Received: 16 December 2022 | Revised: 26 April 2023 | Accepted: 2 May 2023

DOI: 10.1111/bre.12782

RESEARCH ARTICLE

Basin Research IAS EAGE WILEY

The long-term legacy of subvolcanic intrusions on fluid migration in sedimentary basins: The Cerro Alquitrán case study, northern Neuquén Basin, Argentina

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Funding information
Norges Forskningsråd; Universitetet i Oslo

Abstract

Cooling subvolcanic igneous intrusions are known to have a substantial impact on fluid flow in the shallow Earth's crust, for example activation of geothermal systems, circulation of mineralized fluids in ore deposits, fast maturation of organic matter in sedimentary rocks and the potential release of large volumes of greenhouse gases, which have triggered mass extinctions during the Earth's history. However, the long-term post-cooling legacy of subvolcanic intrusions on fluid flow received much less attention. Here we describe a demonstrative geological example in the Andean foothills, Argentina, showing that igneous intrusions have long-term effects on fluid flow after their emplacement and cooling. The case study is a ca. 11-million-year-old, eroded subvolcanic conduit, at the rims of which large volumes of bitumen are naturally seeping out on the Earth's surface. This contribution highlights that intense syn-emplacement fracturing of the magma has created high-permeability pathways that affect the regional fluid circulations, even millions of years after cooling. Our observations reveal how extinct subvolcanic intrusions have long-term consequences on subsurface fluid circulations, which need to be accounted for in the exploration of geothermal energy, drinkable groundwater, hydrocarbons and CO_2 sequestration in volcanic basins and regions hosting ancient shallow magma intrusions.

1 | INTRODUCTION

Hot subvolcanic igneous intrusions have the potential to impart substantial impacts on fluid generation and migration in the shallow Earth's crust (Figure 1), with many sedimentary basins being subject to complex intrusive networks developed as magma migrates to the surface to feed volcanic systems (Holford et al., 2017; Jerram & Bryan, 2015; Magee et al., 2018; Senger et al., 2017). The cooling of subvolcanic intrusions, during and after emplacement, can liberate mineralized fluids that migrate and form ore deposits (Hedenquist & Lowenstern, 1994), and the heat brought by subsurface magma mobilizes groundwater to activate hydrothermal systems (Einsele et al., 1980; Galerne & Hasenclever, 2019; Ingebritsen et al., 2010; Iyer et al., 2017), potentially leading to phreatic volcanic explosions (Gaete et al., 2020; White & Ross, 2011). Large sub-horizontal sill intrusions emplaced in sedimentary basins can also trigger fast maturation of organic-rich formations (Iyer et al., 2017; Kroeger et al., 2022; Spacapan et al., 2018) and the generation of large volumes of methane and CO_2 (Aarnes et al., 2011; Svensen et al., 2004). The catastrophic release of these fluids into the atmosphere triggered extreme climate change and mass extinctions during Earth's history (Aarnes et al., 2010; Courtillot & Renne, 2003; Svensen et al., 2009).

Highlights

- We describe large bitumen seeps along the edges of andesite intrusion of Cerro Alquitrán, Argentina.
- The bitumen migrates along syn-emplacement magmatic breccia and fracture bands within the andesite.
- Our study highlights the long-term implications of igneous intrusions on regional fluid migration in sedimentary basins.

To date, most research looking at the fluid effects of magma intrusions has focused on the fluid flow implications of hot subvolcanic intrusions, focusing on their cooling at short geological times (tens to thousands of years) after their emplacement (e.g., Fjeldskaar et al., 2008; Galerne & Hasenclever, 2019; Iyer et al., 2017; Sydnes et al., 2018). On the other hand, the long-term post-cooling legacy of subvolcanic intrusions on fluid flow

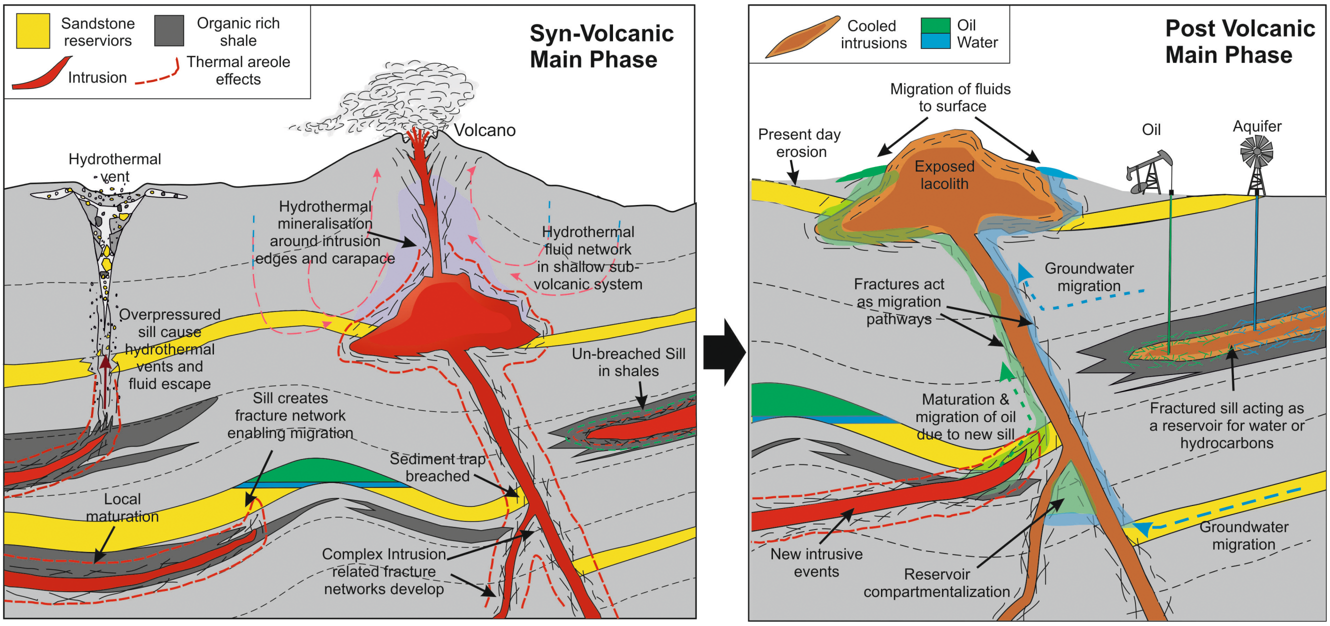

FIGURE 1 Left. Drawing illustrating the effects of active subvolcanic magmatic intrusions on fluid flow (modified from Bischoff et al., 2019; Senger et al., 2017). Magma emplacement triggers fracturing and damage in the host rock, enhancing permeability. The heat brought by cooling intrusions can activate hydrothermal systems and trigger the mineralization of ore deposits, an aureole of maturation (within a red dashed line) of organic-rich sedimentary formations, rapid fluid pressure build-up and the formation of hydrothermal vent complexes. Right. Drawing illustrating the long-term effects of subsurface igneous intrusions on fluid flow. Emplacement-related fractures in the host rock and cooling fractures in the intrusions deeply affect the permeability structure. Fractured sills can be excellent aquifers and other fluids (hydrocarbon, geothermal) reservoirs. Conversely, poorly fractured intrusions may can act as aquitards and compartmentalize reservoirs. Former intrusions can affect fluid flow induced by the emplacement and cooling of new intrusions.

received much less attention (Bischoff et al., 2019, 2021; Planke et al., 2018; Saubin et al., 2019). It can be shown, however, that magma emplacement is commonly associated with fracturing and damage of both the host rock (Agirrezabala, 2015; Delaney & Pollard, 1981; Galland et al., 2019, 2022; Montanari et al., 2017; Wilson et al., 2021) and the magma itself (Burchardt et al., 2019; Lavallée et al., 2008; Mattsson et al., 2018; Rabbel et al., 2021). This fracturing and damage can potentially modify the permeability architecture of shallow crustal domains irreparably, affecting future fluid-flow pathways (Figure 1).

Recent research has investigated the permeability properties of igneous intrusions in volcanic sedimentary basins and discussed their implications on fluid migration and fractured reservoir properties (Rabbel et al., 2021; Rateau et al., 2013; Spacapan et al., 2020; Witte et al., 2012). These studies focused on sheet intrusions (i.e., dykes and sills) of mainly basaltic to basaltic andesitic compositions. However, intermediate to felsic igneous intrusions of massive morphology (i.e., laccolith, plug) have also been documented to be common in volcanic basins (Araujo et al., 2019; Breitkreuz et al., 2009; Cruden et al., 2018; Cukur et al., 2010; de Saint-Blanquat et al., 2006; Galland et al., 2022; Gu et al., 2002; Horsman et al., 2009; Mark et al., 2018; Rocchi et al., 2002; Rodriguez Monreal et al., 2009; Westerman et al., 2004; Wilson et al., 2016). Such andesitic intrusive bodies can be large, and can have complex structural relationships internally and with the host rock (Burchardt et al., 2019), and also form part of complex intermediate to felsic plumbing systems with mixed sill, dyke and laccolith/plug morphologies within the sedimentary basins (Rocchi et al., 2010; Westerman et al., 2018). To which extent such andesitic, massive intrusions and their associated plumbing systems affect fluid flow in sedimentary basins is not well studied.

Here we describe a demonstrative geological case study in the Neuquén Basin, Argentina, that shows how ancient massive, laccolith-shaped subvolcanic intrusions deeply affect regional-scale fluid flow. Our study highlights the relevance of the complex mechanics of subvolcanic intrusion emplacement and cooling on the long-term legacy of permeability properties in sedimentary basins.

2 | GEOLOGICAL SETTING

The Cerro Alquitrán natural laboratory is an exhumed 10.7 ± 0.5 million-year-old subvolcanic intrusion, located at the foothills of the Andes mountains, Argentina (Nullo et al., 2002) (Figure 2). It is an intrusion of andesitic composition emplaced through the Mesozoic and Cenozoic sedimentary formations of the northern Neuquén Basin (Boll et al., 2014; Nullo et al., 2002). The shape of the intrusion is inferred to exhibit a thick laccolithic to plug shape (Dessanti, 1959). The peculiarity of Cerro Alquitrán is the presence of large natural bitumen seeps clustering around the igneous body (Figures 3 and 4) (Dessanti, 1959).

The Neuquén Basin represents one of the Andean foreland basins and comprises a prolific hydrocarbon province with various proven hydrocarbon plays (Brisson, 2015), including commercial oil production, from fractured andesitic sills emplaced in organic-rich shales (Howell et al., 2005; Rabbel et al., 2021; Spacapan et al., 2020).

The geodynamic evolution of the basin comprises three main phases. Initiation of the basin started in the Triassic-Jurassic as a series of elongated rifts forming isolated depocentres (Howell et al., 2005; Yagupsky et al., 2008). During the early Jurassic period, it subsequently transformed into a back-arc basin dominated by regional thermal subsidence (Legarreta & Uliana, 1991, 1996). This phase led to the deposition of the marine sediments of the Mendoza group, which include organic-rich shales of the Vaca Muerta and Agrio formations (Bettini & Vasquez, 1979; Manceda & Figueroa, 1995) that constitute two of the main source rocks of the basin. In the late Cretaceous, the tectonic regime changed to compressive, initiating Andean uplift and the foreland basin phase. This stage created a series of fold-and-thrust belts including the Malargüe fold-thrust belt through reactivation and inversion of the rift-related normal faults as well as older basement faults (Giambiagi et al., 2009; Kozlowski et al., 1993; Manceda & Figueroa, 1995; Mescua et al., 2014; Mescua & Giambiagi, 2012). The sedimentary deposits associated with this foreland phase are the continental deposits of the late Cretaceous Neuquén Gr. and the Top Cretaceous-Palaeocene Malargüe Gr., this later being exposed in the Cerro Alquitrán area (Figure 2) (Araujo et al., 2019; Dessanti, 1959). The latest formations present in the area are Neogene syn-orogenic deposits, which partly consist of volcaniclastic products (Figure 2) (Combina & Nullo, 2011).

The Cerro Alquitrán intrusion is located on the eastern border of the Neuquén basin, where thin and proximal late Jurassic to Palaeocene strata were deposited. As a consequence, the Vaca Muerta and Agrio Fms. at the location of Cerro Alquitrán are not rich in organic matter and did not experience burial maturation. In contrast, the Atuel depocenter located west of the study area (Bechis et al., 2020; Lanés et al., 2008) is filled with over 4000 m of late Triassic to Paleogene sediments and the source rocks are rich in organic matter and were covered by Neogene sediments which led to hydrocarbon maturation (Boll et al., 2014).

During the Neogene, successive magmatic events occurred in the study area between 34°S and 37°S.

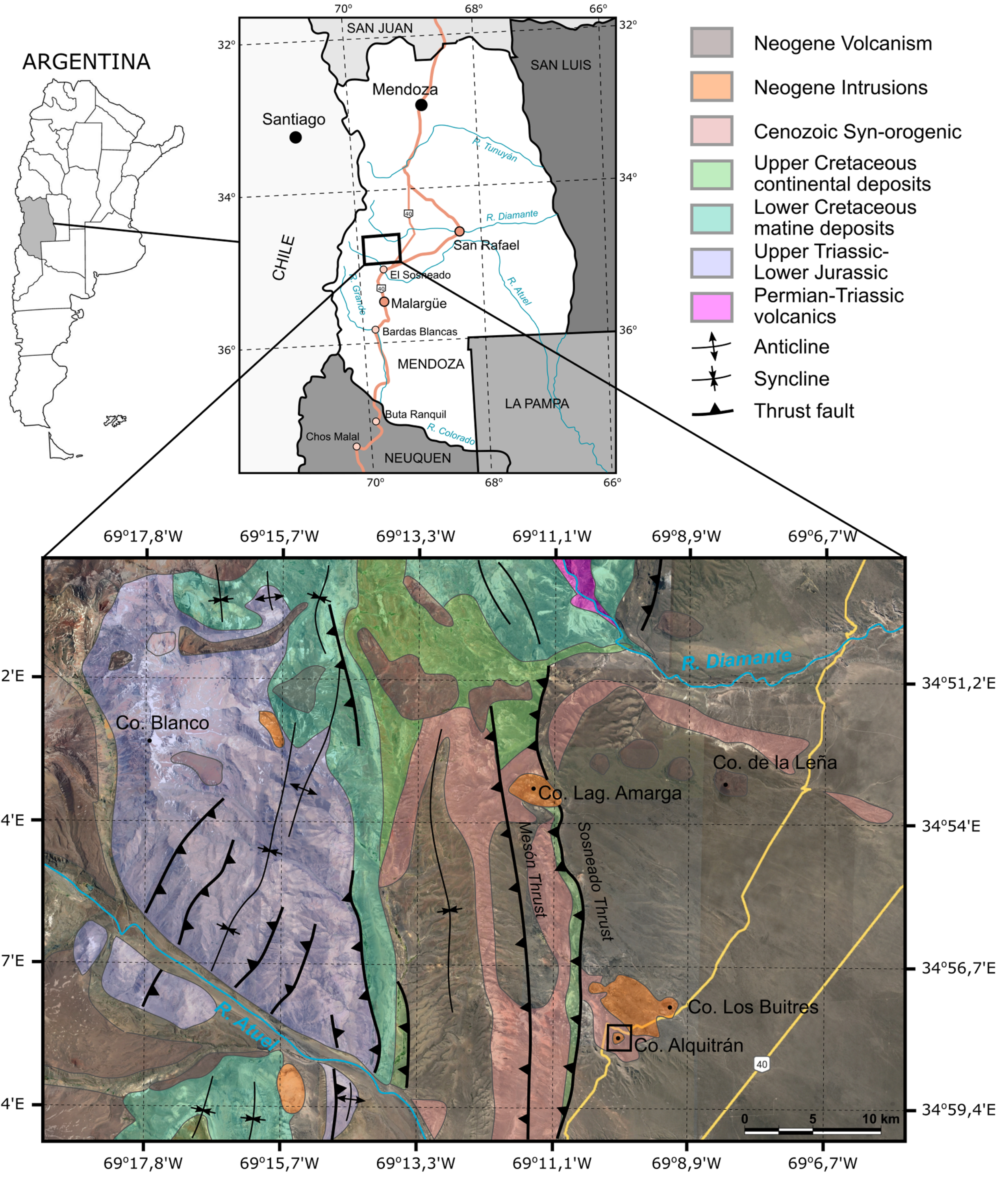

FIGURE 2 Top left: political map of Argentina indicating provinces borders. Mendoza province is highlighted in grey. Top right: simplified geographic map of Mendoza province locating the geological map below. Bottom: simplified geological map of study area locating Cerro Alquitrán (modified from Araujo et al., 2019; Sruoga et al., 2005).

These events can be divided into two magmatic cycles (Nullo et al., 2002; Sruoga et al., 2005): the "Molle" (late Oligocene-Miocene) and the "Huincán" (middle-late Miocene) cycles. The latter Huincán cycle consists of two magmatic pulses; the oldest, named "Huincán Andesite", ranges from 17 Ma to 10 Ma, with a peak of magmatic activity at 14 Ma, and the youngest, "La Brea Andesite", ranges from 10.7 Ma to 4.5 Ma (Baldauf et al., 1997; Giambiagi et al., 2008; Nullo et al., 2002). The La Brea Andesite consists of isolated andesitic massive

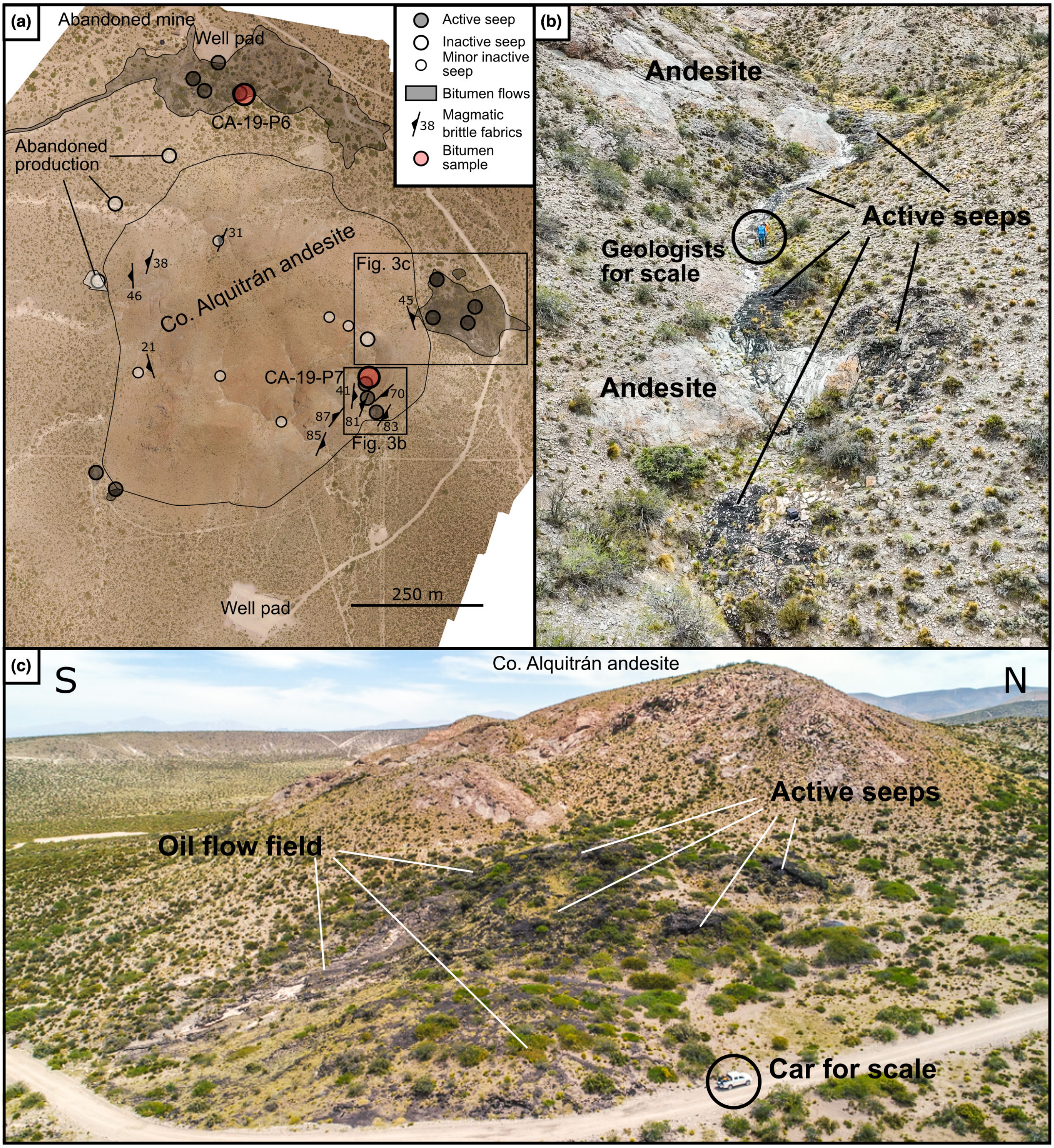

FIGURE 3 (a) Orthorectified image of Cerro Alquitrán computed from drone-survey photographs shot drone survey. The map displays major active and inactive seeps, and minor inactive seeps clustered around and within the igneous body. It displays also structural measurements of brittle magmatic fabric. (b) Drone photograph of bitumen seeping out from andesite outcrops in the southeastern gully (location in a). (c) Drone photograph of the eastern seep that illustrates the extent of the bitumen seep.

sub-volcanic intrusions that include Cerro Alquitrán, Cerro Los Buitres and Cerro Laguna Amarga (Figure 2) (Araujo et al., 2019; Nullo et al., 2002). The name "La Brea" means "tar" in Spanish, highlighting the regional link between the subvolcanic intrusions and the bituminous fluid migration. Note that less voluminous bitumen seeps have also been documented nearby other andesitic intrusions of the La Brea Fm. (Dessanti, 1959).

Cerro Alquitrán is located near the eastern edge of the Malargüe fold-and-thrust belt, in the footwall of the Sosneado and Mesón thrusts, which constitute the Andean frontal thrust (Figure 2) (Giambiagi et al., 2008).

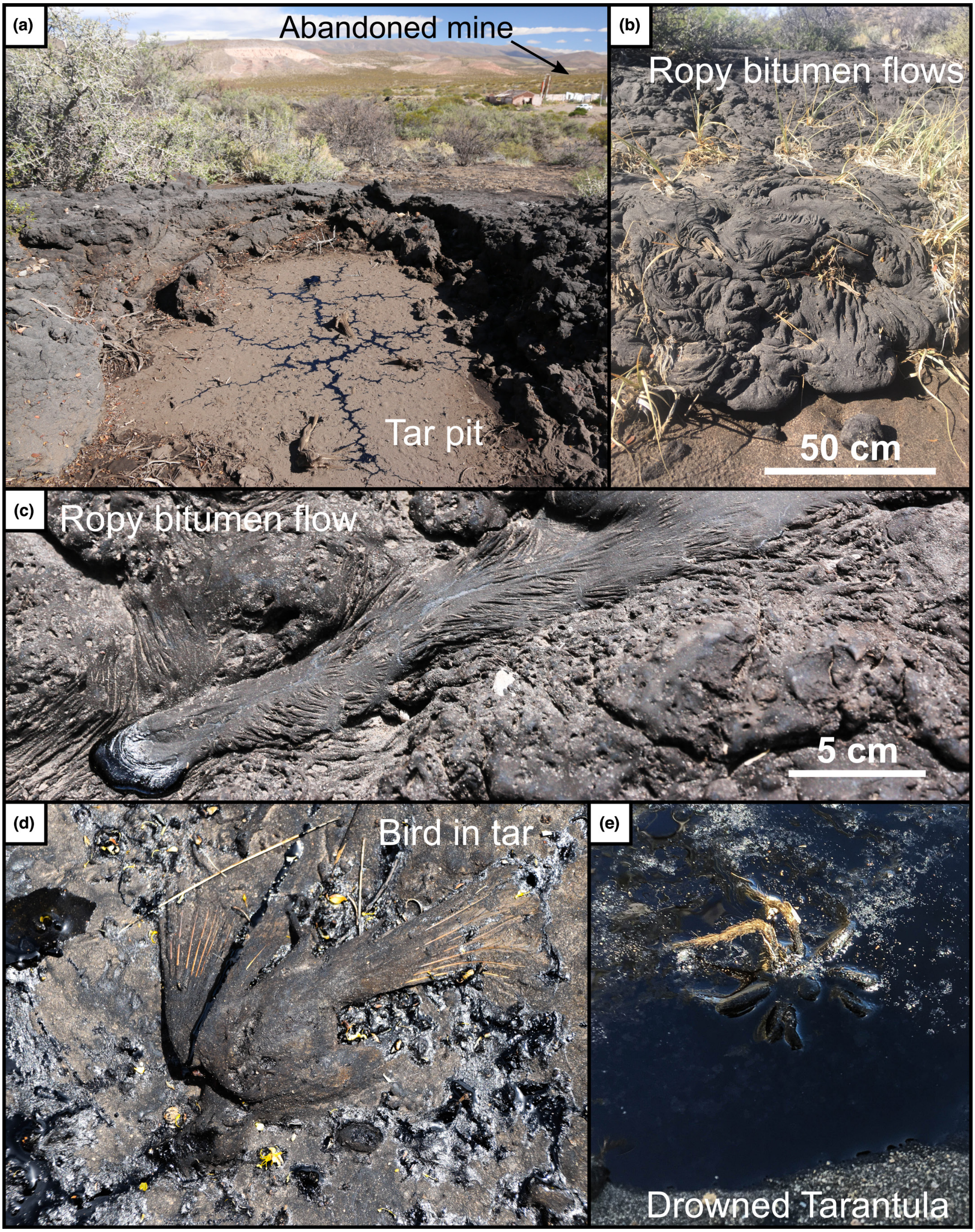

FIGURE 4 Characteristic manifestations of bitumen seep at Cerro Alquitrán. (a) Tar pit. (b) Ropy flow complex. (c) Detail of ropy flow. (d) Dead bird drowned in tar. (e) Dead Tarantula drowned in tar.

The intrusive bodies of the La Brea Fm. were emplaced shortly before and during the development of the compressional tectonic deformation (Baldauf et al., 1997; Combina & Nullo, 2011; Giambiagi et al., 2008; Nullo et al., 2002). Araujo et al. (2019) suggest that the transport and emplacement of magma might have been controlled by thrust faults.

3 | METHODS

3.1 | Geological fieldwork

The fieldwork consisted of the mapping of andesite outcrops of Cerro Alquitrán. In particular, we focused on searching for contacts of the intrusion, mapping all main bitumen seep manifestations, and collecting structural information in the andesite to understand the link between the igneous body and the bitumen seeps. The main target of the fieldwork was also to collect oil samples to perform organic chemical analyses (see Section 3.2).

In addition to outcrop observations, we performed drone flights for digital photogrammetry surveys in order to compute 3D digital models of the study area. The drone was a DJI Phantom 3 Advanced, and the size of the images was 12 MP. The photogrammetric processing of the drone images was performed using Agisoft Metashape.

3.2 | Organic geochemistry

A key question arising is whether the bitumen seeping out at Cerro Alquitrán has a local origin as a result of, e.g., local thermal maturation in the contact aureole of the intrusion (Figure 1), or a more regional origin indicating migration from a distal source. In order to address this question, organic chemical analyses on bitumen samples from the seeps were targeted as a tool to fingerprint the origin of the organic material and hence the fluids. We thus performed organic chemical analyses on two samples collected at the northern and eastern seep areas (CA-19-P6 and CA-19-P7, respectively; location in Figure 3). Both samples provided similar results, so only the results from CA-19-P6 are provided in this paper.

The seeping bitumen is highly viscous and strongly biodegraded, thus a combination of gas chromatography and biomarkers were applied. The methods used to analyse the organic chemical compositions of the bitumen sampled at Cerro Alquitrán are implemented routinely at the GeoLab Sur geochemical laboratory to identify the source rock that generated the bitumen, their degree of maturity and degradation.

The bitumen samples were analysed as “whole oils” by Gas Chromatography-Flame Ionization Detector (GC-FID) using an Agilent 6890 gas chromatograph equipped with a 60 m DB-1 column; the injector was at 275°C, and the heating program was: 30°C (hold 5 min), 3°/min ramp to 320°C (hold for 20 min). Helium was used as carrier gas.

Analysis of saturated and aromatic hydrocarbons for biomarker fingerprinting was performed using gas chromatography–mass spectrometry (GC–MS). The fractions of saturated and aromatic compounds were obtained by Medium Pressure Liquid Chromatography (MPLC). Saturated compounds were molecular-sieved to remove linear from branched and cyclic alkanes.

GC–MS analysis of the saturated hydrocarbons was performed with an Agilent 7890 gas chromatograph coupled to an Agilent 5977 Mass Selective Detector (MSD), using the Selected Ion Monitoring (SIM) mode. The GC column was DB-5, 60 m long, 0.25 mm. The oven heating program started at 100°C, with ramps of 20°C/min to 170°C, 1.5°C/min to 290°C and 2°C/min to 320°C (hold for 20 min). Helium was used as carrier gas.

GC–MS analysis of the aromatic hydrocarbons was performed with an HP 5890 gas chromatograph coupled to an HP 5971 MSD, using the SIM mode. The GC column was DB-1, 60 m long, 0.25 mm. The oven heating program started at 70°C (hold for 3 min), with ramps of 1.5°C/min ramp to 150°C and 3°C/min to 315°C (hold for 20 min). Helium was used as carrier gas.

4 | RESULTS

4.1 | Surface manifestation of bitumen

The major surface bitumen seeps occur in various forms, from tar pits to long bitumen flows (Figure 4a–c). The surface of the bitumen flows often exhibits ropy structures that mimic basaltic pahoehoe lava flows. Numerous animals of different sizes (from insects to armadillos) are found dead in the natural tar (Figure 4d,e), forming a modern-day example akin to the classic “tar pits” that have trapped ancient fossils. Several hitherto undocumented seeps have been located around the intrusion. Three old and currently inactive seeps were previously exploited for tar production along the western edge of the andesite body (Figure 3b). We also discovered a major active seep at the southwestern tip. In all these localities, the bitumen is seeping out through the soil, such that the geological structures controlling the subsurface bitumen migration are hidden.

We also discovered active seeps in a well-exposed gully on the southeastern part of the intrusion, in addition to numerous minor inactive seeps in the middle of the igneous body itself (Figure 3b). In these latter discoveries, the bitumen seeps out directly from fractures in the magmatic rock (Figure 5).

On the map view, the overall distribution of the major seeps follows the edge of the intrusion (Figures 3b and 5), suggesting a relationship between the intrusion and fluid migration pathways.

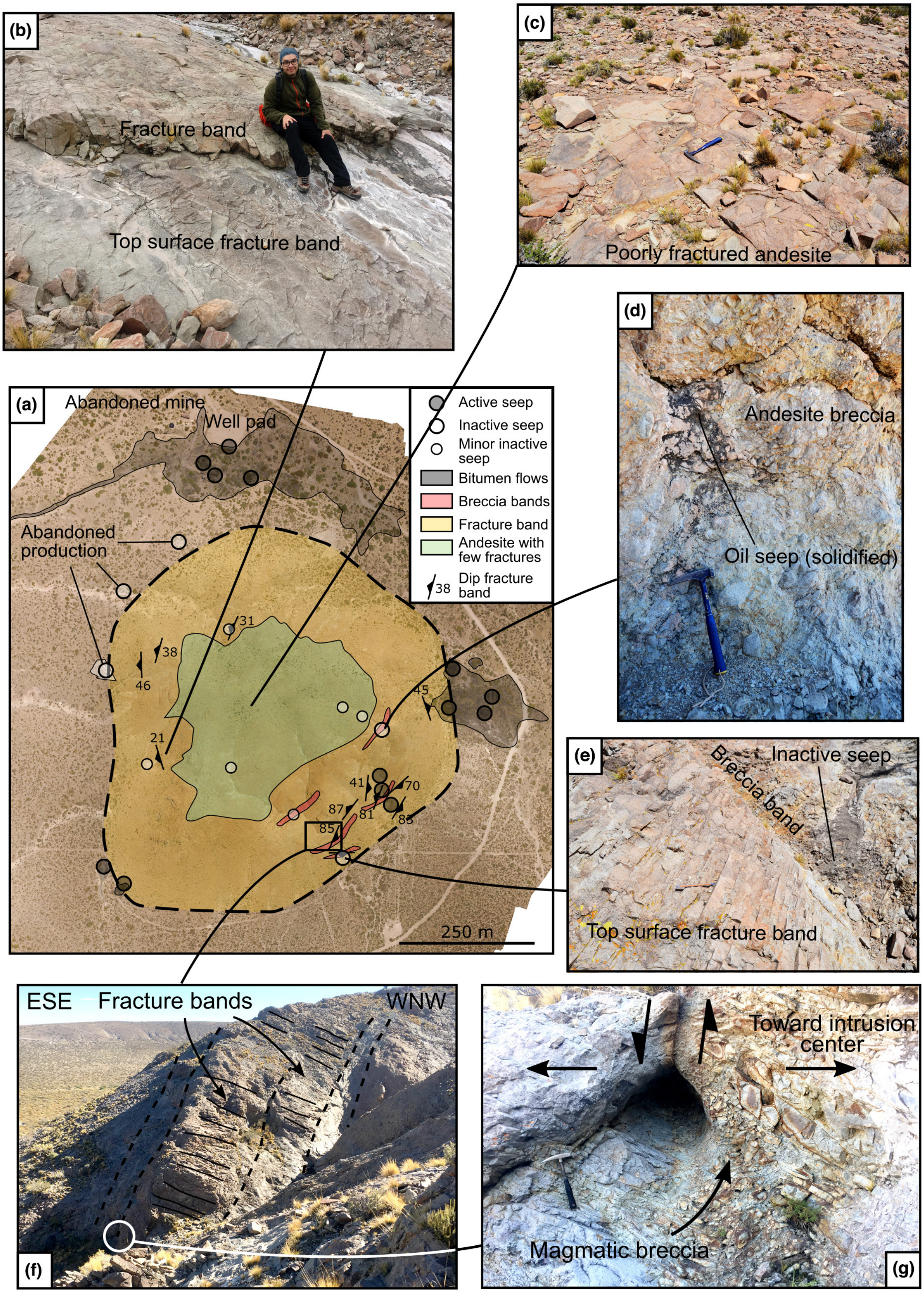

FIGURE 5 (a) Map of Cerro Alquitrán locating zones of breccia bands (red), fracture bands (yellow) and poorly fractured andesite (green), as well as bitumen seeps. (b) Field photograph of gently dipping fracture bands along the western side of Cerro Alquitrán andesite body. (c) Field photograph of poorly fractured andesite near the summit of Cerro Alquitrán. (d) Field photograph of breccia near the eastern edge of the andesite body. Note solidified bitumen that seeped out from the breccia. (e) Field photograph of the top surface of fracture band and thin breccia band near SE edge of Cerro Alquitrán. Note the inactive bitumen seep originating from the breccia band. (f) Field photograph of steep outward-dipping fracture bands near the SE edge of Cerro Alquitrán andesite. (g) Sub-vertical breccia with fault gauge indicating upward movement of the interior of the intrusion.

4.2 | Structure of the andesite body

We mapped the Cerro Alquitrán intrusion to reveal its shape, internal structure and relationship with the bitumen seeps. On the map view, the andesite hill of Cerro Alquitrán exhibits a sub-circular shape (Figure 5a). The contacts of the intrusion are nowhere exposed, making it challenging to constrain its overall shape. Nevertheless, it is likely that the intrusive contacts are relatively close to the outer edges of the outcropping andesite, suggesting a rounded massive intrusion-type laccolith or plug, as already suggested by Dessanti (1959). Other intrusions of the La Brea Fm. are identified as massive laccolithic bodies, strengthening this hypothesis (Araujo et al., 2019; Dessanti, 1959).

The igneous body exhibits variable internal structuring of the andesite. It is possible to recognize three main structure patterns (Figure 5).

The most prominent structures are brecciated andesite (Figure 5d,e,g), distributed along bands. Andesite breccia bands have only been observed near the southeastern edge of the body (Figure 5a). When it was possible to constrain their geometry, the breccia bands are steeply dipping to the SE or even sub-vertical (Figure 5g). Locally, kinematic indicators within the breccia highlight that the inner part of the intrusion moved upward with respect to the outer part.

Structures of less intensity are fracture bands (Figure 5b,e,f). These bands are prominent in the landscape with the top surface often well exposed, and they contain thousands of fractures that are sub-perpendicular to the top surface of the fracture band (Figure 5b,e). The fracture bands are systematically outward dipping. Their dip is much higher near the southeastern edge of the body (50°–90°; Figure 5a) than the other parts of the intrusion where fracture bands are visible. The most gently dipping

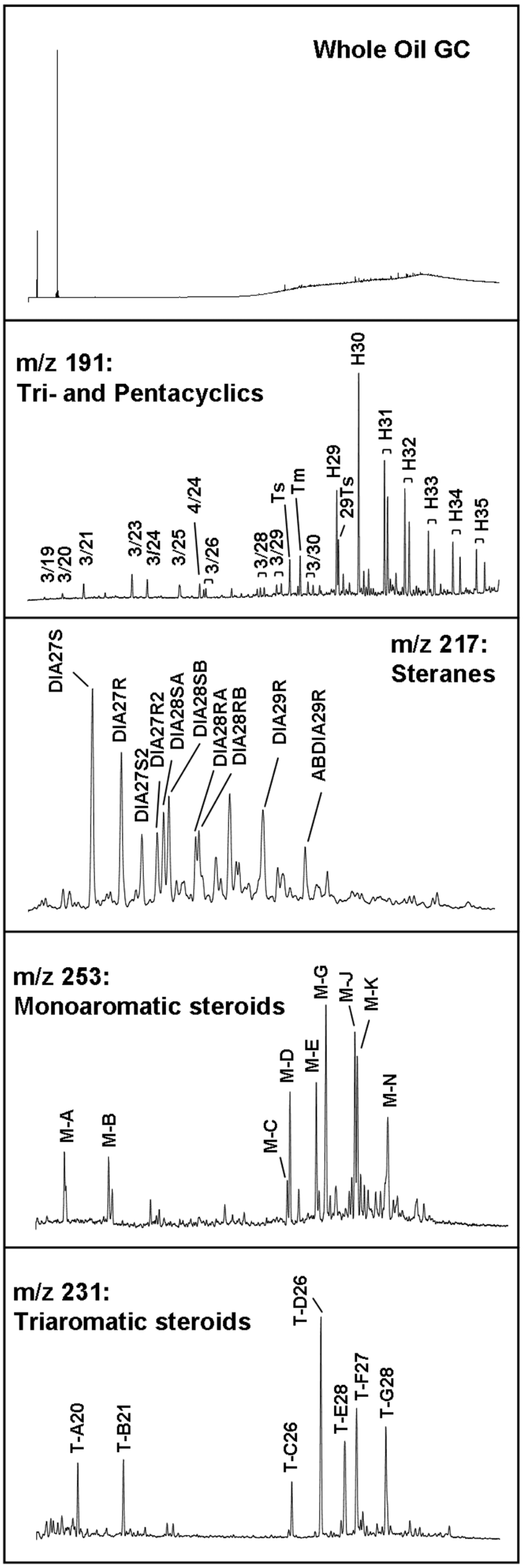

FIGURE 6 Whole oil Gas Chromatography (GC) trace and mass chromatograms for tri- and pentacyclic terpanes, steranes, mono- and triaromatic steroids, of seep oil CA-19-P6. **Tri- and pentacyclics:** 3/C*i* = tricyclic terpane of *i* carbon atoms; 4/24 = tetracyclic terpane of 24 carbon atoms; Ts = 18aH)-trisnorhopane; Tm = 17a(H)-trisnorhopane; H29 = C_{29} Tm 17a(H)21b(H)-norhopane; 29Ts = C_{29} Ts 18a(H)-norneohopane; H30 = C_{30} 17a(H)-hopane; H31 to H35 = C_{31} to C_{35} 22S and 22R17a(H) hopanes. **Steranes:** DIA27S = C_{27} ba 20S diasterane; DIA27R = C_{27} ba 20R diasterane; DIA27S2 = C_{27} ab 20S diasterane; DIA27R2 = C_{27} ab 20R diasterane; DIA28SA = C_{28} ba 20S diasterane a; DIA28SB = C_{28} ba 20S diasterane b; DIA28RA = C_{28} ba 20R diasterane a; DIA29R = C_{29} ba 20R diasterane; ABDIA29R = C_{29} ab 20R diasterane. **Monoaromatic steroids:** M-A: C_{21} ring-C monoaromatic steroid; M-B: C_{22} monoaromatic steroid; M-C: C_{27} Reg 5b(H), 10b(CH3) 20S; M-D: C_{27} Dia 10b(H),5b(CH3) 20S; M-E: C_{27} Dia 10bH,5bCH3 20R+Reg5bH,10bCH3 20R; M-G: C_{28} Dia 10aH,5aCH3 20s+Reg5bH,10bCH3 20S; M-J: C_{28} Dia 10aH,5aCH3 20R+Reg5bH,10bCH3 20R; M-K: C_{29} Dia 10bH,5bCH3 20S+Reg5bH,10bCH3 20S; M-N: C_{29} Dia 10bH,5bCH3 20R+Reg5bH,10bCH3 20R. **Triaromatic steroids:** T-A20: C_{20} triaromatic steroid; T-B21: C_{21} triaromatic; T-C26: C_{26} 20S triaromatic; T-D26: C_{27} 20S and C_{26} 20R triaromatic; T-E28: C_{28} 20S triaromatic; T-F27: C_{27} 20R triaromatic; T-G28: C_{28} 20R triaromatic.

fracture band (21° dip) is located near the western edge of the body (Figure 5a,b).

Finally, the core of the andesite body consists of massive andesitic rock affected by very few fractures (Figure 5c).

Our field observations allow us to document some structural relationships between the seeps and the structure of the andesite. The main seep in the eastern gully occurs in a zone of high fracture intensity, both fracture bands and breccia bands. Locally, it is possible to observe the breccia impregnated with the bitumen that seeps out (Figure 5d,e). A noticeable observation is that not all breccia and fracture bands are associated with bitumen seep. In addition, the seeps often occur punctually along a breccia or fracture band, such that other parts of the structure along the strike are "dry".

4.3 | Organic geochemistry

The seeping bitumen at Cerro Alquitrán is highly viscous and strongly biodegraded, as indicated by severely altered GC traces (Figure 6, Whole Oil GC), characterized by the development of UCM (unresolved complex mixture) humps and complete absence of the paraffin compounds typically occurring in conventional oils. Thus, the GC data alone is not sufficient to identify the source and thermal maturity of the oil. In line with this pattern, the MPLC normalized data show high enrichment in polar compounds, with values of NSOs + Asphaltenes in the range 56.2%–63.05% and limited hydrocarbon participation (saturates: 17.3%–18.6%; aromatics: 19.6%–25.1%). The biomarkers analysis by GC–MS (Figure 6) shows well-preserved distributions of tricyclic and pentacyclic terpanes (Figure 6; m/z 191) that are considered original fingerprints, i.e., not affected by biodegradation processes. On the other hand, the regular steranes (Figure 6; m/z 217) are present in very low relative concentrations and show very significant alteration in their distributions. Conversely, diasteranes, which are typically more resistant to biodegradation, exhibit well-preserved fingerprints and are the dominant compounds. Among aromatic hydrocarbons, monoaromatic (Figure 6; m/z 253) and triaromatic (Figure 6; m/z 231) steroids show good preservation, while two- and three-ring compounds (alkyl-naphthalenes, alkyl-phenanthrenes and alkyl-dibenzothiophenes) are moderately to severely altered. These overall GC–MS patterns point to an intense biodegradation of the seep oils, consistent with a level 7 on a scale of 1–10 (Peters et al., 2005).

Despite the effects of biodegradation on regular steranes, both the saturate and aromatic biomarker fingerprints point to generation in a shaly to marly source rock deposited in a marine-anoxic environment, with little or no terrigenous participation (Peters et al., 2007). According to the regional knowledge of the source facies in this part of the Neuquén Basin (Boll et al., 2014; Brisson et al., 2020; Legarreta & Villar, 2015), the origin of the Cerro Alquitrán seep oils is attributed to intervals within the Mendoza Group, preferentially of the Vaca Muerta Formation.

The maturity-dependent ratios are apparently not affected by biodegradation (Ts/Ts + Tm: 0.48–0.50, C29Ts/C29: 0.48–0.53, aromatic steroid side chain cracking: 0.14–0.16) (Figure 6), the level of thermal maturation of the oils is considered early to moderate, with a VRE (Vitrinite Reflectance Equivalence) assignment in the range ca. 0.7%.

5 | INTERPRETATION AND DISCUSSION

5.1 | Structure of Cerro Alquitrán

Even if the intrusive contacts are not exposed, our field observations allow us to constrain the structure of the andesite body. Similar fracture bands as those described in this study have been documented at exhumed massive intrusions (Burchardt et al., 2019; Goto & Tomiya, 2019; Mattsson et al., 2018; Stewart & McPhie, 2003), intermediate to felsic active volcanic conduits (Hornby et al., 2019; Lavallée et al., 2008) and thick andesitic dykes (Schmiedel et al., 2021). In these examples, the fracture bands are systematically sub-parallel to the intrusion contacts. This suggests that the fracture bands observed at Cerro Alquitrán can be used as a proxy for constraining the shape of the body.

The strike of the fracture and breccia bands exhibit a concentric distribution, suggesting that the intrusion is a rounded body. The large dip angles of the fracture bands also suggest a prominent doming of the overburden, typical of a laccolith (Corry, 1988; Gilbert, 1877). In addition, the asymmetric dip angles of the fracture bands and asymmetrical distribution of the breccia bands suggest that the laccolith grew in an asymmetrical manner according to a trapdoor mechanism (Amelung et al., 2000; Galland et al., 2022), with intense strain localization along a faulted margin at the southeastern flank. Finally, in the inner parts of the body, the fabric is gently dipping, which indicates that the exposure level is likely close to the paleo-roof of the intrusion (Figure 7). From our field observations, however, we cannot constrain the outer extent of andesite hidden by soil.

We did not investigate in detail the mechanism at the origin of the development of the fracture and breccia bands. As discussed above, their concentric distribution shows that they are related to the emplacement of the magmatic body. Mattsson et al. (2018) show that at the Sandfell Laccolith, Iceland, the fracturing in fracture

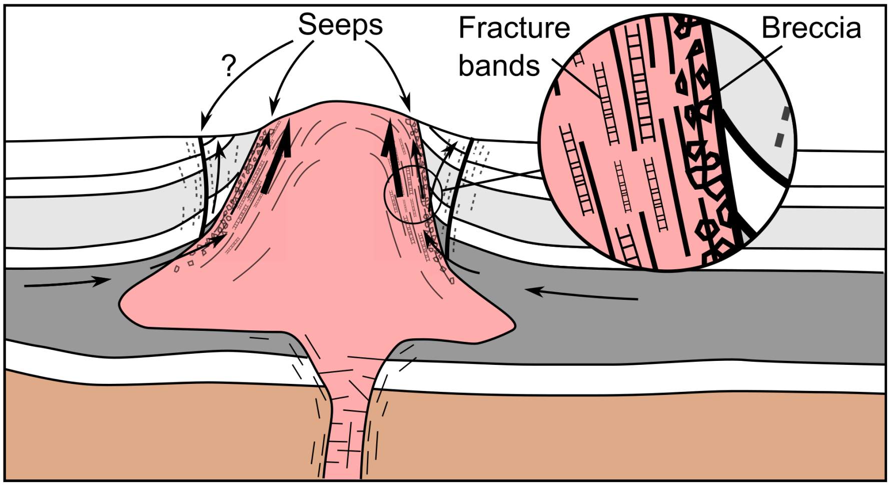

FIGURE 7 Schematic representation of the structure of Cerro Alquitrán intrusive body and associated structures, and how they control hydrocarbon migration and seepage.

bands was coeval with the viscous flow of the magma, suggesting that they resulted from syn-emplacement brittle deformation of the magma. Such brittle deformation shows that the magma deformation mechanism crossed the brittle-ductile transition. Several parameters can affect the brittle-ductile transition in flowing magmas, such as faster shearing rates near the edges of the intrusion or lateral chemical and crystal-content variations (Cordonnier et al., 2012; Hornby et al., 2019; Lavallée et al., 2008, 2013; Mattsson et al., 2018). We infer from these observations that the structural grain in the igneous body results from syn-emplacement brittle deformation of the magma.

We cannot rule out, however, that some tectonic deformation has affected the brittle structures in Cerro Alquitrán, as it is located in the vicinity of the Andean deformation front. However. Seismic and borehole data in the study area have not allowed identifying a fault that is prominent enough to explain the intense fracturing and brecciation of the andesite (Boll et al., 2014; Giambiagi et al., 2008). In addition, the concentric distribution of the fracture and breccia bands are somehow incompatible with tectonic faulting.

5.2 | Bitumen source at Cerro Alquitrán

The VRE value estimate for the oils seeping out at Cerro Alquitrán is significantly higher than those of the subsurface Vaca Muerta Fm. in the Cerro Alquitrán area, where it is considered immature (Boll et al., 2014; Brisson et al., 2020). This mismatch suggests that either the oils migrated from a regional maturation zone due to burial to the West (Boll et al., 2014) or they resulted from local maturation in thermal aureoles of subsurface intrusions of La Brea andesite suite emplaced in the Vaca Muerta Fm., as commonly reported in the Neuquén Basin (Boll et al., 2014; Rodriguez Monreal et al., 2009; Spacapan et al., 2018, 2020). Nevertheless, the Vaca Muerta Fm. in the study area is organic-poor, excluding the possibility of a local origin of petroleum. In addition, there is a strong geochemical similarity between the Cerro Alquitrán seeps and the oils produced in neighbouring productive fields, not only with regard to organic source facies but also thermal maturity (Boll et al., 2014). Such compositional homogeneity does not support local maturation due to igneous intrusions, which is expected to lead to strong compositional variability (Boll et al., 2014). Instead, it indicates that the hydrocarbons of the Cerro Alquitrán broader regional area have a common origin. It is therefore likely that the seeping oils at Cerro Alquitrán have an origin from incipiently mature Vaca Muerta sections located in a regional maturation zone to the west, and have migrated eastward ca. 10–20 km according to published maturity patterns (Boll et al., 2014), highlighting extensive modification of the fluid flow pathways by the intrusive network, and a focusing of the fluid flow towards the present locality.

The combined geochemical and structural data show that the hydrocarbons migrated laterally over a large distance, and the migration has been locally affected by the brittle magmatic structures. The seeps at Cerro Alquitrán thus provide a local surface window of this subsurface regional-scale fluid migration.

5.3 | Igneous intrusions and fluid migrations

Our field observations show that the bitumen at Cerro Alquitrán seeps out along syn-emplacement brittle structures affecting the andesite body, i.e., fracturing of the magma in fracture and breccia bands while the magma was not solidified. Thus, our study highlights how brittle magmatic structures can be prominent permeability corridors that channelize fluid flow at the regional scale for long periods after emplacement and cooling. Such brittle magmatic fabric has been observed within other exposed subvolcanic intrusions (Burchardt et al., 2019; Mattsson et al., 2018). These syn-emplacement brittle structures strongly resemble those observed during the growth of volcanic domes at active volcanoes, which affect magma degassing and gas release during volcanic eruptions (Cordonnier et al., 2012; Lavallée et al., 2008).

The inferred thick laccolithic to plug shape of Cerro Alquitrán also implies substantial deformation and damage of the host rock (Galland et al., 2022; Montanari et al., 2017; Schmiedel et al., 2019; Wilson et al., 2021), leading to fractures and locally intense damage that can also enhance fluid flow. Unfortunately, nowhere the host rock of Cerro Alquitrán is exposed, such that it is impossible to assess whether the northern and eastern seep areas are controlled by structures within the andesite or in the host rock.

Our field observations show that even though numerous fractures affect the andesite in the documented fracture and breccia bands, the bitumen only seeps out along a very small fraction of them. For example, along a single breccia band, the bitumen may seep out punctually while the rest of the structures are dry. This observation highlights the great complexity of predicting fluid migration in strongly heterogeneous rocks.

Regional studies in the Neuquén basin documented that other complexes of sill intrusions exhibit high-permeability fractured reservoir properties (Rabbel et al., 2021; Spacapan et al., 2020; Witte et al., 2012). Rabbel et al. (2021) described various fracturing mechanisms, such as cooling jointing of the sills, the fracturing of the host rock resulting from fast fluid pressure build-up due to contact metamorphism, injection of bitumen veins, hydrothermal circulations along hydraulic fractures, and tectonic fracturing. Our study evidence that syn-emplacement magma fracturing in laccolithic intrusions is another mechanism of permeability enhancement associated with the igneous complex. Basin models in volcanic basins hosting sills and laccoliths thus should take into account such complexity to provide relevant predictive results.

The Cerro Alquitrán is a well-preserved example of igneous intrusion having a primary role in modifying basin-scale fluid migration. Clearly significant research is needed to fully understand fluid flow through and around subvolcanic intrusions, with large implications for exploring geothermal energy (Montanari et al., 2017; Mordensky et al., 2018), groundwater (Chevallier et al., 2001), hydrocarbons (de Miranda et al., 2018; Spacapan et al., 2020) and CO_2 sequestration sites (Senger et al., 2013) in active volcanic regions and volcanic basins.

6 | CONCLUSIONS

This paper presents geological observations from a demonstrative case study that illustrates how massive laccolithic intrusions can significantly affect fluid migrations in sedimentary basins a long time after their emplacement and cooling. The conclusions of our study are:

- The Cerro Alquitrán intrusion clearly demonstrates a direct control of the permeability network in the direct vicinity of the intrusion contacts with the host sediments and within the intrusive body itself.
- Oil/bitumen seeps are located concentrically around the intrusion in the vicinity of the contact zones and within the intrusion itself.
- Complex syn-intrusive fractures (along with post-emplacement cooling fractures) are concentrated along the outer margins of the intrusion, and where exposed provide direct evidence of fluid migration (seeping) within this fracture network. Such marginal fracture associations have been reported from other laccolith bodies (e.g., Burchardt et al., 2019), and may play an important role in the focusing of fluid migration where such bodies reside within sedimentary host basins.
- Oil fingerprinting suggests that the migrating fluid has travelled for some distance to the current seep site, and suggests a linked fluid migration pathway in the subsurface to the Cerro Alquitrán intrusion, which may also be the result of the larger-scale interconnected igneous plumbing system and its structural controls on fluid migration, as highlighted by regional studies that documented numerous sill intrusions emplaced in the source rock formations (Vaca Muerta and Agrio Fms) in the vicinity of the study area. Such sill bodies provide lateral structures where fluids can migrate several kilometres from their origin.

Our study highlights the significant impact of the structure of, and within, subvolcanic intrusions on fluid migrations a long time after their emplacement and cooling. Among others, we show that understanding the shape of intrusions and the processes governing the fracturing of the magmatic rocks is key for properly assessing how volcanic plumbing systems affect the permeability architecture of sedimentary basins.

ACKNOWLEDGEMENTS

Palma's salary is covered by a CONICET and Y-TEC grant. Dougal Jerram is partly funded through a Norwegian

Research Council Centers of Excellence project (project number 223272, CEED). The fieldwork was supported by the DIPS project (grant no. 240467) funded by the Norwegian Research Council and a Småfork grant funded by the Department of Geosciences, University of Oslo. The authors acknowledge the very constructive reviews of Alan Bischoff and Sergio Ricchi, and the fruitful comments of editor Craig Magee.

CONFLICT OF INTEREST STATEMENT

No there is no conflict of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/bre.12782.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Galland, O., Villar, H. J., Mescua, J., Jerram, D. A., Midtkandal, I., Palma, J. O., Planke, S., & Zanella, A. (2023). The long-term legacy of subvolcanic intrusions on fluid migration in sedimentary basins: The Cerro Alquitrán case study, northern Neuquén Basin, Argentina. *Basin Research*, *35*, 1840–1855. https://doi.org/10.1111/bre.12782