# OUTCROP EVIDENCES OF THE EFFECTS OF MAGMATIC INTRUSIONS IN PETROLEUM SYSTEMS: MATURATION OF SOURCE ROCK, SILLS RESERVOIRS AND HYDROCARBON MIGRATION

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## RESUMEN

En este trabajo se evaluará el efecto que genera la intrusión de un complejo de sills en las rocas generadoras de la Cuenca Neuquina, haciendo foco principalmente en la extensión de la aureola térmica y las propiedades como carriers de los intrusivos. El área de estudio es la Sierra de la Cara Cura, ubicada en el sur de la provincia de Mendoza. La metodología utilizada integra mapeo mediante imágenes satelitales y observaciones de campo de detalle, con toma de muestras para análisis petrográficos, de geoquímica orgánica y espectroscopia Raman. El complejo intrusivo está formado por sills, diques, lacolitos y formas híbridas. Los sills presentan variaciones internas y distintos tipos de fracturas, generalmente rellenas con bitumen. Se han identificado fracturas de enfriamiento, de inyección de bitumen, de alteración e hidrotermales, formadas durante la etapa de enfriamiento, y fracturas tectónicas. Los diques y lacolitos presentan en los contactos una zona de brecha denominada "zona de daño" la cual es interpretada como una vía de migración que puede atravesar sellos y promover la conectividad hidráulica entre distintas unidades. Las venas hidrotermales también son vías de migración de hidrocarburos, pudiendo cargar reservorios superiores. El efecto térmico y la extensión de la aureola térmica han sido definidos en base al Índice de Hidrógeno (HI), concluyendo que las Fms. Vaca Muerta y Agrio se encuentran afectadas térmicamente por el complejo intrusivo. En base a la espectroscopia Raman se interpreta que el bitumen en la aureola de contacto está muy alterado y grafitizado, evidenciando que ha sido sometido a altas temperaturas.

## INTRODUCTION

The emplacement of igneous intrusives in sedimentary basins can cause positive and negative effects on petroleum systems (Senger *et al.* 2017). Particularly, intrusives emplaced in organic-rich rocks can promote maturation with the consequent generation of hydrocarbons (Aarnes *et al.* 2010, and references therein). Also, sills can act as reservoirs or as migration pathways

(Spacapan *et al.* 2020b). Delpino and Bermúdez (2009) defined these as igneous petroleum systems.

Examples of these have been studied in the Neuquén Basin, more precisely in the Malargüe Fold and Thrust Belt (Rodriguez Monreal *et al.* 2009; Spacapan *et al.* 2020a), where it has been possible to demonstrate the thermal effect of the intrusives in the source rocks of the Mendoza Gr. (Spacapan *et al.* 2018), and igneous rocks have been reservoirs with commercial hydrocarbon production (Spacapan *et al.* 2022).

Several authors have studied reservoir properties of sill-type igneous intrusives (Delpino and Bermúdez 2011; Schiuma and Llambías, 2014) and laccolith type (Delpino *et al.* 2014). Most of these studies have focused on fractures and have been carried out with subsurface data (seismic, well logs, cores), while outcrops studies are sparse (Rabbel *et al.* 2021). In addition, matrix porosity of this type of reservoirs is poorly documented (Spacapan *et al.* 2020a).

This work presents an outcrop analogue study of an igneous petroleum system located in the Neuquén basin. The main objective is to evaluate the thermal effect of the intrusives in main source rocks (Vaca Muerta and Agrio Formations), their properties as reservoirs, and how they can favor fluid migration through hydrothermal vein systems and damage zones associated with emplacement and tectonism.

## GEOLOGICAL CONTEXT

The study area is located in the Sierra de Cara Cura, in the northern sector of the Neuquén Basin, in the south of the Mendoza Province (Fig. 1a). It is part of the southern edge of the Malargüe Fold and Thrust Belt (MFTB). The mountain range is formed by two asymmetric brachyanticlines with a NNE-SSW strike and W vergence, the Cara Cura anticline to the W and the Chihuidos anticline to the E, limited by the Chihuido thrust (Fig. 1b). In this area, an igneous intrusive complex affects the entire sedimentary column and shows an excellent degree of preservation on outcrops (Fig. 1c and d).

This complex represents the intrusive phases of Paleogene volcanism, integrated by the Molle eruptive cycle, attributed to the upper Oligocene to Miocene (Nullo *et al.* 2002).

## METHODOLOGY

The methodology used in this study integrates satellite image analysis, field work, structural measurements, sampling for petrography, organic geochemical analysis, and Raman spectroscopy.

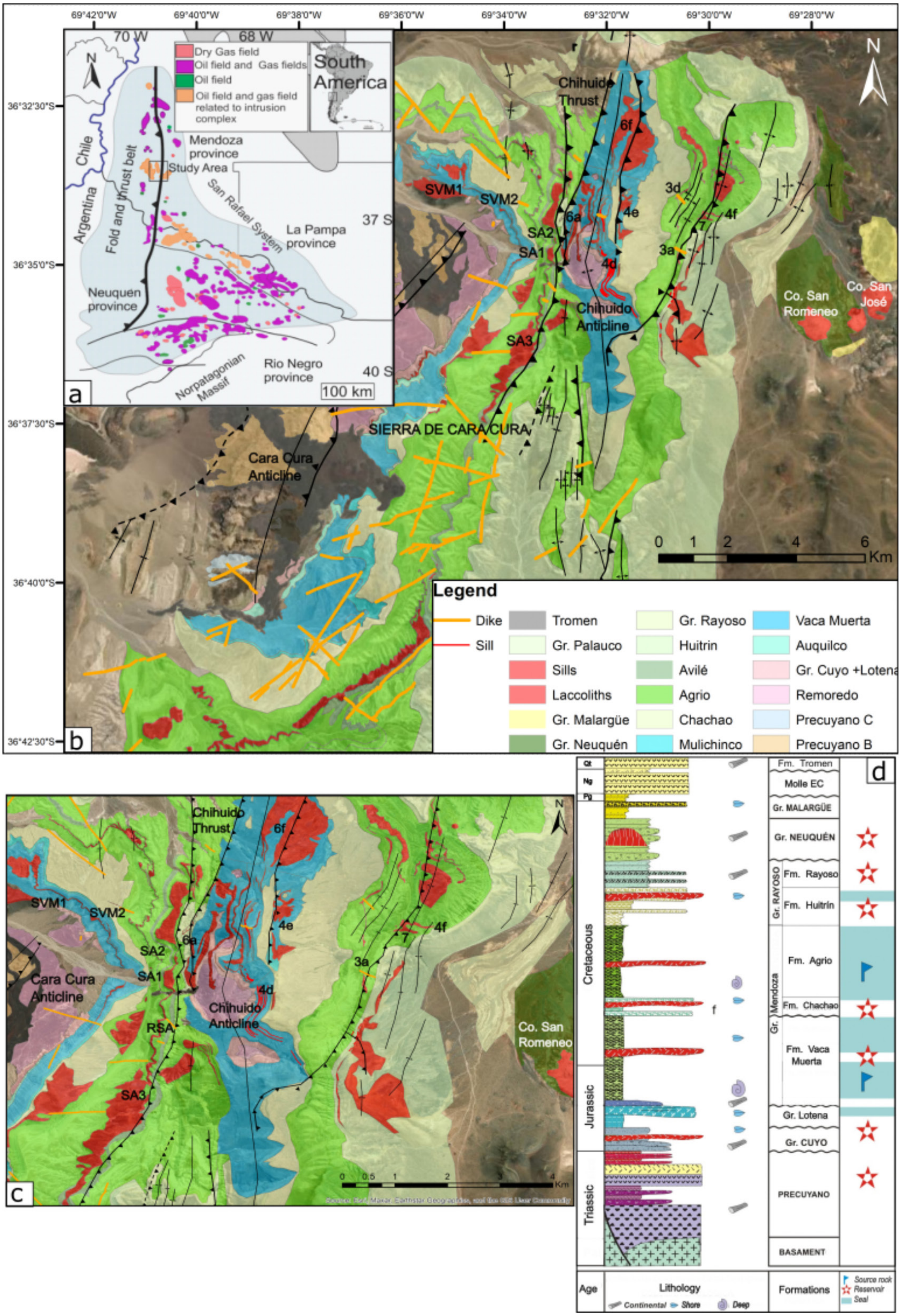


**Figure 1.** a) Map of the Neuquén Basin with the main oil fields related to igneous intrusives (modified from Spacapan *et al.* 2022). b) Geological map of the Cara Cura range. Structures modified from Armisen (2009). c) Main localities described in the text (numbers). c) Stratigraphic column (modified from Pángaro *et al.* 2002).

## Mapping of intrusives through satellite images and field work

The igneous intrusives are easily recognized and mapped in high resolution satellite images. Dikes up to 1 m can be distinguished. Geological observations have been carried out in the Sierra de Cara Cura, providing insight into the overall architecture of the magmatic complex, as well as detailed observations of the different morphologies of the intrusives and their contacts with the host rock. Also, the thicknesses of the sills and dikes were measured, including structural measurements and sampling of various types of fractures, both in the igneous rocks and in the host rocks.

## Petrography

Petrographic sections of the igneous intrusives and hydrothermal veins were made to describe their composition and porosity. Some sections were impregnated with blue resin to facilitate the identification of the pores. Organic petrology analysis was made in samples from Vaca Muerta and Agrio Fms., including vitrinite reflectance (%Ro) and coloration of organic matter in transmitted and fluorescent light (TAI).

## Pyrolisis

114 samples were taken from the Vaca Muerta and Agrio formations for pyrolysis analysis using a Rock-Eval 6 pyrolyser. The pyrolysis parameters allow estimating the thermal maturity and the type of organic matter of the source rocks, and is commonly used to quantify the maturation effect of igneous intrusions (Spacapan *et al.* 2018). During pyrolysis, the samples are progressively heated up to 650°C to identify the amount of free hydrocarbons (S1 peak), the remaining hydrocarbon potential (S2 peak), the total organic carbon (TOC). From these parameters, the oxygen index (OI) and the hydrogen index (HI) can be calculated. The HI is calculated as S2/ TOC x 100, giving milligrams of hydrocarbons per gram of organic matter. Assuming an initial HI from immature samples or literature values, the conversion ratio (TR) of organic matter to hydrocarbons (initial HI – HI / initial HI) can be calculated.

## Raman Spectroscopy

Raman spectroscopy was used to identify the presence of bitumen or hydrocarbons, both in the matrix and in the fractures, and characterize their thermal grade. The analysis was based on the positions and intensities of the spectral peaks at 1345 cm$^{2}$ 1 and 1585 cm 1, designated peaks D (“disorder”) and G (“graphite”), respectively (Potgieter-Vermaak *et al.* 2011).

## RESULTS

### Distribution and morphology of intrusives

The igneous intrusives are emplaced throughout the stratigraphic column of the Neuquén Basin, from the rocks of Precuyano to the Neuquén Gr. (Fig. 1b). They have been identified by satellite images in Cuyo Gr., Mendoza Gr., Bajada del Agrio Gr., and Neuquén Gr. Through fieldwork it was confirmed that the morphology of the intrusives is generally represented by three end members: laccoliths (Fig. 2), dikes (Fig. 3) and sills (Fig. 4, 5 and 6), but also hybrids morphologies between them can be found (Fig. 7).

### Laccoliths

Three laccoliths were identified emplaced in the Neuquén Gr., named Co. San Romeneo, Co. Bayo and Co. San José (Fig. 1a and 2a). Their diameters are in average 850 m, 400 m and 700 m, respectively. Typically, the sedimentary layers are folded throughout the contact with the intrusives, reaching vertical dips, as can be observed in the Co. San Romeneo (Fig. 2b). At the SW contact, a breccia zone of approximately 3 m thick is developed (Fig. 2c, d and e). A different fracture pattern from the inside of the laccolith to the contact can be observed. The inner part is characterized by a flow banding fracture pattern (Fig. 2c) while towards the contact a coarse breccia zone is developed in the laccolith and a fine grain breccia in the host rock (Fig. 2d and e). The coarse breccia is mainly composed by laccolith clasts in an igneous matrix, while the fine-grain breccia is a mixture characterized by clasts of igneous rocks in a fine sedimentary matrix. The contact between the two breccias is transitional, as well as the contact with the flow banding zone (Fig. 2f).

### Dikes

The dikes present in the range are in average one-meter-thick and are oriented according to preferential directions (Fig. 1). Two principal sets were recognized, one NE and other NNE, and a secondary set with NW orientations (Fig. 1 and 3a). Different contacts can be observed. Figure 3b shows the chilled margins of a dike with flow jointing. In the contact, the host rock has contact-parallel fractures and a thermal aureole, distinguished by a darker grey color, can be observed.

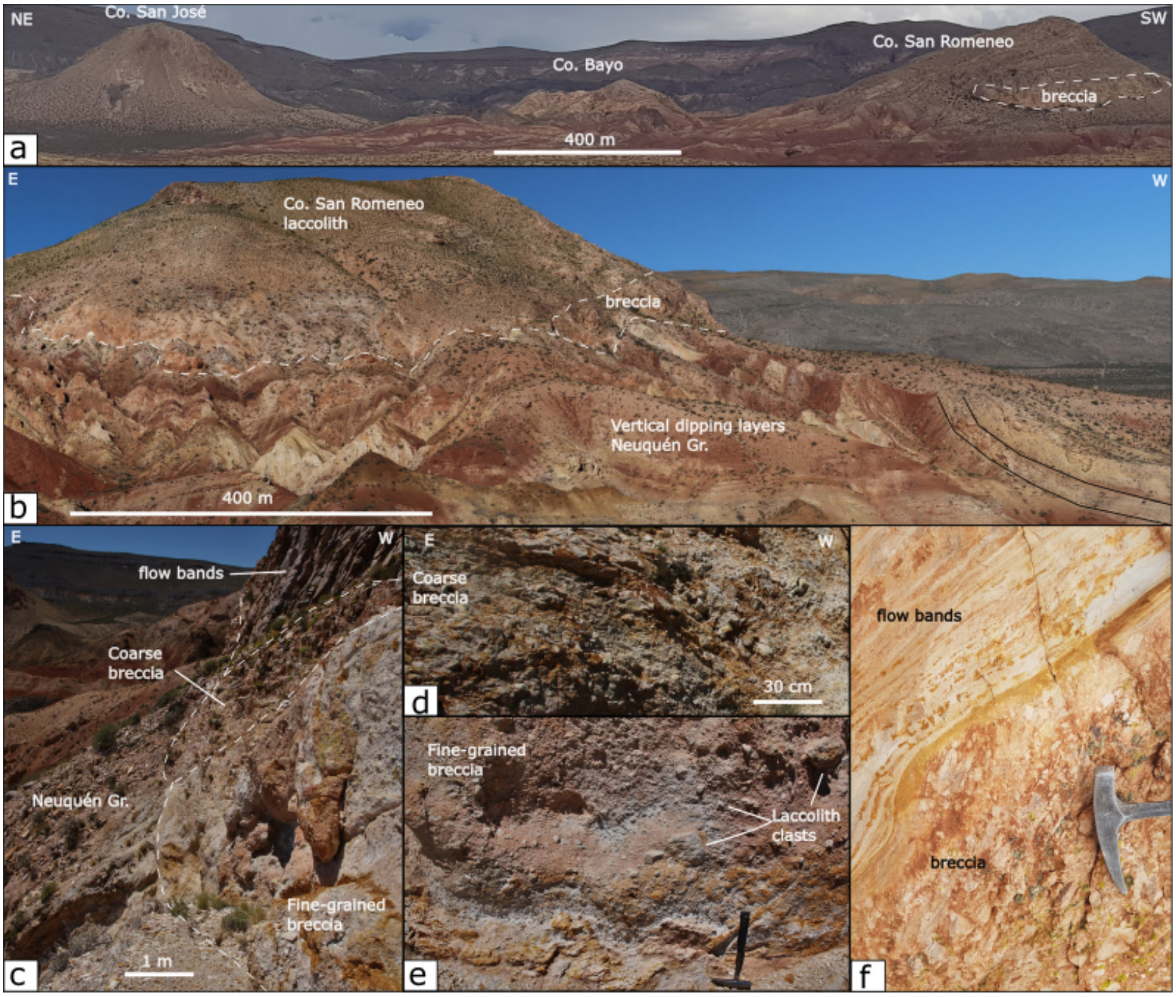


**Figure 2. Laccoliths. a) Three laccoliths emplaced in the Neuquén Gr. b) San Romeneo laccolith, showing the breccia at the SW contact and the folded host rock reaching vertical dips. c) Contact between flow banded jointing zone, coarse-breccia and fine-grain breccia. d) Coarse breccia zone in the laccolith. e) Fine grained breccia in the host rock. f) Close up photograph of the transitional contact between the breccia and the flow banding zone.**

In Figure 3c, a breccia developed in the igneous and sedimentary rock is shown. In some cases, bitumen was found in the veins of the contact parallel fractures (Fig. 3d), and in vesicles inside the dikes (Fig. 3e). Sometimes, the host rock is phagocytosed by the magma and sedimentary clast are entrained inside the intrusive (Fig. 3f). Generally, the dikes have two chilled margin with flowing joints, and to the interior columnar and intracolumnar joints are observed (Fig. 3g). Contact parallel fractures are developed in the host rock (Fig. 3h).

## Sills

Concordant intrusives, defined as sills, were recognized mainly in Vaca Muerta and Agrio Fms., but some were also identified in the Cuyo Gr. and Huitrín Fm. (Fig. 1). They are typically parallel to the stratification at their base and top (Fig. 4a), but occasionally crosscut through stratigraphy, forming an inclined sheet (Fig. 4b). Sills lengths are less than 10 km, but some can reach up to 19 km, and are aligned with the main structures of the area, with NNE orientations (Fig. 1). Their thickness is very variable, ranging from 1 to 30 m (Fig. 4, 5, 6 and 7). They have an andesitic composition, containing phenocrysts of plagioclase, hornblende and pyroxene in a microgranular matrix mainly formed by plagioclase (Fig. 8d and e).

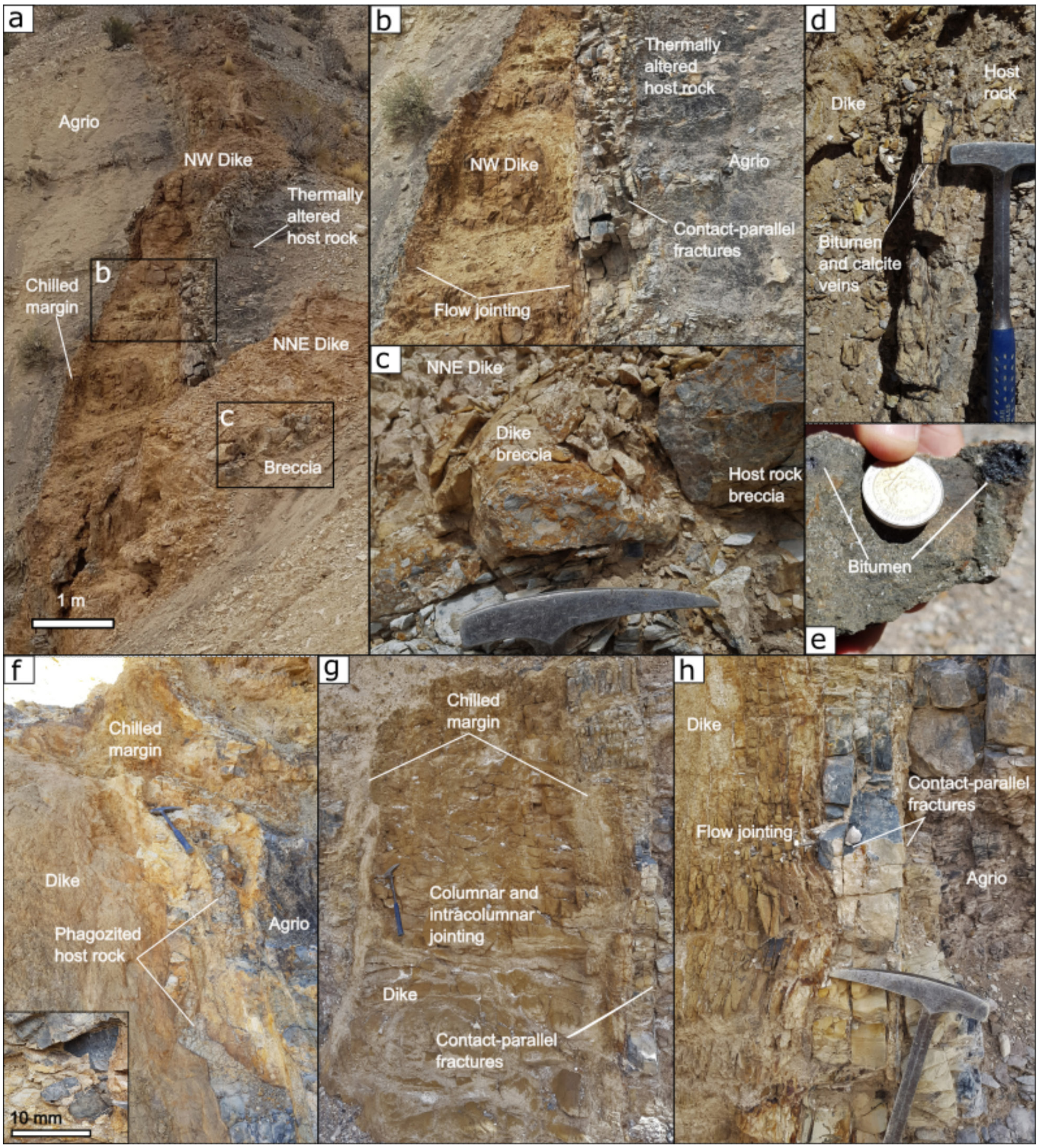


Figure 3. Dikes. a) NNE dike crosscutting NW dike. b) Contact of the NW dike where the chilled margin with flow jointing, contact-parallel fractures and the thermally altered host rock can be observed. c) Contact of NNE dike. A breccia zone is developed in the intrusive and in the host rock. d) Contact parallel veins filled with calcite and bitumen. e) Bitumen in vesicles in a dike sample. f) Phagocytosed host rock in the contact of a dike. Host rock fragment can be observed inside the dike. g) Typical dike with two chilled margin at the contacts and columnar jointing in the middle. h) Zoom up of the chilled margin where the flowing joint in the dike and contact parallel fractures in the host rock can be observed.

Sills typically show chilled margins, characterized by a flow jointing, and an internal part characterized by columnar and intracolumnar joints (Fig. 4a and c).

In the foot wall of Chihuido Thrust, three sills are emplaced in the Vaca Muerta Fm., named SVM1, SVM2 and SVM3 (Fig. 1a, b and 4c), but a higher number has been identified in the hanging wall (Fig. 4d). Also, sills clusters were found in the hanging wall of thrusts (Fig. 4e). In addition, some sills seem to have undergone tectonic folding, since they follow the shape of folded sedimentary layers in anticlines (Fig. 4 f).

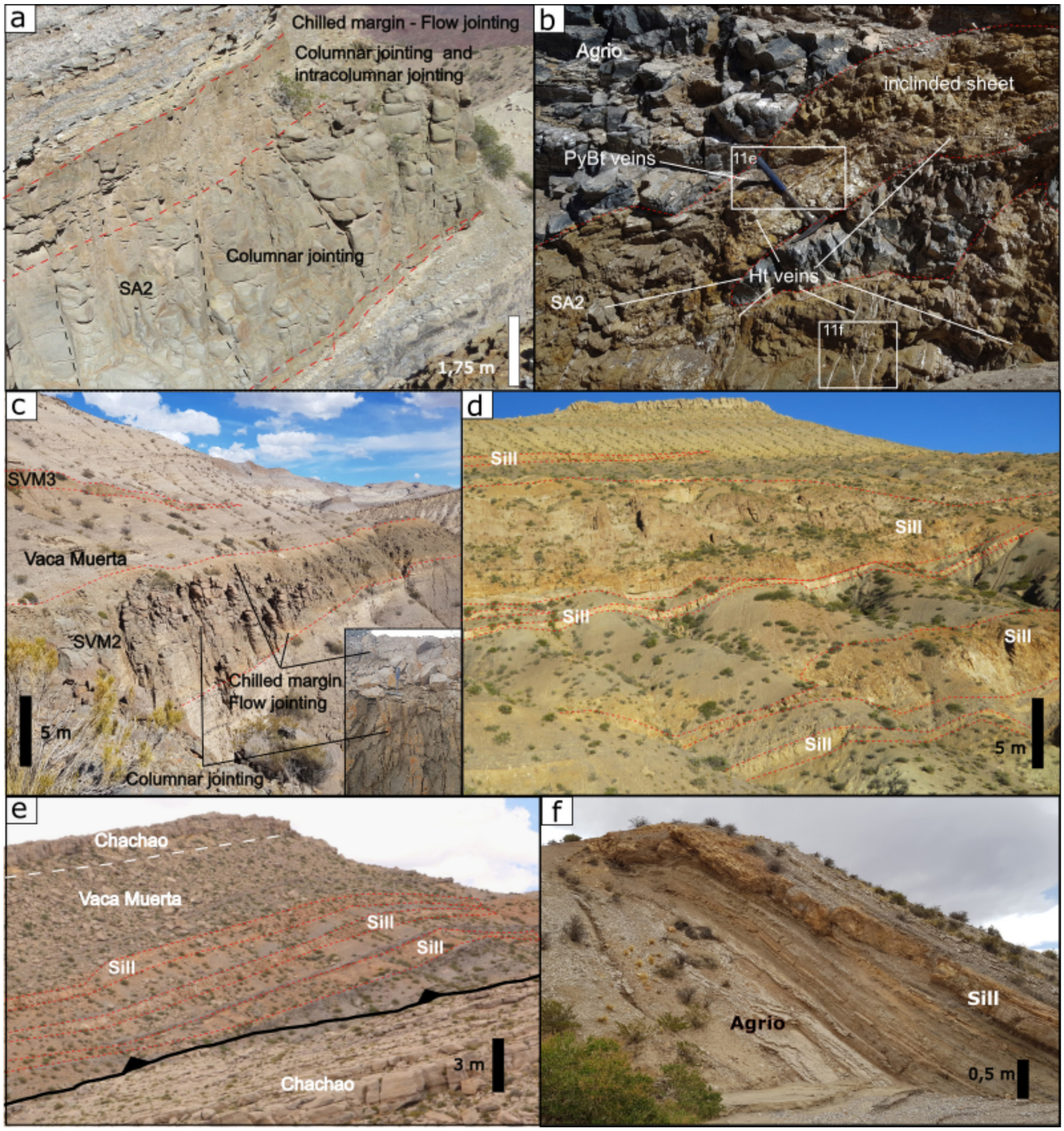


Figure 4. Sills. a) Concordant SA2 with chilled margins. Towards the interior, intracolumnar and columnar joints are observed. b) Discordant inclined sheet in top of SA2. c) SVM2 and SVM3 with flow joints in the chilled margins and columnar joints in the interior. d) Sills emplaced in Vaca Muerta Fm., located in the hanging wall of the Chihuido thrust. e) Sills-cluster in the hanging wall of a thrust. f) Sill in an anticline.

In Agrio Fm, three individual sills were identified (Fig. 1a, b). However, some appear to be composed of multiple sills. They are named SA1 (Fig. 5), SA2 (Fig. 4a) and SA3 (Fig. 6d).

SA1 is composed of two sills interconnected by a dike swarm (Fig. 5 a). Both sills exhibit a fractures zonation, with flowing joints at the contact, followed by a zone of intracolumnar and columnar joints, and finally a columnar joint zone. The dike swarm is formed by several thin dikes (Fig. 5b) which are crosscutted by hydrothermal veins. In the contact with the host rock, a breccia zone with sedimentary clasts entrained in the igneous rock was observed (Fig. 5c).

Some sills show internal variations (Fig. 6). For example, a sill emplaced in Vaca Muerta Fm. is intruded by another that contains abundant host rock fragments (Fig. 6a and b). These fragments seem to be fluidized within the intrusive, generating bitumen and calcite veins (Fig. 6c).

USA3 presents differences in terms of its fracturing, appearing to be formed by three different intrusives (Fig. 6d). In addition, another sill is observed in the riverbed, named LSA3. The USA3 has been divided from top to bottom in TUSA3, MUSA3 and BUSA3. These three sills are differentiated by a different fracturing pattern. The middle sill contains abundant enclaves and shows no net contact with the lower one (Fig. 6e).

Finally, other sills located in Vaca Muerta Fm. show a variation in its alteration degree. It presents a highly altered lower part, a middle part with columnar fractures and an upper part with columnar and intracolumnar fractures (Fig. 4 d).

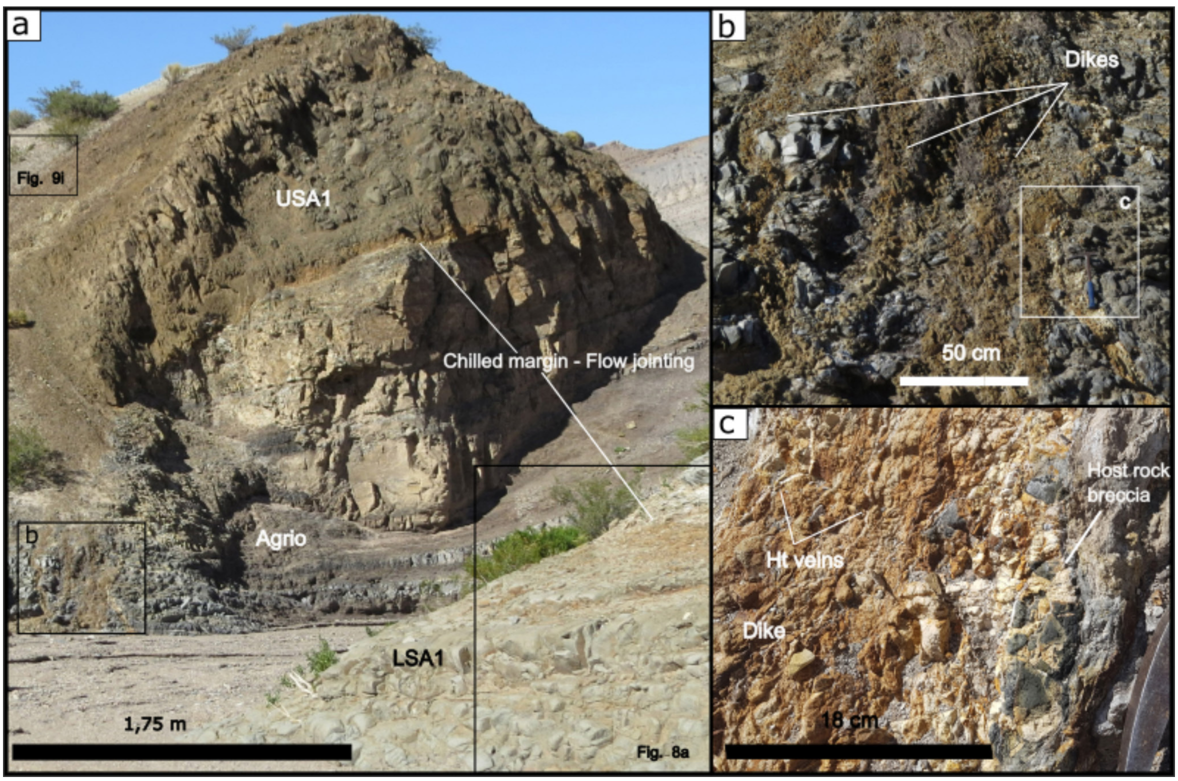


**Figure 5. SA1. a) LSA1 and USA1 connected by a dike swam. b) Dikes swarm. c) Breccia with host rock clasts at the contact of a dike. Also, hydrothermal veins can be observed.**

### Hybrids

Transitional morphologies between the three outlined endmembers were also identified, mainly in the hanging wall of thrusts faults (Fig. 7). Figure 7a shows a dike growing from a sill which propagates from a laccolith. A few tens of meters away, a Christmas tree laccolith was found (Fig. 7 b). It is formed by a central dike from which sills grow laterally. Some sills are affected by faulting.

Other hybrid morphology is shown in Figure 7 c. Here, a dike with a wavy contact feeds a sill. The host rock is very fractured. Finally, a mushroom shape is present in LSA3. In the top of the intrusive, a dike grows and propagates laterally in the form of a thin sill. On the other edge of the dike, a similar feature is observed (Fig. 7e), but, in this place, a small piece of intrusive separated from the sill tip appears to be growing from the wall.

## FRACTURES

Fracture observation were focus on the sills to analyze their properties as hydrocarbon reservoirs. Five different types of fractures were observed: cooling joints, bitumen injection veins, concentric joints, hydrothermal veins and tectonic fractures

### Cooling joints

Cooling fractures can be recognized by their polygonal shape and the formation of columns (Fig. 8). The fractures which are perpendicular to the base and top are called columnar joints, while the horizontal ones are named intracolumnar joints. Towards the chilled margin a flow jointing is developed (Fig. 8a). In LSA1 these fractures are filled with bitumen (Fig. 8b). In SA2, the material filling the cooling joints are calcite and pyrobitumen, characterized by the formation of dissecation cracks (Fig. 8c). Microscope observations show that the bitumen enters the rock matrix, generating a moldic porosity due to dissolution (Fig. 8d). It can be distinguished a decrease in the pore filling with bitumen from the fracture to the interior of the sill. The micrograin texture is mainly formed by plagioclase (Fig. 8e). Pores are filled with calcite and chlorite or bitumen. In the bitumen veins are observed calcite and sill clasts.

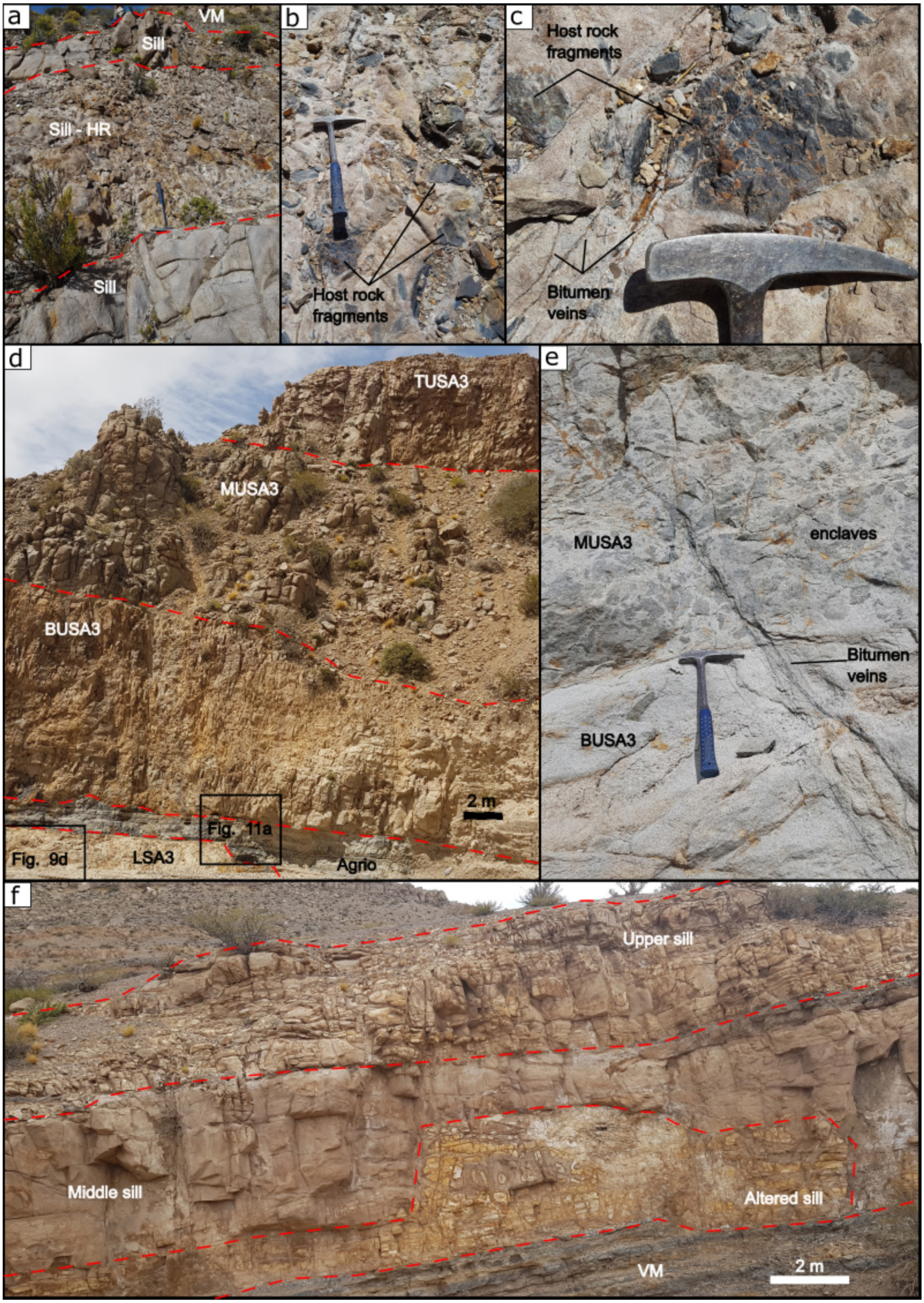


Figure 6. Sills internal variation. a) Inner sill with host rock clasts intruding another sill. b) Host rock fragments in the sill. c) Fluidization of the sedimentary clasts forming bitumen and calcite veins. d) SA3 composed by LSA3 and USA3. e) Contact between BUSA3 and MUSA3. Bitumen veins crosscut both sills. f) Sill emplaced in Vaca Muerta Fm. close to a thrust. It can be observed a very altered base, a middle part with columnar joints, and an upper part intensively fractured.

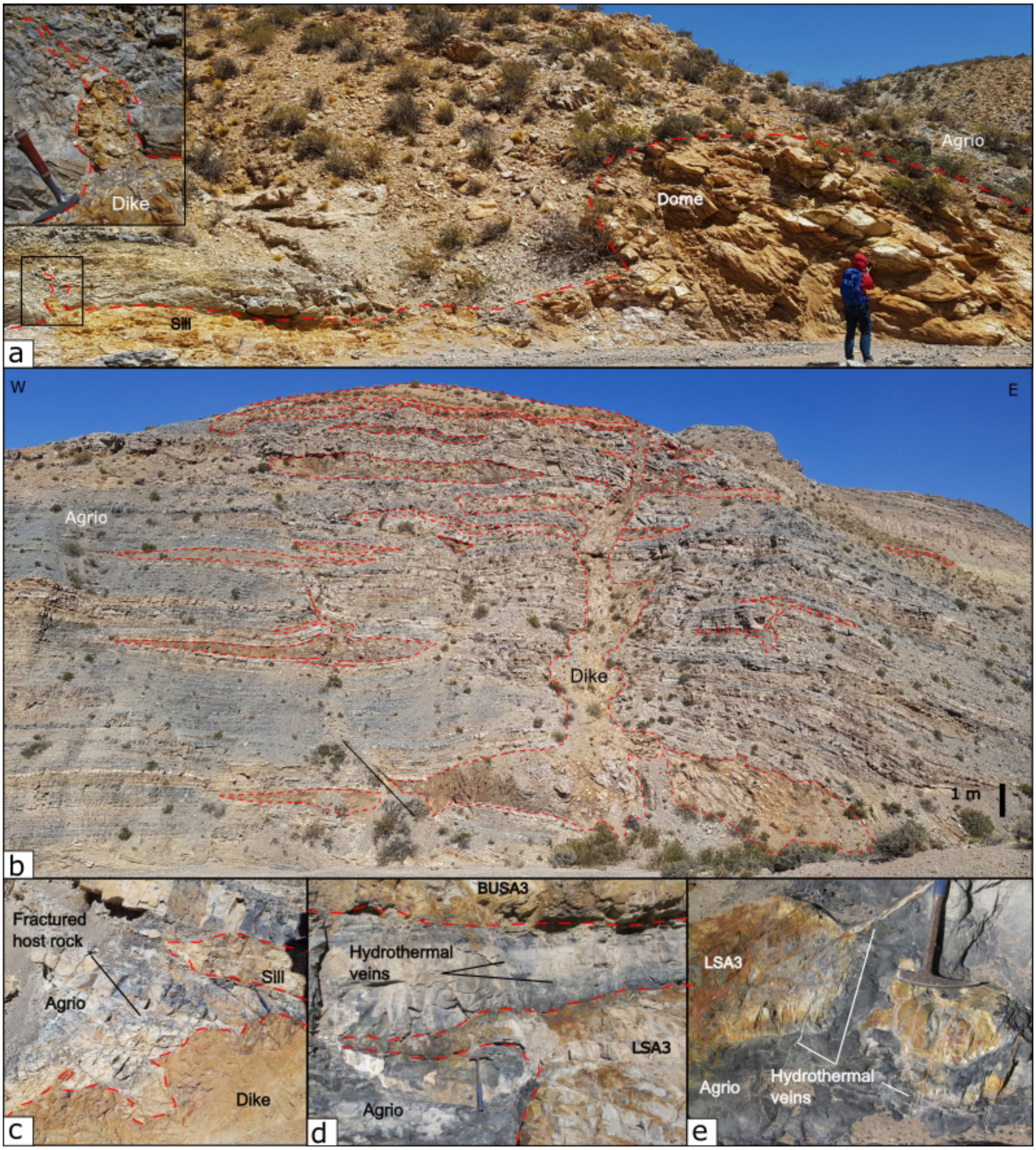


Figure 7. Hybrids. a) Dome-sill-dike. b) Christmas tree laccolith formed by central dike feeding lateral sills. c) Dike and sill. d) LSA3. Sill growing from the top of a small-scale dome. e) Another side of the same outcrop showing the blunt tip of a sill with a hydrothermal vein, and an incipient magma body in the host rock.

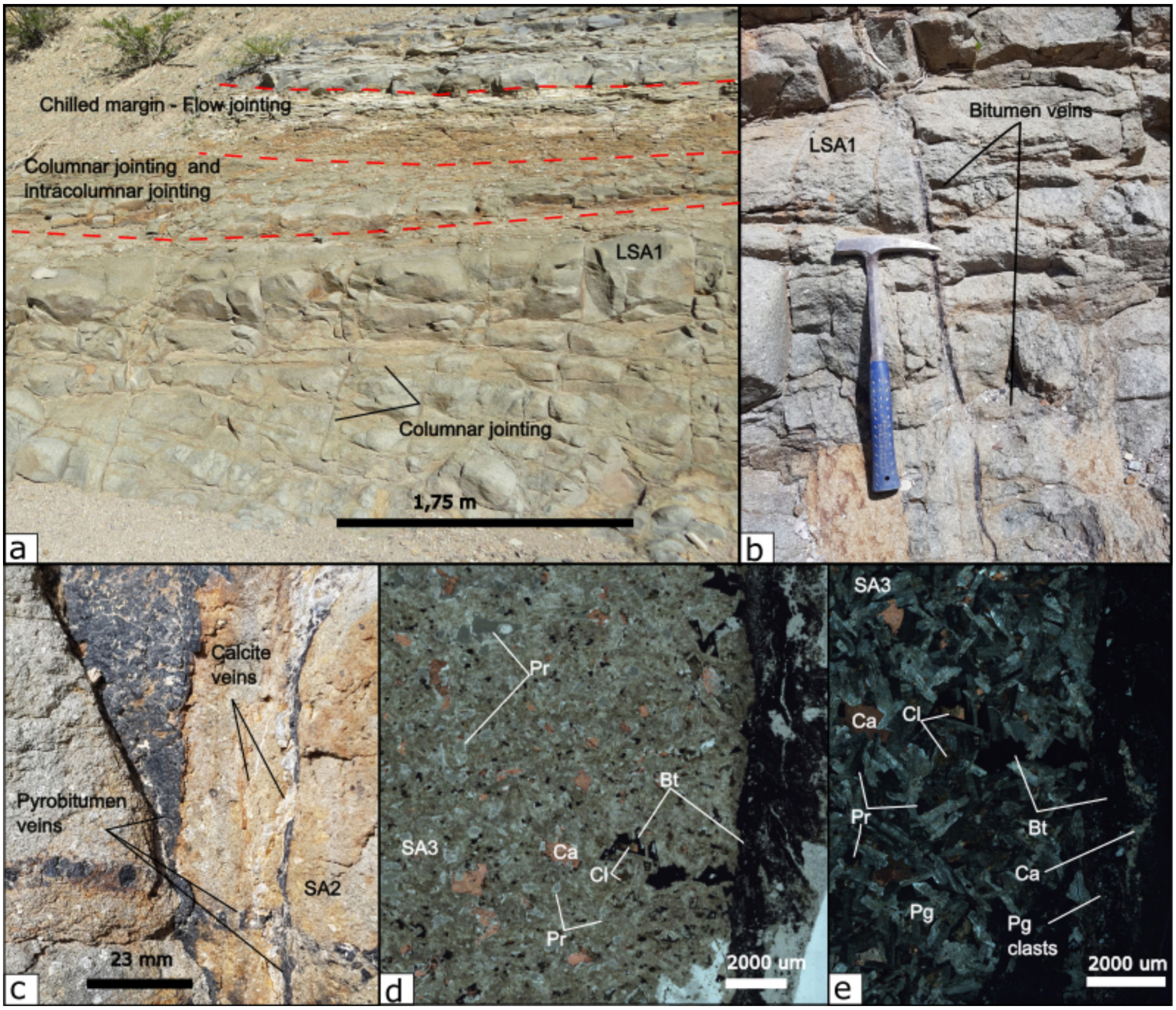


**Figure 8. Cooling joints. a) LSA1. A variation of fracture pattern from the contact to the inner part is observed. b) Columnar and intracolumnar join filled with bitumen. c) Pyrobitumen in the cooling joints of SA2. d) Thin section of a cooling joint filled by bitumen in the BUSA3. Bitumen filled also the matrix porosity. A decrease of the amount of bitumen filled vesicles is observed further from the contact. e) Polarized thin section where the micrograin texture formed mainly by plagioclase is observed. Pores are filled with calcite and chlorite or bitumen. Pr: pore. Bt: bitumen. Cl: chlorite. Ca: calcite. Pg: plagioclase.**

## Bitumen injection veins

In several intrusives, the presence of fractures filled with bitumen or organic matter has been observed. They originate from the contact between the intrusives and the host rock, where the host rock fluidizes and seems to have been injected into the sill (Fig. 9a). In other cases, veins of calcite and bitumen propagates from the host rock into the intrusive through the cooling joints (Fig. 9b). They can produce the brecciation of the igneous rock (Fig. 9c). In some cases, this brecciation can be observed over large areas of the sills (Fig. 9d). Individual bitumen veins have a maximum thickness of 2 cm, and may appear as closely spaced arrays (Fig. 9e). In some parts, clast of the host rock entrained in the sill can be observed (Fig. 9f). In thin sections, the breccia

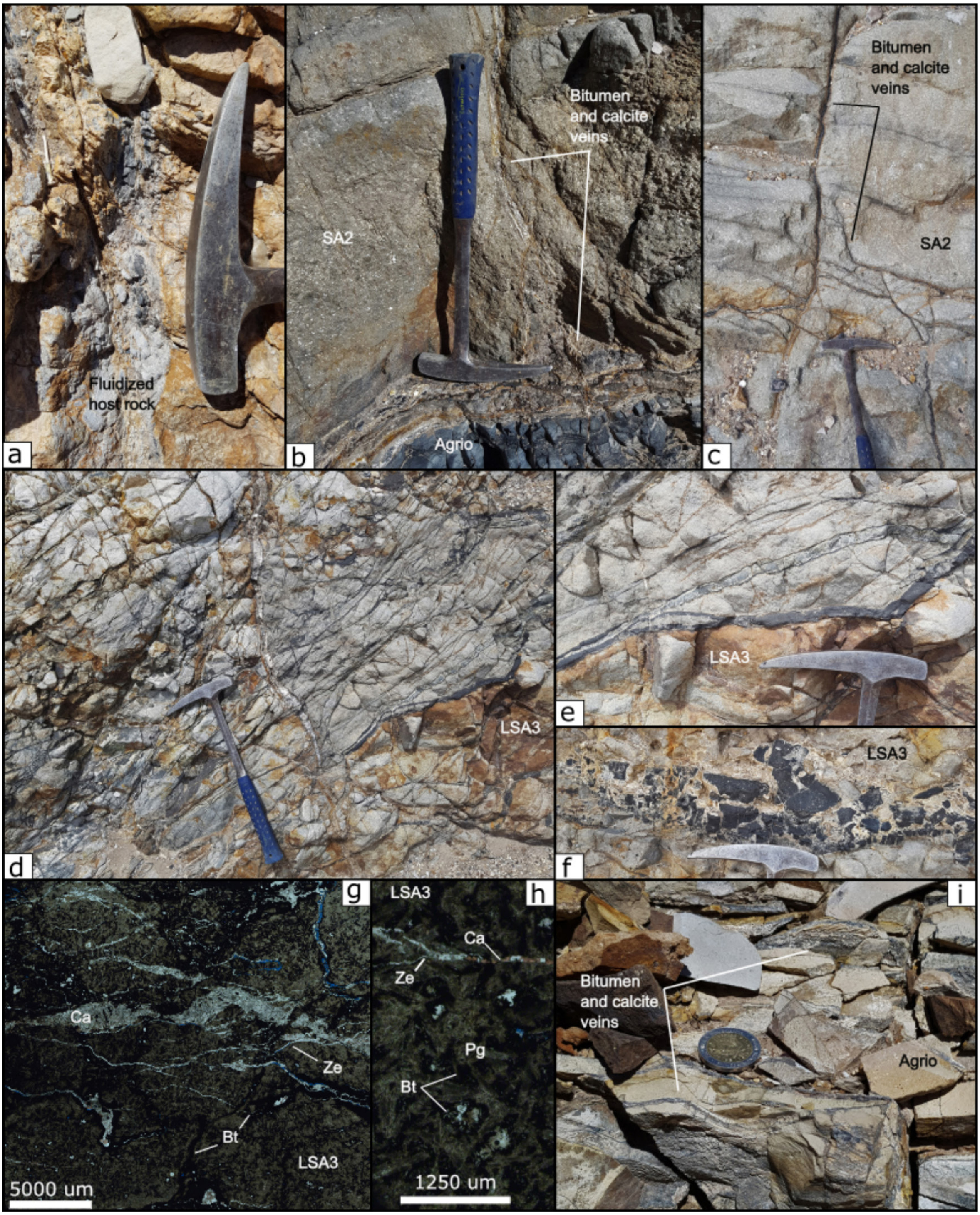


**Figure 9. Bitumen veins. a) Fluidized host rock entering a dike. b) Bitumen and calcite veins in the lower contact of SA2. The veins seemed to be originated in the host rock and injected in the cooling joint of the sills. c) Bitumen and calcite veins fracturing the sill. d) Bitumen breccia in the LSA3. e) Close-up photograph of the bitumen veins. They have 1 cm thick. Some are crosscut by calcite veins. f) Fluidized host rock fragment in the same sill. g) Thin section of the breccia showing fracture cements. h) Matrix porosity. i) Bitumen and calcite veins in Agrio Fm. in the top of USA1.**

presents fractures filled by calcite, zeolites and bitumen (Fig. 9g). It also presents moldic matrix porosity due to dissolution (Fig. 9h). These veins extend to the roof of the intrusive, entering the Agrio formation (Fig. 9i).

According to Raman spectroscopy the veins are filled with high-grade bitumen (Fig. 10).

## Alteration joints

Other type of fractures are those produced by alteration (Fig. 6f). In some cases, alteration seems to be propagating from the cooling joints associated with bitumen and calcite veins, as can be observed in SA2 (Fig. 11a). Different degrees of alteration have been identified. In other sills, the alteration looks like being propagating form the interior of the polygons to the exterior, forming concentric joints (Fig. 6f and 11b,c). The bitumen injection veins extend into the polygons of the cooling joints and altered the sill, forming concentric joints (Fig. 11b and c).

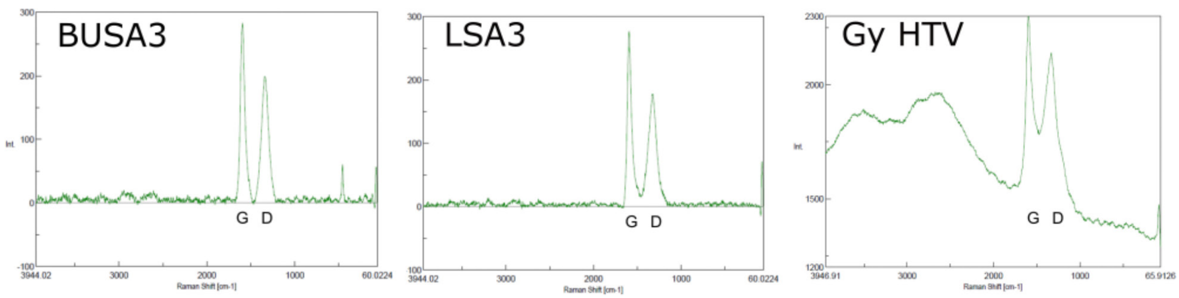


**Figure 10. Raman spectrograms. Narrow and well-developed G and D peaks indicate the presence of graphitic carbon, and therefore high grade bitumen.**

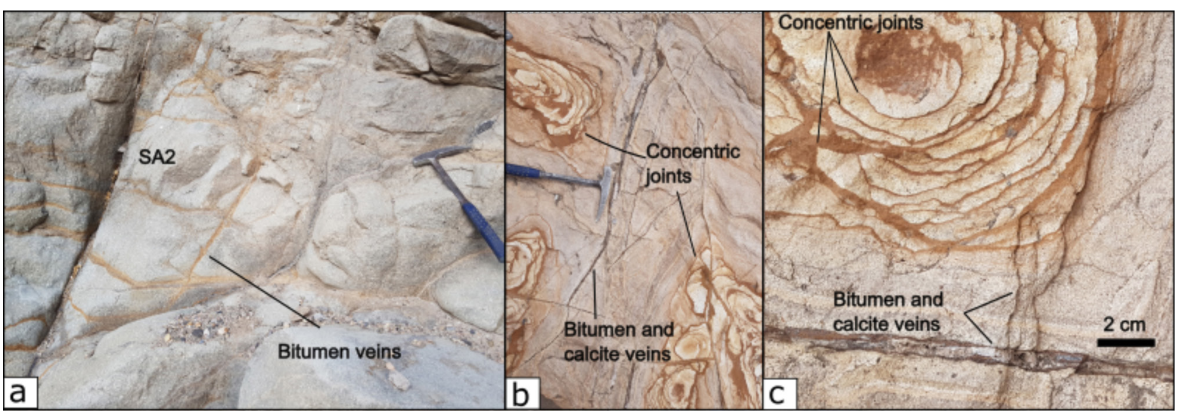


**Figure 11. Alteration fractures. a) Alteration recognized by an oxidized halo near the bitumen veins filling cooling joints in SA2. b) Concentric joints with injection of bitumen and calcite veins. c) Zoom up of the concentric joints. The bitumen and calcite veins are entering the joints producing its alteration.**

### Hydrothermal veins (HTV)

Other type of fractures are those generated by hydrothermalism (Fig. 12). They propagate from the tips of the intrusives (Fig. 7e and 12a), as well as from the center (Fig. 7d, and 12c, d, h). Also, they can follow inclined sheets (Fig. 4b and 12e, f) or dikes (Fig. 5c). The HTV can propagates through the host rock, crosscutting the stratigraphy (Fig. 12g). Sometimes they cut fluidized organic-rich sedimentary layers (Fig. 12h). Also, bedding parallel hydrothermal veins (BPHTV) were observed in the main source rocks (Fig. 12i, j), as well as in the reservoirs of the Avilé Member (Fig. 12k).

The veins show different types of cement composition and texture (Fig. 12). Generally they are cemented with calcite or dolomite which has a coloform texture towards the walls and a brecciated texture in the center, as can be observed in SA3 (Fig. 12b, c), in SA 2 (Fig, 12e,f) and Agrio Fm. (Fig. 12g). In other cases, such as in SA1, the calcite is replaced by silica forming a platicalcite texture (Fig. 12d). The BPHTV are typically filled with gypsum associated with bitumen (Fig. 12i,j,k).

In general, the thicknesses of the veins ranges from few mm to 50 cm. They have a branched shape, show not clear crosscutting relationships, and may include fragments of the host rock.

### Tectonic fractures

As can be expected in laminar-type intrusions, emplaced in a fold-and-thrust belt, they show non-homogeneous jointing. Many of the joints observed might be formed during the cooling stage, but may have been reactivated later by tectonic effects. No clear evidence of faulting was found, as for example fault gauge or slickenside, but the fractures that are oblique to the roof and base of the sills seems to be originated by tectonism (Fig. 13a). In roof section they are recognized by an irregular arrangement (Fig. 13b). Some sills show variability in the fracturing intensity, with strongly fractured zones (Fig. 13c).

## ORGANIC GEOCHEMISTRY

Pyrolisis analysis and organic petrology description were performed in samples of Vaca Muerta and Agrio Fms. for quantifying the thermal impact of the multiple sheet-like intrusions on the TOC, HI and Tmax. Geochemical profiles were performed in two transects, one in each formation, to determine the thickness of the contact aureole caused by the thermal impact of the sills. Pyrolysis results were summarized in Figure 14 and plotted in geochemical logs (Fig. 15). The thermal aureoles were defined base on HI and TR.

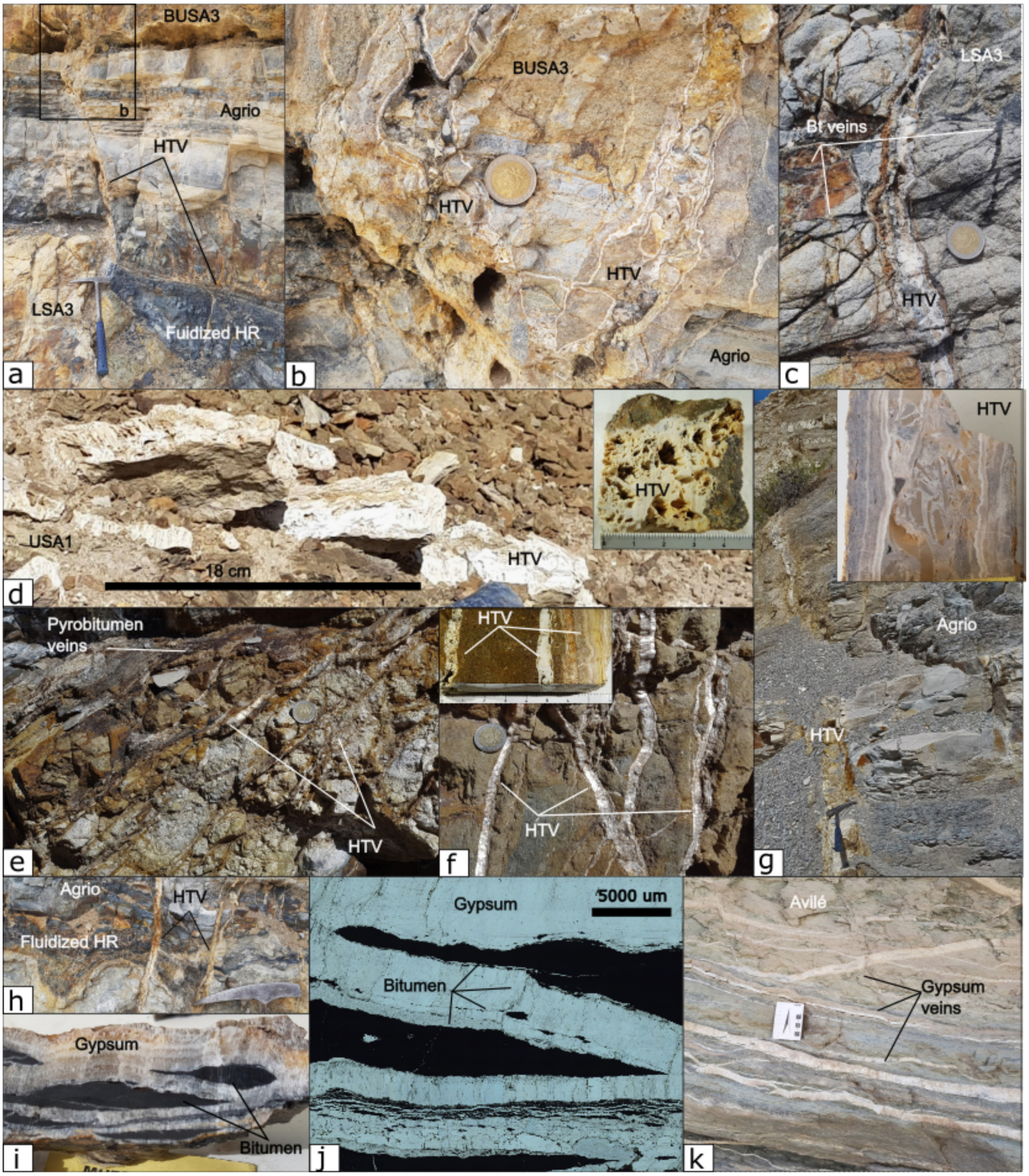


Figure 12. Hydrothermal veins. a) HTV at the tip of the LSA3. Also fluidized host rock can be observed. b) Calcite cement with a coloform texture at the fracture walls and a cocarda texture in the middle. c) HTV crosscutting the breccia in LSA3. It shows the same texture as the previous one. d) HTV at USA1 with a platy calcite cement, where silica is replacing calcite. e) HTV in the inclined sheets in top of SA2 associated with pyrobitumen. f) Zoom up of the HTV. They show coloform textures, indicating different pulses of filling, and also different events. g) HTV crosscutting Agrio Fm. Is characterized by a coloform texture in the margins and a breccia texture in the middle. h) HTV through a fluidized host rock. i) Gypsum HTV interbedded with bitumen. j) Petrographic section of the vein where can be seen the bitumen drops entering the gypsum crystals. k) Gypsum veins in the Avilé Member.

In profile A (Fig. 15a) four sills were identified in the the Agrio Fm. (SA1, SA2, LSA3 and USA3), with thickness of 6, 8, 5 and 10 m respectively, while in the profile B (Fig. 15b) we identified three sills in Vaca Muerta Fm (SVM1, SVM2 and SVM3), of 15 m, 5 m and 2.5 m thickness.

The TOC concentration is variable, showing high and low values close to the intrusive, but in general, it tends to decrease towards the contacts (Fig. 15). High values close to the sills, as those in the contacts of SVM2, SVM3, SA1 and SA2, may be originated due the presence of bitumen in the samples, as was observed in the outcrops previously described. For non-altered Vaca Muerta and Agrio Fms., the average value is around 2% TOC (Fig. 14).

Tmax shows a constant behavior in samples not thermally altered, but is strongly variable in the thermal aureoles (Fig. 15). The majority of the samples close to the intrusives shows high Tmax values, reaching values up to 608°C. Background values for Vaca Muerta and Agrios Fms. are approximately 438°C (Fig. 14).

HI shows a pronounced decrease close to and between the sills, while the TR tends to increase. HI background values are 405 and 696 mgHC/gTOC for Vaca Muerta and Agrio Fms. respectively, while TR is less than 50% (Fig. 14). Close to the sills TR is higher than 90%.

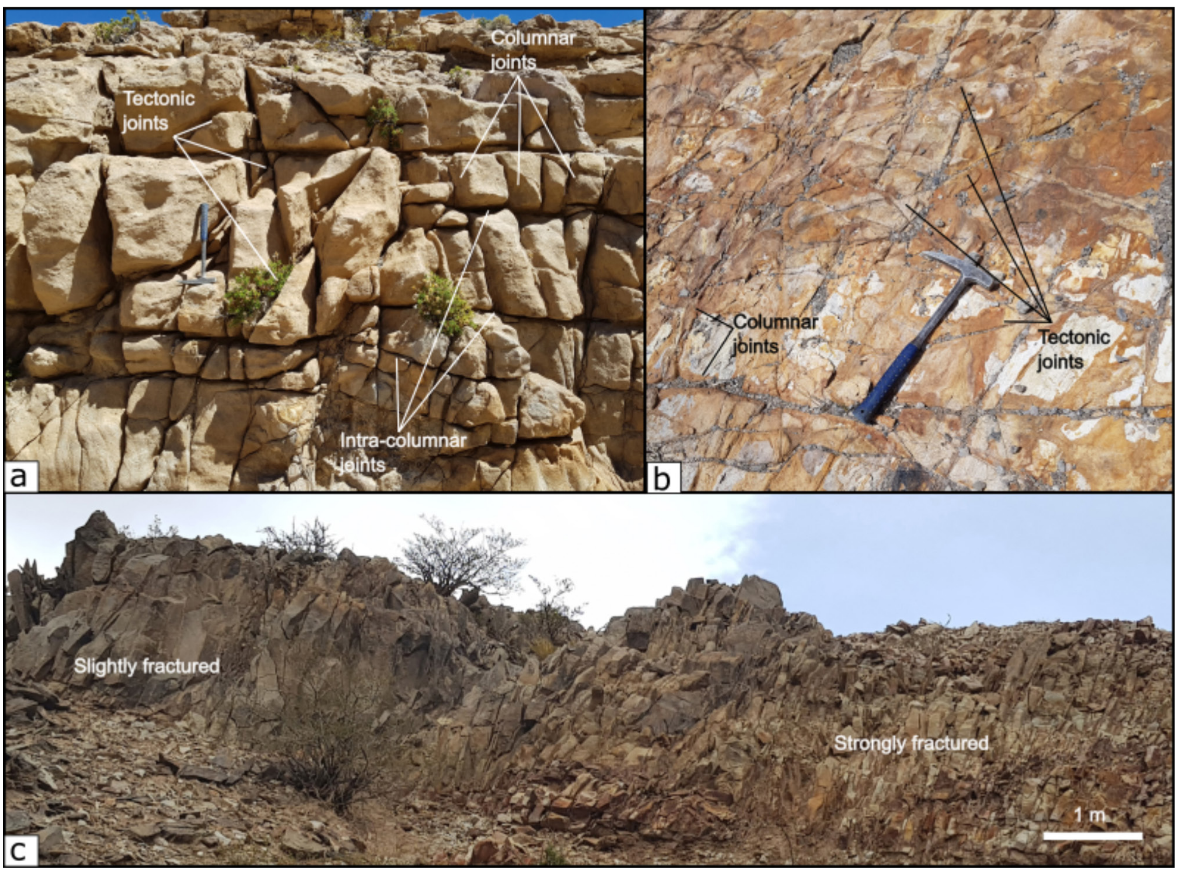


**Figure 13. Tectonic fractures. a) Tectonic fracture crosscutting cooling joints in a sill emplaced in Vaca Muerta Fm. b) View of the roof top of a sill where tectonic fractures crosscutted columnar joints. c) Variation of fracture intensity through a sill.**

| | Agrio | | | Agrio altered | | | Vaca Muerta | | | Vaca Muerta altered | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min |
| **TOC (%)** | 2.35 | 10.89 | 0.31 | 1.22 | 3.75 | 0.01 | 2.03 | 2.65 | 0.91 | 2.09 | 7.01 | 0.05 |
| **Tmax (°C)** | 438.67 | 446.00 | 433.00 | 459.32 | 604.00 | 307.00 | 438.33 | 440.00 | 437.00 | 478.71 | 608.00 | 386.00 |
| **HI (mgHC/gTOC)** | 428.33 | 696.00 | 313.00 | 44.43 | 171.00 | 5.00 | 349.67 | 405.00 | 314.00 | 53.65 | 214.00 | 5.00 |
| **TR (%)** | 30.68 | 47.83 | 0.00 | 92.60 | 99.17 | 71.50 | 48.58 | 53.82 | 40.44 | 92.11 | 99.26 | 68.53 |

**Figure 14. Summary table of pyrolysis results differentiating between altered and unaltered samples.**

Based on IH the thermal aureole thickness (m.) was measured (Fig. 15 a,b). In Agrio Fm. (Fig. 15 a) the upper aureole of LSA3 and the lower aureole of USA3 seems to be overlapped. For Vaca Muerta Fm. (Fig. 15b) upper aureole of SVM2 and lower aureole of SVM3 are overlapping.

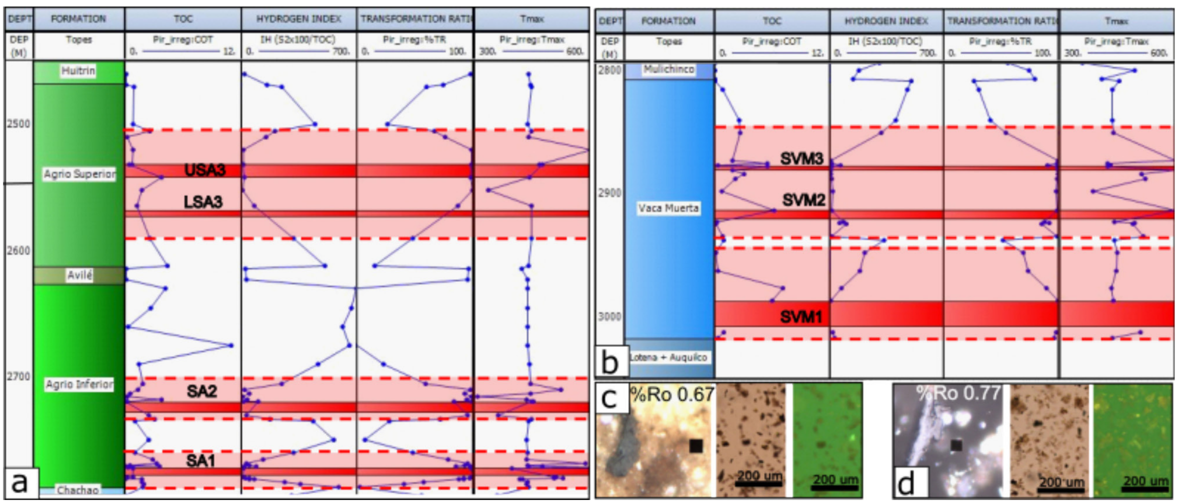


**Figure 15. Pyrolisis results. Profiles of TOC, TR, HI and Tmax measured across the Agrio Fm. (a) and Vaca Muerta (b). c and d) Organic petrology. Vitrinite reflectance (%Ro), thermal alteration index of organic matter (TAI) in transmitted light and fluorescence light in the base of Upper Agrio (c), and in Lower Agrio (d).**

For estimating the background maturity values for Agrio Fm., organic petrology analysis was performed in non-altered samples. According to analysis of coloration in transmitted and fluorescent light (TAI), and vitrinite reflectance measurements (%Ro), the top of Upper Agrio is estimated to be in the beginning of the oil window, while the Lower Agrio is in the peak of hydrocarbon generation. %Ro values are 0.67 and 0.77 respectively (Fig. 15c, d).

Measurements of HI and OI were plotted in a modified Van Krevelen diagram which shows that the predominant kerogen for Vaca Muerta and Agrio Fm. is Type I-II. The altered samples show values of HI lower than 214 mgHC/gTOC, while non-altered values increase up to 696 mgHC/gTOC (Fig. 16a). Figure 16b of Kerogen conversion and maturity relates Production Index (PI) and Tmax. Non-altered samples show low level of conversion, with PI values lower than 0.17. Tmax ranges from 433°C to 453°C. Altered samples, instead, show high values of PI, increasing up

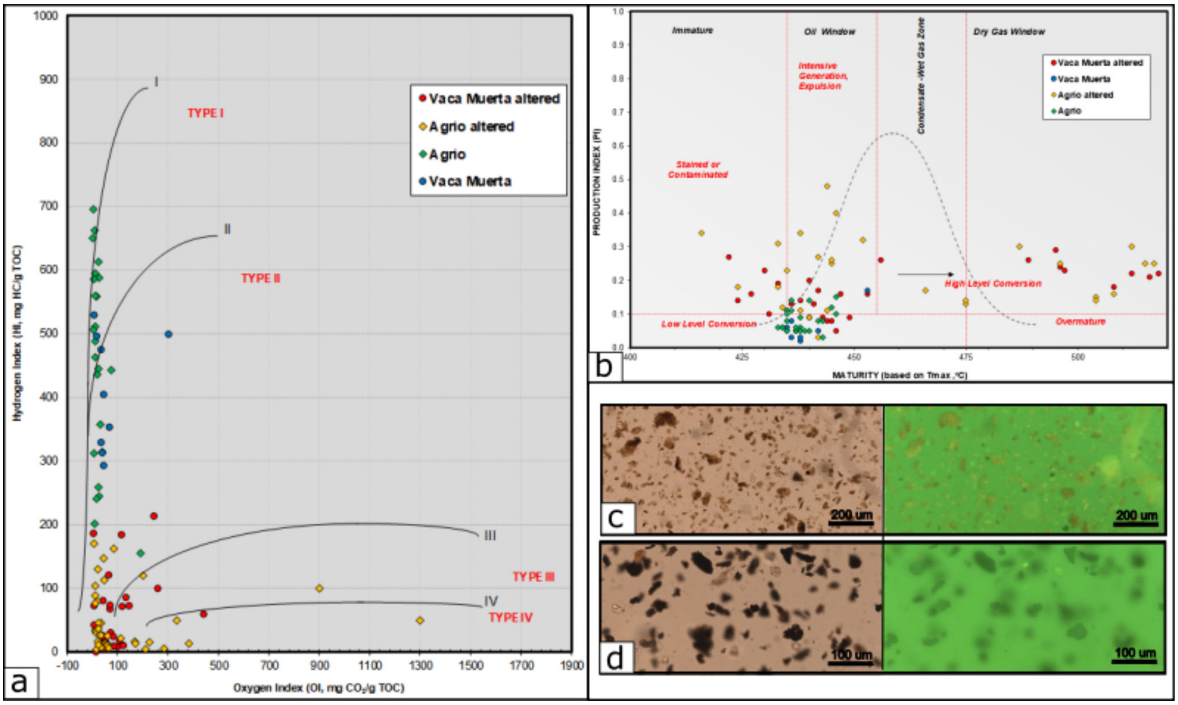


Figure 16. a) Modified Van Krevelen diagram. The altered samples are affected by thermal maturation and have low HI and OI values. b) Maturity based on Tmax vs. Production Index. c) Organic petrology of unaltered Vaca Muerta Fm. in transmitted light and fluorescence light (TAI). d) Carbonization of organic matter in thermally altered samples.

to 0.48. The Tmax varies from 307°C to 608°C. Based on this parameter two sets of samples can be differentiated, one in the oil windows with intensive generation and expulsion, and another with high level of conversion. In Figure 16c can be observed the thermal alteration index of organic matter (TAI) in transmitted light and fluorescence light of altered and unaltered samples of Vaca Muerta Fm. Note the high level of carbonization of the altered samples.

## INTERPRETATIONS AND DISCUSSIONS

The results have been organized based on the description of the Cara Cura sills-complex and its effect on the petroleum system. Focus was placed on the properties of igneous intrusives as hydrocarbon reservoirs and migration pathways for fluid flow. The thermal effect that magmatic bodies have on the main source rocks of the basin is also interpreted.

### Sill-complex architecture

Based on the geological data, it is interpreted that all the intrusives described form the Cara Cura sills-complex, emplaced in the sedimentary units of the Neuquén Basin (Fig. 1). The complex is elongated in the NNE direction, following the main structures. It is 18 km long in the N-S direction and 13 km wide in W-E direction. The dimensions are similar to the ones described by Spacapan *et al.* (2020) in the Río Grande Valley area. The complex is mainly formed by laccoliths (Fig. 2), dikes (Fig. 3) and sills (Fig. 4,5,6), but also hybrids morphologies between them can be found.

**Lithological controls on intrusives distribution**

The laccoliths are formed in the uppermost sedimentary units of the stratigraphic sequence, mainly in Neuquén Gr. (Fig. 2), because of the lower stress pressure, which allows them to grow vertically. The breccia zone at the contact is interpreted to be produced during the punching of the laccolith (Fig. 2c,d,e), according to similar observations performed by Burchardt *et al.* (2019) in the Co. Bayo laccolith.

Sills, instead, are emplaced preferentially in organic rich formations (Vaca Muerta and Agrio Fms.) and evaporites (Huitrín Fm.) because of their low competence and low permeability (Fig. 1). This is consistent with previous works in the region (Rodriguez Monreal *et al.* 2009; Spacapan *et al.* 2018; Witte *et al.* 2012).

Dikes, on the other hand, crosscut through all the stratigraphy, from the older units of the Precuyo Gr. to the Tertiary Malargüe Gr. (Fig. 1), evidencing no lithological control on its distribution.

**Structural controls on intrusives distribution**

An evident relationship between magmatic intrusion and tectonic activity is interpreted. First, it is observed that sills-clusters are located in the hanging wall of regional thrusts (Fig. 1 and 4d,e) and are aligned with the main structures. Galland *et al.* (2007) demonstrate that the thrust faults may act as the main pathways for the rising magma, promoting the formation of sill-clusters above these structures. The sills-clusters have major implications in the petroleum system, as was discussed by Spacapan *et al.* (2020a). They can promote source rock maturation (Fig. 15 and 16) and affect the fluid flow trajectories, acting as seal or reservoirs (Fig. 8 and 9), giving hydraulic connectivity between different units of the sedimentary basin (Fig. 7b), acting as seal bypass system (Cartwrigth *et al.* 2007).

In other cases, sills seem to be folded or copying exactly the form of an anticline (Fig. 4f). This intrusion is interpreted as being pre or syn-tectonic. Araujo *et al.* (2019) show that igneous intrusions are preferentially emplaced through low-angle faults and propose an evolutionary model where igneous intrusions are emplaced during the thrust system building.

Hybrid shapes are interpreted to be produced in the hanging wall due to heterogeneities or anisotropy in the host rock caused by tectonism (Fig. 7). Here magma propagates through weakness zones, showing variations in their morphologies.

Dike orientations (Fig. 1 and 3) are interpreted as being control by the stress field at he the moment of the emplacement, according to the studies made by Guzmán *et al.* (2011).

**Effects of magmatic intrusions in petroleum systems**

Based on geological observations (Fig. 3b, 9 and 12h) and laboratory analyses (Fig. 15 and 16), it is interpreted that the emplacement of the Cara Cura sills-complex affect the thermal maturity of the main source rocks (Vaca Muerta and Agrio Fms.), promoting hydrocarbons generation. Also, intrusives can act as reservoirs (Fig. 6 and 9) or fluid migration pathways for hydrocarbon migration (Fig. 3d, 5c and 9).

**Thermal effect on source rocks**

Based on pyrolysis data is interpreted that most of the thickness of Vaca Muerta and Agrio Fms. was thermally affected by magmatic intrusions (Fig. 15). The best parameter to define the thermal aureole is the HI, which was used to separate between altered and unaltered samples. The last ones show %Ro values of 0.67 to 0.77, being below the peak of the oil window (Fig. 15 c, d). In the aureole, the high TR values, close to 100%, suggest that most of the organic matter has been transformed to hydrocarbons. Also, altered samples show a carbonized organic matter (Fig. 16d).

The Tmax value is not a suitable parameter to determine the size of thermal aureole generated during the emplacement of sills. Tmax depends on the S2 peak, so when the samples are overheated, all the kerogen is cracked to hydrocarbon and the samples becomes barren, making the Tmax measurements unreliable (Spacapan *et al.*, 2020a).

The analyzed data does not show a clear relationship between sills thickness and aureole thickness. Generally, the aureoles are more than twice sills thickness (Fig. 15). Where sills clusters are located, thermal aureoles seem to be overlapped. This is consistent with the works done by Spacapan *et al.* (2018a and b). These authors demonstrate that where sills clusters are located, an overlapping of thermal aureoles is produced, so no relationship 1:1 can be expected.

Other evidence of the thermal effect of magmatic emplacement in source rocks is the presence of bitumen veins close to the intrusives (Fig. 9) and the fluidization of the host rock (Fig. 12a, h). This could explain the high TOC values observed in pyrolysis results in the contact with the sills (Fig. 15). Similar observations were done by Rabbel *et al.* (2021) in the Sierra Azul range.

The extent of source rock maturation will be locally affected by sill-clusters, but also the regional effect of large sill-complexes modifying the thermal gradient in the fold and thrust belt should be considered.

## Igneous reservoirs

The properties of igneous intrusive as reservoirs depends strongly on their fractures characteristics and its matrix porosity.

Laccoliths described in the Neuquén Gr. are interpreted to be homologues of the producing laccoliths of Altiplanicie del Payún (Delpino *et al.* 2014; Rodriguez Monreal *et al.* 2009). These laccoliths, as the Co. San Romeneo, show a breccia at the contact, including igneous and sedimentary rock (Fig. 2). This zone is interpreted to be the most suitable for hosting hydrocarbons.

Sills, instead, show the best reservoirs properties. According to bibliography, they are the main reservoirs in the oil field close to the study area (Schiuma and Llambías 2014). Based on field observations and petrographic descriptions is interpreted that they are dominated by matrix and fracture porosity. The first is controlled by primary vesicles, intercrystalline and moldic pores (Fig. 8d,e and 9g,h), whereas the second is represented by different types of fractures produced by different processes (Fig. 8, 9, 11, 12 and 13).

Sills show internal variations due to the emplacement of different magma pulses, different fractures patterns and degree of alteration (Fig. 6). This is very important when trying to model sills-reservoirs. Most of the works carried out up to date only analyze cooling joints and tectonic fractures without taking in account bitumen injections veins, hydrothermal veins and alteration joints.

## Fractures types

Based on field observations different types of fractures were identified. Columnar joints, bitumen injection veins, concentric joints and hydrothermal veins are interpreted to be formed during the cooling stage of the intrusives (Rabbel *et al.*, 2021), while tectonic fractures are posterior.

Columnar joints are developed because of thermal stress during the crystallization of magma. They are generally filled by bitumen or pyrobitumen (Fig. 8 and 10). A differentiation of fracture pattern can be interpreted from the contacts to the interior according to the model proposed by Delpino and Bermúdez (2009). In the chilled margin a flow jointing is produced due to the shear stress produced by the emplacement of the intrusive (Fig. 4a,c and 8a). Then, a zone with columnar and intracolumnar joint is developed, followed by a columnar joint zone. They are interpreted as being formed due to an increase in grain size and higher cooling times (Delpino and Bermúdez 2009). Rabbel *et al.* (2021) suggest that cooling joints may act as fluid pathways for hydrocarbons when the intrusion is still in the cooling phase.

Bitumen injection veins are interpreted to be formed in the thermal aureole. Here a fluidization of the host rock (Fig. 12a,h) and the generation of hydrocarbons occurs due to the thermal impact of intrusives (Fig. 3b,d, 9b,I and 13). The bitumen injection veins migrate through the cooling joints into the sills, producing its fracturing (Fig. 9). This phenomenon can produce widespread brecciation of the sills (Fig. 9d, e, g). Bitumen veins can be also originated by the fluidization of host rocks fragments entrained in the igneous rocks (Fig. 6c). Rabbel *et al.* (2021) interpret that they are the result from strong heating and subsequent fast hydrocarbon generation in the metamorphic aureole of the sill intrusions, causing hydrofracturing within the shale due to fluid overpressure, sometimes up to the point of disintegration of the sediments. Mutual crosscutting of bitumen dikes or calcite veins shows that new fractures were repeatedly generated with enough pressure to propagate through the previous generation in a "crack-seal" fashion (Fig. 9). Although previously formed cooling joints may have been exploited in some places, the propagation of bitumen dikes through the host rock and into the sill must be related to hydraulic fracturing (Rabbel *et al.* 2021).

Raman spectrograms (Fig. 10) show that bituminous material in the injection structures evidence strong thermal alteration and graphitization. This indicates formation of the injection structures shortly after solidification of the sill intrusions.

Concentric joints (Fig. 6f) are interpreted of being formed by alteration due to the intrusions of bitumen veins (Fig. 10a,b and c). This onion skin texture is frequently assigned to weathering, but according to our field observation we suggest that are formed during the cooling stage of the intrusive. Bermúdez and Delpino (2008) propose that are the result from either the development of natural convective flows or from complex processes of cooling influenced by the joint-bounded planes of the columns.

The pressure-build up that takes place in the contact aureole triggered by fluid expansion and fluid release eventually results in hydrofracturing and formation of hydrothermal systems (Agirrezabala *et al.* 2014). Based on the field observation we interpret different hydrothermal events composed by several pulses (Fig. 12). The main cement is calcite and dolomite (Fig. 12b, c, f and g). Agirrezabala *et al.* (2014) suggest that large calcite veins are produced when the $CO_2$ in the contact aureole reacts with pore water to form carbonate minerals, which precipitate in situ and within the fractures. The calcite can be replaced by silica forming platicalcite (Fig. 12b). Finally, gypsum bedding parallel veins are interpreted of being formed in low temperature hydrothermal systems (Fig. 12 i,j and k). Rabbel *et al.* (2021) suggest that they are likely formed contemporaneously with the bitumen injection veins in a hydrothermal environment. Overpressure-driven hydrofracturing during intrusion-related hydrothermalism may be a potential cause of vein formation, since pieces of host rock are commonly entrained in the calcite and bitumen veins. Additionally, the observation of bedding-parallel fibrous gypsum veins may indicate overpressure in the metamorphic aureole (Fig. 12i,j).

The last type are tectonic fractures. They are interpreted as being secondary porosity generated in the tectonic stage (Spacapan *et al.* 2020a). Witte *et al.* (2012) propose that thrusting after magmatic emplacement can promote oil migration to the intrusions.

## MIGRATION

The emplacement of igneous intrusions triggers fracturing of the host rock, leading to the formation of breccias that were defined as damaged zones (Rabbel *et al.* 2021 and Spacapan *et al.* 2020b). This zone is characterized by higher fracture density than the surrounding host rocks (Spacapan *et al.*, 2017). These fractures can be generated by mechanical deformation during sill emplacement or by buildup of pore pressure close to the contact with the sill. The increment of overpressure in the aureole contact can be related either to hydrocarbon generation or to hydrothermal fluid circulation.

The damaged zones produced by dikes (Fig. 3) can be potential pathways for fluids migrations, as evidenced by the presence of bitumen vein in contact parallel fractures (Fig. 3d). Also, bitumen in vesicles inside the dike support this interpretation (Fig. 3e). Dikes can act as seal bypass systems, promoting hydraulic connectivity between different units (Cartwright *et al.* 2007).

HTV also have an important role in hydrocarbon migration, especially calcite veins crosscutting fluidized host rocks, where bitumen is captured and migrated upwards (Fig. 12h). Also, gypsum veins with bitumen inclusions were described (Fig. 12i, j). Zencich *et al.* (2004) performed analysis of the veins and assume that a hydrothermal system was generated that favored the migration of hydrocarbons to the most permeable sectors of Avilé Mbr.

## CONCLUSIONS

- The sills, dike, laccolith and hybrid morphologies formed the Cara Cura sill-complexes.
- Magma emplacement is related to regional structures, with maximum extension in N-S direction of 19 km.
- Most sills are preferentially emplaced in organic-rich formations such as Vaca Muerta and Agrio. On the contrary, laccoliths tend to be intruded in shallower units of the sedimentary column, such as the Neuquén Group.
- The size and extension of sill-complex have a significant impact on the petroleum system. They can affect the fluid flow trajectories, acting as seal or reservoirs, giving hydraulic connectivity between different units of the sedimentary basin, acting as seal bypass system.
- Vaca Muerta and Agrio Fms are thermally altered by the emplacement of igneous bodies. HI and TR are the best parameters to determine the extension of the thermal aureole.
- Hydrothermal vein in hydrothermal systems resulting from pressure build-up in the contact aureoles could act as channels for hydrocarbons migration, connecting deep source rocks to shallow magmatic reservoirs.

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