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Magnetic Properties of Swiss Flysch*

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Abstract. The principal magnetic mineral present in the flysch units of central Switzerland is magnetite which exhibits susceptibility anisotropy corresponding to a sedimentary fabric. Remanent magnetization directions are consistent for the finer grained (upper) parts of the turbidity flows. Laboratory controlled build-up of viscous remanent magnetization indicates that the natural remanence could have been viscously acquired during the Brunhes epoch.

Key words: Rock magnetism – Viscous remanent magnetization – Anisotropy of magnetic susceptibility – Flysch.

1. Introduction

The flysch units of Central Switzerland are made up of several 1,200–1,600-m-thick series of alternating fine-grained sandstones and shales, which were deposited during the Maastrichtian to Middle Eocene in a South Penninic deep marine ('oceanic') environment (Schaub 1951; Hsü 1960; Caron 1976; Morel 1978; Van Stuijvenberg 1979). The palaeogeographic position of these units is not altogether clear. In the Late Eocene to Oligocene, during the Mesoalpine orogeny (Trümpy 1973), they were torn from their roots and transported northwards over considerable distances and now lie in thrust sheets at the base of the Prealps (Fig. 1).

Outcrop is poor throughout the external Prealps and the sampling was restricted to four quarries in the Gurnigel, and three river beds in the Schlieren and Wägital flysch. The dip of the strata is similar throughout each of the three units, and therefore the palaeomagnetic results from the outcrops were deemed representative for the whole unit.

Originally we had hoped to concentrate on the finest-grained layers by sampling at the top of each turbidite cycle in addition to the calcitic hemipelagic interbeds. Most of these rocks proved too friable to drill successfully or too clay-rich to survive desication and cutting in the laboratory. As a result, most of the samples are from the upper parts of each turbidite cycle and are in general fine grained ($^1/_4$–$^1/_8$ mm) arkosic sandstones with a significant (up to 30%) contribution of volcanic and plutonic detrital fragments (Hubert 1967).

2. Magnetic Properties

The flysch beds are generally turbiditic and therefore show grain size decrease from bottom to top. Prior to the main sampling, two flows from the Gurnigel flysch (Zollhaus quarry) were sampled in detail, and consistent NRM directions were found towards the top of the flows. However, the magnetization intensity decreases to the noise level of the magnetometer at the base of the flows where the magnetization directions cannot be precisely measured. This may reflect either a decrease in ferromagnetic mineral content or increasing turbulent deposition towards the bottom of the turbidite flows.

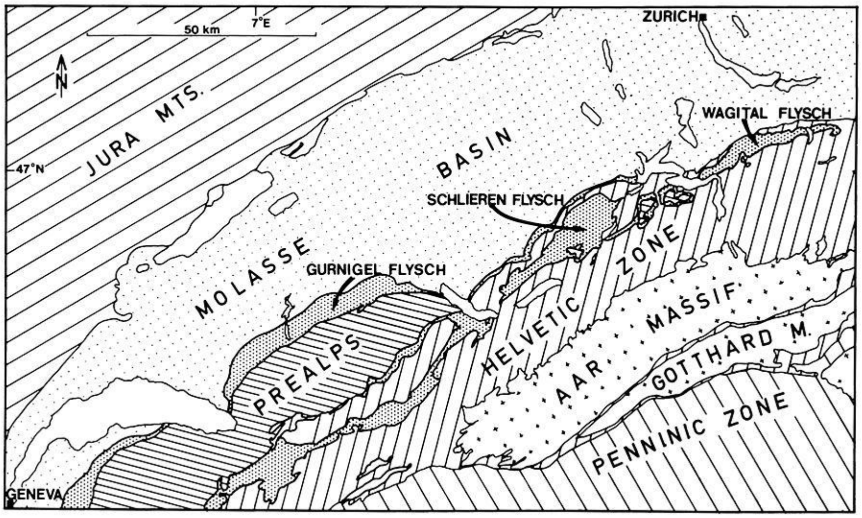

Fig. 1. Location Map

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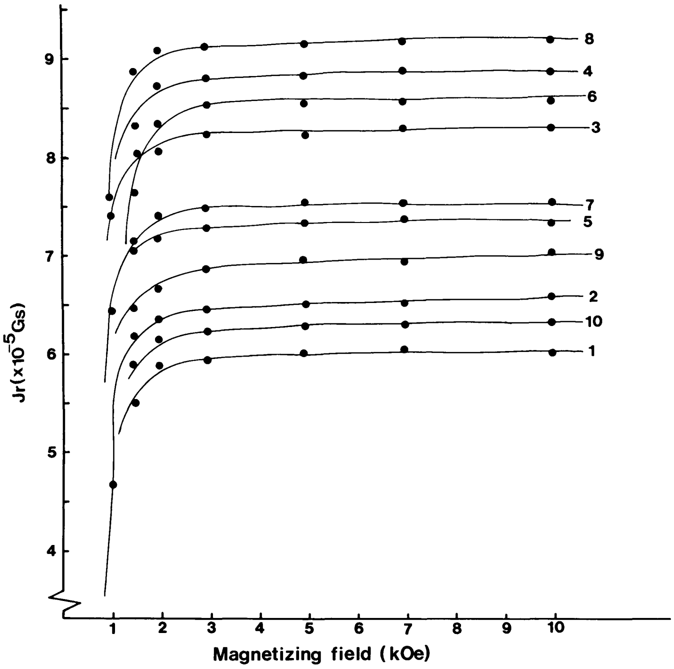

Fig. 2. Acquisition curves of Isothermal Remanent Magnetization (IRM) for a single turbidite flow from the Gurnigel flysch (Zollhaus Quarry), the labels refer to the order of the samples from the top (1) to the base (10) of the flow

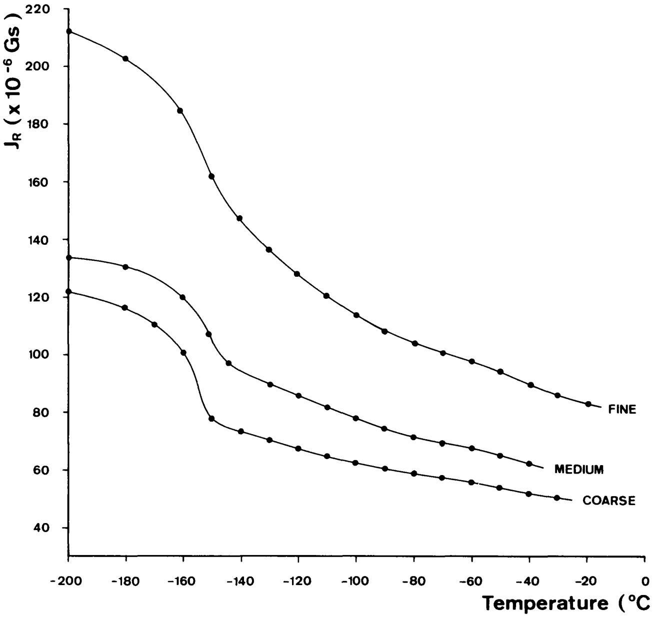

Fig. 3. Decay of an IRM (imposed at liquid nitrogen temperature) during warming to room temperature for three samples from the same flow. Approximate mean grain size. Very fine to fine ($^1/_4$–$^1/_{10}$ mm), Medium ($^1/_2$–$^1/_4$ mm), Coarse (1–$^1/_2$ mm)

(a) Isothermal Remanent Magnetization (IRM)

The acquisition of IRM provides a very useful guide to the coercivity spectrum of magnetic minerals present in a rock sample. The shape of the acquisition curves from a single turbidite flow (Fig. 2), and also from throughout the sampling area, indicates that low coercivity minerals are present in the flysch. All samples are saturated at 2–3 kOe. The value of saturation remanence at room temperature shows no consistent relationship with position of the sample within the graded bed (Fig. 2), suggesting that the weight percent of magnetic mineral does not vary consistently, and that the decrease in NRM intensity is either a function of grain size and/or the alignment efficiency of detrital grains.

The variation in magnetic grain size within the beds is reflected during low temperature treatment (Fig. 3). The samples were given a saturation IRM (in a 10 kOe field), at liquid nitrogen temperature (−196° C) and the remanence was measured during warming to room temperature. In the coarser grained sediments, a sudden decrease of remanence is observed corresponding to the change of sign of the principal magnetic anisotropy constant K_1 of magnetite at about −150° C (Nagata et al. 1964). The transition temperature depends on the concentration of impurity cations in magnetite (Syono 1965) and is depressed by small titanium contents. It is suppressed entirely if the magnetite is single domain, the magnetic anisotropy of magnetite being mainly shape controlled. The form and appearance of the transition depends on the grain size of the sample (Fig. 3). The transition is most distinctly observed in the coarse grained samples where about 30% of the low temperature IRM has been lost. This percentage corresponds to the contribution of multidomain magnetite, therefore, a major portion of IRM must be carried by single domain (perhaps pseudo-single domain) grains. The IRM intensity decreases further when warming from −150° C to room temperature indicating a small contribution from superparamagnetic magnetite. The medium grain-sized samples (Fig. 3) show a slightly broadened, but still pronounced, transition. The portion of the IRM carried by multidomain magnetite is reduced (<25%), and the gradient of the curve above the transition is steeper. Therefore the contribution of single domain and superparamagnetic (at room temperature) grains is enhanced in the medium grained as opposed to the coarse grained samples. In the fine grained samples (Fig. 3), the transition is difficult to recognise, indicating that the multidomain fraction is largely absent. The low temperature IRM intensity is about twice the usual room temperature value (Fig. 2). The shape of the curve indicates a large contribution from very fine grained magnetite which is superparamagnetic at room temperature.

Thus the magnetic mineralogy in the flysch samples is dominated by superparamagnetic and single domain magnetite. Multidomain magnetite is an important contributor to the magnetization of the coarser grained material, but the vast majority of the samples were collected from the fine-grained parts of the turbidite flows.

A maximum blocking temperature of about 540° (Fig. 4) was obtained by giving a sample a saturation IRM at room temperature and monitoring the decay of this IRM progressively during heating, using apparatus designed by Heiniger and Heller (1976). This maximum blocking temperature together with the IRM acquisition curves (Fig. 2) and the low temperature characteristics (Fig. 3) indicate that magnetite is the only magnetic mineral present in the flysch.

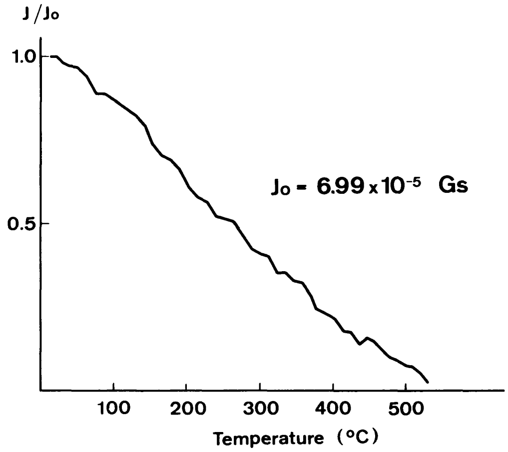

Fig. 4. Continuous measurement of the decay of an IRM (imposed at room temperature) during heating for a fine-grained sample

(b) Natural Remanent Magnetization (NRM)

The NRM directions are consistent for finer grain sizes within a single flow, and for fine grained samples from all exposures (Fig. 5). On AF demagnetization the scatter of directions increases, as the magnetization intensities approach the noise level of the ScT magnetometer. The ScT cryogenic magnetometer measures the magnetization along three orthogonal directions at the same time and almost instantaneously, regardless of the intensity of the magnetization. The samples were measured in the upright and inverted position and the six magnetization component readings were combined to produce eight estimates of the remanent magnetization vector. The parameter ψ is a measure of the deviation of the eight directions about their mean and is a useful reliability parameter for individual sample measurements (Lowrie et al. 1980)

where $\psi = 81\,[(N-1)/(N-R)]^{-1/2}$
and N = number of estimates (8) of magnetic moment vector, R = vector sum of eight estimates of magnetization vector.

The uncertainty in individual sample measurements, quantified by ψ, increases with increasing peak demagnetization field as magnetization intensity decreases. This is due to unstable magnetziation of these samples as well as to the fact that the noise level of the magnetometer is approached. The weak magnetization intensity of the NRM (mean value 10^{-7}G) and the low median destructive field (100 Oe) often causes the magnetization intensity to fall beneath the noise level of the magnetometer after demagnetization at 200 Oe or 300° C (see Fig. 6). However, in many cases the samples picked up a secondary magnetization after treatment at higher fields and temperatures, indicating a tendency for viscous remagnetization.

The significance of the apparently stable NRM directions was tested in two ways, the first being a field test and the second a laboratory test of VRM acquisition.

For the field test, we sampled a drag fold at the base of the Schlieren flysch. From AF and thermal cleaning results we isolated the most stable directions using a criterion based on the minimum change of magnetization direction between two demagnetization steps. The results are plotted in Fig. 7. The directions before fold correction are scattered to some extent and their mean is located near the present Earth's field direction. After correcting for sample attitude in the fold, the dispersion is greatly increased, and the magnetizations from the overturned limb now lie in the upper hemisphere (Fig. 7). This failed fold test indicates that the NRM was acquired after Alpine emplacement.

(c) Viscous Remanent Magnetization (VRM)

The acquisition of VRM for six samples from the main (fine grained) sample collection was monitored by allowing the samples

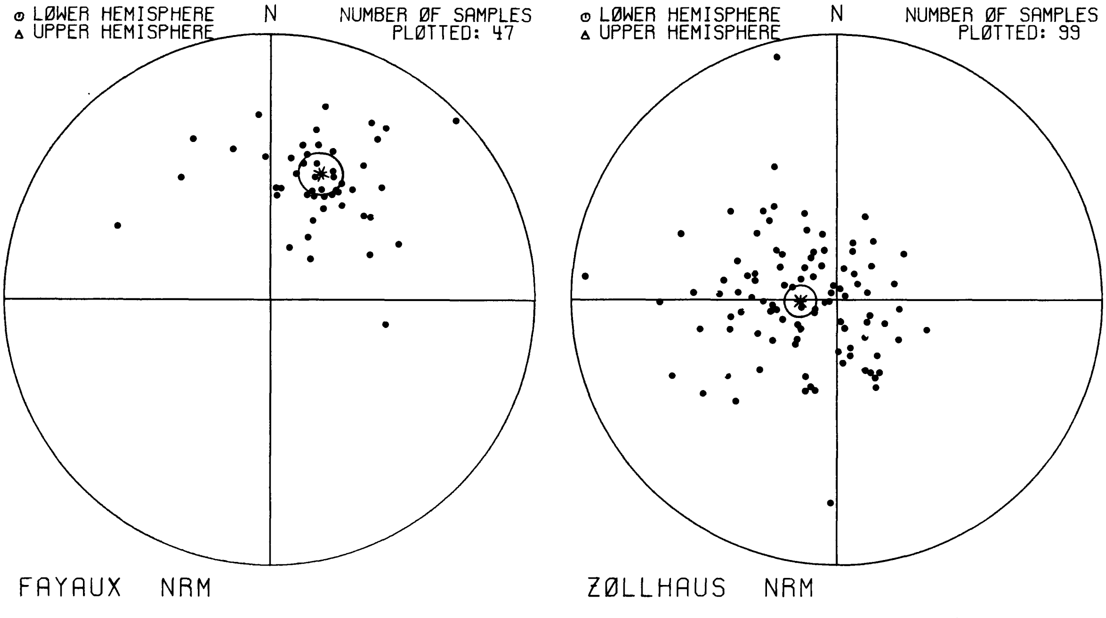

Fig. 5. Natural remanent magnetization directions of fine-grained samples from two Gurnigel flysch quarries before tectonic correction

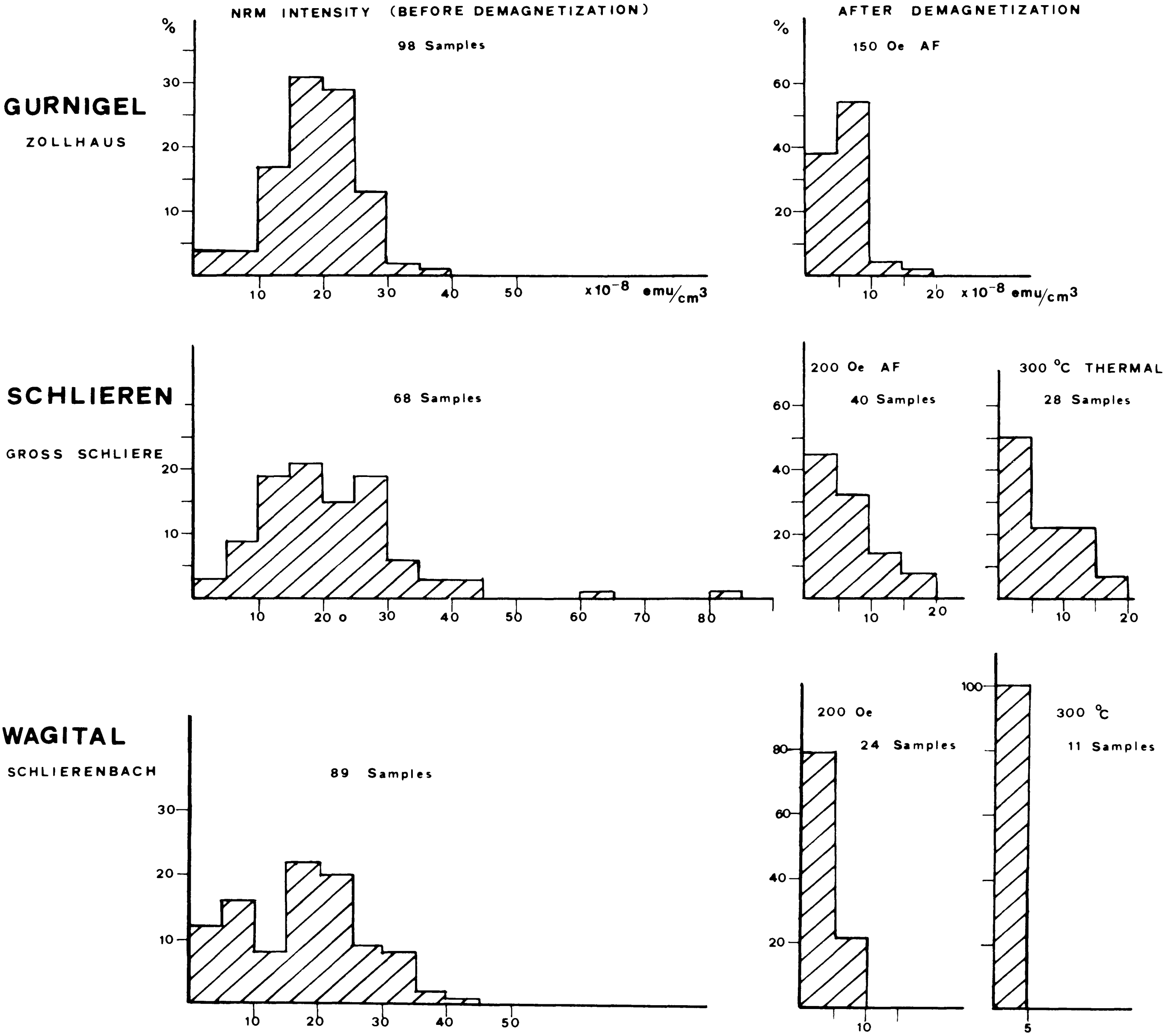

Fig. 6. Histograms of the magnetization intensity before and after AF or thermal demagnetization

to remain in the Earth's field and observing the build-up of magnetic remanence over a 6-month period. These samples were randomly selected and represent the general VRM properties of the flysch. Starting from the momentary NRM state (both undemagnetized and AF cleaned with peak fields of 200 Oe), the acquisition of VRM appears to depend on the logarithm of time (Fig. 8). If we assume no long term changes in the magnetic viscosity behaviour, we can extrapolate the straight-lines to values of log t corresponding to the onset of the Brunhes epoch. It is indicated that considerable build-up remanence may have occurred since the last reversal of the earth's magnetic field. The extrapolated intensity of VRM exceeds the magnitude of the NRM.

The AF demagnetization of the VRM (Fig. 9) shows that the VRM-components acquired during a 6-month period in the laboratory can be totally obliterated in peak fields of 40–80 Oe. The remanence vectors removed (Fig. 9) during AF cleaning are perfectly aligned along the present day field direction (Dec = 358°, Inc = 63°) after the first demagnetization step ($H = 20$ Oe). As demagnetization proceeds, the removed vectors become more and more dispersed reaching a nearly random distribution after demagnetization in peak fields of 100 Oe with values of $\alpha_{95} = 40°$ ($N = 17$). The relationship

$$\frac{H_1}{H_2} = \frac{\log t_1}{\log t_2} \quad \text{(Néel 1955)}$$

where H_1 and H_2 are the peak alternating fields necessary to obliterate the viscous build-up in time t_1 and t_2 respectively, can give an estimate of the field H_2 necessary to remove a VRM acquired during the Brunhes epoch. If $H_1 = 60 \pm 20$ Oe, $t_1 = 6$ months, $t_2 = 700{,}000$ years then $H_2 = 160 \pm 50$ Oe. The values of

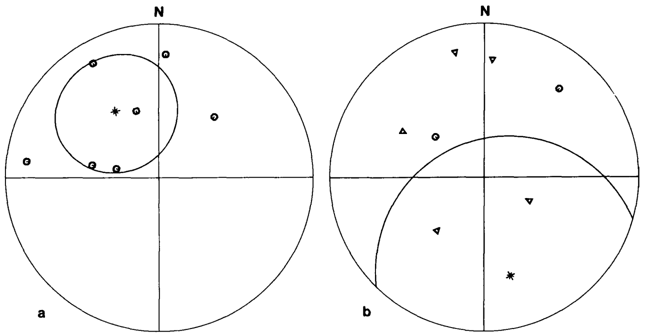

Fig. 7a and b. Fold test in the Schlierenflysch. The small circles represent sample directions in the lower hemisphere while the small triangles are directions in the upper hemisphere. The star locates the mean direction and the ellipse is the projection of the 95% confidence circle. **a** Before fold correction. **b** After fold correction

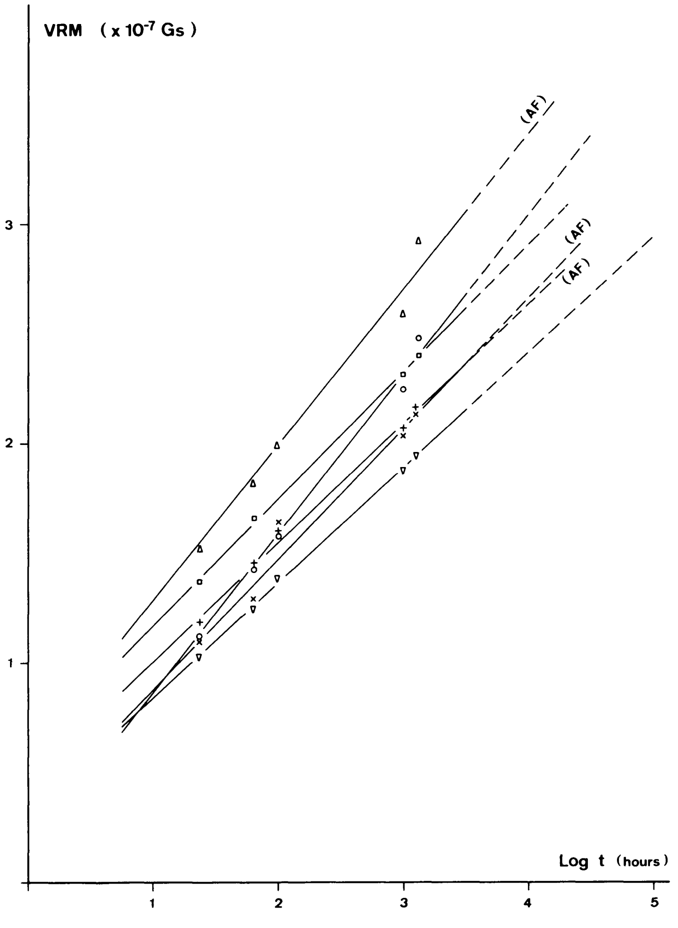

Fig. 8. The intensity of VRM acquired in time (t) plotted against log t. Three of the samples were demagnetized (AF) up to peak fields of 200 Oe at time $t=0$

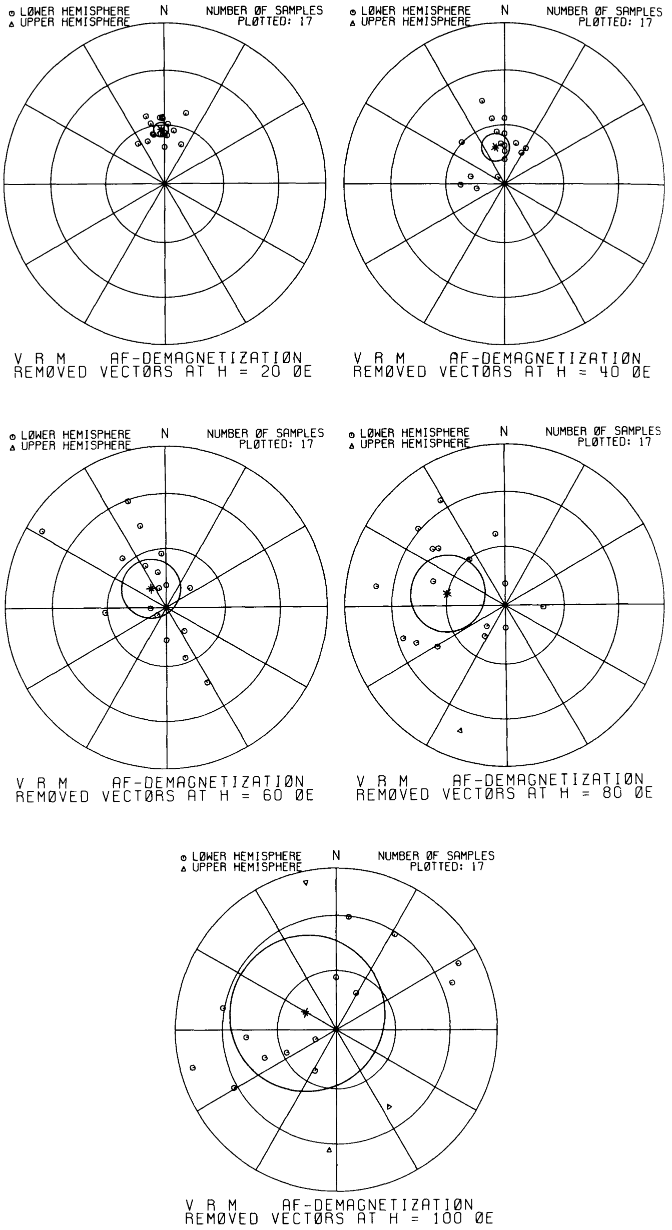

Fig. 9. Removed vectors during various stages of alternating field demagnetization of the VRM acquired in 6 months

H_2 coincide with the range of peak demagnetizing fields at which the NRM reached instrumental noise level. Therefore both build-up of VRM during storage and its subsequent destruction by alternating fields indicate that the NRM of these flysch samples is entirely of viscous origin and acquired during the Brunhes normal epoch.

In order to investigate the viscous behaviour in more detail, we studied several samples which were much more viscous than the norm. In this experiment we continuously recorded the decay of viscous magnetization acquired during 5–400 sec emplacement in the Earth's field (Fig. 10).

Dunlop and West (1969) reviewed the theoretical and experimental evidence showing that multidomain grains have a decay rate of VRM half as big as the growth rate. In these flysch samples, the decay rate was about 1.5 times greater than the growth rate. This evidence further supports the hypothesis that single domain magnetite grains with short relaxation times at room temperature are responsible for the VRM in the flysch.

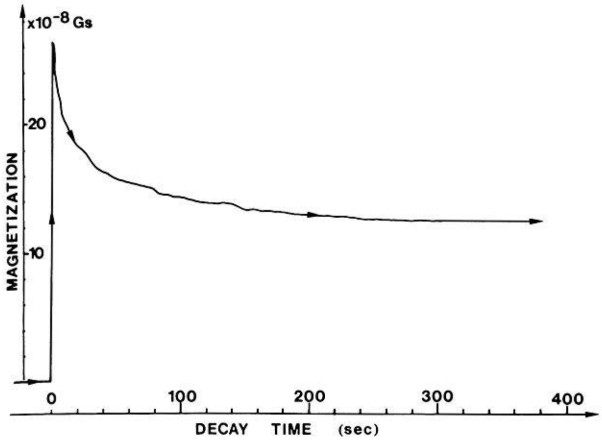

Fig. 10. Decay of the z-component of magnetization of a flysch sample held 360 sec in the Earth's field and then immediately lowered into the measuring region of the cryogenic magnetometer

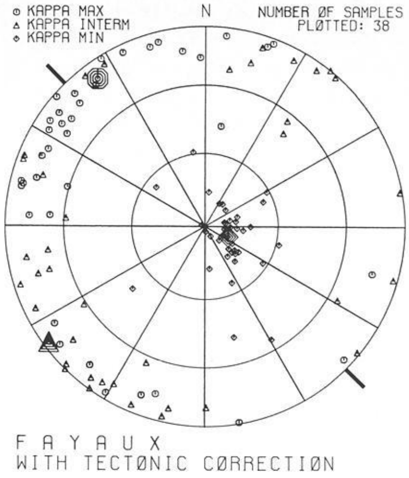

Fig. 12. Axes of the magnetic susceptibility ellipsoid for samples from the Fayaux quarry of the Gurnigel flysch. The *thick lines* at the edge of the circle give the mean elongation axis of flute casts

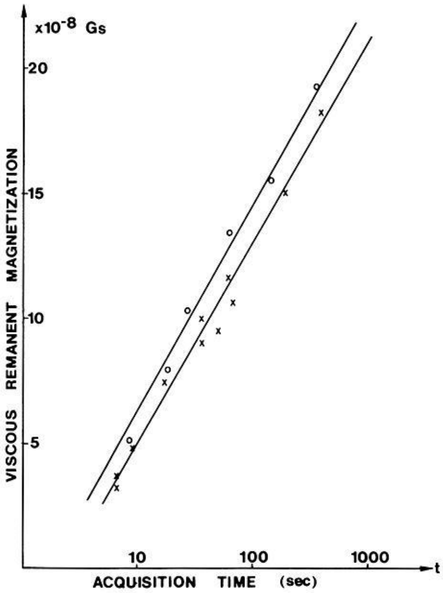

Fig. 11. Short time acquisition of VRM. The slopes are identical for both the undemagnetized (*crosses*) and the demagnetized (*circles*) sample

A plot of the acquired VRM against log t (sec) for an undemagnetized and demagnetized pair of these very viscous flysch samples (Fig. 11) demonstrates the very fast acquisition of VRM. The acquisition behaviour is similar for both magnetization states, and these samples acquired 50% of their NRM values in about 10 min.

The viscosity of the flysch samples may be related to their relatively high content of volcanic and plutonic detritus. X-ray diffraction analysis of a magnetically separated fraction, optical examination of polished sections and microprobe investigations failed to identify any magnetic mineral. Thus the magnetite grains are probably smaller than the resolving power of these methods (ca. 1 μm). However, a large albite component was present in the magnetically separated fraction. Since albite itself is not magnetic, this observation indicates that magnetite might be present as exsolved phases within the twinning lamellae of the plagioclase. Indeed, in thin sections several large grains of albite did exhibit tiny opaque phases – possibly magnetite – aligned along the twinning interfaces. These phases were in the micron to submicron size and may be responsible for the particular viscosity of the rocks investigated.

The viscous nature of the NRM explains the lack of reversed NRM directions (Fig. 5). The time span represented by the deposition of the samples is such that reversed directions would be expected if the magnetizations were primary. The NRM directions before tectonic correction (Fig. 5) are close to, but do not coincide with, the present-earth's field direction. This is probably due to the influence of VRM acquired in the laboratory which would have some consistency in direction for cores drilled with a preferred orientation in a quarry face, and subsequently stored upright in the laboratory.

(d) Magnetic Anisotropy

In magnetite bearing rocks such as the Gurnigel flysch, shape anisotropy in magnetite usually controls the form of the susceptibility ellipsoid. After alternating field demagnetization, the susceptibility of the samples was measured using the ScT cryogenic magnetometer in susceptibility mode as described by Scriba and Heller (1978). The susceptibility in the flysch is anisotropic. The predominant feature of the plots of the major axes of the susceptibility ellipsoids (Fig. 12) is that the minimum susceptibility axes are oriented perpendicular to bedding. The susceptibility ellipsoids are oblate (disc shaped), in other words, the ratio $(k_{\text{int}} - k_{\text{min}})/(k_{\text{max}} - k_{\text{int}})$ is greater than unity. k_{max} and k_{int} are not always distinguished (Channell et al. 1979) but in the case of Fayaux (Fig. 12) the maximum susceptibility axes coincide with the axes of flute casts. This oblate sedimentary fabric is typical for magnetite bearing rocks but the mode of occurrence of magnetite in these flysch leads us to believe that the fabric may not be due to the shape alignment of the magnetite grains themselves. The magnetite grains are smaller than a few microns and occur along the twin planes (010) of albite grains. The predominant cleavage planes of albite are (001) and (010), therefore the elongated clusters of magnetite grains will tend to be oriented parallel to the maximum elongation axes of the host albite. The sedimentary fabric in the flysch is due to the orientation of albite and other detrital grains by gravitational and hydrodynamic forces. It is the coincidence of elongation axes of albites and the elongation of magnetite clusters that gives rise to a susceptibility anisotropy which reflects sedimentary processes.

3. Conclusion

Although not positively identified by X-ray and optical examination, the presence of magnetite in the flysch has been established by coercivity and blocking temperature spectrum analysis. VRM tests and IRM low temperature characteristics suggest that the magnetite grain size is predominantly in the single domain to superparamagnetic range. VRM has totally obliterated any primary magnetization which may have been present, and therefore the NRM of the flysch of Central Switzerland no longer records the direction of the ambient magnetic field at time of deposition. The susceptibility anisotropy records a sedimentary fabric and records preferential alignment of grains and hence palaeocurrent direction.

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