 24 February. These low values persisted until the 12 March, after which they increased rapidly until attaining a maxima of 53–54 % by the end of March. Furthermore, two of the TM-71s presented notable fault displacements during March 2011. At Site No. 2, dextral strike-slip movements were observed, which contrast directly to the long-term sinistral strike-slip trend. At Site No. 3, clear horizontal rotation occurred after the 11 March 2011 (Figure 4).

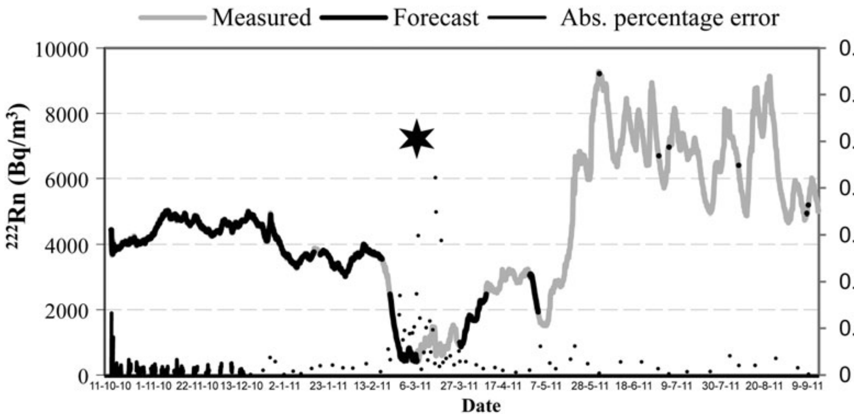

Figure 2. The annual record of radon concentrations measured at Mladeč Caves and the absolute percentage error of the Simple exponential model (star represents the Tōhoku Earthquake).

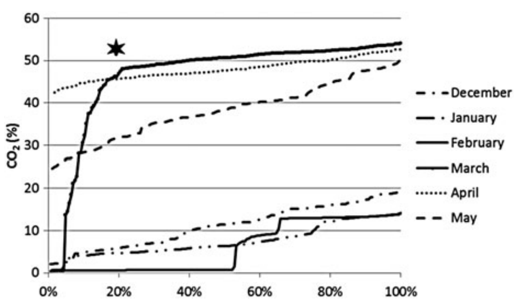

Figure 3. Cumulative percentage curves of CO_2 concentration for the months December 2010 to May 2011 (star represents the Tōhoku Earthquake).

These movements are interpreted to reflect a post-seismic slip associated with the Tōhoku Earthquake. It is important to note that both the horizontal rotation that occurred at Site No. 3 and the measured CO_2 concentrations are characterised by two peaks, demonstrating the association between the active fault displacements and natural gas emanation during times of tectonic instability. In addition, coseismic displacements were observed at a third site, Čachtická Cave, in the Western Carpathians (Figure 4). This site is 89 km south–southeast of the Zbrašov Aragonite Caves.

DISCUSSION

The two sites described in this paper form part of the fault displacement monitoring network EU-TecNet. This network comprises more than 100 sites in the crystalline basement of central Europe. The results obtained during the past decade have established that the underlying tectonic processes are initiated as a result of the widespread redistribution of stress and strain in the crust[2]. More specifically, in the Bohemian Massif and Western Carpathians, it has been demonstrated that active fault displacements reflect the ongoing modification of the regional stress field. Furthermore, it is known that the optical–mechanical crack gauges record nearby earthquakes[15], while it has been proposed that they may also record globally significant seismic events[16]. However, the relationship between active fault displacements and seismic activity is difficult to define: for example, an earthquake may terminate or initiate fault displacements. Perhaps more commonly, however, an earthquake may simply modify the recorded fault displacement trends. This reflects the fact that tectonic processes are characterised by fault movements without necessarily needing to be associated with seismic activity.

The results presented in this paper demonstrate that there was a protracted period of tectonic instability in the Bohemian Massif and Western Carpathians during 2011. This is reflected both by radon concentrations recorded in the Mladeč Caves and by the fault displacements and carbon dioxide concentrations recorded in the Zbrašov Aragonite Caves. Furthermore, at the same time, the data recorded at a number of fault displacement monitoring sites in the Western Carpathians are characterised by modifications to the recorded strike-slip displacement trends (Figure 4). It has been noted that this period of significant tectonic instability relates temporally to the catastrophic $M_W = 9.0$ Tōhoku Earthquake that occurred on 11 March 2011. It is, therefore, tentatively suggested that the recorded tectonic instability in the Bohemian Massif and Western Carpathians and the Tōhoku Earthquake offshore Japan both fit within a framework of contemporaneous global tectonic changes.

The radon concentrations measured in the Mladeč Caves showed anomalies ~10 d before the

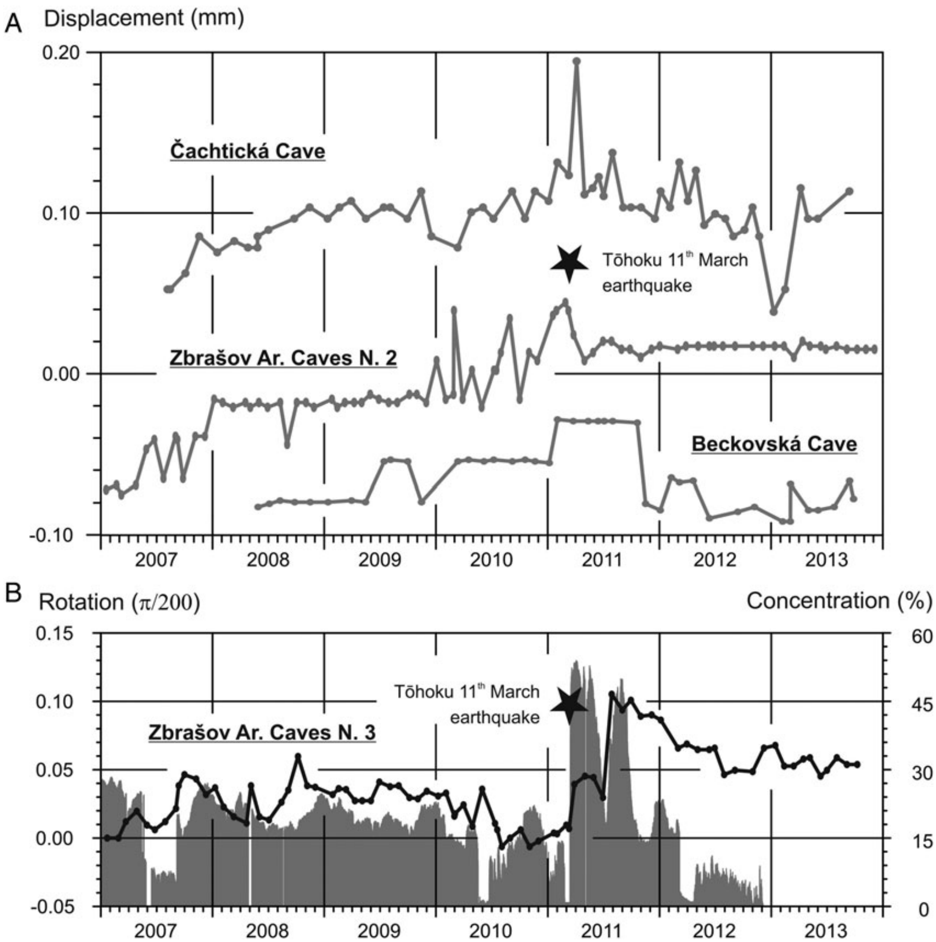

Figure 4. Directly recorded fault movements and CO_2 monitoring results around the Tōhoku Earthquake. (**A**) Significant strike-slip displacements at three monitored caves in the Western Carpathians. (**B**) Horizontal block rotation at Site No. 2 and CO_2 concentrations in Zbrašov Aragonite Caves (star represents the Tōhoku Earthquake).

earthquake. These anomalous concentrations lasted for 1 week and are interpreted to represent a precursor to the Tōhoku Earthquake. The changes to the strike-slip trends recorded from 2010 until the Tōhoku Earthquake at Site No. 2 in the Zbrašov Aragonite Caves, as well as the dramatic decrease in carbon dioxide concentrations recorded after 23 February 2011, suggest that these also reflect far-field precursors to the major earthquake event. Furthermore, a very interesting relationship between the radon and carbon dioxide concentrations has been noted during this period of tectonic instability. The long-term trend of the radon and carbon dioxide curves was found to be identical, with a correlation coefficient of $R^2 = 0.92$, albeit with a shift of 66 d. The reason for this shift is as yet unknown and will form the basis of further research.

CONCLUSIONS

This paper has presented the results of fault displacement monitoring at two caves in the Bohemian Massif. The fault displacement monitoring has been supplemented by radon monitoring at the Mladeč Caves and by carbon dioxide monitoring at the Zbrašov Aragonite Caves. It has been shown that there was a significant period of tectonic instability, reflected by changes in fault displacement trends and anomalous radon and carbon dioxide concentrations, during 2011. This period of tectonic instability was recorded around the time of the catastrophic $M_W = 9.0$ Tōhoku Earthquake on 11 March 2011. It is tentatively suggested that the Tōhoku Earthquake in the Pacific Ocean and the unusual amount of geodynamic activity recorded in the Bohemian Massif and

Western Carpathians reflect contemporaneous global tectonic changes. The recorded anomalous carbon dioxide and radon concentrations, measured only a few days before the Tōhoku Earthquake, suggest that they reflect earthquake precursors.

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REFERENCES

1. Briestenský, M., Stemberk, J., Michalík, J., Bella, P. and Rowberry, M. D. *The use of a karstic cave system in a study of active tectonics: fault movements recorded at Driny Cave, Malé Karpaty Mts (Slovakia)*. J. Cave Karst Stud. **73**, 114–123 (2011).
2. Stemberk, J., Košt'ák, B. and Cacon, S. *A tectonic pressure pulse and increased geodynamic activity recorded from the long-term monitoring of faults in Europe.* Tectonophysics **487**, 1–12 (2010).
3. Heinicke, J., Koch, U. and Martinelli, G. *CO_2 and radon measurements in the Vogtland Area (Germany)—a contribution to earthquake prediction research*. Geophys. Res. Lett. **22**, 771–774 (1995).
4. Spivak, A. A., Kozhukhov, S. A., Sukhorukov, M. V. and Kharlamov, V. A. *Radon emanation as an indicator of the intensity of intergeospheric interactions at the Earth's crust-atmosphere interface.* Izv. Phys. Solid Earth **45**, 118–133 (2009).
5. Briestenský, M., Thinová, L., Stemberk, J. and Rowberry, M. D. *The use of caves as observatories for recent geodynamic activity and radon gas concentrations in the Western Carpathians and Bohemian Massif.* Radiat. Prot. Dosim. **145**, 166–172 (2011).
6. Šebela, S., Vaupotič, J., Košt'ák, B. and Stemberk, J. *Direct measurement of present-day tectonic movement and associated radon flux in Postojna Cave, Slovenia*. J. Cave Karst Stud. **72**, 21–34 (2010).
7. Pizzano, I., Galli, G., Mancini, C., Quattrocchi, F. and Scarlato, P. *Natural gas hazards (CO_2, ^{222}Rn) within a quiescent volcanic region and its relations with tectonics: the case of the Ciampino-Marino Area, Alban Hills Volcano, Italy.* Nat. Hazards **27**, 257–287 (2002).
8. Planinic, J., Radolić, V. and Vuković, B. *Radon as an earthquake precursor.* Nucl. Instrum. Methods Phys. Res. A **530**, 568–574 (2004).
9. Sugisaki, R., Ido, M., Takeda, H., Isobe, Y., Hayashi, Y., Nakamura, N., Satake, H. and Mizutani, Y. *Origin of hydrogen and carbon dioxide in fault gases and its relation to fault activity.* J. Geol. **91**, 239–258 (1983).
10. Chiodini, G., Cardellini, C., Amato, A., Boschi, E., Caliro, S., Frondini, F. and Ventura, G. *Carbon dioxide Earth degassing and seismogenesis in central and southern Italy.* Geophys. Res. Lett. **31**, L07615 (2004).
11. Irwin, W. P. and Barnes, I. *Tectonic relations of carbon dioxide discharges and earthquakes.* J. Geophys. Res. **85**(B6), 3115–3121 (1980).
12. Klimeš, J., Rowberry, M. D., Blahůt, J., Briestenský, M., Hartvich, F., Košt'ák, B., Rybář, J., Stemberk, J. and Štěpančíková, P. *The monitoring of slow-moving landslides and assessment of stabilisation measures using an optical-mechanical crack gauge.* Landslides **9**, 407–415 (2012).
13. Briestenský, M., Košt'ák, B., Stemberk, J., Petro, L., Vozár, J. and Fojtíková, L. *Active tectonic fault microdisplacement analyses: a comparison of results from surface and underground monitoring in western Slovakia*. Acta Geodyn. Geomater. **7**, 387–397 (2010).
14. Marti, X., Rowberry, M. D. and Blahůt, J. *A MATLAB® code for counting the moiré interference fringes recorded by the optical-mechanical crack gauge TM-71*. Comput. Geosci. **52**, 164–167 (2013).
15. Briestenský, M., Stemberk, J. and Petro, L. *Displacements registered around March 13 2006 Vrbové earthquake, $M = 3{,}2$ (Western Carpathians)*. Geol. Carpath. **58**, 487–493 (2007).
16. Košt'ák, B., Cacoń, S., Dobrev, N. D., Avramova-Tacheva, E., Fecker, E., Kopecký, J., Petro, L., Schweizer, R. and Nikonov, A. A. *Observations of tectonic microdisplacements in Europe in relation to the Iran 1997 and Turkey 1999 earthquakes: Izvestiya*. Phys. Solid Earth **43**, 503–516 (2007).