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What does AMS mean in multilayer systems? Regional and detailed study from the Southern Pyrenees (Aragón, Spain)

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Abstract: In this paper we analyse the processes inferred from the magnetic fabric studies and the assumption that the lithology can control the magnetic properties. A detailed regional study is carried out in the Eocene turbidite system from the Southern Pyrenees. The results obtained from rock magnetism analysis and the magnetic fabrics show that neither aspect is controlled by lithological changes. The higher values of paramagnetic contribution to the susceptibility show fabrics related to LPS and cleavage development. The study of subfabrics reveals that the same processes can be interpreted in all the rock types whereas it is not evident from the AMS at room temperature. In the studied samples, the paramagnetic contribution to the susceptibility does not depend on the lithology, but it does control the sensitivity to strain in the RTAMS.

Keywords: Pyrenees, AMS, subfabrics, flysch.

The Anisotropy of Magnetic Susceptibility (AMS) consists in the measurement of the susceptibility in different orientations when a weak magnetic field is applied to a rock. The magnetic susceptibility can be described as a second rank tensor and provides information on the magnetic properties of the minerals present, their morphology, their orientation and their clustering (Tarling and Hrouda, 1993).

Usually, the application of AMS in marls and clays produces good results because the AMS gives information about the orientation of clay particles, which are usually very sensitive to deformation. However, sandy levels can show similar results to the marls, while sometimes there can be problems in understanding the AMS with the change in the mineralogical sources and where the intensity of the deformation on an outcrop scale can be more discontinuous in sandstones.

These changes between marls/shales and sandstone levels assume that the susceptibility in marl levels is mainly related to the paramagnetic contribution from clay minerals. In sandstone levels there is usually a higher variability in susceptibility sources and a lower contribution from clay minerals and the ferromagnetic contribution to the susceptibility can be very important (and it can also be associated with different mineral phases). On the other hand, ferromagnetic particles may show important changes in their behaviour depending on the grain size and their composition (for example SD and MD magnetite particles with the same orientation show different relationships between the shape anisotropy and the susceptibility axes, see Tarling and Hrouda, 1993) and the ferromagnetic contribution may control the AMS even when ferromagnetic minerals are present in less than 2% weight.

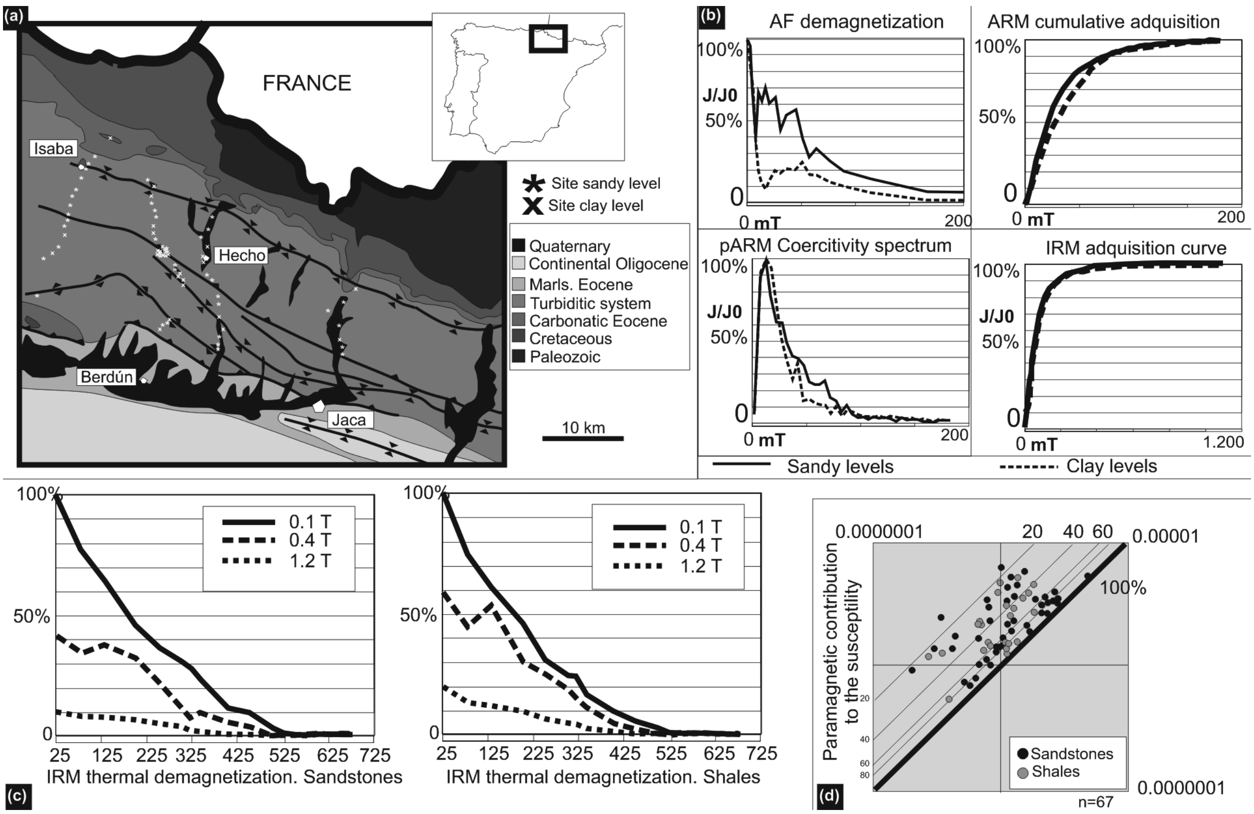

Figure 1. (a) Geological map of the western sector of the Central Pyrenees with the site location, (b) some rock magnetism analyses carried out in representative samples from the Eocene turbidites, (c) three axes IRM thermal demagnetization of two different samples from the turbidites, (d) paramagnetic contribution to the susceptibility obtained from selected samples from all analysed sites.

The processes that can be inferred from the interpretation of the AMS can show different results in different rock types: 1) marl deposits usually develop a sedimentary fabric (magnetic foliation parallel to bedding) and they are more sensitive to deformation on an outcrop scale (for example, cleavage intensity), and 2) sandstone levels can show particle imbrication during sedimentation, related to paleocurrents and, for the same intensity of deformation, be more insensitive to the deformation process. These differences mean that marls/shale levels may be, in the first instance, more suitable for the study of deformation by means of the AMS.

The study of AMS in regional analysis depends not only on the study of the proper lithology but also on the surface representation. We have developed a detailed study in the Eocene Turbiditic system from the Southern Pyrenees (e.g. Mutti *et al.*, 1985; figure 1a) that represents 72 sites and 1499 samples, enabling us to compare the meaning of the AMS in a turbidite system by sampling the marl/shale levels (e-level from Bouma, 1962) and the sandstone levels (a-d levels from Bouma, 1962). A detailed study was done in an outcrop along a length of 15 m, with 10 sites including 220 samples.

Results

Ferromagnetic mineralogy

Different magnetic analyses have been carried out for the characterization of the magnetic particles present in the studied rocks (Figs. 1b and 1c) according to the following routine: (1) AF demagnetization (20 steps from 0 to 180 mT in an SI-4 AF demagnetizer, Shappire instruments), (2) coercitivity spectrum obtained from the application of DC fields in 5 mT steps (methodology of Jackson *et al.*, 1988) and accumulative curve from the same results, (3) IRM acquisition curves in 28 logarithmic steps with an upper step of 1.1 T, (4) IRM thermal demagnetization of three axes (0.1, 0.4 and 1.2 T) in 18 steps and (5) susceptibility heating curves from sister samples from 73 K to room temperature.

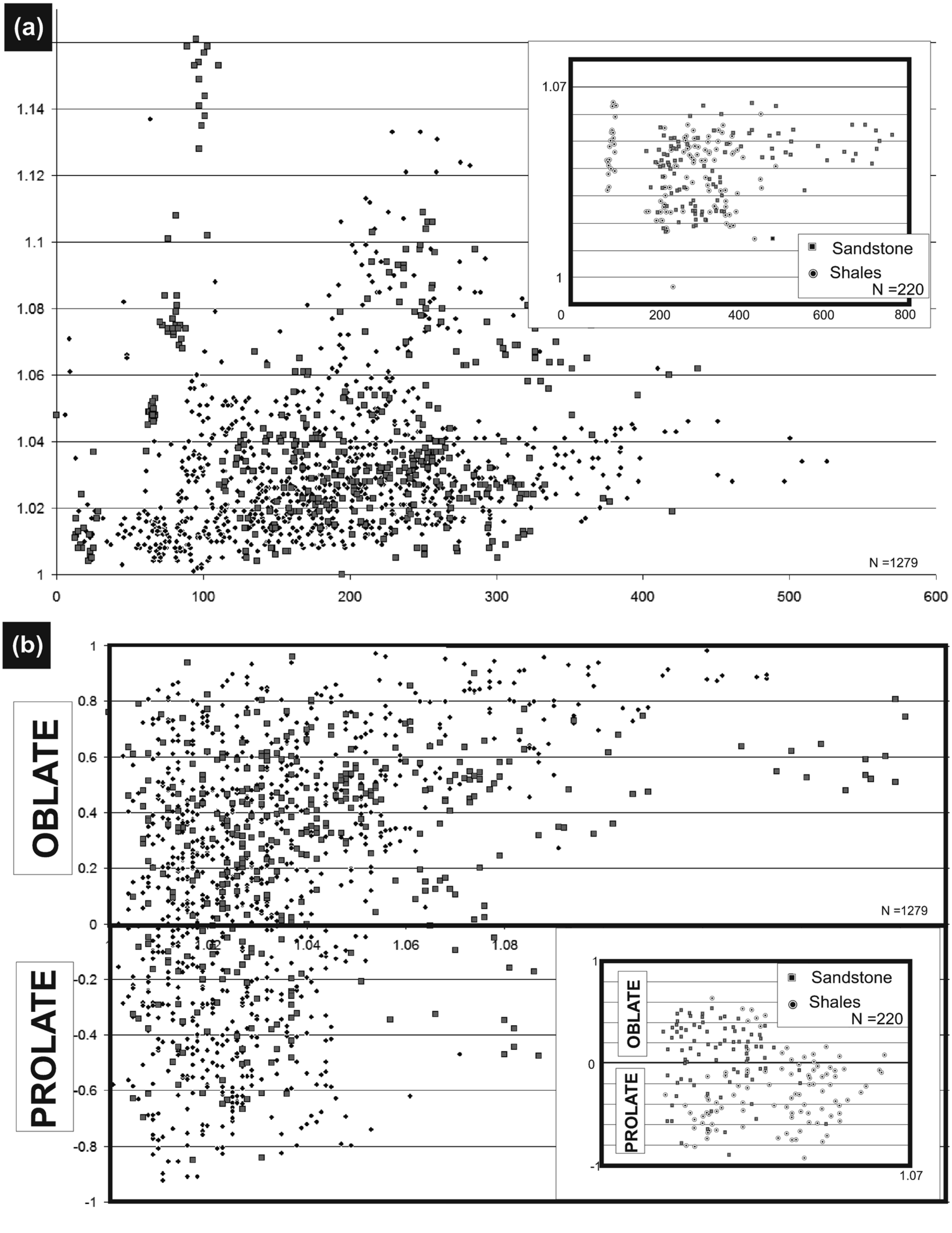

Figure 2. (a) Plotting of mean susceptibility (Km) vs. corrected degree of anisotropy P' (from Jelinek, 1971) for all the analysed samples; in small window results from the analysed outcrop, (b) plotting of P' vs. shape parameter (T) for all the analysed samples; in small window, results from the analysed outcrop.

The results obtained show very similar behaviour in all the analysed samples, the routine from steps 1 to 4 has been carried out in 35 samples (25 came from the selected outcrop and 10 from a similar lithology in different structural positions). At the same time, different routines have been carried out in another 15 sister samples to control the changes in the samples in different steps (measurement of susceptibility after some steps, and to check the results of some analyses, for example, comparison of IRM acquisition curves in samples after pARM and samples where only AF demagnetization had been carried out).

The different analyses show that the magnetic remanence is mainly carried out by low coercitivity phases and when a high coercitivity phase is present, it represents less than 8% (usually between 0 and 5%, results obtained from curve modelization; Kruiver, 2001). The thermal demagnetization of the artificial remanence of the IRM shows that the main part of the remanence is carried out by mineral phases below 550 ºC (90% is lost before 450 ºC). The IRM of three axes show that the main part of the remanence is carried by low coercitivity particles. The curves show a progressive decrease in magnetization with an almost constant decrease in temperature down to 325 ºC. The magnetization is totally lost at 550 ºC.

The main differences observed in the different remanence analyses show that when two different components exit, the first component (lost at lower AF fields) is stronger in the sandstones. In the rest of the analyses, shale levels are undistinguible from sandstones.

Paramagnetic and diamagnetic susceptibility vs. ferromagnetic susceptilibity

The measurements have been carried in a PPMS (Quantum Design), measuring the susceptibility at low field and high field (0.5 mT and 2.5 T). The changes in the susceptibility are related to the saturation of the ferromagnetic phases, the comparison between the susceptibility at high field, where only paramagnetic, diamagnetic and high coercitivity particles contributing to the susceptibility are present with respect to the susceptibility obtained at low field, providing information on the ferromagnetic contribution to the susceptibility and allowing us to infer the paramagnetic contribution (Fig. 1d).

These results indicate that the different samples show paramagnetic contributions to the susceptibility that came from nearly 100% to 10%. The comparison between the results obtained from the sandstones and shale levels is not significant and both rock types show the whole spectrum of variation.

Magnetic susceptibility

The mean susceptibility (Km) values range in the shale levels between 100 and 500×10^{-6} (SI), whereas the sandstone levels range between 200 and 750×10^{-6} (Fig. 2a). This great change is not significant because the susceptibility is higher in the sandstones than in shales but most of the results are indistinguishable in the interval from 200 to 500×10^{-6}. This means that the higher and lower values are obtained in the sandstone and shale levels respectively, and the majority of the samples show intermediate values. The comparison between the regional results and the detailed outcrop shows that the higher differences can occur within the same outcrop.

As regards the shape parameter (T; oblate $T>1$ and prolate $T<1$) (Jelinek, 1981) oblate fabrics are more common in shale samples than in sandstone levels in the studied outcrop, but the range of each lithology is superimposed in the diagram (Fig. 2b). The comparison between the corrected degree of anisotropy (P') and the shape parameter (T) show the possibility of separating the samples from the shales and sandstone levels: lower values of P' and more oblate fabrics for the clay levels and higher values of P' and more prolate fabrics for the sandy levels).

Anistropy of magnetic fabrics

Different techniques have been used in the measurement of magnetic fabrics. This analysis was carried out in the laboratory of magnetic fabrics of the University of Zaragoza and the laboratory of paleomagnetism of the University of Michigan. The study consists in the measurement of RTAMS in a kappabridge KLY-3s (AGICO), AARM and AGRM (methodology of Jackson *et al.*, 1988) and LTAMS (methodology of Parès and Van der Pluijm, 2002). The different techniques offer results for the anisotropy of magnetic susceptibility at room temperature conditions (RTAMS), the anisotropy of magnetic susceptibility at low temperature (LTAMS, measuring the samples at 73 K where the paramagnetic contribution increases according to the Curie-Weiss law), anisotropy of anhisteretic remanent magnetization (AARM, that gives information about the orientation of magnetic particles and depends on the coercitivity spectrum analysed) and anisotropry of giro-remanent magnetization (AGRM that gives informa-

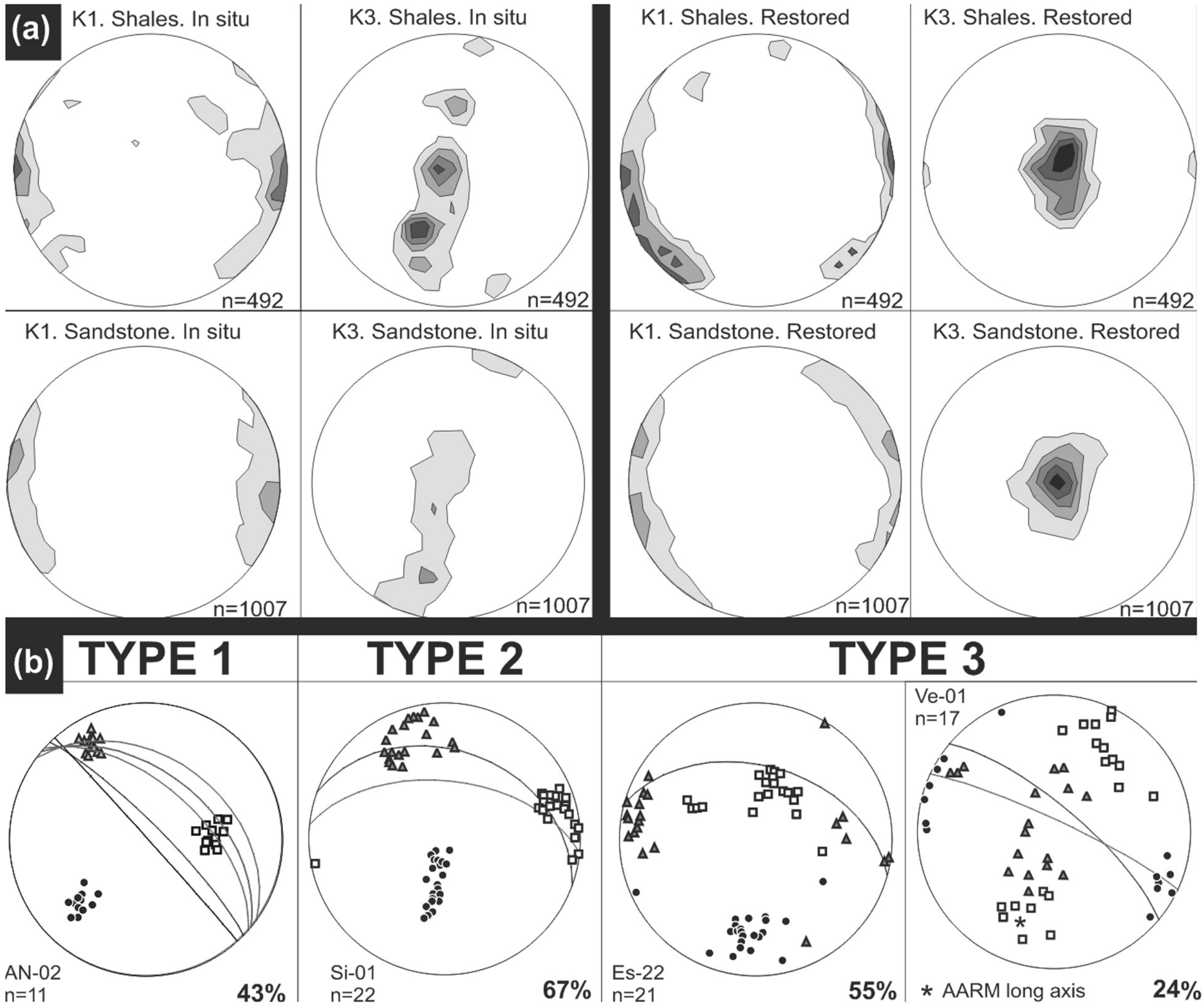

Figure 3. (a) Density diagrams for the K1 and K3 axes for the studied samples in *in situ* position and bedding restored, (b) main types of RTAMS fabrics obtained from the regional study (square K1, triangle K2 and circle K3). The paramagnetic contribution to the susceptibility, from the selected sites as types, has been included.

tion about some sulphides and acicular SD magnetites, e.g. Potter, 2004).

From the geometrical relationships between the AMS and the rock-fabric elements it is possible to describe three fabric types (Fig. 3): (1) magnetic foliation parallel to bedding and clustering of K3 axes parallel to the pole of bedding, (2) magnetic foliation parallel to cleavage and the mean vector of the K3 axes normal to the cleavage, and (3) the magnetic lineation is parallel to the direction of movement of the thrusts, sometimes this disposition is obtained after bedding restoration while in other cases the magnetic lineation does not have any relationship with outcrop elements and the magnetic lineation is horizontal in *in situ* conditions.

The sites with high paramagnetic contribution to the susceptibility usually show the first and second types of fabric, whereas the rest of the sites show the three kinds of fabrics. In some sites other magnetic fabrics have been obtained (Fig. 4), whereas sites with a high paramagnetic contribution to the susceptibility usually show similar results between RTAMS and LTAMS, the AARM showing a different fabric. The AARM fabrics are usually of (1) and (3) types of fabric whereas the LTAMS shows (1) and (2) types. The AGRM usually shows (1) and (2) fabric types.

Discussion

The study of rock magnetism and magnetic fabrics of different sites of the Pyrenees Eocene flysch show unexpected similarities and differences not related with lithology.

The mineralogical sources of the susceptibility show that there are small differences between the shale and sandstone levels. Both lithologies show similar coercitivities of the ferromagnetic particles and similar contributions to the magnetization. The main ferromagnetic sources are related to iron sulphides and magnetite, whereas high coercitivity phases are not significant. The main differences from the point of view of rock magnetism are reflected in the AF curves, where apparently the first component identified shows a higher contribution in the sandstone levels.

On the other hand, the mean susceptibility shows similar results in both lithologies and also the paramagnetic contribution to the susceptibility shows similar patterns. The corrected degree of anisotropy and shape parameter allow, in some cases, the separation between both lithologies, with more oblate geometries in the shale levels and higher P′values in the sandstones with respect to the sandy levels.

The processes inferred from the study of magnetic fabrics show that type (1) can be related with a process of LPS and the development of an early cleavage. The presence of tilted levels with non-Pyrenean trend where the magnetic lineation fits Pyrenean orientation after bedding restoration can be interpreted as the result of pre-folding acquisition of fabrics. This indicates the coaxiality of some tectonic processes and seems to show a direct relationship between the magnetic lineation and the intersection lineation. When no coaxiality exists, fabrics only record a process of LPS (more details in Pueyo-Anchuela *et al.*, 2007). Type (2) represents a cleavage-related fabric, where the magnetic foliation is parallel to cleavage. Type (3) represents processes related to the shear of the thrust movements (K1 and K3 axes contained in the plane

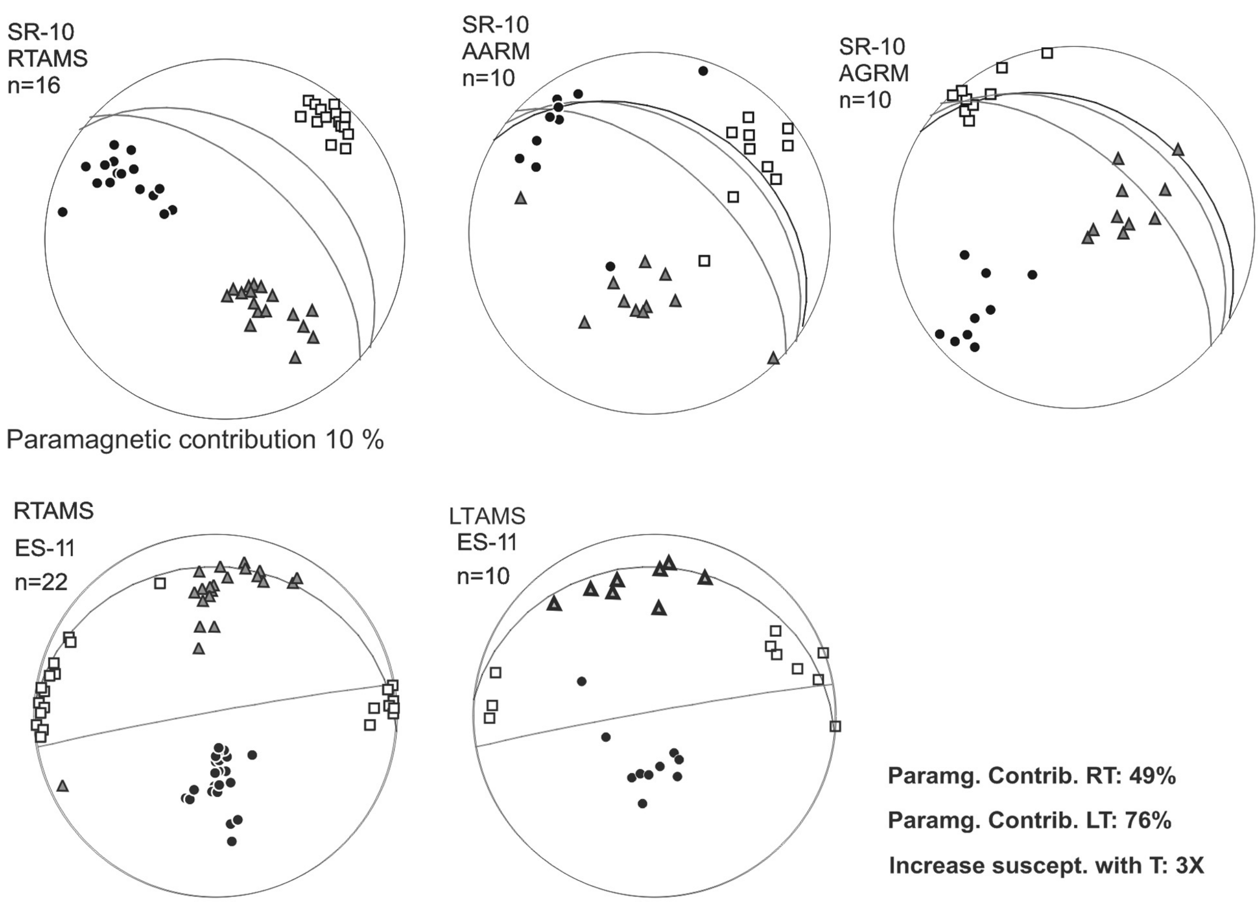

Figure 4. Some examples from the different magnetic fabrics obtained from two different sites (square: long axes of the magnetic ellipsoid, triangle: intermediate and circle: minimum axes

of movement), and magnetic lineation contained in the bedding plane (acquisition in pre-tilting conditions) or horizontal magnetic lineation whatever the bedding orientation (post-tilting acquisition). Sites where the plane of movement contains K1 and K2 axes can be explained by the superposition of two non-coaxial processes: flattening and simple shear (De Paor and Simpson, 1993; Borradaile and Henry, 1997).

The geometrical aspects obtained from the orientation of the different fabrics show that the paramagnetic contribution to the susceptibility has a direct relationship with the processes recorded in the RTAMS, whereas the lithology is not clear evidence of the recorded processes. Fabrics with more paramagnetic contribution show cleavage-related fabrics (or LPS fabrics) whereas the most ferromagnetic sites can show LPS fabrics or fabrics related with the thrust movement.

The assumption that clay particles provide a better record of the strain is generally true, whereas sites with higher paramagnetic contribution record LPS or cleavage related fabrics. In the rest of the sites no fabrics related with cleavage have been clearly observed, whereas LPS fabrics and fabrics consistent with the shear parallel to the thrust movements are usually present. In cases where the RTAMS is controlled by ferromagnetic particles and their arrangement, the fabric is related to the thrust movement. Sometimes the AGRM shows fabrics related to LPS or cleavage related fabrics. The AGRM is related to the presence of some sulphides and also SD acicular magnetite. In this case, the parallelism between the LTAMS and AGRM lead us to think that the particles that show the giroremanent behaviour mimic the clay minerals as inclusions. However, at some sites where the RTAMS is controlled by the ferromagnetic particles, and where the ferromagnetic contribution to the susceptibility at Low Temperature is still high (no clustered results have been obtained from the LTAMS), the AGRM shows fabrics related to LPS or cleavage where no evidence in the RTAMS are present. This argument indicates that the same processes have affected the studied levels even when no evidence is present in the RTAMS.

Conclusions

From the study of rock magnetism and magnetic fabrics of different sites of the turbiditic Eocene system from the Pyrenees it can be concluded that the different fabrics present in the studied rocks with different orientation and carried by different particles makes that the inferred processes obtained from the RTAMS depends upon the paramagnetic contribution to the susceptibility in a first approximation. On the other hand, the results obtained in different rock-types of the turbidites show that there is not a direct correlation between the rock magnetism properties and the granulometry of the deposit, whereas there is an important relationship between the RTAMS, the recorded processes and the paramagnetic contribution to the susceptibility.

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