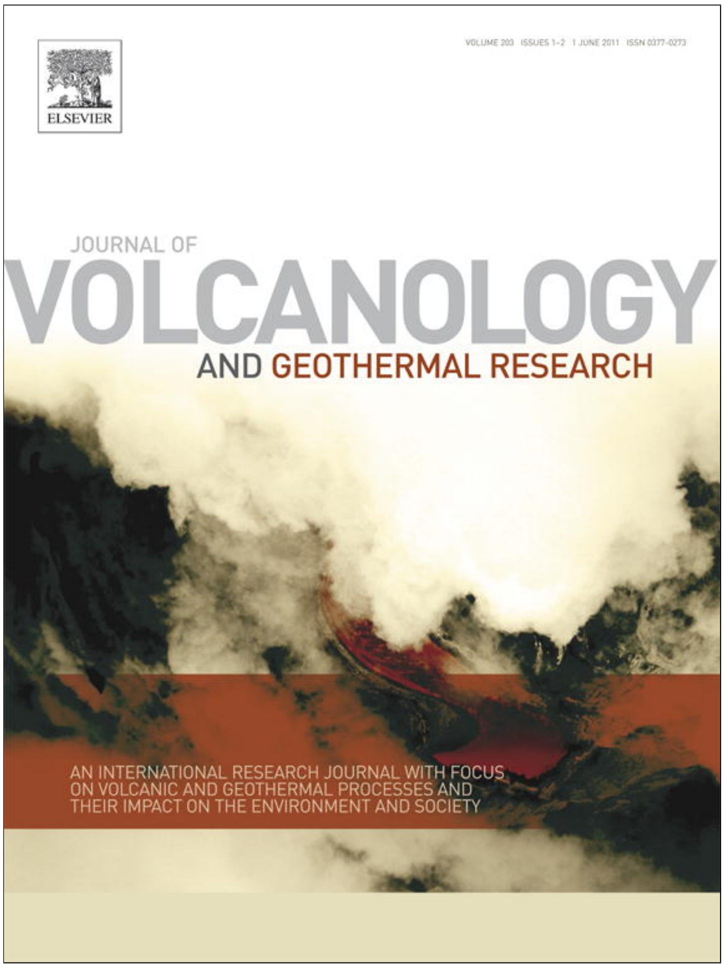
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Jurassic hot spring deposits of the Deseado Massif (Patagonia, Argentina): Characteristics and controls on regional distribution

Diego M. Guido [a,*], Kathleen A. Campbell [b]

[a] CONICET and Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Instituto de Recursos Minerales (INREMI), Calle 64 y 120, La Plata, (1900), Argentina
[b] Geology Programme, School of Environment, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

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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

* Corresponding author. Tel./fax: +54 221 4225648.
E-mail addresses: diegoguido@yahoo.com (D.M. Guido), ka.campbell@auckland.ac.nz (K.A. Campbell).

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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).

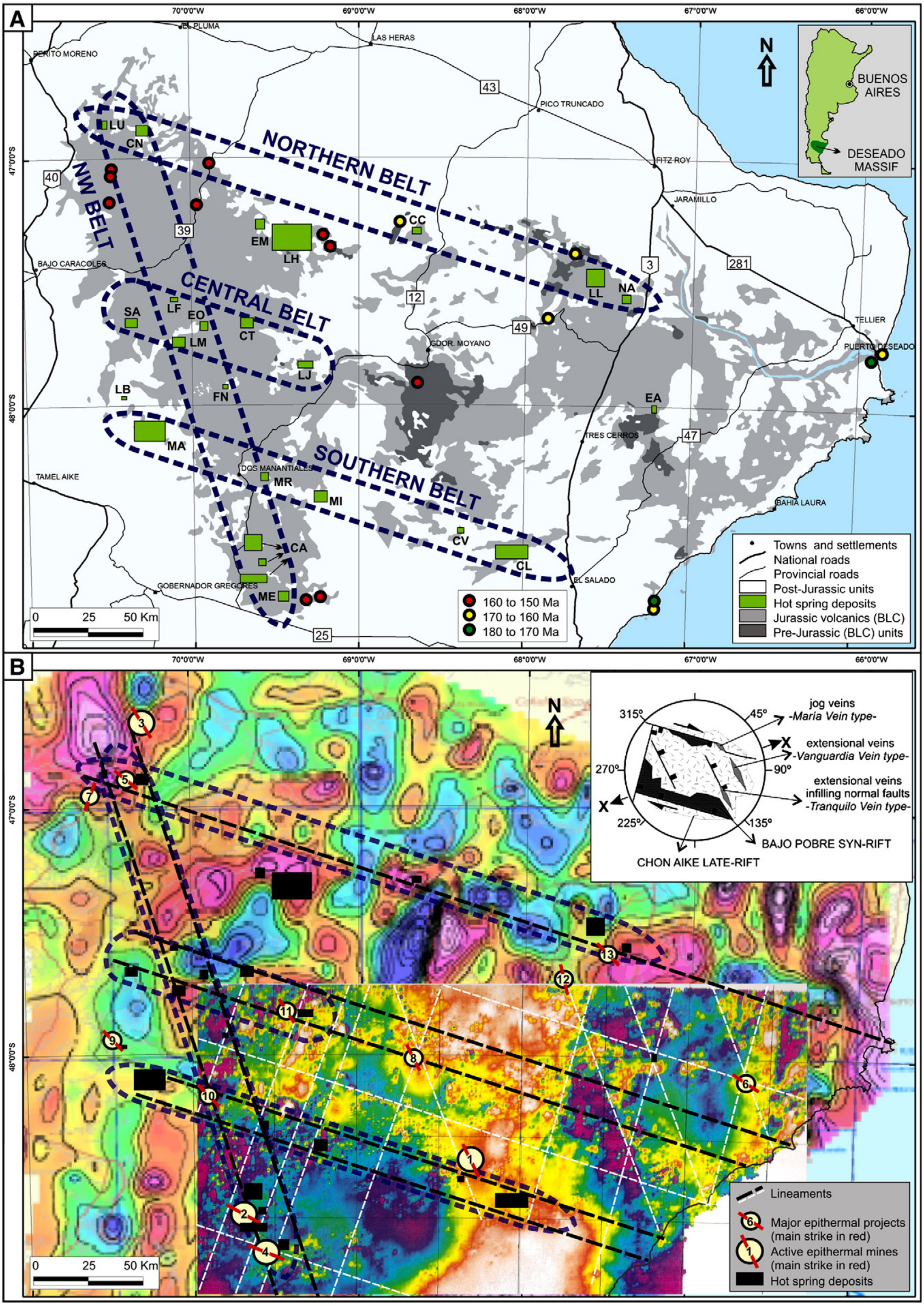
To further illuminate the structural and lithological context of Deseado Massif geothermal manifestations, as well as to gain a deeper understanding of the wide spectrum of facies related to these deposits, we also conducted detailed geological mapping and sample analyses at five study sites representing 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).


A
70°0'0"W
69°0'0"W
68°0'0"W
67°0'0"W
66°0'0"W
47°0'0"S
48°0'0"S
EL PLUMA
LAS HERAS
PERITO MORENO
PICO TRUNCADO
FITZ ROY
JARAMILLO
BAJO CARACOLES
GDOR. MOYANO
TELLIER
PUERTO DESEADO
TRES CERROS
DOS MANANTIALES
TAMEL AIKE
BAHIA LAURA
GOBERNADOR GREGORES
EL SALADO
NORTHERN BELT
NW BELT
CENTRAL BELT
SOUTHERN BELT
LU
CN
CC
EM
LH
LL
NA
SA
LF
EO
CT
LM
LJ
LB
FN
EA
MA
MR
MI
CA
CV
CL
ME
43
40
39
12
3
281
49
47
25
N
BUENOS AIRES
DESEADO MASSIF
0 25 50 Km
160 to 150 Ma
170 to 160 Ma
180 to 170 Ma
Towns and settlements
National roads
Provincial roads
Post-Jurassic units
Hot spring deposits
Jurassic volcanics (BLC)
Pre-Jurassic (BLC) units
B
N
315°
45°
270°
90°
225°
135°
X
jog veins
-María Vein type-
extensional veins
-Vanguardia Vein type-
extensional veins
infilling normal faults
-Tranquilo Vein type-
BAJO POBRE SYN-RIFT
CHON AIKE LATE-RIFT
0 25 50 Km
Lineaments
Major epithermal projects
(main strike in red)
Active epithermal mines
(main strike in red)
Hot spring deposits

illustrates this geological relationship, where four major belts are delineated by the intersection of five or more hot spring sites. The Northwestern Belt, or Manantial Espejo–Cerro Negro trend, is the most significant, in that it encompasses nine localities and has a 460 km geographic extent along a NNW strike. The other three belts have WNW strikes, with the central one, La Josefina–San Agustín, involving six localities. The other two trends are the Northern Belt, or La Unión–Cañadón Nahuel, and the Southern Belt, or La Marciana–Claudia, both with five localities.

Regional aeromagnetic data (Fig. 1B) from SEGEMAR (Chernicoff and Vargas, 1998, available only for the southern half of the study area; and Ferpozzi and Johanis, 2004), verify that major structural features (black dashed lines of Fig. 1B) underlie these regional hot-spring trends. Fig. 1B further shows the orientations (averaged) of the main strikes of epithermal features (hydrothermal breccias, pervasive silicification, quartz veins and veinlets) for 13 important Au–Ag epithermal deposit areas that are actively mined or are undergoing major project development (i.e., those areas that have published minable resources). Additional lineaments may be constructed from the 1998 aeromagnetic data (thinner white dashed lines of Fig. 1B) which also coincide with geographic positions of the significant epithermal mines/prospects and the hot-spring deposits; and are in agreement with the three regional strike directions proposed by Giacosa et al. (2010; Fig. 1B, inset). Thus, Deseado Massif hot spring deposits also appear to be spatially and structurally related to epithermal occurrences (Fig. 1), as first noted more generally by Schalamuk et al. (1997). Structural trends for the Jurassic geothermal–epithermal systems, identified herein using hot-spring distributions and aeromagnetic data (Fig. 1), were developed within an extensional to transtensional brittle deformation regime over a >20 m.y. interval that also was recognized in epithermal veins by Giacosa et al. (2010) for the central part of the Deseado Massif, using geological mapping and analysis of satellite images and seismic and aeromagnetic data. Jurassic epithermal–geothermal features are situated in dilatational fault jogs or releasing bends on strike-slip faults (Sibson, 1987) belonging to this structural setting. In other parts of the world, fluid migration-associated geological features (e.g., geothermal systems, epithermal mineralization, and seabed pockmarks) commonly align with structural zones and lineaments (e.g. Barnes et al., 1978; Le Turdu et al., 1999; Sims et al., 2002; Rowland and Sibson, 2004; Pilcher and Argent, 2007).

2.2. Site specific studies

An examination of the geological context of the five Deseado Massif localities that we studied in detail (Fig. 2) indicates that they are closely associated with lacustrine, fluvial or fluviolacustrine paleoenvironments, which represent pauses in explosive volcanic activity in those parts of the region. In addition, most of these paleo-geothermal systems are associated spatially with silicic to intermediate lava domes and hydrothermal mineralization, all related to regional and local structural lineaments.

For example, in the five localities the hot spring deposits are hosted in reworked volcaniclastic sediments of the La Matilde Formation. These include a lacustrine setting at San Agustín (Guido et al., 2010) and El Macanudo, fluvial at La Marciana (Guido and Campbell, 2009), and fluviolacustrine at Cerro Negro and Claudia. Additionally, four of the five localities (Fig. 2) are associated with lava domes and epithermal features (quartz veins and hydrothermal breccias) within 15 km of the hot spring deposits (e.g. La Marciana, Cerro Negro, San Agustín, and Claudia; Guido et al., 2002a; Guido et al., 2010; Guido and others, unpublished). The only exception is the El Macanudo site, where some silicification and Mn-rich breccias are the only evidence for epithermal activity and no volcanic dome was found. The lack of these two features at El Macanudo could correspond to a shallower level of exposure in relationship to the rest of the localities and/or to extensive younger geological units present, especially Cenozoic basalt flows, which locally may cover a greater area of Jurassic rocks.

In general, the type of geologic setting described herein – one dominated by basin-filling sedimentary reworking during quiet, localized or waning volcanism – has been recognized as conducive to the development and preservation of geothermal systems elsewhere in the world (e.g. White et al., 1989; Bibby et al., 1995; Rice et al., 1995; Christiansen, 2001; Rowland and Sibson, 2004; Fernández-Turiel et al., 2005). In the Deseado Massif, such conditions were related to the final stages in the evolution of the Middle to Late Jurassic Bahía Laura Complex that extends across the region, from ca. 177.8 to 150.6 Ma (Fig. 1A; Féraud et al., 1999; Pankhurst et al., 2000).

3. Facies models for Deseado Massif hot spring deposits

3.1. Overview and analogs

Jurassic Deseado Massif hot spring deposits were recognized by their mappable lateral and vertical facies associations, distinct deposit morphologies, and preserved macro- and/or micro-textures (Sections 3.2–3.4; e.g. Guido and Campbell, 2009; Guido et al., 2010). They constitute travertine (El Macanudo, Cerro Negro: Schalamuk et al., 1999), siliceous sinter (La Marciana, San Agustín: Guido et al., 2002a; Guido and Campbell, 2009; Guido et al., 2010), or siliceous sinter and travertine areas in the same geothermal system (Claudia). Hot spring-associated faults likely delivered silicon or calcium carried in migrating hydrothermal fluids to surface discharge areas. Widespread siliceous mineralization (Schalamuk et al., 1997) may have been derived from the extensive rhyolitic volcanics of the region. With respect to calcium, as there are no limestones in the Precambrian to Late Jurassic stratigraphy of the Deseado Massif (De Giusto et al., 1980), the travertines may have been derived from magmatic CO_2 (e.g., Yoshimura et al., 2004; Gibert et al., 2009), or possibly from reverse solubility of fluids passing through calc-alkaline rocks of shallower levels (e.g. Barnes, 1997).

From detailed observations of the five representative Jurassic geothermal systems shown in Fig. 2, we constructed two generalized facies models for siliceous sinter and travertine applicable to the Deseado Massif (Fig. 3), including both subaerial (i.e. cones, mounds, aprons, and marshes) and subaqueous examples (i.e. submerged spring-vent cones and mounds in lakes). Facies associations for both sinter (Fig. 3A) and travertine (Fig. 3B) were divided into proximal, middle and distal hot spring settings (Table 1), in relation to inferred vent-to-marsh environmental gradients, and akin to Quaternary to Recent analogs in the Taupo Volcanic Zone (TVZ) and Yellowstone. While some morphological and textural characteristics are similar between Deseado Massif sinters and travertines, other features are unique to either silica or carbonate dominated geothermal systems (Fig. 3, Table 1).

Present-day hot spring facies are controlled by several factors such as fluid pH and composition, precipitation temperature, topography, seasonality, water availability, CO_2 supply, hydrodynamics, biological community composition, relationship to active faults, etc. (Weed, 1889; Walter, 1976; Farmer and Des Marais, 1994; Cady and Farmer, 1996; Hinman and Lindstrom, 1996; Jones et al., 1998; Braunstein and Lowe, 2001; Pentecost, 2005; Gibert et al., 2009). Several studies of modern subaerial siliceous thermal spring-aprons and geothermally influenced marshes have divided them into three broad areas along a discharge gradient — proximal near-vent, high temperature (>59 °C); mid-slope apron, moderate temperature (ca. 59 to 35 °C); and distal-slope apron, low temperature (<35 °C) (e.g. Walter, 1976; Cady and Farmer, 1996; Farmer, 2000; Fouke et al., 2000; Channing et al., 2004). Taking into account spring fluid compositions, mineralization along such discharge gradients creates recurring biological and textural associations in siliceous sinter derived from alkali chloride waters

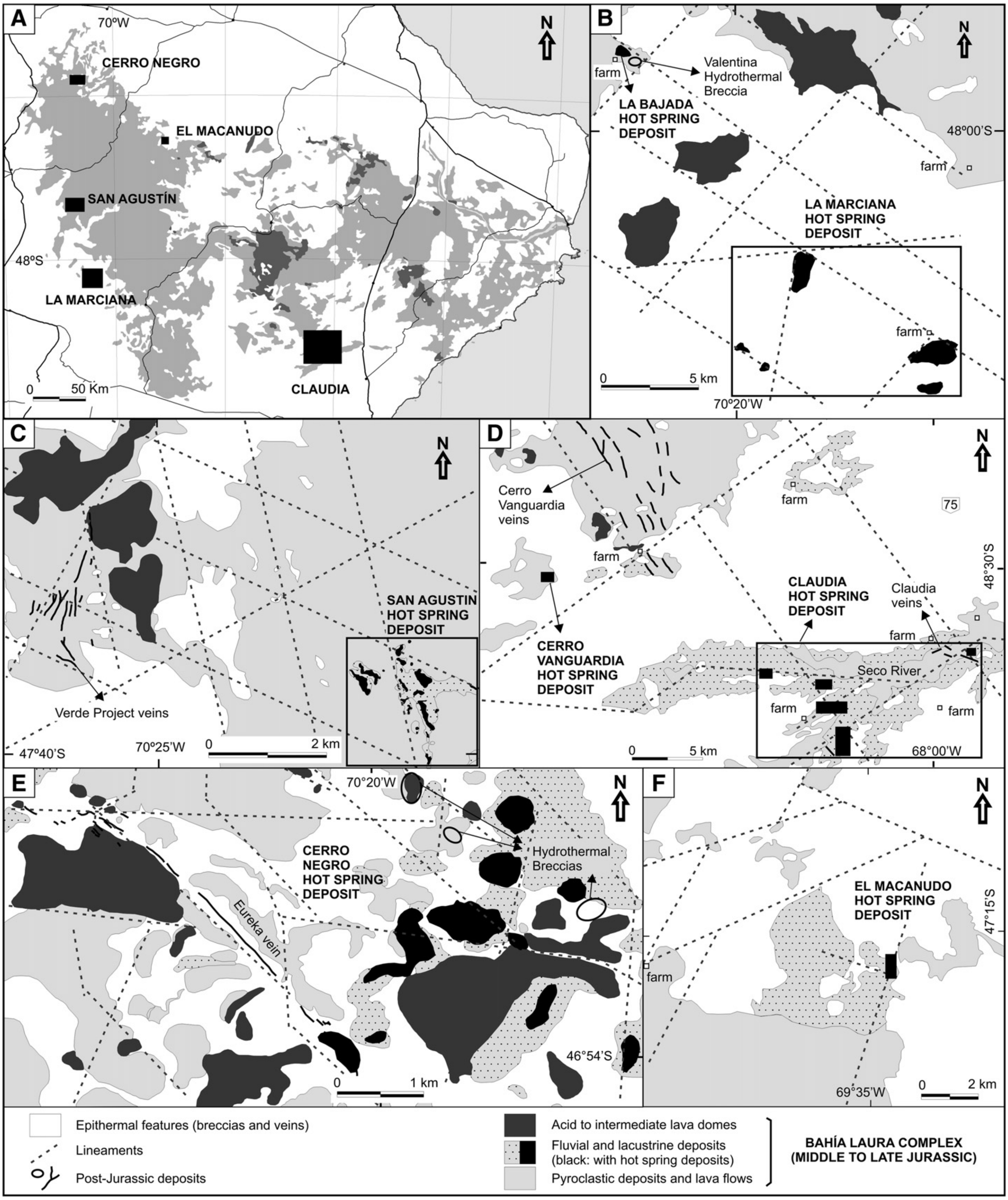


Fig. 2. Simplified geologic maps for the five Deseado Massif hot spring sites studied in detail herein, showing geographic position of the late Jurassic hot spring deposits, lineaments (dashed lines), epithermal mineralization (breccias and veins), and geology of the Bahía Laura Complex, the latter of which is separated into intermediate to silicic volcanic domes, silicic to intermediate pyroclastic deposits and lava flows, and fluvial/lacustrine sediments ± hot spring deposits. (A) Simplified Deseado Massif map showing location of the five hot spring deposits studied for their facies associations (Table 1) in this paper. Geological units follow those in legend for Fig. 1A. (B) La Marciana. (C) San Agustín. (D) Claudia. Vein data from http://www.mirasolresources.com. (E) Cerro Negro. (F) El Macanudo.

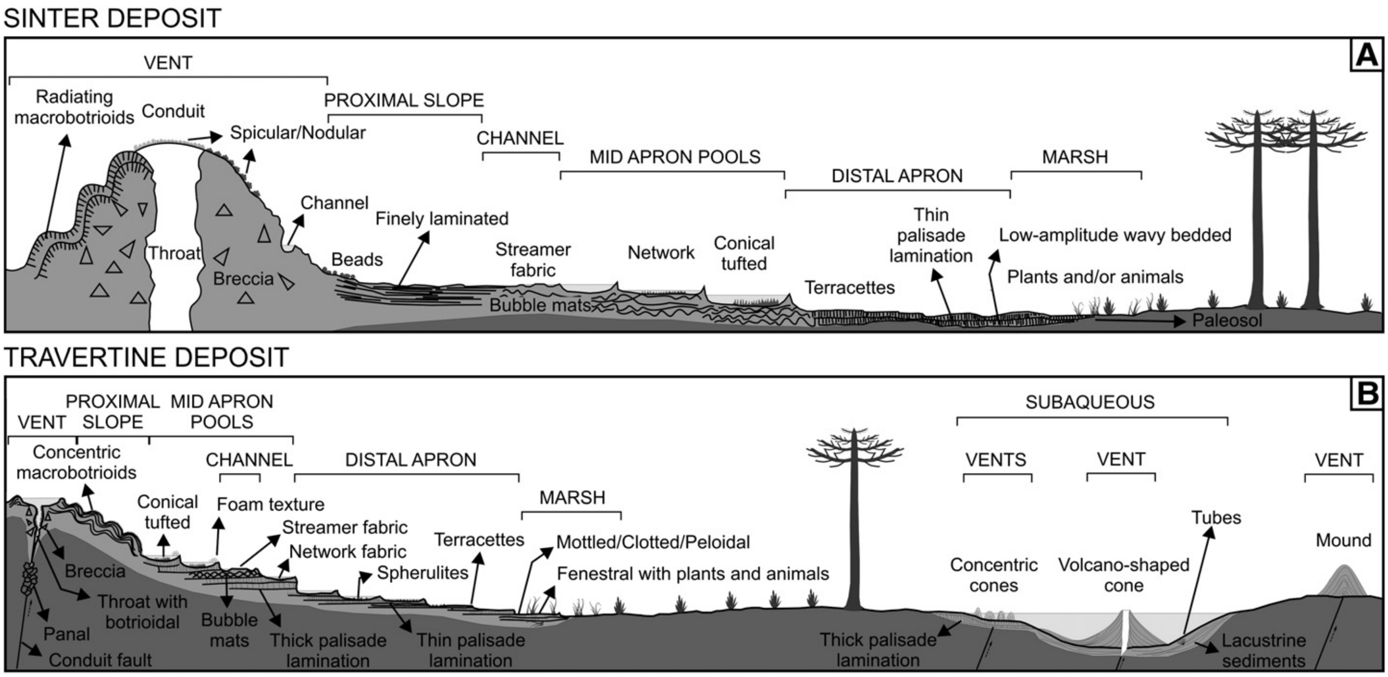


Fig. 3. Schematic cross-section of sinter (A) and travertine deposits (B), based on facies identified in the Deseado Massif, as compared with their analogs in active (Quaternary to Recent) TVZ and Yellowstone geothermal systems.

Table 1
Facies associations delineated in the five studied hot spring deposits from the Deseado Massif (Fig. 2). LM, La Marciana; SA, San Agustín; CL, Claudia; CN, Cerro Negro; MC, El Macanudo; S = sinter; T = travertine; S–T = sinter and travertine.

Facies Assemblage	Facies		Textures	Stromatolitic Association	LM	SA	CL	CN	MC
Proximal	Vent		Conduit/throat				S	T	T
			Breccia/panal		S	S	S	T	T
			Channel				S	T	T
			Spicular/nodular/botrioidal	Surface biofilms*			S	T	
			Beads				S		
			Radiating macrobotrioids		S		S	T	
	Proximal slope		Fine lamination	Surface biofilms*	S				
	Subaqueous	Volcano-shaped cone	Inclined bedding around conduit	Cauliflowers' around basal conduits				T	
		Concentric cone	Crenulated concentric laminae	Primary microbial fabric					T
		Tubes	Radiating cylindrical larval cases	Encrusting 'cauliflowers' on tubes		S			
	Mound/terraces		Concentric macrobotrioids/bedded	Microbes incorporated into structures	S		S	T	T
Middle	Channel		Bubble mats	Primary microbial fabric	S	S	S	T	T
			Packed fragmental	Warm stream-bottom mats (transported)	S		S	T	T
			Streamer fabric	Primary microbial fabric		S		T	
	Mid apron pools		Thick palisade lamination	Primary microbial fabric					T
			Network fabric/conical tufted	Primary microbial fabric	S		S	T	T
			Foam texture				T		T
Distal	Distal apron		Terracettes/thin palisade lamination	Primary microbial fabric	S	S		T	T
			Low-amplitude wavy bedded	Microbial + physical sed structures			T	T	T
			Spherulites/oncoids	Primary microbial fabric			T	T	
	Marsh		Fenestral	Generally formed in microbial sediment				T	
			Mottled/clotted/peloidal	Primary microbial fabric		S	S		
			Plants and/or animals	In places, coated with microbialite		S	S-T	T	
			Paleosol	Weathered S fragments, some microbial		S			

* Archaeal and bacterial biofilms are known from modern geyserites/proximal aprons; as yet undescribed from fossil record.

(e.g. Walter, 1976) or acid sulfate-chloride waters (e.g. Schinteie et al., 2007), and thermal travertine formed from rapid CO_2-degassing (e.g. Pentecost, 2005). Hot-spring related travertines show large thermal gradients (from 5 to 95 °C for western U.S.A., with most of them in the 10–30 °C temperature range; Chafetz and Folk, 1984), and variable morphologies, discussed further below.

Stromatolitic fabrics receive special emphasis here, as they were present in most of the facies described from Deseado Massif fossil hot springs, especially middle slope to distal apron settings (Table 1). Riding (1999) defined stromatolite as 'a laminated benthic microbial deposit'. Stromatolites commonly are constructed by photosynthetic microorganisms (cyanobacteria) that develop a great variety of growth morphologies in hot spring, fresh-water hypersaline lake and marginal marine lagoonal habitats (Walter et al., 1976; Brock, 1978; Holt, 1994; Pentecost, 2005; Handley and Campbell, in press). Microbial biofilms of Bacteria and Archaea also are present in modern hot springs, especially in high-temperature vent areas (e.g. Cady and Farmer, 1996; Currie, 2005; Schinteie et al., 2007).

3.2. Proximal hot spring facies

Proximal hot spring facies associations in the Deseado Massif were most readily recognized in the field by the presence of different types of localized cones or mounds (Fig. 4A–D), both subaerial and subaqueous, and by various conduit features, many of which are preserved as cylindrical holes/tubes (Fig. 4E). This proximal grouping includes the following seven facies: vent conduit/throat; breccia/panal ("panal de abejas" means beehive in Spanish), botrioidal; channels; geyserite spicules/nodules/beads; dense fine lamination; inclined bedding in volcano-shaped cones; and crenulated concentric laminae in steep cones (Table 1). Proximal spring vent areas created both constructional features (cones and mounds) and destructional features (breccia/panal and conduits) related to the intermittent emission of over-pressured hydrothermal fluids.

Mound centers typically contain holes, hydrothermal breccias and/or panal structures (e.g. Fig. 4F). We infer that these panal structures represent shallow subterranean, tortuous fluid flow pathways situated just beneath focused, surface vent emission areas. They are similar to stockwork common in deeper portions of epithermal mineralization systems, but differ from it because the panal structures are regularly distributed and show rounded cube-shaped voids lined with silica. Moreover, radiating macrobotrioids characterized some irregularly shaped, siliceous vent mound areas (Fig. 4G), with microfabrics of spicular, nodular or beaded geyserite preserved at some locales. Travertine mounds and cones showed greater morphological variety at the macro-scale, including large subaerial mounds (Fig. 4A), and subaqueous (lacustrine), steep concentric cones constructed of crenulated (stromatolitic) fabrics (Fig. 4B–C) or volcano-shaped cones with inclined bedding (Fig. 4D). Some of the cones preserved concentric, cauliflower shaped, crenulated (stromatolitic) features around small conduits at their bases (Fig. 4H).

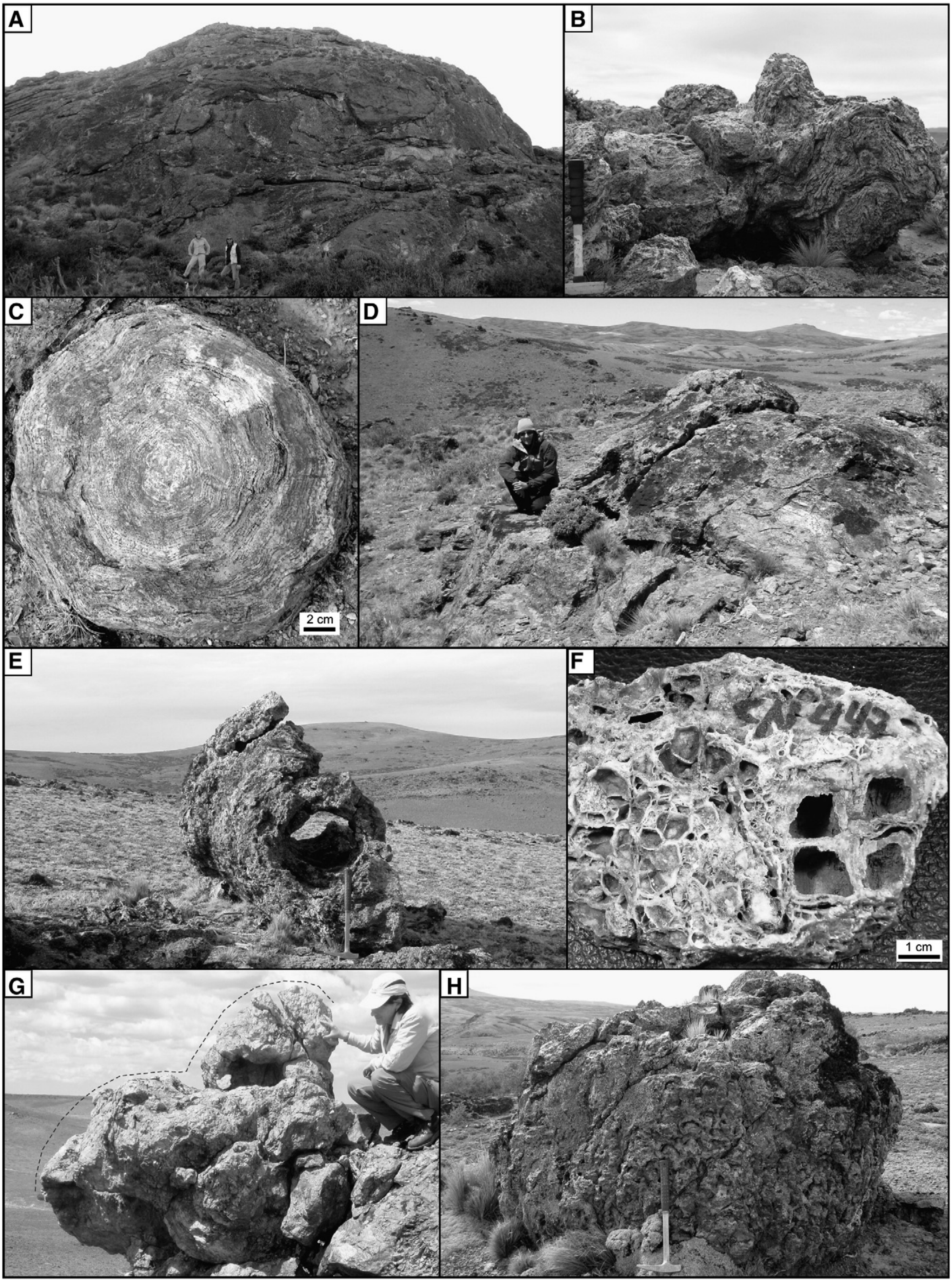
3.3. Middle apron/mound hot spring facies

Middle apron/mound hot spring facies associations in the Deseado Massif were delineated in the field by ubiquitous macrotextures (Fig. 5) also known to form in modern hot springs in association with microbial mats, and specifically indicative of terrace pools or migrating channel discharge areas of varying water depths and velocities. This group encompasses the following six facies: conical tufted/network, streamer fabric, bubble mats, packed fragmental, thick palisade lamination – all various forms of stromatolites – and foam texture (Table 1). In particular, conical tufts and wavy lamination (Fig. 5A) form by phototaxis of finely filamentous cyanobacteria (e.g. '*Phormidium*') in shallow pools of modern hot springs (Walter et al., 1976; Farmer and Des Marais, 1994; Cady and Farmer, 1996), and were preserved in both travertine and sinter deposits in the Deseado Massif. 'Bubble mats' often occur today in association with wavy laminated microbial fabrics, and texturally constitute stacked, spherical to elongated voids (Fig. 5B) formed during photosynthetic degassing within thick mats (Hinman and Lindstrom, 1996; Pentecost, 2005). In places, this facies was distorted into deformed and curled laminae (Fig. 5C) due to disturbance and dessication of the Jurassic mats forming over pool surfaces or at pool margins (Guido et al., 2010). Some deposits displayed a packed fragmental appearance (Fig. 5D), interpreted as transport of partially mineralized mats formed on channel-floors, and their accumulation in shallow point bars along a hot-water creek (e.g. outflow of Frying Pan Lake, Waimangu, TVZ; Guido and Campbell, pers. obs.). Network fabrics (Fig. 5E) represent the silicified or calcified matrix of exopolymeric substances (EPS), exuded by bacteria, and are typically found at the margins of moderate-temperature pools today, in shallow water where the mats intermittently dry out (Campbell, pers. obs.). Streamer fabrics (Fig. 5F) indicate mineralization of filamentous microbes in fast-flowing, shallow and migrating spring-discharge channels in mid-apron sinter and travertine areas (e.g. Farmer, 2000; Pentecost, 2005). Foam texture (Fig. 5G) forms in thermal travertines from CO_2(g) escape and by photosynthetic degassing, producing gas bubbles that rapidly became encrusted with carbonate and trapped in 'calcite ice' films growing quickly across pool surfaces (Chafetz and Folk, 1984; Chafetz et al., 1991; Fouke et al., 2000; Pentecost, 2005).

3.4. Distal hot springs facies

The distal apron-slope and affiliated geothermally influenced marsh facies associations in the Deseado Massif were demarcated in the field by low terraces (Fig. 6A) and wavy bedding (Fig. 6B) in sinter or travertine deposits that contain both fossil prokaryotes (Fig. 6C–G) and eukaryotes (Fig. 6E and G) today (Cady and Farmer, 1996; Farmer, 2000). These features suggest both relatively low temperatures and discharge energy of the geothermal fluids, with much evidence that especially fossil plants and trees were engulfed by the growing spring deposits (Guido et al., 2010). Thermal travertines, in particular, are the most rapidly mineralizing terrestrial sedimentary deposits known (Pentecost, 2005), with up to 30 cm/year recorded in proximal vent areas in the Mammoth area at Yellowstone (Fouke et al., 2000).

The Deseado Massif distal facies association includes: thin palisade laminations, spherulites/oncoids, fenestral fabric, mottled/clotted/peloidal textures, and fossil plants and animals. Specifically, palisade fabric (Fig. 6C) today consists of dense sets of vertical filaments produced by cyanobacteria (e.g. *Calothrix* in modern distal spring aprons; Weed, 1889; Walter, 1976; Cady and Farmer, 1996). Oncoids (Fig. 5D) and similar coated grains, preserved in Deseado Massif hot spring deposits as sinter/travertine clasts comprising concentric laminae of microbes encrusting mobile grains, are common in surface geothermal deposits elsewhere (e.g. Jones and Renaut, 1994; Renaut et al., 1996; Jones and Renaut, 1997; Pentecost, 2005). Spherulites (Fig. 6F) were found in low-temperature, shallow terracettes in thermal travertines, and may have formed from down-slope transport and carbonate nucleation around microbial components (e.g. Guo and Riding, 1992; Fouke et al., 2000). Clotted (microbial) fabrics are common in the Deseado Massif deposits, and fossil plant fragments are coated with dendritic stromatolites (Fig. 6E) or tufted microbial linings (Fig. 6G). Geothermally influenced sediments (*sensu* Channing et al., 2004) in the Deseado Massif typically have been preserved as plant-rich cherts (e.g. Channing et al., 2007), affiliated with veins, and hydrothermal mineralization or alteration, as well as active Jurassic volcanic features or faults that were the likely conduits for the silicifying fluids (Guido et al., 2010; Fig. 2).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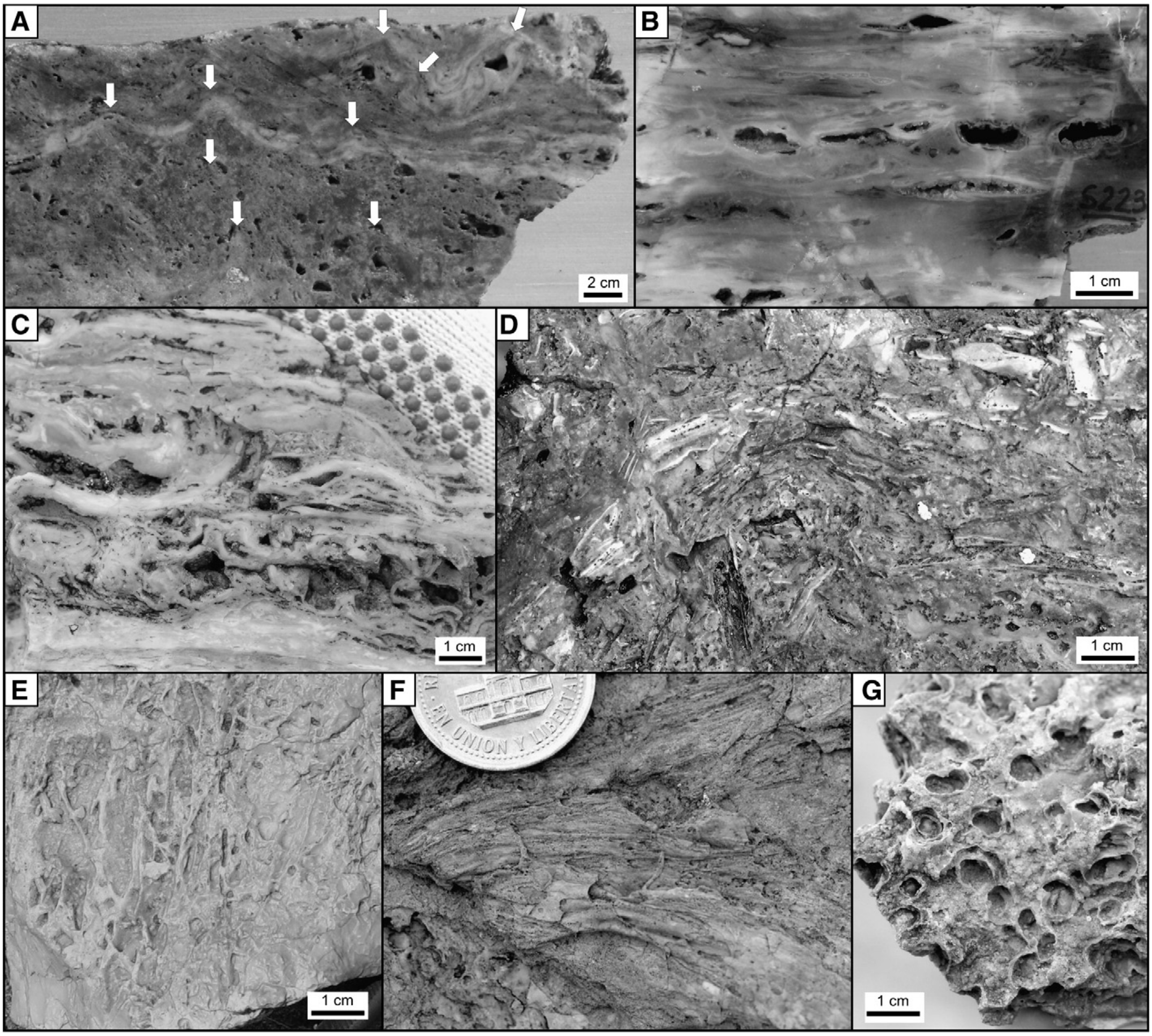

Fig. 5. Middle apron/slope facies assemblages from the Deseado Massif studied examples. (A) Conical tufted sinter in vertical cross-section, with arrows over some of the microbial tufts, San Agustín. (B) Sinter bubble mats (elongated voids) in vertical cross-section, San Agustín. (C) Pool mat sinter in vertical cross-section, showing convoluted microbial laminae, San Agustín. (D) Sinter packed fragmental texture in vertical cross-section, inferred as formed by transport of broken mats in hot-water creek outflow channels, San Agustin. (E) Sinter network texture in plan view, La Marciana. F: Sinter streamer fabric in plan view, San Agustín. (G) Travertine foam texture, El Macanudo.

4. Discussion and conclusions

4.1. Regional geological comparisons between the Deseado Massif and New Zealand geothermal areas

The Deseado Massif (Middle to Late Jurassic) and Coromandel and Taupo volcanic zones (Miocene to Quaternary), New Zealand, have strong geological similarities. Both constitute(d) geothermally active volcanic regions located in extensional back-arc areas with affiliated calc-alkaline rocks. Rhyolites are dominant, although associated andesitic rocks and minor dacitic and basaltic compositions also occur (Wilson et al., 1995; Guido and Schalamuk, 2003). The Jurassic hot spring deposits of the Deseado Massif are distributed over a vast region that is approximately the same size as the geographic extent of geothermal manifestations in the combined Coromandel and Taupo volcanic zones (CVZ and TVZ, respectively), and was of similar duration (~20 Ma, with geothermal activity continuing to the present day in the TVZ; Rowland et al., 2009). Late Cenozoic arc volcanism in New Zealand, and associated evidence for geothermal and epithermal activity, have migrated largely southeastward since the Miocene, owing to differential

Fig. 4. Proximal facies assemblages from the Deseado Massif studied examples. (A) Large travertine mound, Cerro Negro. (B) Travertine concentric cones, El Macanudo. (C) Detail of travertine concentric cone (plan view) showing crenulated calcified microbial fabric, El Macanudo. (D) Travertine volcano-shaped cone, Cerro Negro. (E) Travertine cylindrical vent throat, toppled to ground and lying horizontally, Cerro Negro. (F) Travertine panal structure hand sample, Cerro Negro. (G) Sinter vent mound with radiating macrobotrioidal morphology (dashed outline), Cerro Vanguardia. (H) Travertine cone with central hole and cauliflower botrioidal stromatolites lining basal outer margin (at height of rock hammer handle), Cerro Negro.

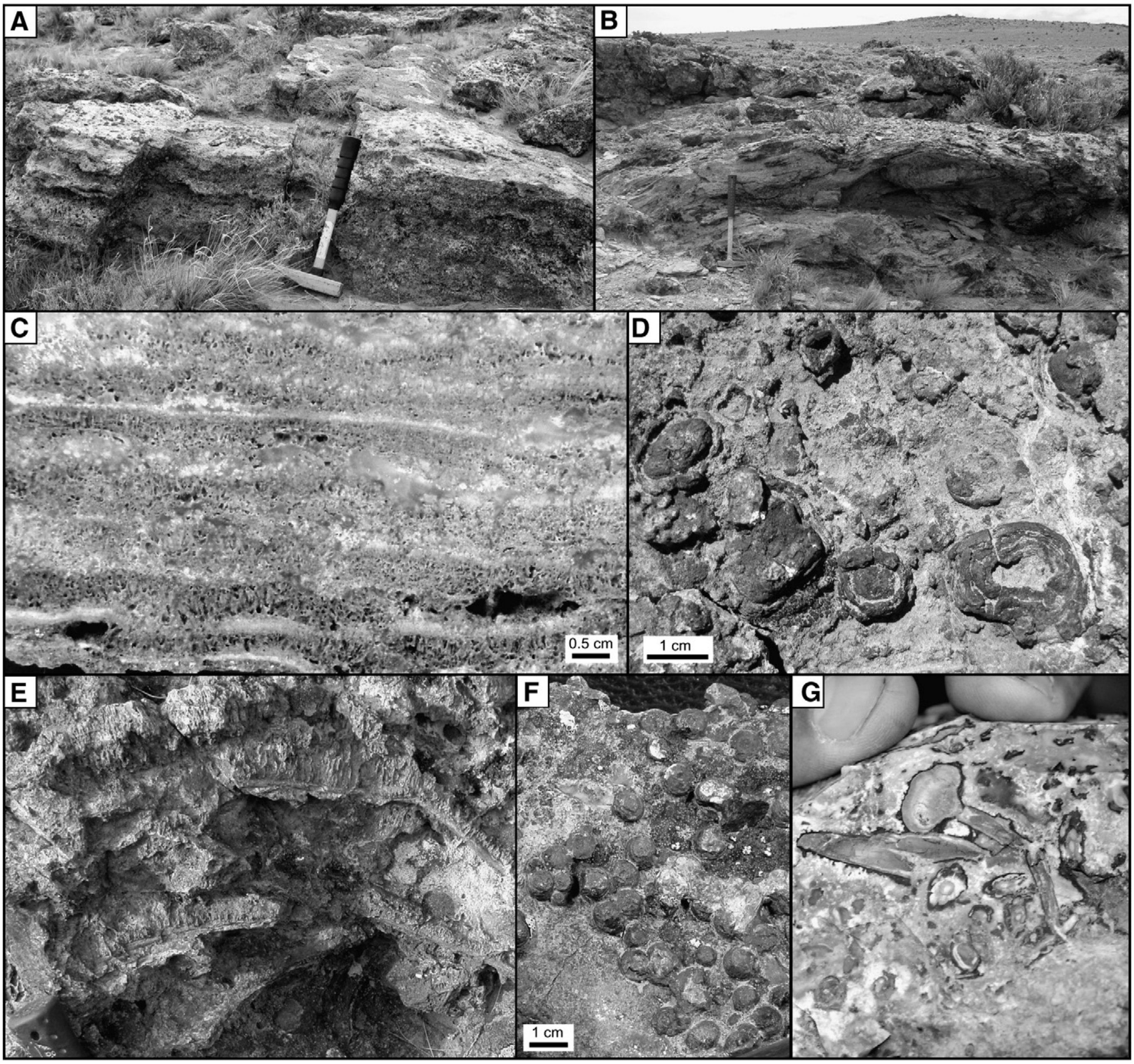

Fig. 6. Distal facies assemblages from the Deseado Massif studied examples. (A) Travertine terracettes, El Macanudo. (B) Travertine low-amplitude wavy bedding, El Macanudo. (C) Travertine palisade texture in vertical cross-section, partially silicified, El Macanudo. (D) Travertine oncoids, Monte Illiria. (E) Travertine dendritic stromatolites on plant stems, Cerro Negro. (F) Travertine spherulites, Cerro Negro. (G) Clotted sinter with tufted, dark microbial linings upon plant seedlings and stems, oblique cross-section view, San Agustín.

opening of arc-parallel rift structures in a stepwise, en echelon pattern (Rowland et al., 2009). Regional structural controls comparable with those in the Deseado Massif can be observed for the active and preserved (<100 kyr old) hot spring deposits of the TVZ, where there is a clear geographic link between geothermal systems and extensional NE striking lineaments and WNW basement faults, as interpreted from geophysical data (Rowland and Sibson, 2004).

The CVZ–TVZ migration of hydrothermal activity (Rowland et al., 2009) occurred over roughly 20 Ma, which is a similar order of magnitude compared to the paleogeographic shift in volcanism (and consequently the affiliated geothermal environments and epithermal mineralization) postulated for the Middle to Late Jurassic in the Deseado Massif. In particular, using U–Pb and Ar–Ar geochronology of regionally sampled Bahía Laura Complex. Féraud et al. (1999) and Pankhurst et al. (2000) recognized a westward migration in magmatism from ~177 to 150 Ma. Notably most hot spring localities are found in the youngest portions of the migration trend for each geologic province: ESE in northern New Zealand and WNW in the Deseado Massif, probably a reflection of better preservation of the youngest phase of hydrothermal activity for each region.

4.2. Facies comparisons between the Deseado Massif and New Zealand and Yellowstone geothermal areas

Comparisons between Jurassic Deseado Massif hot spring deposits and Miocene to Recent geothermal sedimentary fabrics/distributions of Yellowstone and New Zealand have allowed a preliminary classification of facies associations for the Deseado Massif, controlled largely by temperature and fluid composition, in proximal (near vent) to distal (margin) sites (Table 1; Fig. 3). This assessment enables reconstruction of both the paleogeography of geothermally influenced paleoenvironments, as well as paleoflow directions of thermal fluids from high-resolution site maps, which already have been completed for parts of La Marciana (Guido and Campbell, 2009; their Figs. 1C and 2B, p. 618–619) and San Agustín (Guido et al., 2010; their Fig. 2, p. 13 and Fig. 6, p. 17). Similar detailed assessments are in preparation from our field data for the other sites mentioned in this regional overview (e.g. Table 1, Fig. 2). In almost all sites for which we have completed detailed mapping, areas of paleo-spring upflow and other fluid conduit features (e.g. cylindrical tubes/holes, vent mounds, mineralized breccias, and panal structures) correspond with faults, lava domes and epithermal mineralization (Fig. 2; Guido and Campbell, 2009; Guido et al., 2010). The exception is the extensive travertine deposits at El Macanudo, where Cenozoic volcanics largely cover the landscape and Jurassic veins and lava domes are not readily evident.

Analogous sedimentary settings are evident for some TVZ hot spring deposits, where several are associated with lacustrine (e.g. Frying Pan Lake sinter; Jones et al., 2005), fluviolacustrine (e.g. Tahunaatara sinter; Campbell et al., 2004), and fluvial settings (e.g. Orakei Korako and Otamakokore sinters; Lloyd, 1972; Holland, 2000), also related to pauses in volcanic activity. In addition, the affiliation between TVZ hot spring deposits and calderas and/or volcanic domes is quite clear at localities such as Waimangu (Simmons et al., 1993), Orakei Korako (Lloyd, 1972; Hamlin, 1999), and Umukuri, Atiamuri, Wairakei and Waiotapu (Rodgers et al., 2004). Moreover, the largest proportion of hot spring deposits in the TVZ is found in rhyolite-dominated volcanic areas, similar to the Deseado Massif. Finally, while the Patagonian hot spring deposits formed in low paleo-topographic areas (along streams or lakes), their preserved remnants tend to occur today in relatively high areas of the present landscape, favoring inversion relief as the mechanism for their exhumation, akin to sinter preservation in the TVZ (e.g. at Umukuri, Campbell et al., 2001; Tahunaatara, Campbell et al., 2004).

4.3. Overall significance of Deseado Massif hydrothermal associations

Considering the many new Jurassic hot spring discoveries as well as distributions of previously known sites within the extensive Deseado Massif province, the recurring structural, volcanic and lithological controls on geothermal system development identified herein mirror those of the closely associated epithermal deposits of the region. In particular, the geographic affinities among reworked volcaniclastics, intermediate to silicic lava domes, and geothermal and epithermal manifestations in the Late Jurassic also places these geological features regionally on major WNW–ESE or NNW–SSE trends. Two of these major hydrothermal–structural belts (Northern and Northwestern; Fig. 1), in fact, approximate the known outer limits of the 'horst-like' borders of the Deseado Massif province itself, situated as a positive feature between younger basins to the north and south (San Jorge and Magallanes/Austral, respectively; Richardson and Underhill, 2002, their Fig. 1, p. 418). Hence, hydrothermal fluid flow during the Late Jurassic was strongly influenced by one of the most dominant and long-active geological boundaries in the region. Finally, well-preserved facies associations, as compared with younger analogs, and excellent exposure of Deseado Massif deposits, together allow for high-resolution paleoenvironmental and paleogeographic reconstructions of entire volcanic–geothermal–epithermal systems rarely possible in other older or younger terrestrial hydrothermal regimes elsewhere in the world.

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