



Radial patterns of bitumen dykes around Quaternary volcanoes, provinces of northern Neuquén and southernmost Mendoza, Argentina



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ARTICLE INFO

Article history:

Received 16 June 2014

Accepted 22 September 2014

Available online 15 October 2014

Keywords:

Bitumen dykes

Quaternary volcanoes

Neuquén basin

ABSTRACT

Where the Neuquén Basin of Argentina abuts the Andes, hundreds of veins of solid hydrocarbon (bitumen) are visible at the surface. Many of these veins became mines, especially in the last century. By consensus, the bitumen has resulted from maturation of organic-rich shales, especially the Vaca Muerta Fm of Late Jurassic age, but also the Agrio Fm of Early Cretaceous age. To account for their maturation, recent authors have invoked regional subsidence, whereas early geologists invoked magmatic activity. During 12 field seasons (since 1998), we have tracked down the bitumen localities, mapped the veins and host rocks, sampled them, studied their compositions, and dated some of them. In the provinces of northern Neuquén and southernmost Mendoza, the bitumen veins are mostly sub-vertical dykes. They tend to be straight and continuous, crosscutting regional structures and strata of all ages, from Jurassic to Palaeocene. Most of the localities lie within 70 km of Tromen volcano, although four are along the Rio Colorado fault zone and another two are at the base of Auca Mahuida volcano. On both volcanic edifices, lavas are of late Pliocene to Pleistocene age. Although regionally many of the bitumen dykes tend to track the current direction of maximum horizontal tectonic stress (ENE), others do not. However, most of the dykes radiate outward from the volcanoes, especially Tromen. Thicknesses of dykes tend to be greatest close to Tromen and where the host rocks are the most resistant to fracturing. Many of the dykes occur in the exhumed hanging walls of deep thrusts, especially at the foot of Tromen. Here the bitumen is in places of high grade (imponite), whereas further out it tends to be of medium grade (grahamite). A few bitumen dykes contain fragments of Vaca Muerta shale, so that we infer forceful expulsion of source rock. At Curacó Mine, some shale fragments contain bedding-parallel veins of fibrous calcite (beef) and these contain some bitumen, which is geochemically of low grade. In contrast, a large crosscutting bitumen dyke is of higher grade and formed later. At other localities, near basement faults, bitumen dykes have cap-rocks of hydrothermal calcrete. Other dykes or their wall rocks contain hydrothermal minerals. Finally, some dykes splay upward towards the current land surface. We conclude that (1) the bitumen dykes formed during volcanic activity in Pliocene–Pleistocene times, and that (2) heat advection by hydrothermal fluids helped to generate oil, which migrated upwards or downwards from the source rock and filled intrusive veins, before solidifying to bitumen, by loss of volatile elements. This unconventional hydrocarbon system may have significant implications for regional exploration in the foothills of the Andes.

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1. Introduction

The Neuquén Basin occupies large parts of the provinces of Neuquén and southern Mendoza in west-central Argentina (Figs. 1 and 2). Following a period of Palaeozoic orogenesis, the Neuquén

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Basin developed during Early Mesozoic rifting on the western (Pacific) margin of South America, at first in a context of slow subduction of two successive oceanic plates (Phoenix and Chasca plates; Maloney et al., 2013). This led to incursions from the Pacific Ocean and to several phases of marine sedimentation (Legarreta and Gulisano, 1989; Urien and Zambrano, 1994; Vergani et al., 1995; Arregui et al., 2011). In the southern part of the basin, the Huincul Arch, which was an almost E–W trending Palaeozoic feature, possibly a suture, reactivated in right-lateral transpression, at first in the Early to Mid-Jurassic (Silvestro and Subiri, 2008; Mosquera et al., 2011; Naipauer et al., 2012). To the N of it, maximum flooding surfaces were responsible for widespread deposition, in the Jurassic to Early Cretaceous, of three marine organic-rich shale formations, which are the main source rocks for petroleum in the basin: the Los Molles, Vaca Muerta and Agrio formations (Urien and Zambrano, 1994; Leanza et al., 2011). In the mid-Cretaceous, the rate of convergence at the Pacific margin increased (Pardo-Casas and Molnar, 1987; Seton et al., 2012; Maloney et al., 2013). Indeed, it successively involved two new oceanic plates (Farallon and Nazca). Then, the rate of convergence decreased in the Palaeogene, but increased again in the Neogene.

Ever since, its direction has been approximately WSW–ENE (Fig. 1). Inland, resulting compression has been responsible, since the mid-Cretaceous, for development of the Andean Cordillera, inversion of earlier rift basins, growth of the Agrio and Chos Malal fold-and-thrust belts in the eastern foothills of the Andes, and formation of a wide foreland basin further to the East (Manceda and Figueroa, 1995; Kozłowski et al., 1996, 1998; Cobbold and Rossello, 2003; Zamora and Zapata, 2005; Zamora Valcarce et al., 2006; Messenger et al., 2010; Ramos et al., 2011a, 2011b; Sagripanti et al., 2012; Turienzo et al., 2014). Today, Mesozoic strata in the Agrio and Chos Malal fold-and-thrust belts form thin-skinned, as well as thick-skinned structures, the main detachments being within shale or evaporite. Also today, the regional direction of greatest horizontal compressive stress is approximately WSW–ENE, according to data from GPS measurements (Kendrick et al., 2006), borehole breakouts (Guzmán et al., 2007; Guzmán and Cristallini, 2009) and focal mechanisms of earthquakes (see the World Stress Map, Heidbach et al., 2008, 2010). Subduction at the Pacific margin of South America has also resulted in several phases of magmatic activity and volcanism, especially since the Late Cretaceous (Kay et al., 2006). Today, in the northern foothills and foreland of

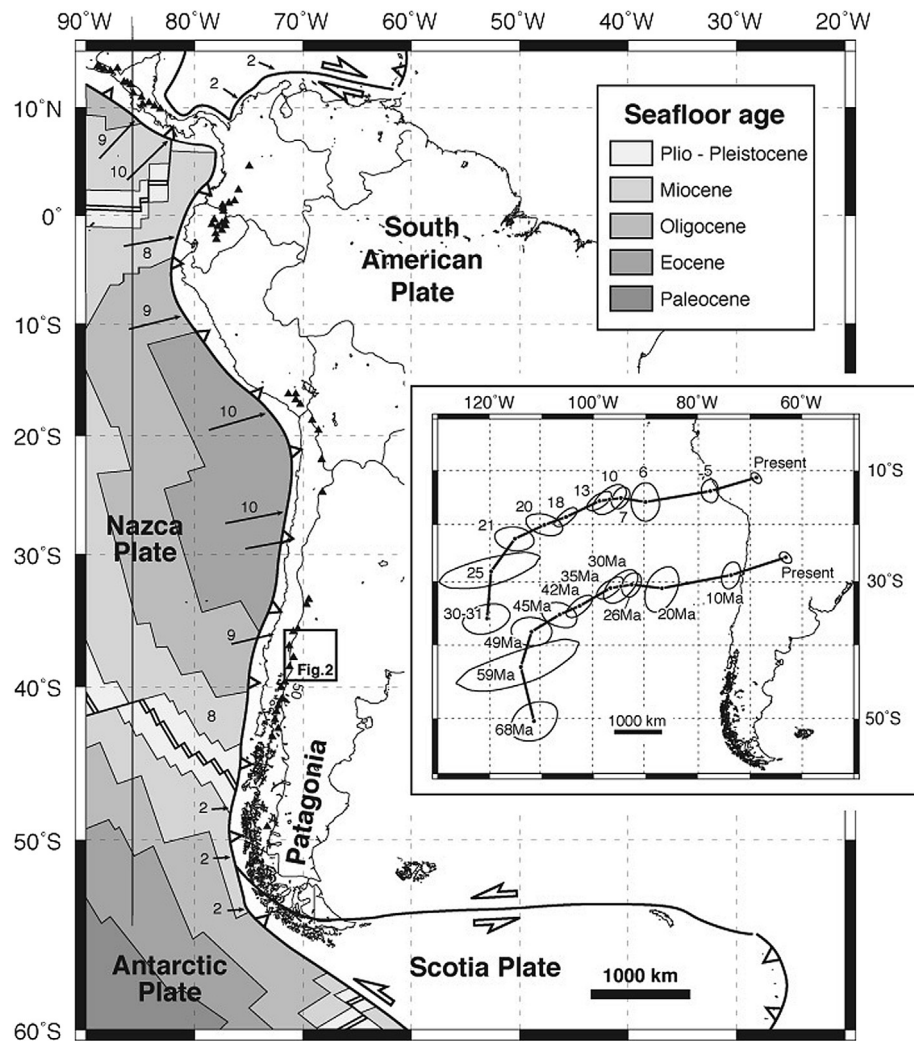


Fig. 1. Plate tectonic setting of Neuquén Basin, Argentina (after Cobbold and Rossello, 2003, their Fig. 1). Main map shows age of sea floor (key at top right), current velocity vectors for Nazca plate, relative to South America (numbers in cm/yr), and main volcanoes of the Andes (black triangles). Box indicates Neuquén Basin (Fig. 2). Large inset (centre right) shows successive positions of two points on Nazca plate (or its precursor, Farallon plate) relative to South America (according to Pardo-Casas and Molnar, 1987). Ellipses represent confidence limits on positions.

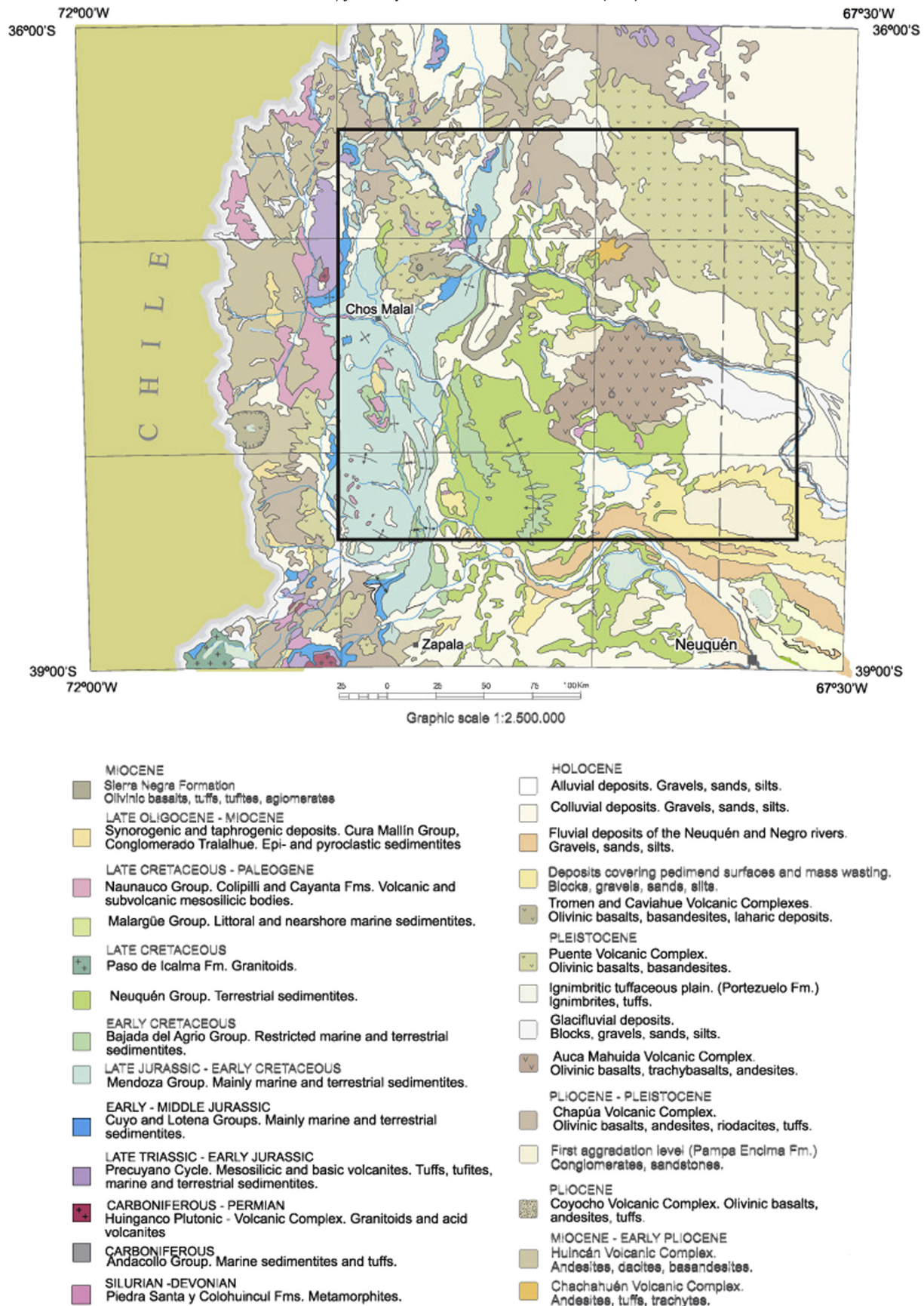


Fig. 2. Geological map of Neuquén Basin, provinces of northern Neuquén and southern Mendoza. Data (year 2014) are by courtesy of SEGEMAR (Argentine Geological Survey). Colours are for main time periods and stratigraphic units (homogenized across both provinces). Thus Mendoza Group (blue-green; Late Jurassic to Early Cretaceous) includes source-rock shales (Vaca Muerta and Agrio Fms) and reservoir sandstones (Tordillo and Mulichinco Fms). Continuous black lines (with diverging or converging arrows) mark axial traces of major folds (anticlines or synclines). Sinuous black line (dashed) marks frontier between provinces of Mendoza (to NE) and Neuquén (to SW). Bold rectangle corresponds to Fig. 3.

Neuquén Province, two large recent volcanoes (Tromen and Auca Mahuida, Fig. 3) are several km high and their volcanic products have yielded Pleistocene ages by ^{39}Ar – ^{40}Ar dating (Rossello et al., 2002; Galland et al., 2007; Llambías et al., 2010).

The Neuquén Basin has been a producer of oil and gas since the early 1900s. In the eastern foreland, the strata at the surface today are mainly flat lying and Late Cretaceous or Tertiary in age (Fig. 2), so that the source rocks are beneath them, at depths of several thousand metres and at various stages of maturity. However, in the foothills of the Andes the source rocks crop out within the Agrio fold-and-thrust belt, as a result of exhumation. In this region also, hundreds of veins of solid hydrocarbon (bitumen) are visible, mainly as a result of erosion or mining (Figs. 3 and 4, Table 1). At first sight, the bitumen resembles coal. Indeed, early settlers and geologists identified it as such (e.g. Hauthal, 1892) and used it for fuel. However the veins are mostly steep dykes, which crosscut (and therefore post-date) the strata. The veins presumably intruded their host rocks, while the organic material within them was liquid oil or asphalt. Later the material solidified, probably by loss of volatile components. Amongst the early geologists, who recognized bitumen veins in the Neuquén Basin, were Keidel (1910) and Windhausen (1912). Later, Groeber (1923) and Rassmuss (1923) both recognized, in consecutive publications from the same volume, that the bitumen, like petroleum, resulted from heating of organic-rich shale of Mesozoic age. They furthermore stated (e.g. Rassmuss, 1923, page 17) that the bitumen veins were always “linked to volcanic centres” and that heating was due mainly to magmatic activity, rather than to burial alone.

In the following decade (1930–1940), new mining companies appeared, to exploit the bitumen resources. Many of these companies benefited from German capital and technical expertise. During World War 2, when imports of coal were no longer possible, the bitumen became useful in Argentina as fuel for railway locomotives or for steelworks. After combustion, geochemical analyses of the ashes showed them to be rich in vanadium (Kyle, 1891; Meyerhoff, 1948; Fester and Cruellas, 1949) and this also became of interest economically. In the following years, the mining of solid fuel increased, under the auspices of state organizations, such as

Yacimientos Carboníferos Fiscales (YCF). This promoted many new geological studies, but the resulting reports remained confidential. Luckily for posterity, Borrello (1956) managed to produce a very informative book (665 pages), in which he synthesized much of the pre-existing work. In particular, he agreed with previous authors that the bitumen veins had formed mainly as a result of magmatic heating, during late Tertiary or Quaternary times, after the main phases of tectonic activity (Borrello, 1956, pages 352–358).

Later the production of bitumen decreased, mainly because liquid oil took its place as fuel. However, some of the larger bitumen mines also suffered disasters, due in part to the explosive nature of the bitumen dust. Thus 4 large mines and their neighbouring camps had to close down (Santa Marta in June 1943, La Esperanza in June 1944, La Escondida in August 1947, San Eduardo in March 1951). Nevertheless the mine workings (trenches, pits, galleries, machines, dumps, platforms, water tanks, houses, and access roads) remained visible, not only at the surface, but also on air photographs. Since then, many of the workings have tended to disappear and access to them has become more difficult. However, the resolution of air photos and satellite images has tended to increase. Thus, since the year 1998, we have been able to relocate and visit many of the old localities (Table 1), so as to study the bitumen veins and their host rocks (Cobbold et al., 2008). Moreover, in 2009 many of the YCF reports on bitumen mines reappeared and are now available from the geological survey, SEGEMAR. On studying these reports carefully, we have been able to locate other old mines (Cobbold et al., 2011a, 2011b). Our publications so far have been in the form of abstracts, posters or catalogues, whereas in the following pages we describe and illustrate the bitumen localities more fully, especially those which are representative of each area.

2. Regional distribution of bitumen veins

For the formation of bitumen veins in the Neuquén Basin, Carey et al. (1993) and Parnell and Carey (1995) favoured a model of progressive heating during Eocene burial. On the basis of this model, Cobbold et al. (1999) noticed that many of the bitumen dykes in Neuquén province trend NE–SW and therefore deduced

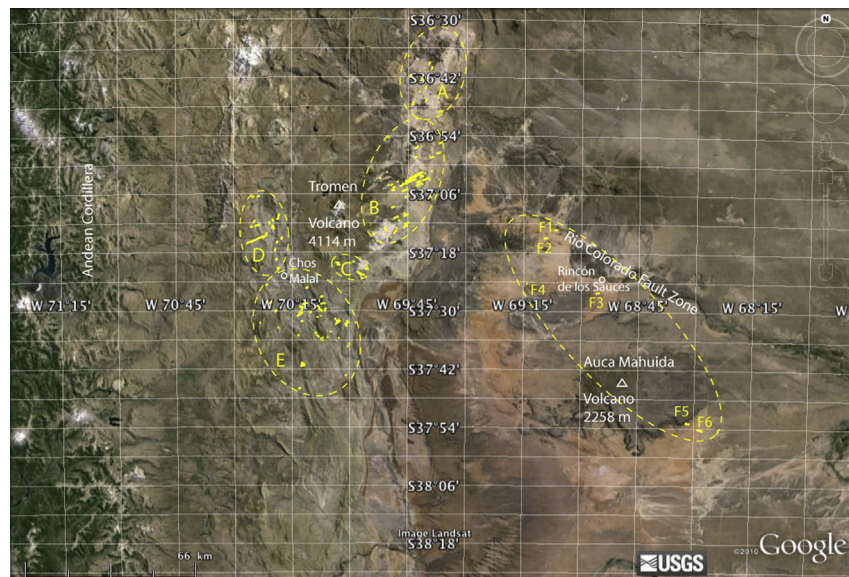


Fig. 3. Map of 103 bitumen localities, provinces of northern Neuquén and southernmost Mendoza (see Table 1). Most veins are dykes (yellow bars), but some are sills (yellow dots). Most (97) localities lie within 5 roughly elliptical domains (A to E), less than 70 km from summit of Tromen Volcano (see Fig. 4 for details). Six more distant localities (domain F) are along Rio Colorado fault zone (Argüello, 2011) or on SE flank of Auca Mahuida Volcano. Background image (Landsat) is from Google Earth (year 2013), so that lines of latitude and longitude are almost straight and orthogonal, allowing for easy comparison with geographical positions (Table 1). Main towns (empty white circles) are Chos Malal and Rincón de los Sauces. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

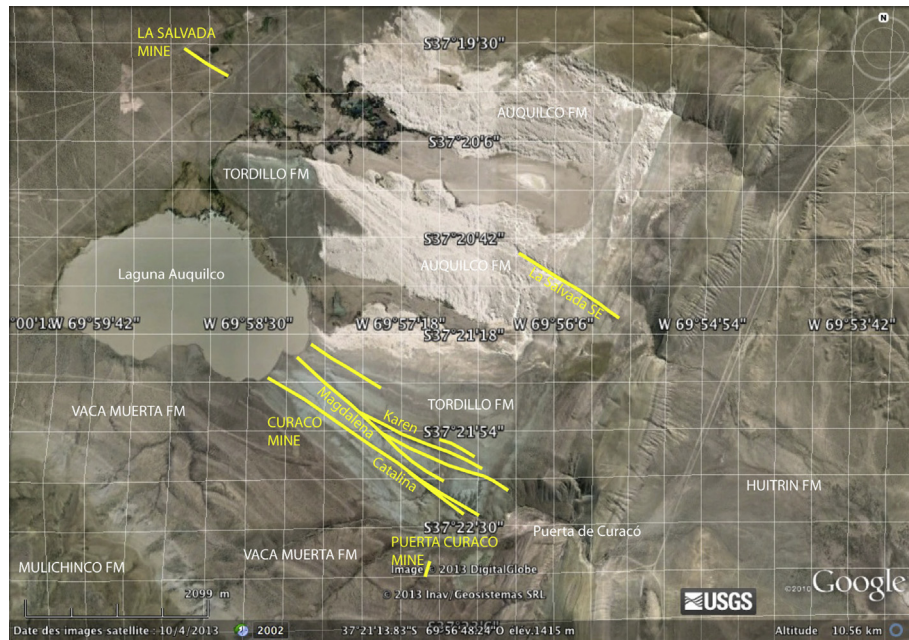


Fig. 5. Map of bitumen veins in and around La Salvadora, Curacó and Puerta Curacó mines, eastern part of Domain C (see also Fig. 4 and Table 1). Most veins are mainly dilational, lie within Tordillo sandstone and trend approximately ESE. At La Salvadora Mine (see Fig. 6, C2), overlying source rock (Vaca Muerta Fm) has downwarped into a vein and is cut by thin bitumen dykes. At Curacó Mine, Magdalena trench consists of central zone of brecciated source rock (Vaca Muerta Fm) and two lateral zones of pure bitumen (Fig. 6, C6). At Puerta Curacó Mine, bitumen dyke trends exceptionally NNE, parallel to strike of steep beds, perhaps as a result of bending in hanging wall of nearby Tromen thrust fault (Fig. 4). In adjacent host rock (Tordillo Fm), hydrothermal minerals include galena. Background image (Landsat) is from Google Earth (year 2013) and shows main geological formations.

the surface, individual dykes tend to be continuous, over distances of hundreds of metres or even kilometres, and they also tend to be parallel, when in swarms. Many of the bitumen dykes crosscut structures in the Agrio fold belt, which has developed since Late Cretaceous times (Cobbold and Rossello, 2003). Also the dykes crosscut all sedimentary formations, from Jurassic to Palaeocene in age (see Fig. 2). At Agua de la Tosca (locality A3, Table 1) bitumen dykes even cut basaltic lava flows, which we have dated by ^{39}Ar – ^{40}Ar as Late Oligocene (ca. 26 Ma). In contrast, like Borrello (1956), we have found no bitumen dykes cutting Quaternary basalt flows.

In the provinces of Neuquén and southern Mendoza, most of the bitumen veins (Table 1) occur around Tromen volcano, within 70 km of its crater (Fig. 3). A few other veins crop out on the SE flank of Auca Mahuida Volcano, or along the Colorado River, where the NE edge of the Neuquén Basin has been subject to strike-slip faulting (Argüello, 2011) and local volcanic activity. In this general area, ^{39}Ar – ^{40}Ar dating of volcanic rocks has yielded Upper Pliocene to Lower Pleistocene ages (Rossello et al., 2002; Galland et al., 2007).

Around Tromen volcano, many of the bitumen dykes strike approximately ENE–WSW (Figs. 3 and 4). Thus they are parallel (or nearly parallel) to the current direction of plate convergence between Nazca and South America (Fig. 1). This correlates with the current direction of greatest horizontal compressive stress in the Neuquén Basin, according to regional data from 115 borehole breakouts (Guzmán et al., 2007; Guzmán and Cristallini, 2009), or from geomorphological studies (Messager et al., 2010). However, along the northern margin of the Neuquén Basin, the greatest stress trends more nearly NE–SW. This may be due in part to a local component of left-lateral strike-slip deformation along the basin margin, which has become the Rio Colorado Fault Zone (Argüello, 2011). If so, the least principal stress in this

area may also be horizontal, accounting for the formation of vertical tensile fractures, trending NE–SW.

In contrast, on the SW and SE flanks of Tromen volcano, some bitumen dykes tend to have other strikes (domains E and C, Fig. 4). In fact, many bitumen dykes appear to point towards the current summit or previous craters of Tromen (for example, Fig. 9, B11). This may have been one factor, which led early geologists to favour a magmatic origin for the genesis of the bitumen (Meyerhoff, 1948). Another factor, which may have influenced them, was the variable thickness of the veins. With distance from the crater of Tromen, some of the radiating bitumen dykes tend to become progressively thinner and even to bifurcate. Their greatest thicknesses (as much as 9.5 m, Table 1) tend to occur near the foot of the volcano, especially within host rocks that are resistant to fracturing. Good examples of such resistant host rocks are sandstones of the Mulichinco, Avilé and Tordillo formations, as well as those of the Neuquén Group (Table 1).

Furthermore, on the SE flank of Auca Mahuida volcano, two major bitumen dykes (F5 and F6, Fig. 3 and Table 1) trend WNW and thus point towards the crater.

The radial arrangements of the bitumen dykes appear to correlate with the relief and with locally abnormal directions of current greatest horizontal stress to the SE of Tromen volcano, according to data from borehole breakouts (Guzmán et al., 2007, their Figs. 4 and 7). In general, circumferential extension around the flanks of a volcano may result from downslope gravitational gliding, either under the weight of the volcanic edifice (Marques and Cobbold, 2002, 2006), or around a source of abnormally high fluid pressure. On the flanks of Tromen, there is also good evidence for a component of radial shortening, which, together with a more general E–W shortening, was synchronous with magmatic development of the volcano (Galland et al., 2007).

We will now describe some representative examples of bitumen localities, from each of domains A to F.

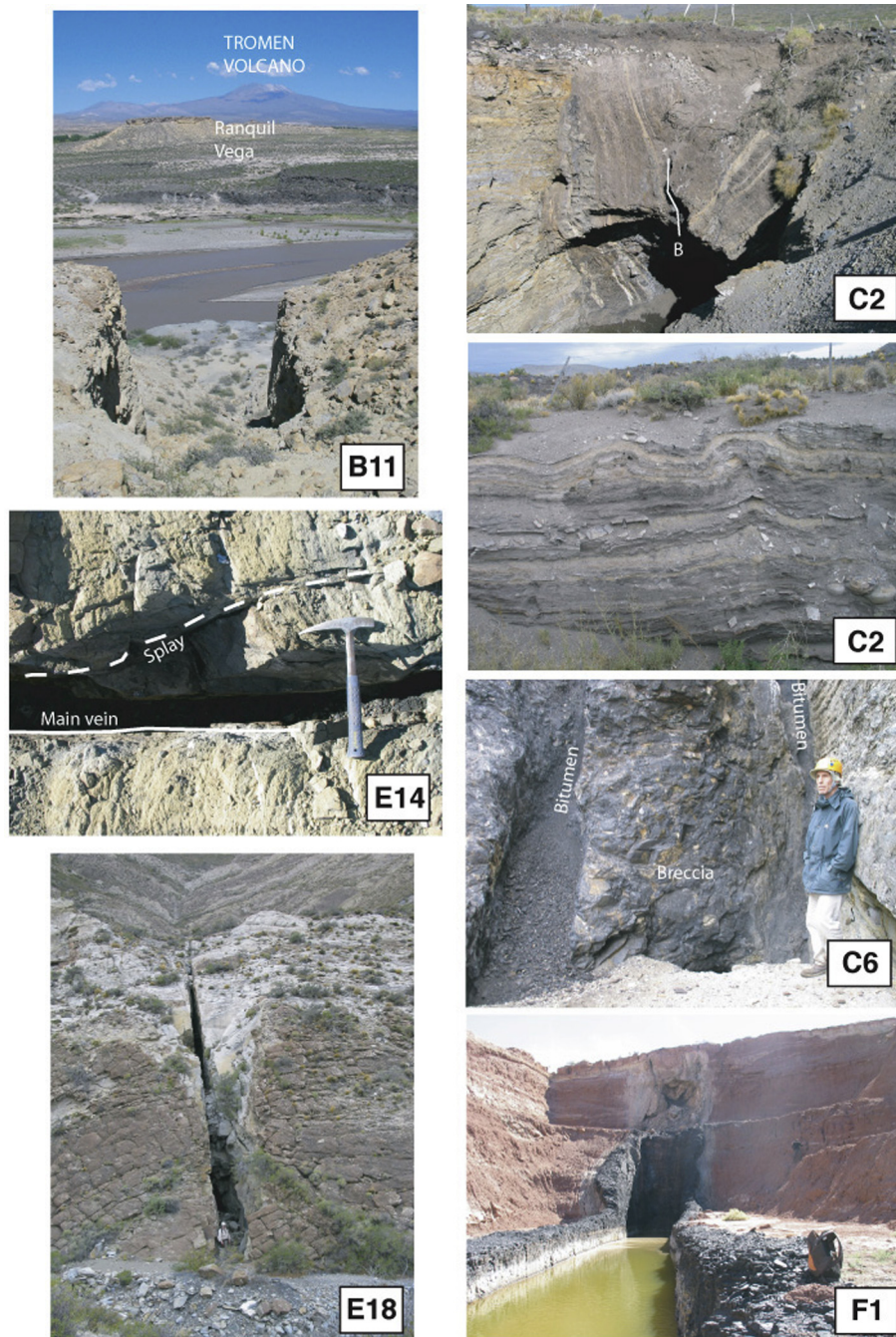


Fig. 6. Photographs of relevant bitumen veins from mines. For locations, see Figs. 3 and 4 and Table 1. For further descriptions, see text. B11. Cable Beta Norte. View (to SW) is from Cable Beta mine (foreground), across Rio Colorado, to summit of Tromen Volcano. Intervening pale scarp (middle background) exposes another vein and small mine (Ranquil Vega; B14, Fig. 4). C2. La Salvada Mine. Top photograph: oblique view (to W) across trench (about 2 m wide) shows syncline of Vaca Muerta shale within Tordillo sandstone. Thin bitumen dyke (B) is parallel to axial surface of syncline and to trench. Bottom photograph: view to SSW, perpendicular to wall of trench, is parallel to axes of late folds. These are evidence for shortening along bitumen dyke. C6. Curacó Mine. View (to NW, year 2006) along Magdalena trench (for location, see Fig. 5) shows central zone of brecciated source rock (Vaca Muerta Fm) and lateral veins of bitumen. Geologist is for scale. For geochemical analyses, see Fig. 10B. E14. Marta bitumen dyke, Santa Marta Mine (for location, see Fig. 8). Downward view shows asymmetric pattern, where small tensile veins (striking NE) splay out of main dyke (striking ENE). This pattern, together with striations, provides evidence for left-lateral strike-slip during formation of Marta dyke. Hammer is for scale. E18. San Eduardo Mine. View NNE along steep Santa Teresita vein (for location, see Fig. 7) shows it cutting across Early Cretaceous strata of Avilé Mbr (Agrio Fm), which here dip steeply towards viewer. Geologist (standing on mine dump) is for scale. F1. Toribia Mine. View SW shows recent workings (year 2012). Black bitumen dyke strikes WSW, cutting through red continental strata of Late Cretaceous Neuquén Group and splaying upward through recent soil layers, as far as current land surface. Sides of dyke have a pencil-like structure, indicating progressive dilation. Pale zoning next to dyke is due to chemical reduction and hydrothermal activity (see Cobbold et al., 2013, their Fig. 4). Backpack (right) is for scale.

3. Domain A

In Domain A (Fig. 4; Table 1), bitumen veins at most localities (perhaps 7) are mainly dykes, trending approximately SSW. Thus they are somewhat oblique to the regional direction of compressive

stress (WSW), but they do point towards the eastern or southern flanks of Tromen volcano.

In contrast, at La Omatina (A1) and Rio Seco de los Baños (A7), bitumen veins are apparently sills, although we did not find them. However we did find Isabel (A10), which was once a productive

Table 1

Data for 103 bitumen localities, provinces of Neuquén and southern Mendoza (updated, after Cobbold et al., 2011b). Code numbers (column 1) refer to elliptical domains (A to G). For locations, see Figs. 3–9. Names of localities (column 2) are from Borrello (1956) or from unpublished reports of state agencies, such as Yacimientos Carboníferos Fiscales (YCF). Information about our visits (column 3) includes first year, localities that we failed to find in situ, or those that we did not attempt to locate. Ease of access (column 4) distinguishes localities that (1) are within a 20 min walk from a main road, (2) are accessible only via secondary roads, (3) also require walks of several kilometres, or (4) require one whole day on foot or on horseback. Geographical coordinates (columns 5 and 6) are from our own GPS measurements in situ (numbers in bold case, accurate to 0.1 s), or from previous reports or satellite images (numbers in standard case, accurate to 1 s). Strike of veins (column 7) and thicknesses (column 8) are from our own measurements (where available) or previous reports. Host rock (column 9) is from geological maps (Fig. 2 and others), our own observations or previous reports. Percentages of total carbon (Column 10) are from Borrello (1956) or more recent YPF reports. Total production of bitumen (Column 11) and reserves (Column 12), both in thousands of tons, are from Borrello (1956).

No. locality	First visit by us	Ease of access	Geographical latitude S	Coordinates longitude W	Strike of vein (°)	Thickness max. (m)	Host rock (unit)	Carbon % (max)	Production × 10 ³ tons	Reserves × 10 ³ tons
DOMAIN A										
A1 La Omatina	Failed	3	36°40'11"	69°46'36"	Sill	0.1	Neuquén Gp	53		
A2 Piedras Azules	Not tried		36°41'14"	69°38'01"	010	0.1	Agrio Fm			
A3 Agua de la Tosca	2002	2	36°41'25.0"	69°39'48.5"	010	0.01	Agrio Fm			
A4 La Costa	Not tried		36°43'55"	69°45'00"	020		Neuquén Gp			
A5 Bardas Bayas	Not tried		36°44'31"	69°41'10"	025	0.7	Agrio Fm	84		
A6 Río Seco de las Escaleras	Not tried		36°45'35"	69°42'01"	020	0.4	Agrio Fm	46		
A7 Río Seco de los Baños	Not tried		36°47'10"	69°43'22"	Sill		Agrio Fm			
A8 Cerro Mayal - Río Seco	Not tried		36°48'45"	69°41'15"	010	2.0	Agrio Fm			
A9 Aguada del Chivato	Not tried		36°50'00"	69°44'01"	020	0.1	Agrio Fm			
A10 Isabel	2008	4	36°50'43.3"	69°37'55.0"	080	4.0	Agrio Fm	52	0.5	1
DOMAIN B										
B1 Butacó	2010	2	36°55'21.7"	69°50'10.6"	Sill	0.5	Agrio Fm	50		
B2 Ciénaga Grande	Not tried		36°55'41"	69°37'00"	060	0.3	Agrio Fm			
B3 Don Josué	Not tried	4	36°57'24"	69°43'01"	065	0.1	Auquínco Fm			
B4 Agua de las Rosillas	Not tried		36°58'36"	69°38'13"	075	0.25	Agrio Fm			
B5 Don Paco	Not tried	4	36°59'00"	69°43'07"	063	0.1	La Manga Fm			
B6 Agua Grande	Not tried		36°59'53"	69°39'45"	075	0.25	Agrio Fm			
B7 Agua de la Salinita	2010	3	37°01'54.5"	69°39'27.0"	020	1.0	Agrio Fm			
B8 Buta Ranquil Norte	Failed		37°02'42"	69°51'42"	Sill	0.2	Agrio Fm			
B9 La Bombilla	2008	3	37°03'12.7"	69°42'39.9"	063	0.4	Mulichinco Fm	55		
B10 Buta Ranquil Oeste	1998	1	37°03'26.9"	69°53'40.1"	Sill	0.5	Agrio Fm			
B11 Cable Beta Norte	2007	3	37°03'34.7"	69°45'22.1"	063	0.95	Mulichinco Fm	55		15
B12 Mine, name not known to us	2008	3	37°03'44.4"	69°40'24.6"	060	0.3	Mulichinco Fm			
B13 El Alamito	2010	3	37°03'45"	69°41'51"	060	0.1	Mulichinco Fm			
B14 Ranquil Vega	2008	2	37°03'54.8"	69°46'19.2"	063	0.3	Mulichinco Fm	30		
B15 Arroyo Chacaycú	Not tried		37°03'56"	69°48'37"	063	0.4	Mulichinco Fm			
B16 Cable Beta Sur	2008	3	37°03'59.6"	69°45'16.7"	055	0.85	Mulichinco Fm			
B17 Señal Borde del Colorado	2008	3	37°04'30.0"	69°42'35.9"	075	0.5	Mulichinco Fm			
B18 Agua del Pato	2010	2	37°04'46.0"	69°47'36.6"	073	0.35	Mulichinco Fm			
B19 Río Seco del Chañar	Not tried		37°05'00"	69°49'45"	063	0.3	Mulichinco Fm			
B20 Buta Ranquil Sur	Failed		37°05'01"	69°51'15"	030	0.5	Mulichinco Fm	37		
B21 Río Seco Santa Elena	Not tried		37°05'01"	69°48'14"	065	0.2	Huitrín Fm			
B22 Cañadón Polcurá	2008	1	37°05'48.5"	69°49'10.8"	065	0.65	Mulichinco Fm			
B23 Cerro Bayo	2010	1	37°05'55.0"	69°49'25.0"	065	0.4	Mulichinco Fm			
B24 La Mona	2010	2	37°06'18.6"	69°47'04.2"	063	0.5	Agrio Fm			
B25 Rincón de Correa	Not tried		37°06'39"	69°39'42"	060		Neuquén Gp			
B26 Bajada de Campos	2010	2	37°07'04.8"	69°46'28.9"	063	0.5	Huitrín Fm			
B27 La Hedionda	Failed		37°09'07"	69°49'11"	063	0.6	Huitrín Fm			
B28 Puesto Escalona	2008	2	37°10'25.4"	69°46'25.8"	060	0.4	Mulichinco Fm			
B29 Río Seco del Alamo	Not tried		37°12'15"	69°44'47"	060	0.2	Mulichinco Fm			
B30 Ciénaga de las Yeseras	Failed		37°12'18"	69°45'44"	060	0.4	Mulichinco Fm			
B31 Tromen	2005	2	37°13'14.0"	69°51'01.6"	050	3.8	Tordillo Fm	51	12.3	25
B32 Cerro Negro del Tromen	Not tried		37°14'15"	69°53'45"	050	1.4	Auquínco Fm	36		
B33 La Riqueza	2005	2	37°14'39.3"	69°49'43.8"	015	3.0	Auquínco Fm	77		
DOMAIN C										
C1 Cerro Tilhué	Not tried		37°18'25"	70°03'00"		0.4	Mulichinco Fm			
C2 Laguna Auquínco (La Salvada)	2005	1	37°19'32.7"	69°58'53.8"	120	1.0	Tordillo Fm			
C3 Alto Arroyo Chacaicó Este	2005	1	37°19'49.7"	70°2'36.3"	015	0.3	Mulichinco Fm			
C4 Alto Arroyo Chacaicó Oeste	Not tried		37°20'04"	70°03'42"	010	0.15	Mulichinco Fm	47		
C5 La Salvada SE	2008	2	37°21'06.9"	69°55'44.8"	120	1.0	Tordillo Fm			
C6 Curacó (Magdalena)	2000	1	37°21'49"	69°57'35"	135	8.0	Tordillo Fm	86	27.6	200
C7 Puerta Curacó	2008	2	37°22'46.5"	69°57'05.2"	010	5.0	Tordillo Fm			
DOMAIN D										
D1 Tricao Malal	2005	2	37°06'28"	70°22'27"	075	0.9	Agrio Fm	50		
D2 Alto Curileuvú	Not tried		37°06'47"	70°23'52"	075	0.02	Agrio Fm			
D3 Arroyo Leuto Caballo	Not tried		37°10'59"	70°17'45"	040	0.5	Avilé Mb			
D4 Cerro Negro	2005	2	37°11'20"	70°19'00"	000	0.3	Agrio Fm			
D5 Cerro Carcarañán Norte	Not tried		37°11'47"	70°23'48"	040	0.03	Avilé Mb			
D6 Curi Mahuida Norte	Not tried		37°12'23"	70°19'56"	170	0.1	Mulichinco Fm			
D7 Curi Mahuida Oeste	Not tried		37°12'26"	70°21'51"	060	0.35	Agrio Fm			
D8 Cerro Carcarañán Sur	Not tried		37°12'31"	70°23'22"	060	0.03	Avilé Mb			

(continued on next page)

Table 1 (continued)

No. locality	First visit by us	Ease of access	Geographical latitude S	Coordinates longitude W	Strike of vein (°)	Thickness max. (m)	Host rock (unit)	Carbon % (max)	Production × 10 ³ tons	Reserves × 10 ³ tons
D9 Arroyo Menucos	Not tried		37° 12' 32"	70° 24' 22"	060	0.05	Avilé Mb			
D10 Curi Mahuida Sur	Not tried		37° 13' 03"	70° 19' 04"	020	0.15	Mulichinco Fm			
D11 Chacay Melehué	Failed		37° 14' 00"	70° 20' 30"	040	0.1	Avilé Fm			
D12 Las Máquinas	Failed		37° 14' 26"	70° 20' 55"	070	2.0	Avilé Mb	47		
D13 Arroyo Chapúa Oeste	Not tried		37° 15' 01"	70° 16' 42"	020	0.05	Avilé Mb			
D14 Arroyo Chapúa Sur	Not tried		37° 15' 35"	70° 16' 57"	020	0.1	Mulichinco Fm			
D15 La Parva	2005	1	37° 16' 06.9"	70° 25' 16.3"	070	0.8	Avilé Mb	43		1
D16 Los Maitenes	Not tried		37° 17' 27"	70° 18' 14"	000	0.1	Vaca Muerta Fm	64		
D17 La Tricahuera	Not tried		37° 19' 34"	70° 18' 08"	020	0.7	Mulichinco Fm			
D18 Curileuvú	Failed		37° 21' 30"	70° 17' 27"	065	0.1	Avilé Mb	69		
DOMAIN E										
E1 Rahueco	Not tried		37° 23' 32"	70° 20' 38"	050	0.03	Agrio Fm			
E2 Loma Alta	Not tried		37° 24' 32"	70° 10' 10"	056	0.1	Mulichinco Fm			
E3 Junta Arroyos Chacaicó y Blanco	Failed	3	37° 26' 43"	70° 06' 34"	020	0.3	Agrio Fm			
E4 Arroyo Truquico	Not tried		37° 26' 51"	70° 19' 03"	040	0.05	Avilé Mb			
E5 Costa Neuquén Oeste	Not tried	4	37° 27' 40"	70° 10' 20"	010	0.3	Mulichinco Fm			
E6 Flanco Oriental Ant. El Porvenir	Not tried	3	37° 27' 41"	70° 06' 30"	010	0.3	Mulichinco Fm			
E7 Arroyo Tilhué Inferior	Not tried	4	37° 28' 42"	70° 06' 18"	025	0.15	Mulichinco Fm			
E8 La Esperanza	2008	1	37° 28' 42.2"	70° 11' 38.8"	020	2.0	Avilé Mb	69	21	10
E9 El Porvenir	2008	4	37° 28' 42.2"	70° 07' 42.4"	020	1.9	Mulichinco Fm	74		
E10 San Daniel	2008	1	37° 28' 46.7"	70° 12' 00.6"	020		Avilé Mb			
E11 Cerro Pitrén	2008	3	37° 29' 10.2"	70° 17' 56.9"	035	1.9	Mulichinco Fm			
E12 Costa Neuquén Este	Failed	4	37° 29' 12"	70° 07' 27"	020	0.15	Mulichinco Fm			
E13 San José	Failed		37° 29' 39"	70° 10' 55"	050	0.8	Mulichinco Fm			
E14 Santa Marta (Marta vein)	1998	1	37° 29' 54.0"	70° 11' 59.8"	055	9.5	Avilé Mb	65	44	10
E15 Tilhué	2010	3	37° 30' 59.7"	70° 02' 47.1"	020	4.5	Avilé Mb	59	12	23
E16 Cerro Curacó	2008	1	37° 31' 25.7"	69° 58' 28.4"	065	1.1	Mulichinco Fm	53	17	2.5
E17 La Argentina	2008	2	37° 31' 27.8"	70° 21' 12.9"	Sill	1.2	Avilé Mb	81		
E18 San Eduardo (S. Teresita)	1998	1	37° 31' 56.0"	70° 00' 27.7"	025	4.3	Avilé Mb	63	100.7	7
E19 Buta Huenul	Failed		37° 32' 20"	70° 17' 15"	Sill	0.4	Agrio Fm			
E20 Santa Elena	Failed	4	37° 33' 18"	70° 12' 39"	050	0.5	Avilé Mb			
E21 Sierra de los Leones	Failed	4	37° 33' 44"	70° 07' 40"	170	0.95	Mulichinco Fm			
E22 Anticlinal del Tilhué	Not tried		37° 34' 23"	70° 04' 13"	050	0.2	Mulichinco Fm			
E23 Rio Neuquén	2012	3	37° 34' 35.2"	70° 02' 36.1"	065	2.4	Pilmatué Fm	59	1.8	0
E24 Huitrín	2008	2	37° 35' 47.2"	70° 0' 7.7"	065	2.4	Avilé Mb	58	1	
E25 Naunauco	2010	2	37° 39' 44.9"	70° 11' 48.8"	010	1.0	Mulichinco Fm			
E26 Cerro Visera	Failed	3	37° 42' 46"	70° 01' 24"	Sill		Agua Mula Fm			
E27 Pichi Neuquén	Not tried	3	37° 44' 46"	70° 01' 39"	070	0.05	Huitrín Fm			
E28 Veta Afloramiento	2012	2	37° 28' 07.0"	70° 11' 19.2"	050	0.30	Avilé Mb			
E29 Veta 9	2010	2	37° 31' 27"	70° 12' 00"	045°	1.00	Avilé Mb			
DOMAIN F										
F1 Toribia	1998	1	37° 13' 24.7"	69° 06' 46.3"	070	10.0	Neuquén Gp	45		
F2 Fortuna 4	1998	2	37° 14' 53"	69° 09' 05"	070	4.8	Neuquén Gp	48	0.7	
F3 Rio Colorado	Failed	3	37° 26' 29"	68° 53' 51"	077	1.5	Neuquén Gp	45		
F4 Mesillos de los Overos	Not tried	3	37° 24' 23"	69° 14' 34"	Sill	1.0	Neuquén Gp			
F5 La Escondida	1998	3	37° 53' 06"	68° 31' 07"	102	5.5	Neuquén Gp	38		25
F6 Auca Mahuida	1998	2	37° 54' 21"	68° 28' 14"	115	3.0	Neuquén Gp	45	96	15

mine. Here the workings reveal several large sills or laccoliths of bitumen within shale of the Agrio Fm, as well as one bitumen dyke, trending WSW. Interestingly, the bitumen sills at La Omatina and Isabel are of relatively high grade (impsonite). The same is true for the bitumen dykes at Bardas Bayas (A5).

4. Domain B

In Domain B (Fig. 4; Table 1), bitumen veins at 30 localities are mostly dykes. Their host rocks are mostly sandstones of the Mulichinco Fm (immediately above shale of the Vaca Muerta Fm), but at Mina Tromen (B31) they are sandstones of the Tordillo Fm (immediately below the Vaca Muerta Fm) and at 5 other localities they are underlying or overlying evaporites of the Auquino or Huitrín formations. Most of the bitumen dykes trend approximately WSW. Thus they follow the direction of regional compressive stress, but they also point towards the main summit of Tromen volcano, or towards two subsidiary volcanic centres (Cerro Negro

and Cerro Tilhué). Of these the main summit, as well as Cerro Negro, are dominantly late Pleistocene in age, whereas Cerro Tilhué is early Pleistocene (Galland et al., 2007).

Near the southern end of Domain B, at Mina Tromen (B31), the host rocks are Tordillo sandstones. Here the bitumen dykes contain fragments of Vaca Muerta shale, which presumably dropped into the injecting hydrocarbons, perhaps under the action of overpressure in the source rock. At a nearby locality (La Riqueza, B33), bitumen dykes trend anomalously (NNE), perhaps as a result of bending at the outer arc of a frontal anticline, above the Tromen thrust fault (Fig. 4). At both localities, bitumen dykes are of high grade (impsonite). The same is true for bitumen dykes at localities La Bombilla (B9) and Cable Beta Norte (B11) in the NE part of Domain B. It is perhaps no coincidence that all these localities are in the hanging walls of large thrust faults.

In the NW part of Domain B, bitumen veins at 2 localities (Butacó, B1; Buta Ranquil Oeste, B10) are mainly sills, once again within shale of the Agrio Fm. The same may be true for Buta Ranquil Norte (B8),

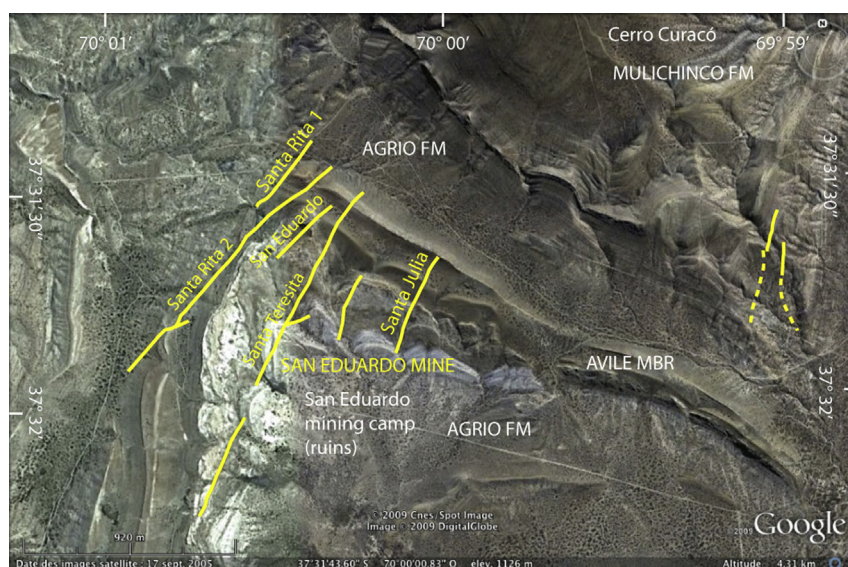


Fig. 7. Map of bitumen dykes (yellow lines) in and around San Eduardo Mine, Domain E (see also Fig. 4 and Table 1). Most dykes trend approximately NNE, cut across previous structures in Avilé sandstone and are mainly dilational. Longest is Santa Teresita (Fig. 6, E18). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Background image (Landsat) is from Google Earth (year 2005).

which we did not find. La Mona (B24), which is in the central part of Domain B, consists mainly of bitumen dykes, trending WSW, but it also has a few sills, all of these being within shale of the Agrio Fm. At Butacó, the sills are of high grade (impsonite).

5. Domain C

In Domain C (Figs. 3 and 5), bitumen veins at 6 localities are dykes. Most of these are within sandstones of the Mulichinco or Tordillo formations, which either overlie or underlie shale of the Vaca Muerta Fm. In the eastern part of the domain, all the dykes, except one, trend SE to ESE (around Curacó and La Salvada mines). Such directions are almost at right angles to the regional stress field in Neuquén Province. However they converge, not so much towards the main summit of Tromen volcano, as towards Cerro Tilhué (Fig. 4), where andesitic domes, younger than 2.27 Ma and defining an E–W lineament (Fig. 4), lie unconformably upon the Vaca Muerta Fm (Galland et al., 2007). In detail, several of the bitumen dykes at Curacó and La Salvada follow vertical zones of brecciated Vaca Muerta source rock (Fig. 6, C6). Locally, one of these zones (Magdalena vein, Fig. 5) displays horizontal striations, indicating left-lateral strike-slip. In contrast, dykes striking ESE (such as Karen) are more dilational. Thus at Curacó Mine, the local compression direction probably was ESE. At La Salvada mine, late folds with axes perpendicular to the vein are visible on the SW side of the trench (Fig. 6, C2). These folds indicate vein-parallel shortening, which is radial with respect to Cerro Tilhué. At Curacó (C6) the bitumen dykes are of high grade (impsonite).

In the SE part of Domain C (Fig. 5), one dyke (Puerta Curacó, C7) has an unusual trend (NNE), perhaps as a result of bending at the outer arc of a frontal anticline, above the Tromen thrust fault (Fig. 4).

In the western part of Domain C (Fig. 4), bitumen dykes also trend approximately NNE. Nevertheless, because of their locations, these dykes point towards the eastern side of Cerro Tilhué or towards Cerro Negro del Tromen.

6. Domain D

In Domain D, out of 18 localities (Fig. 4, Table 1), we have visited only Tricao Malal (D1), Cerro Negro (D4) and La Parva (D15).

According to previous work, the bitumen veins are almost all dykes and their host rocks are sandstones, either of the Mulichinco Fm, or of the Avilé Member (Agrio Fm). In the western part of the domain, bitumen dykes trend roughly NE, following the regional direction of compressive stress for the Neuquén Basin, but also pointing towards Tromen volcano or Cerro Tilhué. In contrast, in the eastern part of the domain, some of the bitumen dykes trend more nearly NNE or N. The reason for this is not yet clear to us.

At Tricao Malal (D1), Los Maitenes (D16) and Curileuvú (D18), bitumen dykes are of high grade (impsonite).

7. Domain E

In Domain E, most of the bitumen veins are dykes (Fig. 4). In the eastern part of the domain, San Eduardo (Fig. 7) was for many years the biggest and most productive of the bitumen mines in the Neuquén Basin (Table 1). Indeed, in the 1950s the mining camp became a large village. In this area, several steep bitumen dykes trend approximately NNE, cutting across Early Cretaceous strata and tectonic structures. The main host rock for the dykes is resistant sandstone of the Avilé Member, Agrio Fm (Fig. 6, E18). The dykes are almost purely dilational and they point, not directly towards the summit of Tromen volcano, but somewhat to the E of it. We suspect that this direction may be a compromise, between that of the regional stress (NE–SW) and the radial effect of Tromen volcano.

In the north-central part of Domain E (Figs. 4 and 8), Santa Marta, San Daniel and La Esperanza were also historically very productive mines (Table 1). At these localities also, most of the bitumen dykes are almost purely dilational, within sandstone of the Avilé Member, Agrio Fm. The dykes strike approximately NNE. Thus from these, more western, localities the dykes point much more nearly towards the summit of Tromen volcano. Exceptionally, the southernmost vein, by the name of Marta (Fig. 8), strikes more nearly ENE and has good evidence (in the form of splays) for left-lateral strike-slip during bitumen emplacement (Fig. 6, E14). In fact, the vein follows a pre-existing transfer fault, which right-laterally offsets some adjacent folds (Fig. 8). Thus the Marta fault must have reactivated left-laterally, during formation of the



Fig. 8. Map of bitumen dykes (yellow lines) in and around Santa Marta, La Esperanza and San Daniel mines, Domain E (see also Fig. 4 and Table 1). Most dykes trend approximately NNE, cut across previous structures, and are mainly dilational. In contrast, Marta vein (in SW) trends approximately NE and carries evidence (see Fig. 6, E14) for opening during left-lateral reactivation (yellow arrows, this figure) of an older right-lateral transfer fault (white arrows), which offsets folds, including an anticline in sandstone of Avilé Member (Agrio Fm). In general, bedding traces (dashed white lines) trend almost N–S in this domain, as a result of Tertiary folding. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Background image (Landsat) is from Google Earth (year 2013).

bitumen dykes. We infer that the compression direction at that time was NNE–SSW (approximately radial to Tromen).

In the western part of Domain E (furthest from Tromen volcano), bitumen veins in at least 3 localities are mainly sills, within or close

to shales of the Agrio Fm. At one of these localities (La Argentina, E17), the bitumen is of high grade (impsonite). The same is true for dykes at 5 other localities, spanning the north-central part of the domain, from W to E.

8. Domain F

In Domain F (Fig. 3, Table 1), most of the bitumen veins are dykes. Along the Rio Colorado fault zone, the dykes trend ENE–WSW. The fault zone trends ESE and has undergone left-lateral strike-slip displacements since the Late Cretaceous, accounting for flower structures at depth (Argüello, 2011). Thus the greatest and least principal stresses in this area should have been horizontal, accounting for the formation of vertical tensile fractures, which trend ENE–WSW. Not only do bitumen dykes have this orientation, but also some basaltic dykes. These underlie and have fed a few small volcanoes or spatter-cones (Figs. 6 and 9). Thus the Rio Colorado is also a zone of Pleistocene volcanic activity (Llambías et al., 2010). In this area there have been 3 bitumen mines: Toribia (Fig. 9, F1), Fortuna IV (F2) and Rio Colorado (F3). Of these, Rio Colorado has not been active for many years, but Fortuna IV has been sporadically active, so that the main bitumen vein was clearly visible until the year 2005 or so. It cuts through continental strata of the Neuquén Group and overlying units and thins towards the current ground surface.

In contrast, Toribia has been a very active mine, for the last 10 years or so, and the main bitumen dyke is highly visible at the advancing mine front (Fig. 6, F1). Again, the dyke cuts through continental strata of the Neuquén Group and overlying units. The sides of the dyke have a pencillate structure, due to progressive horizontal dilation. Towards the current ground surface, the dyke subdivides into U-shaped spalls, which traverse recent soil and calcrete (Cobbold et al., 2011b, their Fig. 3D). At each side of the dyke, white zones reveal bleaching of ferric iron to ferrous iron, as a result of hydrothermal activity. Moreover, these zones contain bedding-parallel veins of fibrous gypsum (gypsum beef), which are evidence for overpressure at temperatures of 60 °C or so (Cobbold et al., 2013, their Fig. 4). It is almost certainly no accident that the bitumen dyke at Toribia is parallel to (and within 1.5 km of) a chain



Fig. 9. Area of active Toribia mine, Domain F (see also Fig. 3 and Table 1). Main trench (Mina Toribia) is about 1.5 km N of line of volcanic spatter cones (dashed red line). Both features crosscut sandstones of Late Cretaceous Neuquén Group (Fig. 2) and trend approximately ENE. Neither feature points towards crater of Volcan Los Loros (top right). Instead, both are compatible with left-lateral motion along Rio Colorado fault zone, which has been active since Late Cretaceous times (see text for details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Background image (Landsat) is from Google Earth (year 2013).

of basaltic spatter-cones, which overlie a volcanic dyke and have generated recent lavas and breccias (Fig. 9). These lavas we have dated at 0.16 ± 0.09 Ma (late Pleistocene).

To our knowledge, bitumen sills are common at only one locality (Mesillo de los Overos, F4). However, we have not been able to visit it.

In all of Domain F the bitumen veins are of relatively low grade (grahamite), despite the presence of a large volcano (Auca Mahuida).

9. Source, maturity and age of the bitumen

Generally, throughout the northern Neuquén Basin, many of the bitumen veins occur within, above, or even just below the Vaca Muerta Fm, which is the main source rock for oil. Indeed, many workers (for example, Carey et al., 1993; Parnell and Carey, 1995) have already suggested that the Vaca Muerta Fm was also the main source rock for the bitumen veins. The idea is that the bitumen solidified from oil, which had already migrated into the veins. Parnell and Carey (1995) described evidence for progressive opening of the veins, as a result of overpressure or tectonic stress. Despite the evidence that the Vaca Muerta Fm has been the main source rock for oil, as well as for bitumen, we have observed some bitumen sills, as well as dykes, within shale of the Agrio Fm, which is also a source rock for oil or gas. Thus there is a possibility that the Agrio shale was a source rock for some of the bitumen.

Regionally, the maturity of the bitumen varies. For 33 of the veins, we have had access to unpublished reports, describing their carbon content (Table 1), which is one indicator of maturity. In Domain F, which is the furthest from Tromen volcano, the carbon content is systematically in the range of 38–48% (Table 1). This is typical of grahamite, which is bitumen of moderate maturity (Abraham, 1960). In contrast, in domain E and in some parts of domains A, B, C and D, which are all closer to Tromen volcano, the carbon content is in places higher, in the range of 50–85% (Table 1 and Fig. 4). Such values are typical of impsomite, which is bitumen of high maturity. On the basis of other physical and chemical properties (such as solubility in organic fluids, melting temperature and density), Piscione (1947) obtained the same distribution of grahamite and impsomite amongst the various domains. Where we have been able to identify impsomite, it tends to occur mainly in the hanging walls of deep-seated thrust faults (Fig. 4). From this we imagine that heat advection might have involved fluids, which migrated up thrust faults, before deviating into steep open fractures. Moreover, progressive exhumation of the hanging walls since the Pliocene may have brought to the surface the deeper parts of the bitumen veins, which were more mature. In some examples (such as La Salvada and Curacó mines, C2 and C6, Fig. 6), even the Vaca Muerta source rock has reached the surface, as a result of exhumation.

At Curacó Mine (Fig. 4, domain C; Figs. 5 and 6, C6), bitumen occurs in veins, but also around shale fragments of breccia zones or as inclusions within fibrous bedding-parallel calcite veins (beef; Rodrigues et al., 2009). Outside the main veins (dykes), we found that geochemical spectra of biomarkers in the bitumen were similar to those of immature or early mature source rock (Vaca Muerta Fm) from Picún Leufú (Fig. 10A), which is a type locality in the southern part of the Neuquén Basin. In contrast, within the dykes the bitumen had little pyrolyseable material and produced much simpler spectra (almost single peaks, Fig. 10B). From this we infer that the dykes reached higher temperatures than the surrounding rock. Thus the evidence is for injection of hot oil, forming the dykes. At nearby La Salvada Mine (Fig. 4, domain C; Fig. 5), we observed fragments of source rock (Vaca Muerta Fm) within the main bitumen dyke, which locally has traversed the underlying

(stratigraphically older) Tordillo sandstone. Moreover, on each side of this dyke and even on top of it, the source rock itself has bent downwards, forming a syncline (Fig. 6, C2). This suggests that overpressure in the source rock was responsible for downward expulsion of oil and shale into an opening fracture.

At some localities, bitumen dykes splay upward towards the current land surface, crosscutting recent soils. A good example is Toribia mine (locality F1, Figs. 3 and 9). Here aqueous fluids rising next to the dyke have caused reduction of ferric iron to ferrous iron (Fig. 6, F1) and formation of bedding-parallel veins of gypsum (gypsum beef) in the adjacent host rock (Cobbold et al., 2013, their Fig. 14). Hence, at Toribia, upward injection of bitumen and aqueous fluids has been a relatively recent and hot phenomenon, synchronous with volcanic activity.

At other localities, calcrete at the overlying free surface provides good evidence for upward migration of hot aqueous fluids. A good example is the area around Tromen mine, on the eastern flank of Tromen volcano (locality B31, Fig. 4). Here a layer of calcrete, close to bitumen dykes of high maturity (impsomite), contains bipyramidal crystals of quartz, as well as sulphides. Further to the NE, the calcrete also contains volcanic bombs, which we have dated at 1.71 ± 0.05 Ma by ^{39}Ar – ^{40}Ar . Thus the calcrete is as young as that, or even younger. At a few other localities, the host rocks adjacent to bitumen dykes contain chalcidony, barite, sphalerite, galena, or copper sulphides. At Puerta Curacó mine (Fig. 5) galena has impregnated the wall rock next to the main bitumen dyke.

10. Discussion and conclusions

In the Neuquén Basin, because so many bitumen veins are within or close to source rocks, but also are close to volcanoes or magmatic intrusions, Groeber (1923), Rassmuss (1923), Piscione (1947), Meyerhoff (1948), Fester and Cruellas (1949) and Borrello (1956) all inferred that the bitumen was due to maturation of organic-rich shale, during volcanic activity of Jurassic or Cretaceous age. Fester and Cruellas (1949) argued that hydrothermal activity was the main mechanism of heat transfer. Later, from stratigraphical data, Borrello (1956) deduced a more recent age (Pliocene or Pleistocene) for the formation of the bitumen veins.

In contrast, Carey et al. (1993) and Parnell and Carey (1995) considered another model, which by then was more in favour, for maturation of source rock (Vaca Muerta Fm) as a result of regional subsidence. For the Neuquén Basin, this should have occurred in Late Cretaceous to Early Tertiary times, especially during the Eocene. According to this model and taking into account the average orientation (NE–SW) of bitumen dykes in Neuquén Province, Cobbold et al. (1999) argued that this was the shortening direction in Eocene times.

However, now that we are more familiar with previous historical work and have studied many of the bitumen localities, especially around the volcanoes, we believe that the early geologists were right in emphasizing the importance of magmatic heating. We also accept that many bitumen veins, in the provinces of northern Neuquén and southernmost Mendoza, formed in Pliocene or Pleistocene times, when large volcanoes (Tromen and Auca Mahuida) were active, as well as the Rio Colorado fault zone. In the provinces of northern Neuquén and southernmost Mendoza, the bitumen veins are mostly sub-vertical dykes. They tend to be straight and continuous, crosscutting regional structures and strata of all ages, from Jurassic to Palaeocene. Most of the localities lie within 70 km of Tromen volcano, although four are along the Rio Colorado fault zone and another two are close to Auca Mahuida volcano. On both edifices, volcanic products are of Pleistocene age. Although regionally many of the bitumen dykes tend to track the current direction of maximum horizontal compression (ENE),

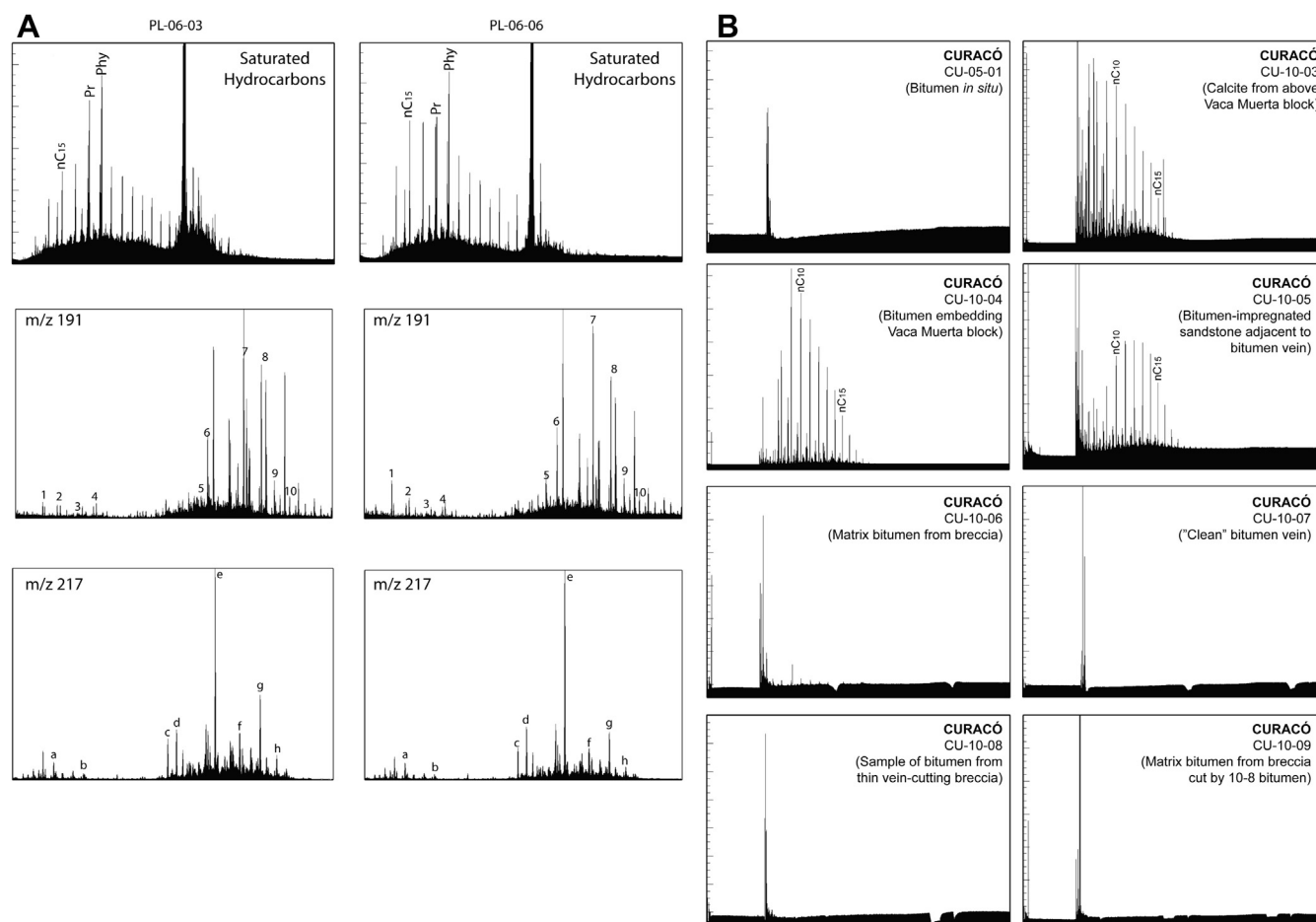


Fig. 10. A. Gas chromatography and combined gas chromatography–mass spectrometry data for the saturated hydrocarbon extract fraction of two immature to early mature samples (PL-06-03 and PL-06-06) from the Vaca Muerta Fm at Picún Leufú, southern Neuquén Basin. The unimodal homology of *n*-alkanes in the gas chromatogram and the prominent cholestane peak in the *m/z* 217 mass fragmentogram are consistent with an origin from marine organic matter. B. Thermal extraction chromatograms (S1 Py-GC) of bitumen samples from Curacó Mine (locality C6, Figs. 4, 5 and 8, and Table 1). Bitumen in continuous veins contains little pyrolyseable material and produces single narrow peaks. Probably this bitumen reached higher temperatures than that in adjacent host rock or in clasts of calcite beef or of Vaca Muerta source rock. We infer two generations of bitumen, the first due to burial only and the second due to later heat advection during volcanic activity around Tromen.

locally they radiate outward from the volcanoes. Thicknesses of dykes tend to be greatest, where the host rocks are the most resistant to fracturing. Many of the dykes occur in the exhumed hanging walls of deep thrusts, especially at the foot of Tromen. Here the bitumen is in places of high grade (impsonite), whereas elsewhere it tends to be of medium grade (grahamite). A few bitumen dykes contain fragments of Vaca Muerta shale, so that we infer forceful expulsion of source rock. At Curacó Mine, bitumen within calcite veins (beef) is of low grade, whereas bitumen in the main dyke is of higher grade and formed later. Also near basement faults, some bitumen dykes have cap-rocks of hydrothermal calcrete. Other dykes or their wall rocks contain hydrothermal minerals. For the transport of heat, we argue that hydrothermal activity was probably more important than thermal conduction through solid rock. Finally, some dykes splay upward towards the current land surface, indicating recent intrusion.

We conclude that (1) bitumen veins in the provinces of northern Neuquén and southernmost Mendoza formed during volcanic activity in Pliocene–Pleistocene times, and that (2) heat advection by hydrothermal fluids generated oil, which intruded adjacent rocks and occupied various kinds of veins (especially dykes), before solidifying to bitumen, by loss of volatile elements. As source rocks for bitumen, we have good evidence for the Vaca Muerta Fm (especially in Domain C), but some evidence also for shale of the Agrio Fm.

Acknowledgements

Of the many people, who helped us during this long-lasting project, we are especially grateful to (1) Eberhardt Rupert Gessler Panten, whose father, Ernst, was manager of Curacó mine, (2) Nora Vázquez, of the Municipality of Buta Ranquil, (3) José Daniel González, of Ranquil Vega, and (4) María Laura Pardo Duró, of the SEGEMAR (Argentine Geological Survey) in Buenos Aires. Statoil provided funding for fieldwork in Argentina and geochemical analyses in Trondheim. The SEGEMAR made available to us a recent geological map (Fig. 2), as well as a collection of unpublished reports by state agencies (such as YCF).

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