

## **SUCCESSFUL PALEOMAGNETIC AZIMUTHAL ORIENTATION OF DRILL CORES FROM A HYDROCARBON SOURCE ROCK RESERVOIR: THE CASE OF THE VACA MUERTA FORMATION, NEUQUEN BASIN, ARGENTINA**

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### **ABSTRACT**

The Tithonian-Berriasian thick bituminous shale and marls of the Vaca Muerta Formation have become in recent years a major objective of intense research for hydrocarbon exploration and production purposes. This may represent one of the world largest unconventional hydrocarbons reservoirs. A paleomagnetic study was carried out on 193 m of drill cores from the lower and upper levels of this formation in order to determine the feasibility of an alternative orientation method of rock cores. One hundred and thirty two standard specimens from 31 samples of eight drill cores were submitted to detailed stepwise alternating field demagnetization revealing the presence of a very well defined and consistent characteristic remanent magnetization in most samples. This allowed the precise orientation of all recovered cores as well as determining the presence of intra-core relative rotations. Considering the lithological homogeneity of the Vaca Muerta Formation and the success of the paleomagnetic orientation in all cores, a standard approach using this technique in this unit is recommended. Trial of this precise and low-cost methodology in other source rock reservoirs is encouraged.

**Keywords:** Paleomagnetic orientation, drill cores, Vaca Muerta Formation, Neuquina Basin, Unconventional reservoirs

### **RESUMEN**

La espesa sucesión titoniana-berriasiana de pelitas y margas bituminosas de la Formación Vaca Muerta se ha transformado en años recientes en un objetivo principal de investigación intensa en relación a la exploración y explotación de hidrocarburos, pues puede representar uno de los yacimientos de hidrocarburos no convencionales más grandes a nivel mundial. Se llevó a cabo un estudio paleomagnético sobre coronas de pozo de los niveles superiores e inferiores de la Formación Vaca Muerta que abarcan un total de 193 metros. El objetivo de este estudio fue determinar la factibilidad de utilizar la remanencia magnética como método alternativo de orientación acimutal de las coronas. Ciento treinta y dos especímenes estándar correspondientes a 31 muestras de 8 coronas fueron sometidos a una detallada desmagnetización escalonada por campos magnéticos alternos. Este procedimiento reveló la presencia de una magnetización remanente característica consistente y muy bien definida en la mayoría de las muestras. Esto permitió la orientación precisa de todas las coronas recuperadas así como determinar la presencia de rotaciones relativas dentro de las mismas. Considerando la homogeneidad litológica de la Formación Vaca Muerta, y el éxito de la orientación paleomagnética en todas las coronas, se recomienda el uso rutinario de esta técnica en las coronas de esta unidad. Se alienta el ensayo de esta metodología económica y precisa en otros reservorios de roca madre.

**Palabras clave:** Orientación paleomagnética, testigos corona, Formación Vaca Muerta, Cuenca Neuquina, Reservorios no convencionales



## Introduction

Precise orientation of drill cores is often of great interest in exploration and development of hydrocarbon reservoirs, in particular, for structural, sedimentological and geomechanical investigations. Unconventional reservoirs (*i.e.*, shale-gas, shale-oil, tight-sands, etc) have become a major focus of exploration in the last decade. For most of these reservoirs, production is followed after sophisticated exploitation methodologies for which spatial anisotropies of different physical properties are crucial.

There are three known methods for orientation of drill cores. Two of them comprise either using special drill tools (*i.e.*, Hailwood and Ding, 1995) or by matching features of the drill hole as seen in photographs with those in the recovered cores. The third is accomplished by using the remanent magnetization of the drilled rocks which tend to carry a remanence parallel to the paleomagnetic field of the Earth at time of its acquisition (Butler, 1992). This method can either be used in cores not oriented during drilling or as a checking system of proper orientation by the other methods. In any case, the paleomagnetic method has the advantage of its economy and precision, being its major setback the dependence of its successful use on the remanence characteristics of the drilled rocks, which are normally unknown in advance.

Another problem of the paleomagnetic re-orientation method is the possibility of the cores to acquire a drilling induced remanent magnetization parallel to the core axis which may obscure or even obliterate the original remanence (*e.g.* Burmester, 1977; Jackson and Van der Voo, 1985, Shi and Tarling, 1995).

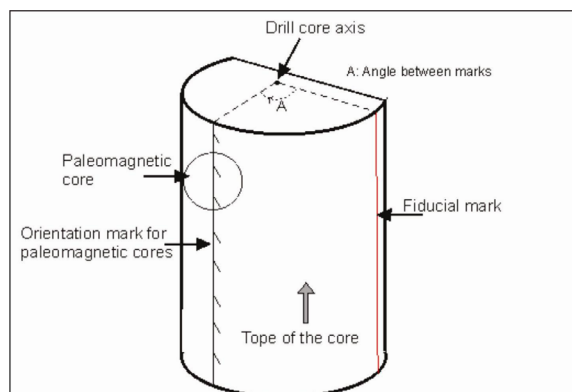
These problems have conspired against adopting this methodology as a standard practice in the hydrocarbon industry despite being a very precise and economic procedure.

The Tithonian-Berriasian thick bituminous shale and marls of the Vaca Muerta Formation are the major source rocks of hydrocarbons in the Neuquen Basin of Argentina (Hogg, 1993; Urien and Zambrano, 1994; Cruz *et al.*, 2002). They have become in recent years a major objective of intense research with hydrocarbon exploration and production purposes, as it may represent one of the world largest unconventional hydrocarbons reservoirs. Considering the importance that detailed geomechanic and structural studies have in production strategies in this kind of reservoirs, precise and unambiguous azimuthal orientation of drill cores appears as of high relevance.

In order to test the feasibility of the paleomagnetic re-orientation method in these rocks, a paleomagnetic study was carried out on 193 m of drill cores of the Vaca Muerta Formation from a well in the Neuquen Basin.

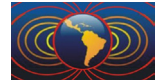
## Paleomagnetic Results

Eight drill cores of the Vaca Muerta Formation, with variable lengths between 7 and 27 meters, were submitted to the paleomagnetic re-orientation study. Cores were recovered from a vertical well and were distributed on two stratigraphic sections of the formation. Cores 1 and 2 correspond to the upper level of 55 meters, while cores 3 to 8 correspond to the lower section of 137 meters. The total thickness of the formation in this well is over 340 meters.



Core 2 comprises a 5 meter thick andesitic sill of Tertiary age that intrudes the Vaca Muerta Formation subhorizontally. The sedimentary rocks are subhorizontal. Thirty-one samples (core fragments) were selected from all cores (two to five per core). Sixty-six one-inch diameter cores were drilled in the laboratory (fig. 1) out of those samples (generally two per sample). These were subsequently sliced into 2.2 cm high standard paleomagnetic specimens.

**Figure 1.** Sketch showing the procedure of paleomagnetic sampling of drill cores of the Vaca Muerta Formation and orientation systems.

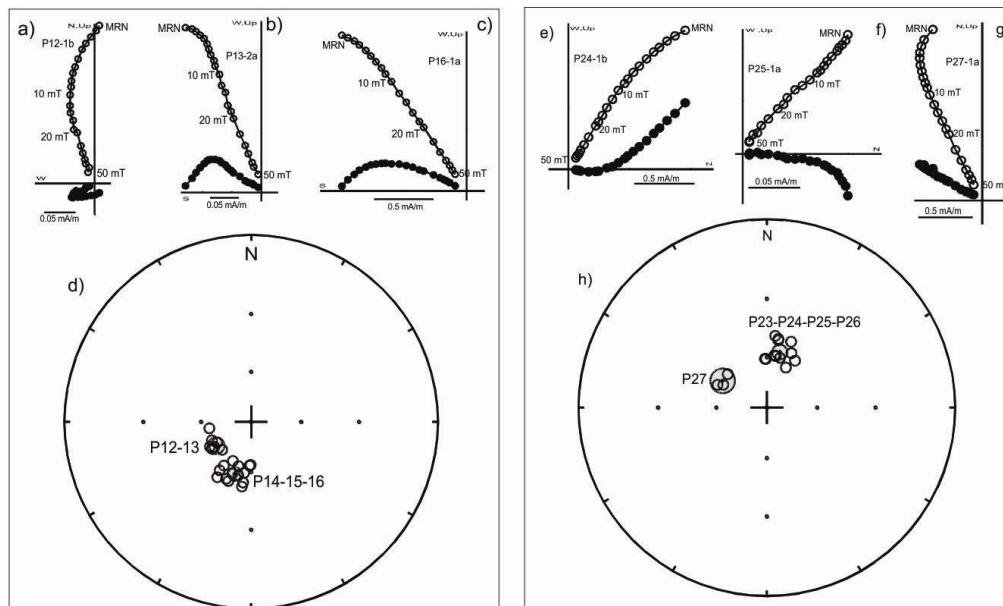


A total of 132 specimens were submitted to detailed alternating field demagnetization. In order to determine the presence of a recent viscous magnetization that may be used as an alternative or complementary direction for core re-orientation a very detailed stepwise demagnetization was performed. Steps of one mT were followed from 1 mT up to 10 mT, followed by steps of 2 mT up to 20 mT and of 5 mT from 20 to 50 mT. In some specimens, demagnetization continued up to 70 or even 100 mT.

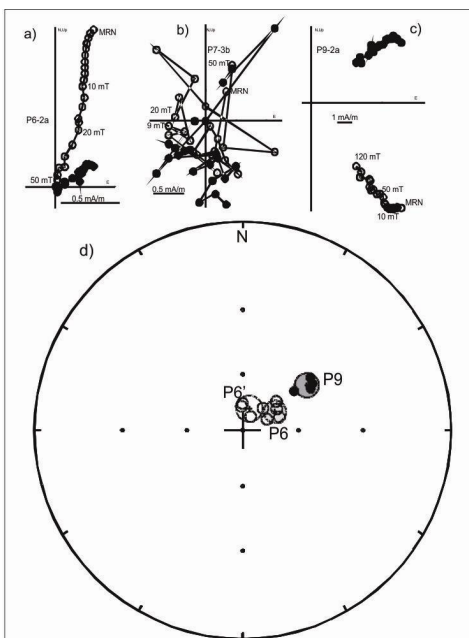
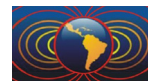
Twenty-seven out of 31 samples showed high magnetic stability and consistent characteristic remanent magnetization (ChRM). In most cases the ChRM was determined at fields higher than 10 mT. In many cases, as well, a viscous magnetic component was found at very low magnetic fields ( $\leq 5$  mT).

Figure 2 shows paleomagnetic results obtained for cores 4 and 7. They are representative of most samples. This is consistent with the apparent lithological homogeneity of the Vaca Muerta Formation represented in the cores. As shown in Figure 2 and Table 1, ChRM determined by principal component analysis (PCA; Kirschvink, 1980) showed high within sample consistency and in many cases among several consecutive samples. A good example is presented in Figure 2d. As shown there, specimens from samples P12 and P13 show high directional consistency and permit to obtain a single mean ChRM, while samples P14, P15 and P16 show a significantly different mean direction also with high consistency. This clearly indicates that the upper part of the core, represented by P12 and P13 rotated as a whole relative to the lower part, represented by the other three samples. This allows independent azimuthal reorientation of both sections. Inclinations values for most samples were comprised between  $55^\circ$  and  $65^\circ$  (only exceptions P1:  $-49.5^\circ$  and P6:  $-69.8^\circ$ ). A dominant normal polarity (negative inclinations) was observed in samples from the Vaca Muerta Fm., with the exception of samples P21 and P28 that showed antipodal directions to those of neighbouring samples. At low magnetic fields, a viscous (generally random) or drilling-induced (higher inclinations) secondary remanences could be isolated in many samples.

Significantly different paleomagnetic behaviour was observed in the Miocene andesitic sill (fig. 3), which showed either unstable or very low inclination remanences. Sample P9 was collected immediately close to



**Figure 2.** a), b), c) Zijderveld diagrams showing AF demagnetization of specimens from samples of core 4; d) equal area stereographic projection of characteristic remanent directions and their means from specimens of samples 12 and 13 and 14, 15 and 16 from core 4. Note significant rotation between both sections of the core (P12-P13 and P14-P15-P16). Grey circle indicates mean remanence direction for each subgroup of samples and their a95. e), f), g) idem a), b) and c) for specimens of core 7; h) idem d) for core 7. Note that in this case only the basal section of the core (P27) is rotated relative to the rest of the core. In all cases declination values are in core coordinates.



**Figure 3.** Idem Figure 2 for core N. 2. Sample 6 produced two different remanent magnetizations (P6 correspond to the ChRM used for orientation of the sample; P6' is a secondary magnetization suspected to be or to be affected by drilling induced remanence). P9 correspond to a sample immediately below a volcanic sill, note the opposite polarity and higher coercivities.

the lower contact of the 5 meter thick sill and consists of massive dark shales with apparent signatures of baking by the intrusion. These rocks presented a well defined and consistent magnetic remanence (of reverse polarity) but with significantly higher coercivities.

Although detailed rock-magnetic characterization of the Vaca Muerta reservoir rocks is still under way, median destructive fields of natural remanent magnetizations suggest a dominant ferrimagnetic carrier for the ChRM. Whether this mineral is of detrital or early diagenetic origin or it was produced during Late Cretaceous hydrocarbon generation phase (Veiga *et al.*, 2001; Cruz *et al.*, 2002) is under investigation. In any case, different magnetic behaviour shown by samples close to the Miocene volcanic sill indicates that ChRM is pre-Miocene.

Considering the possibility of a primary magnetization for the Vaca Muerta Formation, and mean inclination values for all samples and core sections consistent with expected paleomagnetic inclinations for the well locality at the Jurassic- Cretaceous boundary, all cores (or core-sections) were re-oriented by comparing the ChRM mean directions with that expected from the 140 Ma mean paleomagnetic pole for South America (Besse and Courtillot, 2002). Only exception was sample P9, undoubtedly affected by the Miocene sill intrusion (Fig.3 c, d). In that case, assuming a secondary remanence of that age for this sample, the reference paleomagnetic pole was that of 20 Ma (Besse and Courtillot, 2002).

## Conclusions

A paleomagnetic study performed on samples from eight drill cores of the Vaca Muerta Formation obtained from a single drill in the Neuquen Basin permitted the independent azimuthal orientation of each core as most samples were carrier of a well defined and consistent characteristic remanence magnetization that could be defined by AF stepwise demagnetization. Detailed rock magnetic studies are under way to characterize the remanence carriers and to determine the origin and age of the magnetic mineralogy. Effects of a Miocene intrusion in the remanence of the formation indicate that the ChRM is pre-Miocene. Homogeneous magnetic behaviour and directional consistency suggest that this core re-orientation method should be used in a standard way in cores from this formation and encourage paleomagnetic research in other source-rock reservoirs.



Core	Sample	Azimuthal Orientation (°)	95% confidence limits (°)
1	P1	330.6	10.6
	P2	147.5	11.5
	P3	230.4	15.0
	P4	150.4	17.8
2	P6	80.3	15.1
	P9	240.7	7.6
3	P10	77.2	7.2
	P11	59.8	9.3
4	P12-13	256.6	10.9
	P14-15-16	217.3	8.3
5	P17-18	75.2	12.3
6	P20-21-22	42.6	11.8
7	P23-24-25-26	33.2	8.5
	P27	321.0	11.2

**Table 1.** Values of Azimuthal orientation and confidence limits determined for each core of the Vaca Muerta Formation

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