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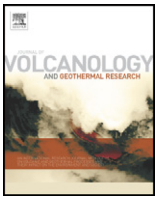

Jurassic hot spring deposits of the Deseado Massif (Patagonia, Argentina): Characteristics and controls on regional distribution

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ABSTRACT

The Deseado Massif, Santa Cruz Province, Argentinean Patagonia, hosts numerous Middle to Late Jurassic age geothermal and epithermal features represented by siliceous and calcareous chemical precipitates from hot springs (sinters and travertines, respectively), hydrothermal breccias, quartz veins, and widespread hydrothermal silicification. They indicate pauses in explosive volcanic activity, marking the final stages in the evolution of an extensive Jurassic (ca. 178–151 Ma) volcanic complex set in a diffuse extensional back-arc setting heralding the opening of the Atlantic Ocean. Published paleo-hot spring sites for the Deseado Massif, plus additional sites identified during our recent field studies, reveal a total of 23 locations, five of which were studied in detail to determine their geologic and facies associations. They show structural, lithologic, textural and biotic similarities with Miocene to Recent hot spring systems from the Taupo and Coromandel volcanic zones, New Zealand, as well as with modern examples from Yellowstone National Park, U.S.A. These comparisons aid in the definition of facies assemblages for Deseado Massif deposits – proximal, middle apron and distal siliceous sinter and travertine terraces and mounds, with preservation of many types of stromatolitic fabrics – that likely were controlled by formation temperature, pH, hydrodynamics and fluid compositions. Locally the mapped hot spring deposits largely occur in association with reworked volcaniclastic lacustrine and/or fluvial sediments, silicic to intermediate lava domes, and hydrothermal mineralization, all of which are related to local and regional structural lineaments. Moreover, the numerous geothermal and significant epithermal (those with published minable resources) deposits of the Deseado Massif geological province mostly occur in four regional NNW and WNW hydrothermal–structural belts (Northwestern, Northern, Central, and Southern), defined here by alignment of five or more hot spring deposits and confirmed as structurally controlled by aeromagnetic data. The Northern and Northwestern belts, in particular, concentrate most of the geothermal and epithermal occurrences. Hence, Jurassic hydrothermal fluid flow was strongly influenced by the most dominant and long-active geological boundaries in the region, the outer limits of the Deseado Massif 'horst' itself.

1. Introduction

Geothermal systems are of interest from a geological point of view because they may indicate potential energy resources at depth, have a close spatial relationship with epithermal mineralization, and their surface manifestations as hot springs serve as analog 'extreme environments' for settings where life may have taken hold on early Earth and possibly other planets (e.g. Sillitoe, 1993; Farmer and Des Marais, 1999; Farmer, 2000). Terrestrial hot springs typically develop in topographically low areas where the phreatic water level intercepts the land surface (Sillitoe, 1993). They occur mostly in active volcanic regions wherein hydrothermal activity also may form metalliferous deposits at depth (Sillitoe, 1993). Hot springs commonly precipitate siliceous sinter from near-neutral pH alkali chloride or acid-sulfate-chloride waters, or travertine from bicarbonate waters, derived from circulation of magma-heated fluids with variable inputs of groundwater (e.g. Fournier, 1985; Pentecost, 2005; Schinteie et al., 2007). Geothermal fluids emit from spring vents at the Earth's surface, cooling as they discharge (~100 °C to ambient) along channels, into pools, over terraces, and finally spreading out in their distal reaches to create geothermally influenced wetlands — all the while mineralizing and entrapping biotic or abiotic materials intercepted by the outflow (e.g. Weed, 1889; Walter, 1976). Many terrestrial hot springs are situated along rivers (e.g. Lloyd, 1972), or are found in lakes (e.g. Renaut et al., 2002; Pentecost, 2005; Jones et al., 2007). Gradients in temperature, pH and fluid composition largely dictate the biotic make-up of modern spring inhabitants in vent-to-marsh transects, many of which are microbial, especially in mid-slope and distal apron settings (e.g. Cady and Farmer, 1996; Fouke et al., 2000; Channing et

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al., 2004; Schinteie et al., 2007). Sinter aprons or travertine cones, mounds and terraces build up archives of surface hydrothermal activity, with variable preservation potential in the geologic record depending on regional volcanic and burial/erosional cycles (White et al., 1989; Simmons et al., 1993; Guido and Campbell, 2009). Where hot spring deposits are preserved, they may provide excellent records of paleoenvironmental information owing to rapid *in situ* mineralization (e.g. Walter et al., 1976; Campbell et al., 2001; Trewin, 2001; Pentecost, 2005; Guido et al., 2010; Channing et al., 2011).

The Deseado Massif (Santa Cruz, southern Patagonia) is a 60,000 km^2 geological province (Fig. 1) characterized by extensive (>30,000 km^2), Middle to Late Jurassic bimodal volcanic and related rocks of the Bahía Laura Group (Chon Aike and La Matilde formations) and Bajo Pobre Formation, including calc-alkaline rhyolites and minor andesites and dacites. Herein, we favor the use of the term Bahía Laura Complex (BLC) to encompass both the Bahía Laura Group and Bajo Pobre Formation for these genetically related units because Chon Aike silicic volcanics are intercalated with Bajo Pobre andesites (Echeveste et al., 2001; Guido et al., 2006), and La Matilde strata constitute reworked Chon Aike volcaniclastic materials (Guido, 2004). In general, La Matilde strata, including fossil hot spring deposits, are found at the top of the sequence, together with intermediate to silicic lava domes of the Chon Aike Formation, which together formed in a mature (quiescent) phase of volcanism during the Late Jurassic (Guido, 2004). Collectively, these rocks are part of the Chon Aike Silicic Large Igneous Province (Argentinean Patagonia to Antarctica; Pankhurst et al., 1998), which traditionally have been interpreted to mark the beginning of supercontinent break-up owing to both slow subduction rates at the Pacific margin of Gondwana and a mantle plume active in the Jurassic (Pankhurst et al., 2000; Riley et al., 2001). Herein, we adopt a more recent tectonic model encompassing Jurassic events from Patagonia to the Falklands (Islas Malvinas), based on a study of North Falkland Basin exploration wireline logs, cores, petrography and geochemistry, in which a diffuse back-arc extensional zone was inferred for the Deseado Massif (Richardson and Underhill, 2002; their Fig. 20, p. 440).

During the Middle to Late Jurassic, extension, magmatism and a high thermal gradient produced Bahía Laura volcanics and related hydrothermal mineralization in the Deseado Massif, including economic gold- and silver-bearing, mainly low-sulfidation type epithermal deposits (four mines are in current production), and numerous hot spring occurrences (Fig. 1; Guido and Schalamuk, 2003). The hot spring deposits comprise mostly travertines, some siliceous sinters, and geothermally related cherts that are hosted in tuffs, breccias, and reworked volcaniclastic sediments within fluviolacustrine settings over a 230 × 230 km area (Fig. 1). The Jurassic Patagonian rocks subsequently were buried by Cretaceous and Cenozoic continental and marine passive margin successions (Giacosa et al., 2010), and then unearthed with minimal structural disturbance to expose intact, erosional windows into exhumed geothermal and epithermal systems.

The regional geological setting and geographic distribution of the 23 total known Jurassic hot spring systems of the Deseado Massif (Fig. 1), discussed further below, suggest that they are structurally controlled. To date, some of these systems have been the subject of published contributions such as those described at La Josefina (Echeveste et al., 1995; Schalamuk et al., 1997; Moreira et al., 2002), Manantial Espejo (Schalamuk et al., 1997; Echeveste, 2005), El Macanudo (Schalamuk et al., 1997; Schalamuk et al., 1999), La Marcelina (Marchionni et al., 1999), La Marciana (Guido et al., 1999, 2002a; Guido and Campbell, 2009), Mariana–Eureka–Las Margaritas (also referred to as Cerro Negro; Guido et al., 2002b; Lopez et al., 2003), Cerro Tornillo (Mykietiuk and Lanfranchini, 2004), Cerro Contreras (Moreira et al., 2005), La Esperanza Oeste (Andrada de Palomera et al., 2005), Flecha Negra (Channing et al., 2007), La María (Moreira et al., 2008), Cerro Primero de Abril (Ruiz et al., 2008) and San Agustín (Guido et al., 2010). In addition, we have identified several new sites, based on recent reconnaissance field studies, from Cañadón Nahuel, Claudia, Cerro Vanguardia, Monte Illiria, La Bajada, La Herradura, La Leona, El Águila, La Flora and La Unión (Fig. 1). From a global perspective, the Deseado Massif geothermal systems substantially increase the number of known Mesozoic examples of hot spring-related travertines and siliceous sinters (Steinen et al., 1987; Pentecost, 2005; Guido and Campbell, 2009; Guido et al., 2010). They also partially fill a gap in the geological record of reported sinters, between those of Paleozoic age from Scotland (Rice and Trewin, 1988) and Australia (Cunneen and Sillitoe, 1989; White et al., 1989), and the numerous deposits known from the Cenozoic (e.g. Sillitoe, 1993).

To further illuminate the structural and lithological context of Deseado Massif geothermal manifestations, as well as to gain a deeper understanding of the wide spectrum of facies related to these deposits, we also conducted detailed geological mapping and sample analyses at five study sites representing the variety of hot spring deposits in the region — namely La Marciana, San Agustín, Claudia, Cerro Negro and El Macanudo. As a result, we identified typical proximal-to-distal (hot spring vent-to-margin) outcrop patterns and textural characteristics in a suite of facies associations for the Jurassic sinters and travertines, allowing us to infer paleoenvironmental conditions during their formation (*sensu* Reading, 1996). We find that they readily compare to much younger (Miocene to Recent) hot spring deposits from the Taupo and Coromandel volcanic zones in New Zealand, and Yellowstone National Park, U.S.A.

2. Structural and lithological controls on Deseado Massif hot spring distributions

2.1. Regional overview

Most of the Deseado Massif hot spring deposits are situated in the western part of the geological province, as was observed by Guido and Schalamuk (2003), with other groupings evident along its northern and southern boundaries (Fig. 1). The current data set, comprising the 23 known paleo-hot spring sites listed herein, suggests they are located on regional lineaments striking WNW (~N290°) or NNW (~N340°). Fig. 1A

Fig. 1. Major hydrothermal–structural trends inferred for Late Jurassic Deseado Massif geothermal–epithermal systems. (A) Generalized geological data for the Deseado Massif, including outcrop extent of the Bahía Laura Complex (BLC), and geographic position of the Massif in Argentina (inset). U–Pb and Ar–Ar ages of Bahía Laura Complex volcanics (dark green circles, 180–170 Ma; yellow circles, 170–160 Ma; red circles, 160–150 Ma) are from regional geochronological studies (Féraud et al., 1999; Pankhurst et al., 2000). Green boxes highlight hot spring localities compiled for this study (LU: La Unión, CN: Cerro Negro, CC: Cerro Contreras, LL: La Leona, NA: Cañadón Nahuel, EM: El Macanudo, LH: La Herradura, EA: El Águila, SA: San Agustín, LF: La Flora, LM: La Marcelina, EO: Esperanza Oeste, CT: Cerro Tornillo, LJ: La Josefina, FN: Flecha Negra, LB: La Bajada, MA: La Marciana, MR: La María, MI: Monte Illiria, CV: Cerro Vanguardia, CL: Claudia, CA: Cerro 1 Abril, ME: Manantial Espejo). Four major linear belts were identified – Northwestern (NW), Northern, Central, and Southern – based on alignment of five or more hot spring deposits; one shows NNW orientation and three show WNW orientation. (B) Geophysical and structural data in relation to location of geothermal and epithermal deposits of the Deseado Massif region. Main vein orientations (red lines, averaged strikes) of significant (having published resources), active epithermal Au–Ag mines and projects also are shown. Mines: 1, Cerro Vanguardia; 2, Mina Martha; 3, San José; 4, Manantial Espejo. Projects: 5, Cerro Negro; 6, Cerro Moro; 7, Lomada de Leiva; 8, Pingüino; 9, Cap Oeste; 10, Manchuria; 11, La Josefina; 12, La Paloma; and 13, Las Calandrias. RTP (reduced to pole) magnetic maps sourced from SEGEMAR (Chernicoff and Vargas, 1998; and Ferpozzi and Johanis, 2004). Black dashed lines represent major lineaments in agreement with hot spring deposit belts. Inset shows Giacosa et al.'s (2010) structural data for late Jurassic extensional to transtensional brittle deformation manifest in epithermal veins from a smaller central area of the Massif. Additional lineaments (thinner white dashed lines) were recognized from the aeromagnetic data that also coincide with geographic positions of significant epithermal mines/prospects, hot spring deposits, and the three regional strike directions proposed by Giacosa et al. (2010).