AMS interpretation of major shear zones with contrasting rock rheology (Bragança Massif, NE Portugal)

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SUMMARY
We used AMS to help analyse two major shear zones in the Bragança Massif, one corresponding to the contact between the overlying Continental Allochthonous Terrane (CAT) and the underlying Northern Ophiolite Terrane (NOT), and the other to a duplex structure within the CAT. AMS results revealed the existence of lineations not observed in outcrop as mineral lineations, and showed possible relationships between superposing tectonic events through the interference between the corresponding magnetic ellipsoids. The lineations detected in rhelologically contrasting rocks can not be directly associated by trending alone, because they were generated in distinct metamorphic conditions. Post-kinematic recrystallization is common and tends to erase structural features that can be detected by AMS and are critical to kinematic and dynamical characterization and interpretation

1. INTRODUCTION
Shear zones (especially those separating terranes) are major features of orogenic belts, and hence the importance of analysing them in terms of geometry, kinematics and dynamics. AMS studies can be of great help in the kinematic analysis and interpretation, through the determination of the magnetic ellipsoid. Although not directly comparable to the finite strain ellipsoid in terms of axial dimensions (or ratios), they tend to be coincident in terms of axial orientations (Borradaile and Henry, 1997). For instance, the longest principle axis of the magnetic ellipsoid tends to be parallel to the mineral stretching lineation observed in mylonites.

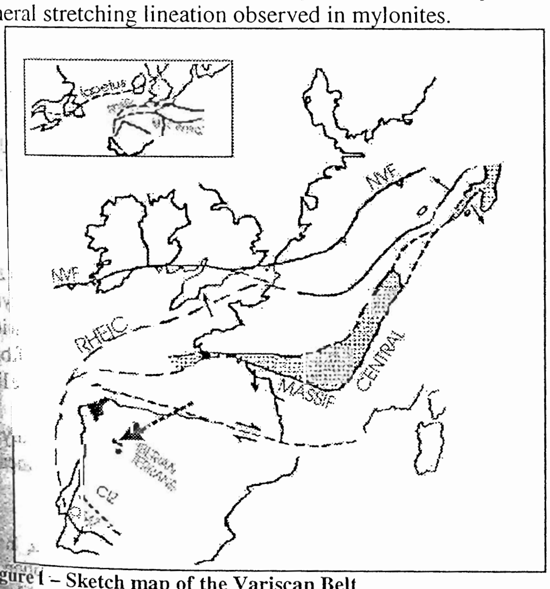

Figure 1 – Sketch map of the Variscan Belt

In this work we analysed two major shear zones in the Bragança Massif to characterise them geological and magnetically. In some rocks the mineral stretching lineation is not observed, mainly because of post-kinematic recrystallization, but AMS proved to be an excellent tool to obtain the kinematic marker. The mylonitic foliation is also sometimes erased by recrystallization but AMS could also find it. These magnetic data can be checked with field observations carried out in outcrops where recrystallization did not erase the structures produced by shear during emplacement of the allochthonous terranes.

The Bragança Massif is located in NE Portugal and comprises 3 terranes, which are, from bottom to top, the Iberian Terrane, the Northern Ophiolite Terrane (NOT) and the Continental Allochthonous Terrane (CAT). The present work took place in the contact between NOT and CAT, and in a major shear zone within the CAT (a duplex structure that duplicates the lithotectonic units within the CAT). The CAT/NOT contact in the N is clean cut and puts amphibolites of the base of the CAT directly on top of greenschists of the NOT, and in the S puts gneisses of the CAT on top of amphibolites (Marques *et al*, 1996). CAT amphibolites sometimes show a N-S trending mineral stretching lineation but this kinematic marker is not observed in the greenschists. In the duplex, the shear zone on top of the horse puts gneisses and serpentinites on top of mafic granulites. These show a prominent E-W trending mineral stretching lineation, which is not the case in gneisses and serpentinites. Metamorphic isograds within the CAT are reversed by thrust because of retrogression and fluid income during transport of hot and dry CAT over colder and hydrated NOT.

This work is part of a major study in which we used microprobe to analyse the mineralogy of 10 samples, and Curie curves of 13 samples and high field measurements of 23 samples for discrimination of the magnetic mineralogy. We analysed approximately 300 samples from 32 sites for AMS measurements.

2. AMS DATA AND MINERALOGY

2.1. CAT/NOT CONTACT (NORTH)
Transport of the CAT over the NOT took place first under amphibolite facies conditions, and later in greenschist facies.

2.1.2. AMPHIBOLITES (CAT)
Microprobe analyses showed that the paramagnetic minerals hornblende and plagioclase are the most common. The amphibolite samples display two distinct groups, one with low magnetic susceptibility values (less than $3*10^{-3}$SI), and another formed by two samples with higher susceptibility values that reach $90*10^{-3}$SI. These results agree with microprobe analyses and magnetic measurements that revealed the existence of multi-domain magnetite. These results also suggest that the samples with lower susceptibility values present a similar contribution of paramagnetic and ferromagnetic (s.l.) minerals for the magnetic fabric, while in samples with high susceptibility values the magnetic fabric result from the magnetite contribution. Both types of samples display the same shape of the magnetic ellipsoid (oblate shape) but with greater corrected degree of anisotropy for the samples richer in magnetite. However, all the samples of this site display coincident orientation of the principal axes of the magnetic ellipsoids, which agrees with a sin-kinematical recrystallization of the magnetite minerals. The magnetic ellipsoid has K1 oriented N-S.

2.1.2. GREENSCHISTS (NOT)
The greenschists result from retrogression of the amphibolites of the NOT. The magnetic susceptibility measurements revealed a very homogeneous behavior in what concerns the bulk anisotropy

values. The low values of the magnetic susceptibility found for this lithotype agree with the microprobe analyses, which revealed mainly paramagnetic minerals (mostly actinolite and chlorite) with a low content of diamagnetic minerals.

The magnetic fabric displays an oblate shape. However, it is possible to identify a good cluster of the principal axes of the average magnetic ellipsoid, putting in evidence a cluster of the K1 axis along an E-W direction, which is not marked in the outcrop by a mesoscopic mineral lineation.

2.2. CAT/NOT CONTACT (SOUTH)

Here the ophiolitic rocks still preserve the earlier amphibolite facies.

2.2.1. GNEISSES (CAT)

The magnetic susceptibility measurements display a homogeneous behavior. This reflects a stable mineralogical composition that was revealed by microprobe results to be of dominantly diamagnetic and paramagnetic minerals, with a small percentage of ferromagnetics (s.l.). The low values of magnetic susceptibility ($<500*10^{-6}$SI) agree with these results.

The magnetic fabric displays an oblate shape for the samples of the two involved sites. The geographical orientation of these two ellipsoids display a preferential cluster of the K1 axes along a NNW-SSE trend, coincident with the mesoscopic mineral lineation, not present in these sampled sites but observed in other outcrops of the same contact.

2.2.2. AMPHIBOLITES (NOT)

The amphibolite samples of this contact display lower bulk values of the magnetic susceptibility than the amphibolite samples of the Northern contact. These magnetic results are typical of a mineralogy poor in ferromagnetic (s.l.) minerals, which suggests that the magnetic fabric is the result of the paramagnetic mineralogy (mostly plagioclase and hornblende). The magnetic ellipsoid defined by the samples of this site display a homogeneous behavior in what concerns the oblate shape and geographical orientation of the principal axes, with K1 trending NNW-SSE as in the overlying gneisses.

2.3. DUPLEX WITHIN THE CAT

This shear zone developed under amphibolite facies conditions and puts gneisses on top of peridotites and mafic granulites.

2.3.1. GRANULITES

In these rocks, the high field and thermomagnetic measurements reveal the presence of a titanomagnetite poor in Ti, with pseudo-single-domain. Because they present low values of magnetic susceptibility, we suggest that the magnetic fabric is a result of a similar contribution of paramagnetic and ferromagnetic minerals, as also revealed by microprobe analyses.

The magnetic fabric displays a slight tendency for an oblate shape. However, the principal axes of the magnetic ellipsoids appear very well clustered, with K1 axes trending approximately E-W.

2.3.2. PERIDOTITES

In this duplex structure, just over the granulites, we find more incompetent peridotites. The thermomagnetic analyses indicate magnetite as the main magnetic carrier. These magnetite grains display a population that fall in the pseudo-single/single domain transition (Day *et al*, 1976; Dunlop, 1986), a result that can be responsible for some anomalies in the directions of the principal axes of the magnetic ellipsoids (Borradaile, G. J. & Henry, B., 1997). The magnetic fabric of these samples display an intense oblate shape ($T > 0.8$) with the corrected degree of anisotropy values ranging from 80% to 180%. The directional analyses display a K1 and K2 dispersion on a well marked magnetic foliation plane.

2.3.3. GNEISSES

These samples display similar magnetic behaviors when compared with the gneisses of the southern CAT/NOT contact. The magnetic fabric is probably carried by the paramagnetic minerals as suggested by the low values of magnetic susceptibility.

The magnetic fabric displays an oblate shape with the pole of the magnetic foliation sub-vertical. The principal axes of the magnetic ellipsoid, K1 and K2, display a dispersion along the primitive, only allowing a conclusion of a sub-horizontal magnetic foliation.

3. DISCUSSION

The CAT/NOT contact puts competent amphibolites directly on top of incompetent greenschists, and we come to the conclusion that these have taken up most deformation after the N-S event recorded in the amphibolites. Then, E-W magnetic lineation detected by AMS in greenschists is younger than the N-S lineation in amphibolites.

The duplex shear zone within the CAT puts incompetent gneisses on top of competent mafic granulites, through a thin sheet of incompetent serpentinites. Then, the incompetent rocks must take up most shearing and granulites preserve the earlier structures. We come to the conclusion that, here, the E-W lineation observed in granulites is older than the N-S lineation detected by AMS in gneisses and serpentinites. In the footwall peridotites and hangingwall gneisses the magnetic foliation is very strong (as well as the mylonitic and metamorphic foliations) but there is a great dispersion of K1 and K2 (which agrees with the absence of a mesoscopic mineral lineation), indicating a "pancake" shape of the magnetic ellipsoid. This could be the result of a superposition of two high angle transport directions (with incomplete generation of a new ellipsoid by the youngest deformation) and/or pervasive post-kinematic recrystallization.

Although there are 2 E-W lineations, one can not directly associate them just because they have the same trend: E-W lineation in the CAT/NOT contact was generated in greenschist facies conditions, and E-W lineation in the duplex under granulite facies conditions. Besides, it is known from regional geology that the high-grade lineation is associated with transport to the W, and the low-grade lineation with transport to the E. The N-S lineations can be the result of the same tectonic event because they were produced under similar amphibolite facies conditions and are associated with the same transport to the N of the CAT over the NOT.

In sampled locations where mineral lineation and mylonitic foliation are observed, AMS results agree with mesoscopic observations. In outcrops where the mineral lineation is absent, AMS data revealed a magnetic lineation that is in agreement with linetions and transport directions known from regional geology.

4. CONCLUSIONS

Amphibole is in general post kinematically recrystallized and/or in mosaic replacement of higher grade minerals (e.g., pyroxene), which masks the true finite strain and magnetic ellipsoids. Then one must look for rocks that preserve the mylonitic fabric (which is sometimes not possible) to try and assess the actual ellipsoids.

AMS prooved to be an excellent tool in the kinematic analysis of mylonitic shear zones, especially those lacking mineral lineations as a result of post-kinematic recrystallization.

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