Distinguishing the effect of diapir growth on magnetic fabrics of syn-diapiric overburden rocks: Basque–Cantabrian basin, Northern Spain

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Abstract
An analysis of Anisotropy of Magnetic Susceptibility was done on Aptian–Albian sediments from the Basque–Cantabrian basin. Samples were collected from 39 sites in the halokinetic sequences of the Bakio, Bermeo, Guernica and Mungia diapirs; 28 sites were sampled close to diapirs, and 11 sites were far from the diapir edges. The magnetic foliation is parallel to bedding, suggesting it reflects depositional and compaction processes, whereas the orientation of magnetic lineation varies. Far from the diapir edges, the magnetic lineation is interpreted as being related to the regional Pyrenean compression. Close to diapir edges, the observed behaviour shows that diapirs, predominantly formed by rigid ophites, have acted as buttresses, with shadow areas at their northern faces being protected from the Pyrenean compression. The high sensitivity of AMS makes it a very useful tool to distinguish deformation in halokinetic sequences related to diapir growth from that related to subsequent compression.

1 | INTRODUCTION

The full characterisation of strata adjacent to salt structures is fundamental in the exploration and exploitation of geologic reservoirs; however, they often appear hidden in seismic lines, and good outcrop examples are scarce. Deformation studies in these strata have been mostly based on the analysis of mesoscale structures from outcrop examples (e.g., Alsop, Weinberger, Levi, & Marco, 2015, 2016; Giles & Rowan, 2012; Hearon et al., 2015; Poprawski et al., 2014; Rowan, Jackson, & Trudgill, 1999; Rowan, Lawton, Giles, & Ratliff, 2003). In this work, we propose the use of Anisotropy of Magnetic Susceptibility (AMS) to analyse the deformation of salt-related synkinematic strata. This use is important because it can give information even in the absence of strain markers and/or poorly developed mesoscale brittle structures. It can also be applied to subsurface diapirs, as AMS data can be reoriented to geographical coordinates using palaeomagnetic data.

Anisotropy of Magnetic Susceptibility represents a powerful tool for geologists, as it gives information related to the petrofabric of rocks. In structural studies, it is a recognised indicator of deformation (e.g., Hrouda, 1982), even in very subtly deformed rocks that lack strain markers (e.g., Kissel, Barrier, Laj, & Lee, 1986). When applied to salt tectonics, AMS data obtained from rocks outcropping in the interior of salt structures can give information on diapirc flow or internal deformation (Santolaria, Casas, & Soto, 2015; Smid, Schultmann, & Hrouda, 2001; Soto et al., 2014). We have selected several diapirs in the Basque–Cantabrian basin, which display well-exposed halokinetic sequences and suitable rocks for AMS analysis, to study the power of this approach in such geological settings.

2 | GEOLOGICAL SETTING

The study area is located in the northern margin of the Basque–Cantabrian basin, nowadays part of the southern Eurasian plate (Figure 1). The Basque–Cantabrian basin developed during Mesozoic Pyrenean rifting associated with the opening of the North Atlantic Ocean and Bay of Biscay (Garcia-Mondejar, 1996). From the Late Cretaceous, the African plate began to drift northwards, leading to convergence between Iberia and Europe and the inversion of the Basque–Cantabrian basin in the context of the Pyrenean orogeny (Gómez, Vergés, & Riaza, 2002; Figure 1).
The study area is characterised by Triassic to Cenomanian rocks deformed by a large WNW–ESE fold locally pierced by several salt diapirs (Bakio, Bermeo, Guernica and Mungia diapirs) (Cuevas & Tubia, 1985; Figures 1 and 2). These diapirs are composed of Triassic evaporites, red clays and basic subvolcanic rocks (ophites) and flanked by Jurassic to Cretaceous materials. The ophites comprise their caprock and, due to their high resistance to erosion, dominate the outcrops (Figure 2). They are flanked by Aptian–Albian syn-diapiric rocks organised in sequences limited by angular unconformities, becoming conformable as distance to the diapir edges increases. These sequences are characterised by lateral facies variations and mass-transported deposits created at the diapir roofs, typical of halokinetic hooks and wedges triggered by diapir growth (Ferrer et al., 2014; Poprawski, Basile, Jaillard, Gaudin, & López, 2016; Roca et al., 2016).

The geometry of these halokinetic sequences was not modified during the subsequent Pyrenean compression, with the exception of the NNW–SSE folds located to the south of the Bakio diapir and a slight E–W folding to the west of the Bermeo diapir (Figure 2). The Pyrenean compression inverted the northern part of the Basque–Cantabrian basin by means of north-directed thrusts that propagated from south to north and the development of a cleavage mostly oriented E–W to ENE–WSW in the study area (e.g., Gómez et al., 2002; for example Figure 3, site BK01). Locally, as in site BK03, cleavage, faults and tension gashes are associated with syn-diapiric layer-parallel slip of a thick bed of breccias with an irregular base above marls, which occurred during syn-diapiric drape folding (Figure 3).

### 3 | SAMPLING AND LABORATORY ANALYSIS

Samples from 39 sites (6–12 cores per site) of Aptian–Albian marls, marly limestones, fine sandstones and lutites were analysed by means of low-field AMS measured at room temperature. All samples were collected from halokinetic sequences related to the Bakio, Bermeo, Guernica and Mungia diapirs (Figure 2). Twenty-eight sites were close to diapir edges (sites located less than 1 km from the diapir walls, except sites BK15 and BK59, which were situated between two diapirs, were further from their walls, and were considered to be related to the Bermeo diapir), and 11 were far from diapirs (Table 1). The AMS analysis was done using a KLY3 (AGICO) from Zaragoza’s University. Data were processed using Anisoft 4.2 (Chadima & Jelinek, 2009) to obtain the directional and tensor data (where $K_{max}$, $K_{int}$ and $K_{min}$ are the maximum, intermediate and minimum principal axes of the magnetic ellipsoid, respectively) and the parameters defined by Jelinek (1981), the corrected anisotropy
Additionally, three types of experiments were performed to characterise the ferromagnetic (s.l.) minerals: (1) thermal demagnetisation of the natural remanent magnetisation (NRM) of all samples using the thermal demagnetisers TSD-1 (Schenstedt) and MMTD-80 (Magnetic Measurements) and a superconducting rock magnetometer SRM 755R (2G), (2) isothermal remanent magnetisation (IRM) acquisition up to 1 T and three-axis IRM (in fields of 1.2, 0.3 and 0.1 T) thermal demagnetisation as in Lowrie (1990) using an IM10-30 pulse magnetiser (ASC Scientific Carlsbad, CA, USA), a TSD-1 thermal demagnetiser and a magnetometer JR6A (AGICO Brno, Czech Republic), all measured in the Paleomagnetic Laboratory of Barcelona (CCiTUB-CSIC), and (3) K–T curves of selected samples using a KLY3.

4 | RESULTS

4.1 | Magnetic properties and ferromagnetic (s.l.) mineralogy

The bulk magnetic susceptibility (Km) of the studied rocks ranges from 50 to 412 × 10⁻⁶ SI (Table 1). Most magnetic ellipsoids are oblate, and the corrected anisotropy degree Pj is low (Pj ≤ 1.1), typical of weakly deformed sediments. A significant correlation between Pj and lithology is observed, with variable Pj values in a wider range.
| Site          | Age                        | Lithology                  | n  | Km  | SD  | Pj  | SD  | T   | SD     | D/I (K_{max}) | E11.1 (e12/e13) | D/I (K_{max}) corrected | SO (D/D) |
|--------------|----------------------------|----------------------------|----|-----|-----|-----|-----|-----|--------|---------------|-----------------|----------------------|-----------|
|              | CLOSE to Bakio diapir edges|                            |    |     |     |     |     |     |        |               |                 |                      |           |
| BK-09        | Aptian-Lower Albian        | Marls                      | 10 | 310 | 77.1| 1.015| 0.004| 0.293| 0.142  | 062/28        | 19.9/5.4        | 085/4                | 146/70    |
| BK-27        | Aptian-Lower Albian        | Marls                      | 10 | 222 | 50.3| 1.048| 0.010| 0.354| 0.222  | 282/79        | 7.7/5.1         | 135/21                | 322/103   |
| BK-54        | Aptian-Lower Albian        | Fine sandstones            | 10 | 14.5| 4.28 | 1.026| 0.016| 0.757| 0.363  | 334/60        | 46.8/6.8        | 159/9                 | 343/69    |
| BK-01        | Lower Albian               | Lutites/fine sandstones    | 6  | 391 | 31.6| 1.009| 0.003| 0.410| 0.490  | 350/45        | 51.2/8.6        | 166/10                | 336/56    |
| BK-03        | Lower Albian               | Marls/fine sandstones      | 10 | 308 | 125 | 1.018| 0.010| –0.272| 0.392  | 094/47        | 9.1/6.0         | 275/59                | 100/128   |
| BK-12        | Lower Albian               | Marls/fine sandstones      | 11 | 63.4| 22.7| 1.061| 0.055| 0.483| 0.260  | 014/9         | 22.0/6.3        | 018/1                 | 096/46    |
| BK-50        | Lower Albian               | Marls                      | 10 | 285 | 15.8| 1.023| 0.007| 0.296| 0.137  | 016/21        | 4.5/2.9         | 019/1                 | 062/28    |
| BK-51        | Lower Albian               | Marls                      | 10 | 308 | 37.3| 1.018| 0.006| 0.383| 0.161  | 034/43        | 8.9/5.8         | 194/0                 | 336/61    |
| BK-55        | Lower Albian               | Marls                      | 9  | 43.3| 10.2| 1.016| 0.008| 0.793| 0.244  | 066/20        | 50.6/12.0       | 024/47                | 292/60    |
| BK-62        | Lower Albian               | Marls                      | 10 | 362 | 41.8| 1.012| 0.005| 0.262| 0.212  | 018/50        | 15.7/10.3       | 354/4                 | 240/62    |
| BK-08        | Middle–Upper Albian        | Marls                      | 12 | 54.0| 14.0| 1.036| 0.011| 0.648| 0.188  | 266/7         | 14.0/4.9        | 088/2                 | 348/56    |
| BK-11        | Middle–Upper Albian        | Marls                      | 11 | 56.9| 10.6| 1.080| 0.009| 0.812| 0.115  | 061/36        | 19.3/6.8        | 084/1                 | 134/66    |
| BK-13        | Middle–Upper Albian        | Fine sandstones            | 8  | 51.0| 14.1| 1.041| 0.012| 0.813| 0.153  | 215/0         | 9.7/6.6         | 038/8                 | 136/46    |
| BK-14        | Middle–Upper Albian        | Fine sandstones            | 12 | 87.2| 23.3| 1.072| 0.047| 0.623| 0.270  | 29/12         | 13.1/4.7        | 031/3                 | 098/23    |
| BK-17        | Middle–Upper Albian        | Marls                      | 12 | 55.1| 16.4| 1.067| 0.024| 0.762| 0.070  | 037/9         | 9.9/5.9         | 217/7                 | 088/25    |
| BK-56        | Middle–Upper Albian        | Marls                      | 8  | 40.9| 7.59| 1.055| 0.019| 0.680| 0.165  | 076/29        | 8.6/5.1         | 268/4                 | 140/58    |
| BK-04        | Upper Albian               | Marls                      | 7  | 188 | 17.5| 1.100| 0.030| 0.815| 0.074  | 039/16        | 25.6/15.8       | 222/1                 | 093/27    |
|              | CLOSE to Bermeo diapir edges|                            |    |     |     |     |     |     |        |               |                 |                      |           |
| BK-15        | Aptian–Lower Albian        | Marls, marly limestones    | 11 | 396 | 20.6| 1.009| 0.003| 0.007| 0.455  | 352/43        | 34.0/11.6       | 189/14                | 046/75    |
| BK-16        | Aptian–Lower Albian        | Marls                      | 6  | 234 | 25.5| 1.047| 0.007| 0.525| 0.143  | 266/33        | 25.9/7.7        | 248/3                 | 196/56    |
| BK-22        | Aptian–Lower Albian        | Marly limestones           | 12 | 249 | 20.0| 1.016| 0.006| 0.393| 0.270  | 282/28        | 13.4/9.0        | 099/2                 | 252/34    |
| BK-28        | Aptian–Lower Albian        | Marly limestones           | 11 | 412 | 40.9| 1.006| 0.003| –0.125| 0.473  | 046/63        | 14.1/7.1        | 027/19                | 012/47    |
| BK-59        | Aptian–Lower Albian        | Fine sandstones            | 10 | 317 | 25.9| 1.013| 0.002| –0.255| 0.241  | 139/38        | 6.5/5.4         | 169/1                 | 220/78    |
| BK-19        | Lower Albian               | Fine sandstones            | 8  | 168 | 12.5| 1.061| 0.018| 0.866| 0.103  | 295/6         | 26.2/3.3        | 115/4                 | 220/37    |
| BK-57        | Lower Albian               | Marls                      | 10 | 169 | 28.3| 1.100| 0.023| 0.809| 0.047  | 247/2         | 14.8/3.6        | 248/1                 | 336/44    |
| BK-58        | Lower Albian               | Marls                      | 8  | 204 | 16.3| 1.073| 0.011| 0.745| 0.045  | 264/17        | 12.8/4.3        | 086/4                 | 308/28    |
|              | CLOSE to Guernica diapir edges|                            |    |     |     |     |     |     |        |               |                 |                      |           |
| BK-61        | Aptian–Lower Albian        | Fine sandstones            | 9  | 205 | 34.3| 1.043| 0.008| 0.552| 0.086  | 210/34        | 4.4/3.4         | 227/5                 | 277/52    |
| BK-20        | Lower Albian               | Marls                      | 6  | 252 | 90.5| 1.041| 0.022| 0.534| 0.643  | 240/28        | 45.3/9.0        | 060/1                 | 238/29    |

(Continues)
between 1 and 1.1 in marls and fine sandstones, and values between 1 and 1.03 in marly limestones (Figure 4). Km, Pj and T parameters do not show any significant variation with distance to the diapir edge (Figure 4).

K–T curves display a concave–hyperbolic shape in their initial parts indicating paramagnetic behaviour up to 300–400°C (Figure 5). Thermal demagnetisation of three-axis IRM shows a predominance of low coercivity minerals (<0.1–0.3 T) and complete demagnetisation below 590°C in all samples (Figure 5). Maximum unblocking temperatures of the NRM demagnetisation range between 480 and 550°C (Figure 5). Altogether, this points to magnetite as the main ferromagnetic (s.l.) phase. Although the formation of new magnetic phases upon heating obscures some of the thermomagnetic experiments, the main decrease in magnetic susceptibility below 590°C

**TABLE 1** (Continued)

| Site       | Age            | Lithology       | n  | Km   | SD  | Pj   | SD  | T    | SD  | D, I (K_{max}) in situ | E11.1 (e12/e13) | D/I (K_{max}) corrected | S0 (D/D) |
|------------|----------------|-----------------|----|------|-----|------|-----|------|-----|------------------------|------------------|-------------------------|----------|
| CLOSE to Mungia diapir edges |   |                 |    |      |     |      |     |      |     |                        |                  |                         |          |
| BK-10      | Middle–Upper Albian | Marls          | 8  | 222  | 18.7| 1.009| 0.004| 0.279| 0.773| 161/25                  | 58.1/8.2        | 339/20                  | 128/52   |
| BK-29      | Aptian–Lower Albian | Marly limestones| 9  | 112  | 11.9| 1.028| 0.008| 0.373| 0.139| 288/20                  | 35.8/6.6        | 289/3                   | 314/19   |
| BK-02      | Middle–Upper Albian | Marls          | 7  | 138  | 9.25 | 1.063| 0.022| 0.472| 0.464| 301/10                  | 34.2/11.4       | 123/4                   | 009/36   |
| BK-18      | Middle–Upper Albian | Marls          | 8  | 190  | 12.9| 1.083| 0.008| 0.727| 0.059| 082/4                  | 9.2/4.8         | 081/3                   | 359/06   |
| BK-21      | Middle–Upper Albian | Marls          | 11 | 187  | 36.5| 1.082| 0.029| 0.808| 0.197| 254/16                  | 33.5/3.5        | 073/3                   | 240/19   |
| BK-23      | Middle–Upper Albian | Marls          | 10 | 114  | 19.9| 1.066| 0.026| 0.774| 0.099| 083/2                  | 15.3/4.7        | 263/9                   | 081/11   |
| BK-24      | Middle–Upper Albian | Marls          | 8  | 179  | 27.5| 1.098| 0.031| 0.756| 0.115| 268/15                 | 14.3/3.5        | 087/0                   | 252/16   |
| BK-25      | Middle–Upper Albian | Fine sandstones| 7  | 44.9 | 21.4| 1.049| 0.030| 0.575| 0.388| 142/60                 | 39.7/10.8       | 097/21                  | 066/58   |
| BK-26      | Middle–Upper Albian | Marls          | 10 | 138  | 11.5| 1.077| 0.019| 0.856| 0.118| 083/3                  | 20.0/7.5        | 268/31                  | 058/38   |
| BK-05      | Upper Albian      | Marls          | 9  | 166  | 14.1| 1.049| 0.015| 0.352| 0.164| 251/18                 | 6.4/3.7         | 070/1                   | 239/19   |
| BK-06      | Upper Albian      | Marls          | 12 | 117  | 24.6| 1.019| 0.009| 0.245| 0.184| 245/11                 | 24.9/7.8        | 064/6                   | 190/29   |
| BK-07      | Upper Albian      | Marls          | 9  | 63.7 | 10.0| 1.028| 0.011| 0.579| 0.325| 281/19                 | 24.0/5.1        | 101/7                   | 275/26   |

Km = (K_{max} + K_{int} + K_{min})/3 (mean susceptibility, in 10^{-6} SI units).
Pj = \exp \{(2[(n_1 - \eta_1)^2 + (n_2 - \eta_2)^2 + (n_3 - \eta_3)^2])^{1/2}\} (Jelinek, 1981).
T = (2n_2 - n_1 - n_3)/(n_1 + n_2 - n_3) (shape factor; Jelinek, 1981).
D, I (K_{max}) = Declination and inclination of K_{max}.
For each site the line shows the arithmetic means of the individual site mean values (standard deviation in parentheses).
E11.1 (e12/e13), e12 and e13 are half confidence angles of K_{max} from Jelinek’s statistics.
S0 (D/D) = Bedding (Dip direction/Dip).

**FIGURE 4** Pj–T graphs for different lithologies indicating sites sampled close to or far from the diapir edges (circle and square symbols, respectively) [Colour figure can be viewed at wileyonlinelibrary.com]
also supports the occurrence of magnetite. Thermal demagnetisation of three-axis IRM reveals an additional and progressive IRM drop below 350°C (Figure 5), which might be attributed to the occurrence of either pyrrhotite and greigite (Larrasoña et al., 2007) or maghemite (Liu et al., 2005). The increase in bulk susceptibility at low temperature relative to its value at room temperature is similar in all
The magnetic foliation at all sites, except for site BK03, is parallel to bedding and has been interpreted as being related to depositional and compaction processes. However, the orientation of the magnetic lineation varies throughout the studied area and has been interpreted as being controlled by tectonic processes. Far from the diapir edges, the magnetic lineation shows a WSW–ENE orientation (Figure 8). We interpret it as being related to the N–S Pyrenean compression. This interpretation is justified because a cleavage associated with the Pyrenean orogeny is observed in the studied area. Formation of cleavage and/or incipient cleavage can reorient a previous magnetic fabric (Oliva-Urcia et al., 2013; Soto, Casas-Sainz, Villalain, & Oliva-Urcia, 2007). Sedimentary processes triggering the magnetic lineation acquisition can be discarded, as its orientation does not coincide with either palaeocurrents (turbidites were sourced in the north, but they were driven by the diapir relief) or slumping (triggered by the diapir growth) directions detected in the Bakio diapir by Poprawski et al. (2014) (Figure 2).

Close to the diapir edges, two different types of behaviour are observed (Figure 9). Sites located on the southern sides of diapirs show a magnetic lineation parallel to the diapir walls. We interpret the magnetic lineation observed at the southern walls to be associated with the Pyrenean compression stresses deviated around the diapirs. These diapirs are mainly composed of hard subvolcanic rocks (ophites), which act as buttresses, hindering the northward propagation of deformation and producing stress perturbations that

![Figure 6](https://example.com/figure6.png)

**Figure 6** Ratio between the magnetic susceptibilities (Km) at low and room temperatures (LT/RT), where LT/RT = 3.8 corresponds to perfect paramagnetic behaviour (Lüneburg et al., 1999) [Colour figure can be viewed at wileyonlinelibrary.com]
are able to reorient the magnetic lineation parallel to the diapir walls (Figure 9). On the northern sides of diapirs, however, the magnetic lineation is either perpendicular/highly oblique to the diapir walls or could not be defined. In this case, we interpret the magnetic lineation to be associated with the outer-arc extension that occurred during salt rise (e.g., Giles & Rowan, 2012; see Figure 10). Magnetic lineation in extensional scenarios coincides with the stretching direction (e.g. Mattei, Sagnotti, Faccenna, & Funiciello, 1997); therefore, it is expected that outer-arc extension related to salt rise will also orient the magnetic lineation parallel to the extension direction, which would be perpendicular to the salt wall ridge (Figure 10). The occurrence of sites without defined magnetic lineation and with magnetic lineations acquired during Mesozoic diapir growth points to the existence of areas (“shadow areas”) protected from the subsequent Cenozoic Pyrenean compression at the northern edges of the diapirs due to the presence of rigid ophites (Figure 9). This work highlights the potential of AMS studies applied to halokinetic sequences to characterise their outer-arc deformation and thereby identify the trend of the diapir edges. It also indicates that caution is required in interpreting magnetic lineations from halokinetic sequences if subsequent tectonic events are present.

**FIGURE 7** Stereoplots of the RT-AMS (left), LT-AMS (middle) and T-Pj diagrams (right) differentiating the RT- and LT-AMS values for each site. Confidence ellipses for AMS principal axes are shown. Lower-hemisphere equal-area stereoplots after bedding tilt correction [Colour figure can be viewed at wileyonlinelibrary.com]
The application of AMS to syn-diapiric overburden rocks highlights its potential in studying deformation in halokinetic sequences related to passive salt rise. Aptian–Albian turbiditic series from the Basque–Cantabrian basin have been analysed. Paramagnetic minerals dominate the total AMS, indicating that the AMS results reflect the petrofabric of the studied rocks. The observed magnetic foliation is parallel to bedding, and the orientation of the magnetic lineation is variable and related to different deformation processes. Far from the diapir edges, magnetic lineation is related to the Cenozoic Pyrenean compression, which propagated from south to north. Close to the diapirs, it reflects the effect of diapirs filled with ophites acting as rigid bodies and deflecting Pyrenean compression at their southern faces while protecting Mesozoic syn-diapiric deformation in their shadow areas to the north.

**FIGURE 8** Stereoplots showing $K_{\text{max}}$ (magnetic lineation), density plot and rose diagram after bedding tilt correction for sites located far from the diapir edges and for sites located close to the Bakio and Bermeo diapirs. Lower-hemisphere equal-area stereoplots [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 9** Geological map of the study area showing the magnetic lineation ($K_{\text{max}}$) after bedding tilt correction and magnetic lineation trajectories. Magnetic lineations of sites located close to diapir edges are represented in red, whereas black lines represent magnetic lineations of sites located far from the diapir edges. Sites BK01, BK10, BK20, BK54 and BK55 do not show a defined magnetic lineation, and site BK03 was discarded from further structural interpretations (see text for further explanation). A magnetic fabric acquired during or shortly after deposition in syn-diapiric rocks is only observed in the shadow areas on the northern faces of diapirs (see text for further explanation) [Colour figure can be viewed at wileyonlinelibrary.com]

**6 | CONCLUSION**
DEFORMATION RELATED TO DIAPIR GROWTH:

Active stretching area (arching salt wall roof)

Inactive stretched areas of rocks previously placed in the arching salt wall roof

Main stretching direction (perpendicular to the salt wall ridge)

Inflating salt wall

FIGURE 10  Active/inactive outer-arc deformation model related to salt rise in halokinetic sequences. The main stretching direction in the active stretching area is perpendicular to the salt wall ridges. The analysis of inactive stretched areas of rocks previously placed in the arching salt wall roof reveals that magnetic lineation would also be oriented perpendicular to the salt wall ridge in protected areas (i.e., where subsequent Pyrenean compression was not able to reorient the magnetic fabric) [Colour figure can be viewed at wileyonlinelibrary.com]

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