XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos
Actas T° I (401-406)

TRABAJO 52

TECTONIC AND PORE-FLUID PRESSURE CONTROLS UPON THE FORMATION OF SOLID BITUMEN VEINS IN THE NEUQUEN BASIN, SOUTH-WEST ARGENTINA

[1]Carey, P.F., Parnell, J.
& [2]Prozzi, C.R.

[1]*School of Geosciences, The Queen's University of Belfast, BT7 1NN, U.K.*
[2]*Departamento de Geología, Universidad Nacional del Sur, Bahia Blanca, Argentina*

ABSTRACT. The Neuquén basin of south-west Argentina was, for most of its history, a back arc basin with a volcanic arc to its western side. The occurrence of solid bitumen veins in petroliferous basins is a well documented phenomenon. The Neuquén Basin has the largest concentration of such veins described from any basin, and these veins show a diversity of morphology, content and structural association uncommon in such a small region. The Neuquén Basin provides a unique opportunity to study the effects of overpressuring, compressional and extensional tectonics on the style of solid bitumen vein within a single basin. The veins have been classified into four main types, based on their structural associations, and in most cases there is evidence for elevated pore-fluid pressures in their mechanism of formation. These elevated pressures arose as a result of rapid burial and isolation of three rich source rocks in a region which periodically had high geothermal gradients. The consequent introduction of large quantities of hydrocarbons resulted in many of the features observed in the veins. The formation of bedding-plane parallel solid bitumen veins also enhanced the initiation of thrust faulting in the sequence. The combination of elevated pore-fluid pressures and low frictional resistance of the bitumen veins made them natural movement surfaces for the thrusts.

INTRODUCTION

Veins of solid bitumen have been described from many of the petroliferous regions of the world (Abraham, 1960). These veins contain the solid or semi-solid residues of migrating hydrocarbons. Perhaps the most widespread group of such bitumen veins is found in the Neuquén Basin of south-west Argentina. The veins occur in the foothills of the Argentinean Andes in a region exceeding 500km in length and 100km in width which parallels the axis of the Andes. The veins have been noted for their high sulphur content and an association with copper and vanadium. Bitumen (known locally as asphaltite) has been mined in the Neuquén Basin since the last century, mainly as a source of fuel, and some is still mined for this purpose although the mines are small and the production is limited. The locations of the mines are detailed in Figure 1. The bitumen has been used, in more recent times, in the preparation of wood stains, insulating varnishes, acid-resistant coatings, plastics, printing inks, roofing material, more recently as a drilling additive in the petroleum industry, and a variety of other products which make use of its particular chemical and physical properties.

STRUCTURAL HISTORY AND STRATIGRAPHY OF THE BASIN

The Neuquén Basin formed initially within an intra-arc setting during the early Triassic developing into a back-arc basin in the early Jurassic. Extension within the basin persisted from middle Triassic (230ma) to late Cretaceous (70ma, Uliana, Biddle & Cerdan 1989) causing subsidence and thickening of the sedimentary pile as a result of half-graben formation. The basin underwent vigorous extensional faulting and subsidence in the early Jurassic. This was followed by a marine transgression and the development of a late Liassic anoxic basin. A further phase of extension in the Cretaceous effectively followed trends established in the Jurassic.

Overprinting of many of the earlier extensional structures occurred during the compressive phases of the Andean orogeny. In the Late Cenozoic, the back-arc basins received up to 15km of immature sediment from the rising Andean mountain chain, resulting in rapid burial of the source rocks. The major phase of the orogeny, corresponding with the Laramide orogeny (80-40Ma) involved folding and thrusting of the rear-arc area. The folds and thrusts within the basin generally trend N-S and NE-SW and it is this structural fabric that appears to have exerted the greatest influence on the orientation and position of solid bitumen veins within the basin, as demonstrated in Figure 2. The solid bitumen veins generally parallel these structures, although in some regions local tectonics have had a stronger influence on vein formation, causing deviance from the general trend (e.g. La Escondida). Veins of solid bitumen formed within a variety of structures: tear faults on the limbs of folds (La Salvada), extensional faults (Mitre), thrust faults (Los Castaños), explosion breccias (Auquilco), and extension fractures on fold hinges (La Escondida), but the veins are linked by a common feature. In most veins, independent of formational mechanism, there appears to have been a component of elevated pore-fluid pressure associated with the injection of bitumen into the veins.

Figure 1: Location of the solid bitumen mines of the Neuquén Basin.

Figure 2

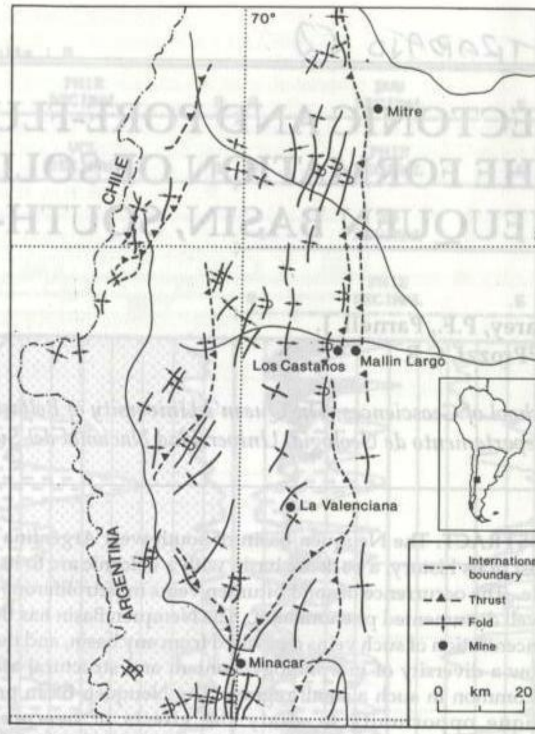

Figure 2: Current trends of compressional structures in the Mendoza region (after Méndez, Zanettini & Zappettini 1987).

The succession for the Neuquén Basin is summarised in Figure 3. Within the succession, there are three notable organic-rich horizons thought to source the oil fields of the region and, we believe, the solid bitumens. These are:

(a) the Lower Jurassic Los Molles Formation.
(b) the Lower Cretaceous Vaca Muerta Formation and
(c) the Lower Cretaceous Agrio Formation.

CHEMICAL ANALYSIS OF THE SHALES AND SOLID BITUMENS

The three shales were analysed for hydrogen and carbon contents and by Rock-Eval Pyrolysis. Two of the solid bitumens were examined by Nuclear Magnetic Resonance (NMR) spectroscopy. The results are summarised in Tables 1 and 2.

NMR spectroscopy shows the two bitumens from the La Valenciana and La Escondida veins to be quite different in their composition (Fig. 4). The La Valenciana bitumen contains considerably more carbon in aromatic compounds than the La Escondida bitumen. Both veins are believed to be sourced from the Vaca Muerta Formation. The increased maturity of the La Valenciana vein may reflect the influence of the thrusting event in this vein. Rock-Eval pyrolysis of the three shales reveals more information on the their quality as potential source rocks.

They all have moderately high hydrogen indices and very low oxygen indices.

Plotting these results on a Van Krevelen diagram (Fig. 5) demonstrates the Vaca Muerta and Agrio Formations to contain good quality kerogen (the shales plot in the range of type 1 kerogen).

The rate of deposition of the three shales in the region of the asphaltite veins was very rapid (stratigraphic sections prepared by Legarreta & Gulisano (1989)).

Rapid deposition could have facilitated the generation and migration of hydrocarbons early in the basin's development. The burial history of the shales was modelled using a Lopatin reconstruction after the method of Waples (1980) (Fig. 6). Hydrocarbon generation began as early as 110Ma (upper Lower Cretaceous) for the base of the Los Molles Formation and 70Ma (Upper Cretaceous) for the base of the Vaca Muerta Formation.

The chemical analysis of the three source rocks show them to be composed of good quality kerogen, and it is proposed that this resulted in the introduction of large quantities of liquid hydrocarbons into the succession before the end of the Cretaceous period, producing the solid bitumens now found in the mines.

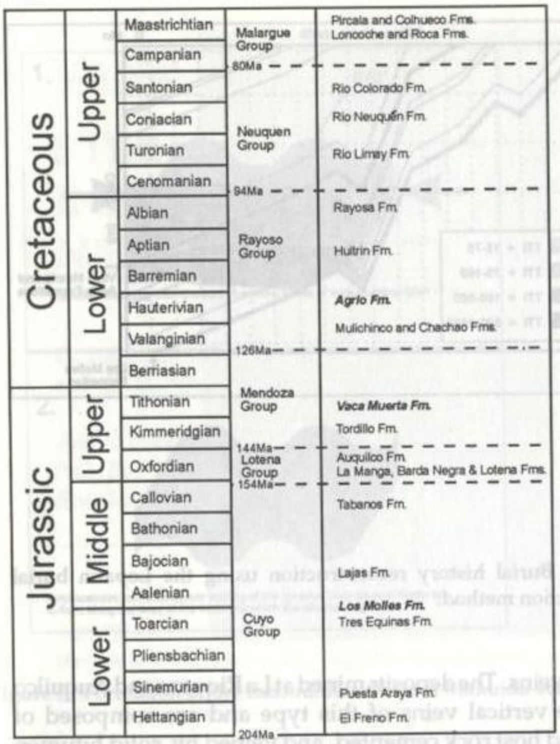

Figure 3: Stratigraphic succession for the Neuquén Basin (adapted from Legarreta & Gulisano 1989).

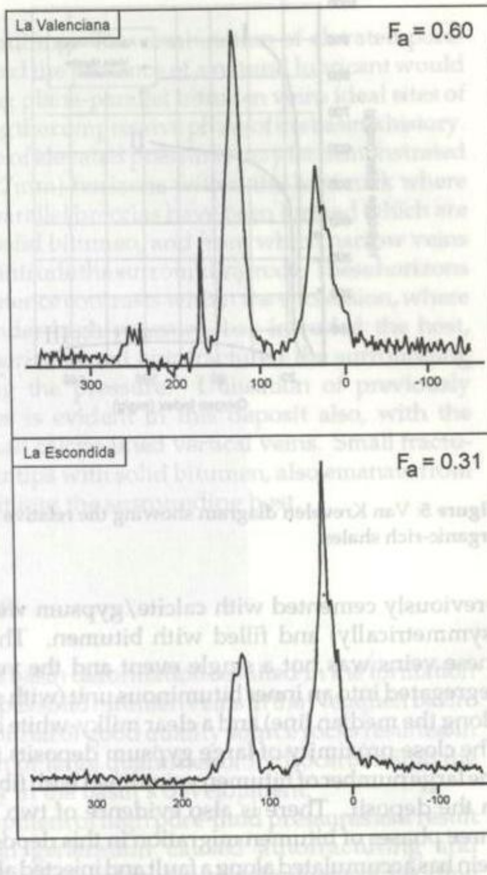

Figure 4: NMR spectra for two solid bitumens from the Neuquén Basin. The more mature spectrum for the La Valenciana bitumen may reflect the effects of thrusting.

STYLES OF FRACTURE FORMATION AND THE IMPLICATION OF ELEVATED PORE-FLUID PRESSURES AT THE TIME OF BITUMEN EMPLACEMENT

The bitumen veins of the Neuquén Basin can be classified into four main groups on the basis of their formational mechanisms and relationship with basinal structures (Table 3). The fractures which host the solid bitumens of the Neuquén Basin show a diversity of structure, composition and formational mechanism rarely encountered in the bitumen veins of other petroliferous basins. Veins of types 2-4 show evidence of having been formed during a period of elevated pore-fluid pressure within the succession.

Type 1 Veins

The majority of veins in this classification can be directly attributed to the phase of igneous activity resulting in the emplacement of the Andean plutons of the region. In the Chos Malal area it is possible to see that the two main veins (La Escondida (Fig. 1) and nearby Auca Mahuida), which were produced by thermal relaxation after emplacement of the Auca Mahuida pluton, formed parallel to the crests of a series of anticlines which were produced by a local thrust from the north. The veins trend 070° and bedding dips away perpendicularly from the veins in both directions (Fig. 7). The dominant easterly thrusting of the region as a whole is less pronounced in the vicinity of these veins.

Type 2 Veins

The best example of a Type 2 vein is that at La Valenciana. The La Valenciana solid bitumen accumulated in a shallow syncline between two anticlines. The hydrocarbon migrated along a normal fault into its present position and field evidence suggests that the fault was active during the bitumen accumulation process (the bitumen thickens dramatically towards the fault and the fault does not continue into the succeeding beds). The emplacement of the bitumen was a high-pressure process. The floor of the deposit was heavily faulted and large amounts of host rock were incorporated into the vein as the bitumen migrated. Also, bitumen was injected into hydraulically-formed fractures along bedding planes. These fractures are devoid of any other minerals and fracture bridges have not been identified. The fractures have been filled to their tips with solid bitumen. The migrating bitumen also utilised previously existing fractures and veins

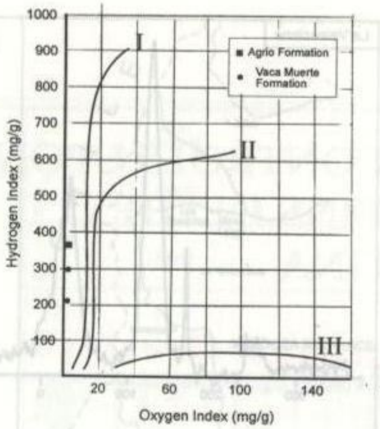

Figure 5: Van Krevelen diagram showing the relative positions of the organic-rich shales.

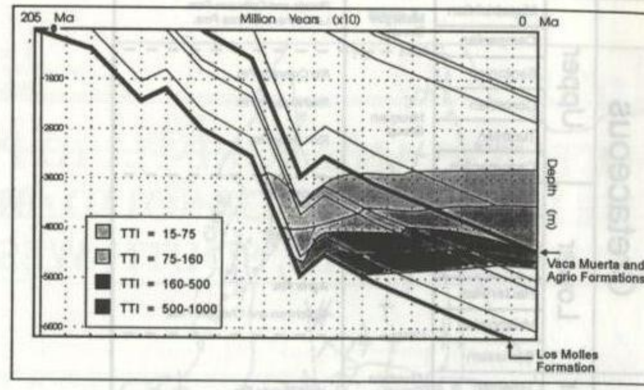

Figure 6: Burial history reconstruction using the Lopatin burial reconstruction method.

previously cemented with calcite/gypsum were re-opened (symmetrically) and filled with bitumen. The opening of these veins was not a single event and the veins are often segregated into an inner bituminous unit (with solid bitumen along the median line) and a clear milky-white outer margin. The close proximity of large gypsum deposits is reflected in the large number of bitumen veins lined with fibrous gypsum in the deposit. There is also evidence of two and possibly three phases of bitumen migration in this deposit. The main vein has accumulated along a fault and injected along bedding. Secondary vertical veins comprising bitumen with calcite lining cut the bedding-parallel veins and offset them, indicating a later migration event.

The presence of more than one generation of veins, particularly late-stage vertical veins offsetting earlier bedding-parallel veins, is common throughout most of the Argentine deposits and reflects the ongoing deformation of the basin.

Another feature of bitumen-filled fault planes in the basin is the development of zones of bitumen impregnation in the host rocks either side of the faults. The mine at Mitre shows the most pronounced development of this feature. The bitumen migrated along a normal fault plane through these beds, and impregnated the sandstones either side of the vein. The host rocks at Mitre are the Upper Cretaceous Diamantiano continental beds. These show considerable grain size variation in the vicinity of the deposit, varying from a medium-grained sandstone to a clast-supported conglomerate. The depth of the impregnation zone is largely dependent on the grain size of the host rock and where this increases, so too does the depth of impregnation. This impregnation zones are similar to those described in association with the gilsonite veins of the Uinta Basin, Utah, where its formation has been attributed to the injection of a semi-liquid hydrocarbon under pressure (Monson & Parnell, 1992).

Type 3 Veins

Type 3 veins show the clearest evidence for the elevated pressures present during formation of the Argentine solid bitumen veins. The deposits mined at La Riqueza and Auquilco are large vertical veins of this type and are composed of brecciated host rock cemented, and veined by, solid bitumen (Fig. 8). The suspension of large blocks of host rock in the bitumen suggests that these veins were initially filled with a very viscous hydrocarbon. The breccia clasts have not been transported any great distance, nor have they been rotated to any great degree. Bitumen veinlets extend from the matrix into the clasts, further brecciating them. The bitumen must have been under considerable pressure to have brecciated the host rock in this manner. The process was a very rapid one. If it had not been rapid, the host rock fragments would have collapsed to the base of the vein before the bitumen solidified.

Type 4 Veins

The final group of veins are those which have a very shallow dip or are parallel to bedding. The best examples of these veins are found at Mina Los Castaños. The main vein at Los Castaños is much larger than the bedding plane-parallel veins identified at La Valenciana but shows many features in common with them. The vein is conformable with the underlying sediments and has been broken by numerous thrust planes, often highlighted by the displacement of fibrous gypsum veins which approximately parallel bedding in the deposit (Fig. 9). The deposit also contains slabs of host rock, heavily slickensided by the thrusting event. These slickenfibres are composed of solid bitumen with or without gypsum/calcite, showing the bitumen to have been closely associated with the thrusting process. The main body of bitumen is also heavily slickensided along planes parallel to bedding, showing an easterly movement in concordance with the major thrusts nearby.

The deposit also has a second generation of calcite-lined solid bitumen fractures which cut the bedding plane-parallel veins at steep angles. Injection of bitumen across bedding into the host rock can be seen at the base of the deposit. The vein

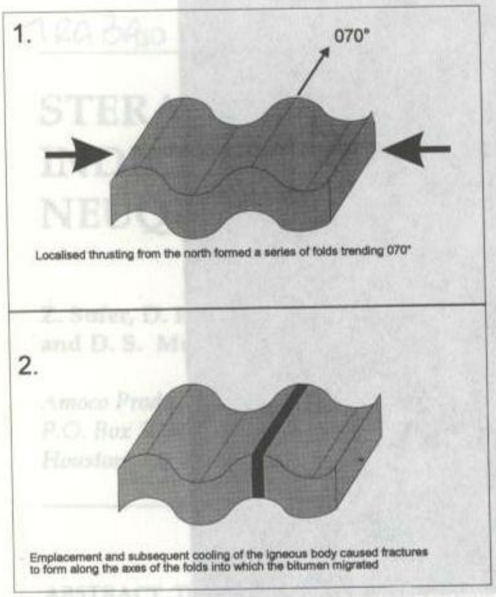

Figure 7: Formation of the Escondida and Auca Mahuida veins.

is lined for much of its length with fibrous gypsum, which is itself bituminous. This veining event preceded the thrusting of the deposit since the gypsum veins are also faulted. Gypsum veining of the deposit is a common feature of the low angle veins. The presence of these bedding plane-parallel veins of solid bitumen is indicative of elevated pore-fluid pressures. The opening of these fractures and maintenance of a space into which the bitumen could migrate would require fluid pressures in excess of overburden pressure, since no evidence for any fracture-bridging minerals have been identified. These elevated pore-fluid pressures would also have facilitated the onset of thrust faulting. The combination of elevated pore-fluid pressures and the presence of a natural lubricant would make the bedding plane-parallel bitumen veins ideal sites of movement during the compressive phase of the basin's history. Further evidence of elevated pressures may be demonstrated along narrow (<7mm) horizons within the host rock where bedding plane-parallel breccias have been formed which are cemented with solid bitumen, and from which narrow veins of solid bitumen intrude the surrounding rock. These horizons represent competence contrasts within the succession, where the bitumen, under high pressure, has intruded the host, brecciated the horizons and autofractured the surrounding matrix, releasing the pressure. Utilisation of previously formed fractures is evident in this deposit also, with the formation of small calcite-lined vertical veins. Small fractures, filled to their tips with solid bitumen, also emanate from the main deposit into the surrounding host.

CONCLUSIONS

1. Progressive basin deformation resulted in the formation of a variety of types solid bitumen veins in the Neuquén Basin.

2. The rapid burial of good quality source rocks resulted in the introduction of large quantities of hydrocarbon into the succession early in the basin's development.

3. The development of high pore-fluid pressures as a result of hydrocarbon generation caused autofracturing and brecciation of the succession, the development of bedding plane-parallel veins of bitumen, and enhanced the onset of thrust fault development.

4. The presence of solid bitumens in bedding plane-parallel veins offered planes of low frictional resistance to the thrusts and deformation and movement was preferentially concentrated on these planes during the thrusting event.

Figure 8: Explosion breccia at Mina Auquilco. The host rock fragments can be seen to approximately parallel the walls of the fracture. They have not fallen any great distance in the vein.

Figure 9: Thrusting of the Los Castaños deposit highlighted by displacement of the gypsiferous veins which are present in the solid bitumen vein.

Mine	%C	%H	Atomic H/C
Mitre	83.25	7.64	1.10
Valenciana (brittle)	52.02	2.58	0.67
Valenciana (oil)	57.54	6.70	1.40
Minacar	86.17	7.23	1.01
Cablé Beta Norte	83.78	7.14	1.02
La Argentina	83.09	4.56	0.66
Auca Mahuida*	82.42	8.58	1.24
La Escondida*	83.45	8.24	1.18

Table 1: H/C ratios for some of the Neuquén Basin bitumens (*data from Fester & Cruellas 1943).

Locality (unit)	TOC (%)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Production Index	Hydrogen Index	Oxygen Index	Tmax (°C)
La Primavera (Los Molles)	1.7	0.26	0.12	0.18	0.68	0.71	10.6	382
La Valenciana (V. Muerta)	7.57	1.39	15.17	0.19	0.08	200.4	2.5	452
Los Castaños (V. Muerta)	14.2	1.94	41.87	0.31	0.04	294.9	2.2	450
San Eduardo (Agrio)	9.57	0.26	34.7	0.28	0.01	362.6	2.9	450

Table 2: Rock-Eval pyrolysis results for the Neuquén Basin organic-rich shales.

Type 1	Veins injected around major intrusions (Chos Malal region) whose formation is related to the period of thermal contraction following the intrusion process.
Type 2	Veins formed along Andean fold crests/troughs and in extensional faults.
Type 3	Veins composed of bitumen-cemented breccias, formed as a result of explosive injection of a hydrocarbon fluid into the sequence.
Type 4	Low-angle and bedding plane-parallel veins, representing bedding plane-parallel movement horizons and horizons of abnormal pore-fluid pressures.

Table 3: Classification of the Argentine solid bitumen veins on the basis of their structural associations.

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