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The Application of Magnetic Susceptibility Anisotropy Analyses to the Study of Tectonic Events on the Periadriatic Line

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With 10 Figures

Zusammenfassung

Zwischen Lana (S-Tirol) im Westen und Villach im Osten wurden entlang der Judikarien- bzw. der Pusterer-Gaillinie Untersuchungen der magnetischen Suszeptibilitätsanisotropie an 2945 Kernen aus 453 Aufschlüssen in 4 Teilabschnitten der "Periadriatischen Naht" (Abb. 1) durchgeführt. Sämtliche Proben wurden in der Anisotropie-Apparatur von Digico gemessen, die Analyse jedoch bisher nur für die Bereiche 1 und 2 abgeschlossen (Bereiche 3 und 4 sind in Vorbereitung). Ziel der Arbeit war es, einen Überblick über die tektonische Geschichte dieses Gebietes zu gewinnen. Im allgemeinen zeigt das "magnetic fabric" der Proben entlang der gesamten "Periadriatischen Naht" Kompression mit sehr hohen Anisotropieverhältnissen und hohen Elliptizitäten, die kompressionellen Strain anzeigen. Die Analyse der Ellipsoidrichtung zeigt im Bereich 1 mehrere "fabrics". Diese sind tektonischen Ereignissen in diesem Gebiet zuzuordnen, und eine Kurzanalyse ist hier vorgelegt. Die Daten des Bereiches 2 (dem Umschwenken der Pusterer-Gailrichtung in die Judikarienrichtung bei Mauls) erscheinen von größtem Interesse, da aus ihnen ein tektonisches Modell der Aktivierung (oder Reaktivierung) des Lineaments ableitbar ist (Rechtsseitenverschiebung an Pusterer-Gaillinie, Linksseitenverschiebung an der Judikarienlinie). Die weiter im S gewonnenen Daten vom Mt. Croce sprechen ebenfalls für dieses Modell, wo, trotz der durch die Intrusion des Mt. Croce-Granites und das Ouarzporphyrereignis von Bozen komplexeren Situation, eine Linksseitenverschiebung beobachtbar ist. Die Netto-Gesamtbewegung an der Pusterer-Gailtallinie erfolgte dextral, obwohl einige Teilstücke sinistralen Bewegungssinn zeigen (Abschnitt 1, Fig. 1). Laut L. BRIGO (mündl. Mitt.) ist im Bereich Hermagor-Nötsch lokal ein solcher Bewegungssinn aus geologischen Befunden ableitbar. An der Judikarienlinie ergibt sich jedoch im gesamten ein sinistraler Bewegungssinn (RATHORE 1979 d). Aus mechanischdynamischen Überlegungen heraus ist dieserVerschiebungssinn auch eine logische Folge der Rechtsseitenverschiebung an der Pusterer-Gaillinie.

Summary

Magnetic susceptibility anisotropy methods have been applied to large suite of samples from 4 sections of the Periadriatic Line (P.L.) to try and construct a

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dynamic model of the tectonism of the line. The analyses yield an overall dextral movement along the Pusterer-Gailtal Lines and a sinistral movement along the Judicarian Line. The results have been incorporated into a plate-tectonic model whereby the P.L. was activated or reactivated by a collision of a plate containing the P.L. against the Briançonic Platform (FRISCH 1977). The energy of the collision appears to have been dissipated in compression and sinistral movement along the Judicarian Line and dextral movement along the Pusterer-Gailtal Line.

Introduction

Most rocks, whether sedimentary or igneous in origin, contain small percentages of ferromagnetic minerals arranged randomly in their matrix. Under deformational stress these minerals respond in the same way as the rest of the matrix, i. e. they become deformed and/or reoriented, and, as a part of the whole rock they are strained. The individual grain shapes and their orientations within a rock constitute the rock petrofabric. The analysis of strains, i. e. petrofabric analysis by means of microscope or X-ray goniometry methods, is a major help to the structural geologist in determining the tectonic history of the rock. However, these petrofabric determinations are usually tedious and time consuming, and in slightlystrained rocks, unreliable (private communications, G. OERTEL, D. J. SANDER-SON). The presence of magnetic fabric) which is readily available using magnetic methods. The magnitudes of the principal magnetic susceptibilities and their orientations within the rock, the magnetic susceptibility anisotropy, constitute the magnetic fabric of the rock.

The magnetic fabric

For low fields (i. e. less than 100 oersteds) the intrinsic magnetic susceptibility of a material (χ , gauss oe⁻¹ cm⁻³) is defined as $\chi = J/H$ which is a second rank tensor that depends only on the intrinsic properties of the magnetic material. The intrinsic magnetic susceptibility of magnetite is c. 10^{-2} gauss $0e^{-1}g^{-1}$, which is much greater than that of hematite c. 10^{-5} gauss $oe^{-1}g^{-1}$, so that the bulk susceptibility of a rock is controlled by the presence of only small quantities of magnetite. Cubic magnetite shows "shape effect" anisotropy due either to reorientation of elongated primary magnetite grains during deformation, or to anisotropic growth of secondary magnetite in deformed non-magnetic material, whereas hematite (trigonal) tends to align its easy magnetic axes to create a "magnetocrystalline" anisotropy effect (STACEY 1960). Curie point determinations on the samples investigated here indicated magnetite as the mineral responsible for the magnetic fabric. The anisotropic susceptibility of a rock can be represented as an oriented ellipsoid with three mutually perpendicular axes, χ maximum, χ intermediate and χ minimum. Since the susceptibility χ , is the ratio J/H, for a fixed field (H, oersteds) the magnetization (J, gauss) can only vary from sample to sample if there is a variation in either the concentration or

the average orientation of the magnetic minerals from place to place within the site. It is not uncommon to find a variation in the respective magnitudes for the six samples from a given site. However, it is to be expected that a localised region such as a half meter cubed should experience a uniform strain field, thus the susceptibility axial ratios should remain constant from sample to sample. Hence, in magnetic fabric analysis, the magnitude and nature of the susceptibility ellipsoid is expressed in terms of the anisotropy parameters P_1 , P_2 and P_3 and E, where

 $P_{1} = \frac{\chi \text{ max.}}{\chi \text{ int.}}; \quad \text{lineation (L)}$ $P_{2} = \frac{\chi \text{ max.}}{\chi \text{ min.}}; \quad \text{anisotropy factor}$ $P_{3} = \frac{\chi \text{ int.}}{\chi \text{ min.}}; \quad \text{foliation (F).}$

The ratio, $P_3/P_1 = E$, is the ellipticity of the susceptibility ellipsoid, thus if E>1 the ellipsoid is oblate and the foliation is more developed than the lineation, and conversely if E<1 the ellipsoid is prolate and the lineation is more developed than the foliation within the rock.

Use of magnetic fabrics in petrofabric studies

The study of magnetic fabric as a petrofabric element was initiated by GRAHAM (1954) and it is now well established that the magnetic susceptibility anisotropy ellipsoid in a rock reflects the strain ellipsoid. The magnetic foliation plane, the plane containing the magnetic maximum and intermediate axes, in sedimentary rocks is found to lie in or very close to the bedding plane and the minimum axis is normal to this plane (GRANAR, 1958, GRAHAM, 1966). In metamorphic rocks the magnetic foliation plane lies within any observed cleavage plane and the minimum axis thus parallels the pole to the cleavage (STONE, 1963, SINGH et al., 1975, WOOD et al., 1976, RATHORE, 1979a). To date only a few correlations have been carried out between the magnitudes of the strain ellipsoid axes and the anisotropic susceptibilities. Where studied, it has been found that the axial ratios of the susceptibility ellipsoid are related exponentially to the strain axial ratios of the strain ellipsoid (WOOD et al., 1976, RATHORE, 1979a, 1979c), indicating the possibility of obtaining complete strain ellipsoid data from the magnetic technique, which is both quick and repeatable on a number of samples from a given locality and gives reliable results. The speed of the technique (2 minutes per sample) makes it possible to carry out large scale regional studies and lends itself to the study of large scale tectonic events (RATHORE 1979b). The measurements of the magnetic fabric are carried out on a computer linked slow-spinner magnetometer (MOLYNEUX, 1971) described as the complete Result Anisotropy Delineator, CRAD (RATHORE, 1975), which yields the magnitudes and orientations of the principal susceptibilities in a rock with respect to an orientation mark on the rock.



Fig. 1: A map of the study region showing the four sections of the Periadriatic Line that have been studied using magnetic susceptibility anisotropy method.

The study region

A study of the magnetic fabric along the length of the Periadriatic Line (P.L.) between Lana (South Tyrol) in the W and Villach in the E has been carried out in order to obtain a picture of the tectonic history and the dynamics of the movements on the P.L. The P.L. was sampled in 4 regions (fig. 1) and a total of 2945 cores comprising 453 sites were collected and measured. Analyses on regions 1 and 2 have been completed and the results are presented here; regions 3 and 4 are still in preparation (RATHORE and BECKE, 1979, RATHORE, 1979d).

Any data presentation here is on the site or locality basis since it is found that the mean values of the anisotropy parameters have standard deviations usually less than 5% and the grouping of the ellipsoidal exes has a cone of confidence α_{95} usually less than 10°.

Region 1: Between Naßfeldpaß and Nötsch

The magnetic fabric from this region led to the following conclusions:

- 1) The P.L. is a compressional fault zone in which very high compression is localised to within a kilometer or so to the N and S of the line.
- 2) There have been at least 2 major phases of compression in this region; the former being the stronger and having a compression direction c. N 25° W S 25° E and the latter being the weaker having a compression direction c. N 35° E S 35° W.
- 3) The above fabrics exist both to the N and S of the P.L., hence ruling out the possibility of relative rotation N and S of the line; however, horizontal and vertical movements are possible.
- 4) Along this section of the P.L. the movement along the line was sinistral.

Figure 2 shows an enlargement of this region indicating the locations of the 145 sampled sites in 53 localities and their respective positions relative to the P.L. About 50% of the sampled sites have a diamagnetic bulk susceptibility, these are mainly carbonates in the form of unmetamorphosed reef dolomites and limestones and metamorphosed banded marbles and dolomite marbles. These carbonates have a distinct and repeatable magnetic fabric, the analysis of which can be attempted on the assumption that a minute quantity of ferromagnetic grains exists within the rock. Individual grains of magnetite have been identified by Dr. HEINZ in thin section studies under the microscope of some of these carbonates. Thus the directions of the susceptibility anisotropy axes in these diamagnetic sites become of use whereas the magnitudes are of no real assistance in the fabric analysis. The analysis of the axial data of the ferromagnetic sites is carried out with the aid of a strain plot (fig. 3).

Log ratios of log P1 vs. log P3 are plotted in analogy with the log X/Y vs. log Y/Z as used in strain analysis where X, Y and Z are the principal strain axes in a rock. The strained ferromagnetic sites lie mainly in the oblate – compressional field $(E^{>1})$ with a few sites showing prolate – tensile fabrics $(E^{<1})$. The sites







Fig. 4: Two anisotropy factor (P_2) profiles and two ellipticity profiles (E) with respect to distance from the P.L. are presented. 4(a) and 4(b) are from a profile going northwards from the P.L., and 4(c) and 4(d) are from a profile going southwards from the line. It is seen that the anisotropy on the line is very high and falls very rapidly with distance away from it. This suggests that the P.L. has been subjected to a shearing compression.

with the extremely high ellipticities are found to be sites from directly on or immediately to the N and S of the P.L.

Ellipticity and anisotropy factor profiles (figs. 4a-4d) show that the extremely high anisotropy on the P.L. falls rapidly to low values to the N and S of the line, leaving no doubt that the P.L. is a compressional zone. The fact that the anisotropy factors fall so rapidly with distance from the line suggests that the compression was not a simple compression, whereby the pressure acted normally to the compression zone, but rather a shearing compression acting at an angle to the P.L., causing vertical or horizontal movements. In order to obtain the sense of this movement an analysis of the minimum magnetic axes is presented. Since the minimum axes parallel the pole to the cleavage in cleaved rocks and thus parallel the direction of straining force, an analysis of the minimum axes should yield the sense of action of compression and hence movement along the P.L.

Figure 5a is a direction rose of the minimum susceptibility axes for all sites. There are 3 major directions to be seen:

- a) The c. N 25° W S 25° E direction,
- b) The c. N 35° E S 35° W direction,
- c) The approximately due East direction (RATHORE et al. 1977).

A breakdown of these directions into sites with bulk ferromagnetic and bulk diamagnetic susceptibilities is seen in figs. 5b and 5c. It is seen that only one of the three directions is dominant in both diagrams, namely the N 35° E – S 35° W. The due East directions are observed in 15 diamagnetic sites from S of the P.L. and the cause for their fabric orientation is as yet unknown and work is in progress to try and determine this. The N 25° W - S 25° E direction is predominant in the ferromagnetic sites (fig. 5b). A large majority of these sites was found to be also non-metamorphic when the sites were re-arranged into metamorphic and non-metamorphic groups (figs. 4d and 4e). The metamorphic sites show a maximum concentration of axes in the NNE-SSW direction. The diamagnetic sites with a due East direction are also metamorphosed. The group of sites giving the SSE grouping comes from the "Granit von Nötsch", which will not be discussed here. The non-metamorphic sites have 2 dominant maximas, the N 25° W maxima and the NE maxima. A further analysis of the non-metamorphic sites showed that the majority of these sites were of young Palaeozoic ages (Permian to Carboniferous), whereas the metamorphic sites are mainly younger, of Triassic age (fig. 4f). Hence it can be concluded that the fabric directions in 5(e)are definitely older than those observed in 5(d), and that there have been 2 major phases of deformation over this area. Furthermore, a classification of the rocks into a) extremely brittle, b) extremely slatey and c) extremely plastic showed that the plastic group contained all the metamorphic sites with the grouping of axes along the NNE-SSW direction. It is argued that since the plastic rocks are the most easily deformed they must carry the fabric due to the latest tectonic event. Seven sites lying in the "Gailtal Kristallin" on the P.L. in very schistose and some extremely brittle rocks also show this fabric direction. Rock types similar to these further removed from the P.L. show only the young Palaeozoic directions (fig. 5f). This tends to suggest that the highly brittle and schistose sites have been subjected



Fig. 5: An analysis of the magnetic susceptibility minimum axes is presented. 5(a) is a direction rose showing the directions of all 145 sites. 3 major directions are to be seen: NNW—SSE; NNE—SSW and due East (see text). 5(b) is a direction rose of ferromagnetic sites only and 5(c) diamagnetic sites only. 5(d) is a direction rose of all the metamorphic sites and 5(e) of till the non-metamorphic sites. 5(f) is the direction rose of all the young Palaeozoic sites.



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to different amounts of stress depending upon the distance from the P.L. Those close to and on the P.L. were subjected to high stresses, enough to alter their fabrics to the NNE-SSW fabric, and those further away retained their previous fabric because the stresses were not high enough to overprint their existing fabrics. So the young Palaeozoic fabrics in the hard rocks have to be older than the NNW-SSW fabric, otherwise the softer plastic material would also show the same fabrics. Hence it can be concluded that the NNE-SSW fabric is definitely younger than Palaeozoic, and it is possible that the older fabric is also younger than Palaeozoic, at the most a late Hercynian fabric. Since the above two fabrics are to be found both to the N and S of the line it is to be concluded that any relative rotations between the Northern and Southern blocks are ruled out. The NNE-SSW compression direction cuts the P.L. such that there is an acute angle between this direction and the trend of the P.L. If this compressional direction is resolved into two components, one normal and one parallel to the P.L. it is seen that the parallel component acts such that the movement takes place anticlockwise (sinistrally) along the P.L. in this region. This result is in agreement with geological observations in this area (L. BRIGO, personal communications). However, the co-existence of the two fabric directions in this region leaves the same of movement inconclusive, and further studies on other sectors of the P.L. were initiated.

Region 2: Pusterer Line — Judicarian Line junction at Mauls

In this region the magnetic fabric led to the following conclusions:

- 1) The Judicarian Line (J.L.) is a highly compressed fault zone.
- 2) The Pusterer Line (Pu.L.) is a weakly compressed zone, and maybe continues to the west of the junction.
- 3) The sense of movement along the Pu.L. was dextral and on the J.L., sinistral (RATHORE and HEINZ, 1979).

395 samples from 58 sites in 27 localities were collected along 3 profiles cutting the P.L. in the region of Mauls (South Tyrol) at the Pu.L. and J.L. junction (fig. 6). Of the 27 localities measured, 19 have a dominant foliation and 8 a dominant lineation (fig. 7).

The ellipticities of the sites from the Brixen Granite form 2 distinct groups: the localities from near the contact of the granite with the "Altkristallin" have a dominant foliation whereas the sites from deeper in the body of the granite show dominant lineations. These lineations are however very weak as seen in the ellipticity profiles (fig. 8(c), (e)).

A study of these profiles gives a good picture as to the variation in the degree of deformation. Profile A-A shows oblate fabric along its entire length and has high ellipticities at its two ends with a low in the middle (fig. 8a). The P₂ value, which is a guide to the degree of deformation, follows the same pattern (fig. 8b). The E and P₂ values at the cross-over of the J.L. are 1.483 and 1.701 respectively in the Brixen Granite. This indicates a very high degree of deformation because of the relative hardness of the granite. The magnetic foliations are very steep in



Fig. 6: From RATHORE and HEINZ (1979). A map of section 2 indicating the sampled localities and locality mean fabrics. Note that within the body of the Brixen Granite all but one locality have a prolate fabric. In the prolate sites the lineation direction is shown and the inclination to the horizontal is indicated. The fabrics of the oblate localities are presented on lower hemisphere equal-angle projections.



Fig. 7: From RATHORE and HEINZ (1979). This is a strain plot of the localities in this section. All prolate points are in the Brixen Granite. The high ellipticities in this plot belong to sites from the southern end of profile A—A (fig. 6), i.e. from the cross-over at the Judicarian Line. Points along the Pusterer Line plot in the middle of the compressional deformation field.



this region dipping to the NW. The trend of the minimum axes are such as to produce a resolved part of the compression which would effect a sinistral movement along the J.L. in this region. This sense of movement is supported by geological observations (SEMENZA, 1974). Preliminary results from the Mt. Croce region (region 3) further support this high compression on the J.L. accompanied by the sinistral movement along it. The other highly deformed region on profile A-A is at locality 11, west of Frienfeld. This locality lies very near to the continuation of the Pu.L. to the W. The fabric orientations of sites 11 and 2 fit this extension well, although the fabric of locality 13 is rotated through 90° . The extension of the Pu.L. to the W has been proposed by Tollmann (TOLL-MANN, 1976, 1977) from the study of satellite pictures of the region and the magnetic fabric tends to confirm this. The etched region containing localities 2, 13, 12, 4 and 5 shows complications in the magnetic fabric and the fabric parameters in this region are generally low. It has been shown that this region has undergone a late thermal metamorphism and that the cooling in this region took place as recently as 15-20 My. ago (FRANK et al. 1977, 1979, personal communications). As a result the fabric in this region is obviously overprinted due to this thermal metamorphism.

Profile B-B crosses the Pu.L./J.L. junction at Mauls and the localities in the "Altkristallin" show a dominant foliation whereas those in the Brixen Granite show a dominant but weak lineation. The deformation profiles 8(c) and 8(d) are different to those of profile A-A. Here the parameter values fall to very low values at the Pu.L. and remain low on crossing. Similar behaviour is seen for profile C-C where the parameter profiles fall to 1.0 at the cross-over of the Pu.L. The fabric orientations along the two profiles in the "Altkristallin" and in the Rensen Granite in profile C-C are compressional oblate fabrics. Hence, looking along the Pu.L., the fabric results can be interpreted as resulting from a compression which acted mainly on the J.L. and to a lesser extent along the Pu.L.

Once again if the directions of the minimum axes of the oblate sites are resolved normal and parallel to the Pu.L. it is seen that the effect of the component parallel to the line is such as to cause a net dextral movement along the Pu.L. (fig. 9). A model for the dynamics of the Pu.L. and the J.L. is presented (RATHORE and HEINZ, 1979) whereby the P.L. is considered to have been a zone of weakness on a plate which moved northwards and rotated anticlockwise at the same time (fig. 10).

On collision of this plate with the Briançonic Platform the Periadriatic Line was activated or re-activated such that the energy of the collision was dissipated in compression and sinistral movement along the Judicarian Line and dextral movement along the Pusterer-Gailtal Line (this model is in agreement with that of FRISCH 1977). Initial analyses on the "Gailtalkristallin" from the Lesachtal

Fig. 8: From RATHORE and HEINZ (1979). Ellipticity (E) and anisotropy parameter (P₂) profiles along A—A (8a, 8b), B—B (8c, 8d) and C—C (8e, 8f) field profiles. Note that in 8c and 8e the E values on the Pusterer Line have dropped to 1.0 and in 8d and 8f the P₂ values are less than 1.1. The compression in this region of the P.L. is entirely different to that observed in section 1 (figs. 4a—4d).



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Fig. 9



confirm the net dextral movement along the Pusterer-Gailtal Line, although the movement has taken place blockwise where some small blocks have moved sinistrally.

Conclusions

Magnetic fabric analyses along the Pusterer-Gailtal Line and the Judicarian Line showed that the lower Gailtal (section 1, fig. 1) is a compressional fault zone in which very high compression is localised to within a kilometer or so to the N and S of the line. In this region, at least two phases of compression occured, a stronger one in a direction c. NNW-SSE followed by a weaker one, c. NNE-SSW. The existence of identical fabrics to both N and S of the line rule out the possibility of relative rotations taking place. An analysis of the fabric directions in connection with th relative hardness of the rocks concerned yielded that the sense of the movement along the line in this section was anticlockwise (sinistral). Geological evidence supports this conclusion (L. BRIGO, personal communications). In the section of the Periadriatic Line where the Pusterer and the Judicarian Lines meet, near Mauls in South Tyrol, the magnetic fabric yielded that the Judicarian Line is a highly compressional fault zone, where sinistral movement has taken place. Evidence for this is found also in section 3 (fig. 1), and geological observations (SEMENCA, 1974) verify this result. The sense of movement on the Pusterer Line is dextral, and a tectonic configuration of the region is presented (fig. 10). Tentative evidence for the continuation of the Pusterer Line to the West has also been found.

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- Fig. 9: The minimum axis directions schematically represented as unit resultant compressional force vectors have been resolved into vectors normal and parallel to the Pu.L. and J.L. From the sense of the parallel vectors it can be deduced that the motion along the J.L. is sinistral and that along the Pu.L. is dextral.
- Fig. 10: From RATHORE and HEINZ (1979). Schematic representation of the (re)activation of the P.L. in the Cretacious.

 - Compression free zone
 Directions of compression
 Rotation direction of the whole block
 - 4. Etched-Brixen Granite.

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