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Continuous monitoring of radon gas as a tool to understand air dynamics in the cave of Altamira (Cantabria, Spain)

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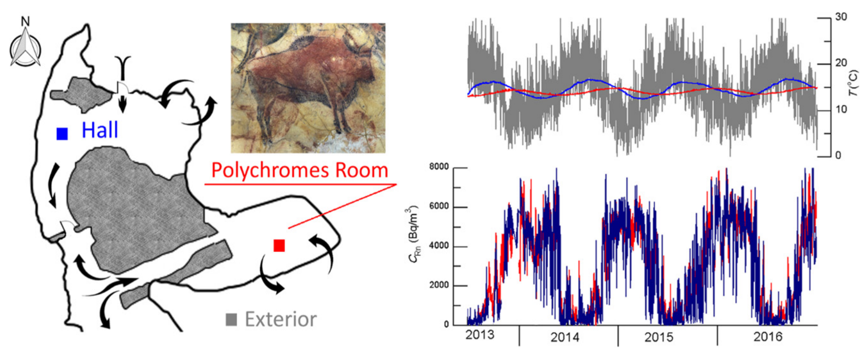
HIGHLIGHTS

- The distribution of radon concentration reflects the air exchange rates in the cave.
- Knowledge of environmental conditions is relevant in the rock art conservation.
- Main gaseous charge-discharge processes occur seasonally at Altamira cave.
- Radon continuous monitoring is a valuable tool for studying atmospheric dynamics.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of radon as an atmospheric tracer in the Altamira Cave over the past 30 years has provided relevant information about gaseous exchanges between the Polychromes Room, the adjoining Chambers inside the cave, and the outside atmosphere. The relatively simple physico-chemical behaviour of radon gas provides a marked advantage over other tracer gases that are usually present in high concentrations in hypogeous environments, such as CO_2. Two types of continuous radon measurement were undertaken. The first involves active detectors located in the Hall and Polychromes Room, which provide radon concentration values at 1-hour intervals. In addition, nuclear solid track etched detectors (CR-39) are used in every chamber of the cave over 14-day exposure periods, providing average radon concentrations. In this paper we show some of the specific degassing and recharge events identified by anomalous variations in the concentration of radon gas in the Polychromes Room. In addition, we update knowledge regarding the degree of connection between chambers inside the cave and with the outside atmosphere. We verify that the connection between the Polychromes Room and the rest of the cave has been drastically reduced by the installation of the second closure in 2008. Except for point exchanges with the Crossing zone generated by a negative temperature gradient in that direction, the atmosphere of the Polychromes Room remains stable, or else it exchanges matter with the outside atmosphere through the karst interface. The role of radon as a tracer is demonstrated to be valid both to reflect seasonal cycles of degassing and recharge, and to analyse shorter (daily) period fluctuations.

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1. Introduction

The Cave of Altamira is known worldwide for the ancient rock art that it contains. The pictorial representations dating back about 15,000 years, mainly concentrated in the so-called Polychromes Room, are rank among the best artistic manifestations in the history of Humanity, their value being not only symbolic, but also technical and representative (Lasheras et al., 2014). Altamira Cave was named a World Heritage Site in 1985 by UNESCO (http://whc.unesco.org/en/list/310).

Since its discovery in around 1868, the cave has been visited by a large number of people attracted by the beauty and realism of the pictorial representations it contains. In 1977, the great influx of visitors led to the decision to close the cave in order to conserve its cultural heritage due to increase in CO_2, temperature and lighting which promote the development of Lampenflora (Pfendler et al., 2018). During this first closure, scientific studies began to investigate how best to conserve the paintings. These studies included a detailed analysis of both the geological and environmental setting of the paintings, and the impact that the presence of visitors exerted on their state of conservation (Villar et al., 1984b, 1986). These studies provided the first integral view of the physico-chemical conditions under which the paintings were preserved, and provided the first models to explain the dynamics of gaseous exchanges between the various chambers inside the cave and between the cave and the outside environment (Villar et al., 1983, 1984a, 1985; Villar, 1986). Thanks to the systematic acquisition of further environmental data, and to the improvement of the theoretical models over successive research projects, we currently have quite a complete and complex vision of the main thermal, hydric and atmospheric processes that affect the conservation of the paintings, and also of the possible impacts that the ingress of visitors would have on those processes (Soler et al., 1999; Sánchez-Moral et al., 1999, 2010).

All work to date has used the concentration of radon gas (^{222}Rn) inside the cave to investigate the atmospheric dynamics of the Altamira Cave, (Fernández et al., 1986; Lario et al., 2005; Cuezva et al., 2011; Garcia-Anton et al., 2014). It is well known that radon is a natural radioactive gas that comes from the disintegration of the ^{226}Ra present in variable amounts in most rocks and soils of the earth's crust; radon tends to accumulate in poorly ventilated ground or underground enclosures (Quindós et al., 1991). Radon gas has been used as a tracer of dynamic processes in aqueous and aerial media on numerous occasions (Fernández et al., 1984; Frisia et al., 2011; Kowalczk and Froelich, 2010; Sainz et al., 2016). The relatively simple physico-chemical behaviour of radon gas means that it has a marked advantage over other tracer gases, such as CO_2, which are usually present in high concentrations in hypogeous environments (Batiot-Guilhe et al., 2007; Nazaroff and Nero Jr, 1988). The generation of radon gas inside the cave can be considered practically constant as there are no processes that significantly alter either the concentration of ^{226}Ra in the rock or the emission of radon over its surfaces. For this reason, positive increments in radon concentration inside a rock chamber can only be due to its increased isolation with respect to the outside atmosphere, which typically has very low radon concentrations, or to a supply of air from adjacent chambers containing significantly higher concentrations of the gas. Likewise, reductions in radon concentration in such a chamber can only be produced by radioactive decay or due to an air supply containing a lower concentration of the gas, usually from more superficial or external locations. Radon is a noble gas, which makes it highly unlikely that its concentration reduces by means of chemical reactions with the environment in which it is found (Nazaroff and Nero Jr, 1988).

Over the past 30 years, the use of radon as an atmospheric tracer in Altamira Cave has provided relevant information about gaseous exchange between the Polychromes Room, the adjoining chambers inside the cave, and the exterior atmosphere. During the 1980s the first estimates of the rates of air exchange between the Polychromes Room and the large hall inside the cave entrance, called the Hall, were made (Fernández et al., 1986). By also using the CO_2 concentrations, they proposed a model of air exchange which was driven by the temperature gradient between the two chambers at different times of the year. In 2008, this connection was significantly altered with the installation of a second seal door designed to reduce the ingress of organic matter into the Polychromes Room and to stabilise its temperature. Later studies provided detailed descriptions of the exchange processes between the Polychromes Room and the exterior through the karst host rock (Sánchez-Moral et al., 2009, 2012; Somavilla et al., 1978).

As in other caves, the seasonal loading and discharging of gases in the Altamira Cave – particularly in the Polychromes Room – are easily visualised by continuous monitoring of radon and CO_2 concentrations (Cuezva et al., 2011). In deep caves, with a single point of connection with the outside, usually the entrance, concentrations of radon and CO_2 are at a maximum in summer, and at a minimum in winter. These dynamics can be easily explained by the mass displacements that are caused by differences in air density between the cave interior and exterior at different times of year. However, the Cave of Altamira is quite shallow – the overburden above its ceilings varies from 2 to 10 m, although it can reach 18 m in places (Elez et al., 2013). Its karstic configuration favours gaseous exchange with the exterior through parts of the cavity other than the main entrance. For this reason, the dynamics of tracer gas concentrations (such as Rn and CO_2) can be very different, or even opposite to what is usually observed in deep caves.

This overall dynamics of gas exchange within Altamira Cave has various exceptions, such as in the event of an abrupt change or inversion of the temperature gradient between the outer and inner atmosphere of the cave. This article outlines some specific degassing and recharges events identified by anomalous variations in radon gas concentration in the Polychromes Room. In addition, knowledge about the degree of connection between Chambers inside the cave and between these and the outside atmosphere is updated.

2. Material and methods

2.1. Location and characteristics of the Altamira Cave

The Altamira Cave is located in Santillana del Mar (Cantabria, Spain) at an elevation of more than 150 m above sea level. Its entrance faces North and the cave as a whole is oriented northwest. It is a rather shallow cave, with a difference in elevation of around 16 m between the level of the entrance and its deepest point of (Fig. 1).

About 25 m from the entrance, just beyond the second artificial door, is a junction, called El Cruce ('The Crossing'). Ahead lies the access to the deeper chambers of the cave, while to the left, descending about 2 m *via* some stairs, is the access to the Polychromes Room. This chamber is about 15 m long and 7 m wide, with an average height of less than 3 m; it is here that the spectacular coloured pictorial representations on the ceiling were made, which led to the cave being dubbed the 'Sistine Chapel' of Quaternary Art (Déchelette, 1908; Elez et al., 2013) The volume of the Polychromes Room is approximately 342 m^3 and the ceiling area is 159 m^2.

The microclimate inside the cave is characterised by very stable temperatures throughout the year, with a thermal oscillation in the Polychromes Room of less than 2 °C. This oscillation is described by a sinusoidal wave that is out of phase and damped with respect to the annual thermal oscillation outside. This is due to the layer of rock between the ceiling of the chamber and the ground surface immediately above.

2.2. Radon gas concentration measurements

Two types of continuous radon measurement are made inside the Cave of Altamira. The first involves active detectors located in the Hall and Polychromes Room, which provide radon concentration at 1-hour intervals. In addition, in every chamber of the cave, nuclear solid track etched detectors (CR-39) provide averaged radon concentrations over exposure periods of two weeks.