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Anisotropies of anhysteretic remanence and magnetic susceptibility of marly clays from Central Italy

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Abstract
Marly clays from an Upper Pliocene unit at Valle Ricca (Rome) were investigated for their Anisotropy of Anhysteretic Remanence (AAR) and Anisotropy of Magnetic Susceptibility (AMS). The study of AAR was accomplished for the first time in Italy, developing a suitable laboratory technique and adapting a standard statistical procedure. The comparison between anhysteretic remanence and magnetic susceptibility anisotropies discriminates the fabric of the ferromagnetic fraction from that of the paramagnetic matrix of the rock. The separation of fabric components was applied to distinguish subsequent geological processes that affected the total rock fabric. The results indicate that the clayey units are particularly suitable for the empirical investigation of fabric to strain relationship in weakly deformed rocks.

Key words *anhysteretic remanent magnetization – magnetic susceptibility – anisotropy – clays*

1. Introduction

Anhysteretic Remanent Magnetization (ARM) is acquired by a ferromagnetic grain exposed to the simultaneous action of an alternating magnetic field and a steady magnetic field of lower intensity. The ARM acquired by a rock sample is usually parallel to the steady field and its intensity is a function of the intensities of both the applied magnetic fields (*e.g.* Nagata, 1961; Patton and Fitch, 1962; Stacey and Banerjee, 1974). The ARM of a rock specimen also depends on the relative orientation between the steady field and the assembly of magnetic particles; the study of the Anisotropy of Anhysteretic Remanent magnetization (AAR) is a relatively new method in rock-magnetism (McCabe *et al.*, 1985), useful to determine the fabric of only those grains that are able to hold a remanent magnetization, discriminating them from the paramagnetic and diamagnetic fractions. Therefore, this technique is employed to investigate only the preferred orientation of the stable remanence carriers, that is mainly single-domain and pseudo single-domain ferromagnetic grains. The method is complementary to the study of the Anisotropy of the low-field Magnetic Susceptibility (AMS), which is due to all the rock fractions. Particularly, the combined use of AMS and AAR analyses may help in discriminating the different sources and processes that contributed to the origin of the total fabric of a rock (Jackson, 1991).

In paleomagnetic studies, AAR analysis is important to recognize the preferred orientation of the ferromagnetic particles in a rock, in order to evaluate the fidelity with which a natural remanence records the paleofield orientation (Jackson *et al.*, 1991).

In petrofabric studies, AAR analyses are suitable to investigate rocks whose susceptibility, or degree of AMS, are too low to be measured successfully (*e.g.* McCabe *et al.*, 1985 and Jackson, 1991).

It is also noteworthy that the study of remanence, instead of susceptibility, always gives unambiguous determination of the magnetic fabric, showing the minimum remanence axis perpendicular to the easy magnetization axis of both single-domain and multi-domain ferromagnetic grains (Potter and Stephenson, 1988).

This study describes the laboratory technique that we set up to give an ARM to a standard paleomagnetic specimen and to compute its anisotropy. Results are shown for fifteen samples taken from a 10 m-thick interval in the Upper Pliocene marly clays exposed at the Tini quarry section in Valle Ricca, near Rome (fig. 1), whose magnetostratigraphy and rock-magnetism were investigated previously (Arias *et al.*, 1980, 1990; Florindo and Sagnotti, 1993). Strong variations in the ferromagnetic mineralogy were evidenced in the section (Florindo and Sagnotti, to be submitted). Magnetite is a ubiquitous magnetic carrier, ferrimagnetic iron sulphides (greigite, pyrrhotite?) dominate the magnetic behaviour at two thin (≈ 1 m) levels around a 50 cm-thick volcanic ash layer.

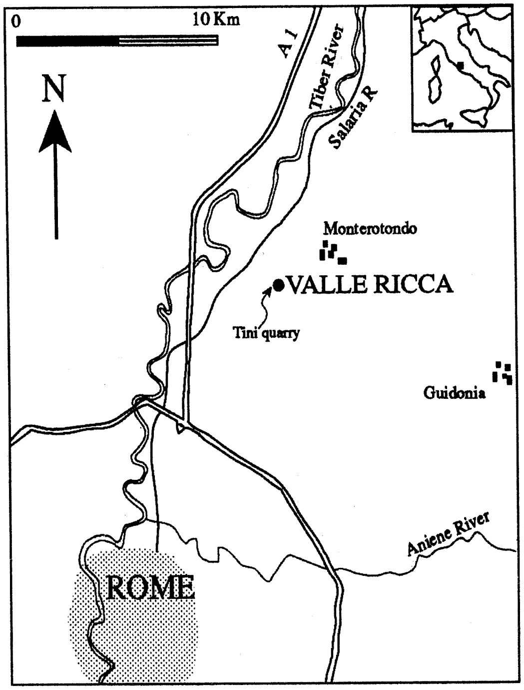

Fig. 1. Location of the investigated section.

Both AMS and AAR were studied on all samples, in order to check the validity of AAR as a rock-magnetism investigation tool, and to discriminate the fabrics due to the ferromagnetic fraction and the paramagnetic matrix, in relation to the sedimentary, compactional and tectonic processes which occurred during the rock's geological history.

2. Methodology

Fifteen standard specimens were analyzed, sliced from different oriented cores sampled by *in situ* drilling. All the measurements were performed at the paleomagnetic laboratory of the Istituto Nazionale di Geofisica, in a magnetically shielded room.

A Molspin AF demagnetizer was employed as source of the alternating magnetic field; the superimposition of a steady field was attained by a small coil inside and coaxial to the demagnetizer one. Since the steady field is a function of the coil current, this current should be kept as constant as possible. The constancy of the coil current was achieved using a current generator as power supply (instead of a more common voltage-generator, that would be unsuitable for induction between the alternating magnetic field and the coil). The current generator that we developed is a high-output impedance ($> 1\,M\Omega$) feedback amplifier. The uniformity of the magnetic field inside the coil, over the volume of a 2.5 × 2.2 cm standard cylindrical specimen, was also checked. The uniformity was satisfactory at ± 3% (Collinson, 1983).

The procedure used to study the AAR was that described by McCabe *et al.* (1985), consisting of a cycle of measurements and demagnetization steps to give an ARM along nine different directions to each specimen. At each step, the ARM was determined as the difference between a remanent magnetization base level and the remanence measured after the action of both the alternating and the steady fields. The remanent magnetization base level was established demagnetizing the sample in an alternating field of 30 mT peak value, while the ARM was imparted in an alternating field of 20 mT peak value, with a steady field of 0.1 mT. All remanences were measured on a JR-4 spinner magnetometer. The choice of the AF peak values, slightly different from those (30 mT and 40 mT) used by McCabe *et al.* (1985), follows the consideration in Jackson *et al.* (1989), who noticed that for the higher (≥ 30 mT) AF windows several shale specimens did not yield well-resolved AAR ellipsoids.

The AAR tensor is resolved from the nine ARM measurements. The computation of the best-fit AAR tensor, the evaluation of the statistical errors and the determination of the confidence intervals on the ARM principal axes follow the classical Jelinek's statistics (Jelinek, 1977), originally developed for the AMS analysis in a fifteen-position measurement cycle. Maximum, intermediate and minimum ARM are the tensor eigenvalues. The resolution of the anisotropy tensor was evaluated as the percentage ratio between the root-mean-square residual and the difference ($\mathrm{ARM}_{\mathrm{max}} - \mathrm{ARM}_{\mathrm{min}}$). The anisotropy tensor is considered well defined when this ratio is less than 10% (Jackson, 1991).

The AMS of the same rock-specimens was measured on a KLY-2 Kappabridge and determined by an up-to-date version of the Aniso 11 computer program for Jelinek's statistics (Jelinek, 1977).

Finally, the mean site data for both the AAR and AMS tensors were evaluated statistically grouping the results from each specimen and using the ANS 21 program (Jelinek, 1978).

The most common anisotropy factors (L, F, P' and T; see Hrouda, 1982) were computed for each specimen for both anisotropies.

3. Results and discussion

AMS and AAR tensors were resolved with satisfying approximation for all specimens; the main results are listed in table I and table II. The mean susceptibility of each specimen is fairly low. It ranges between 109.6×10^{-6} and 332.4×10^{-6} SI units, suggesting a poor contribution of the ferromagnetic fraction to the bulk susceptibility, that can be mainly referred to the paramagnetic clayey matrix. The mean ARM ranges between 1704×10^{-3} A/m and 1831×10^{-2} A/m, and shows a more pronounced variability. Also, the remanent magnetization base level at 30 mT AF for different specimens shows differences up to two orders of magnitude, indicating remarkable changes in the ferromagnetic mineralogy.

The ARM and bulk susceptibility values are plotted against stratigraphic height in fig. 2a. They are both larger for the specimens collected in the upper part of the sequence, above the volcanic ash layer. The agreement between the two trends shows that larger amounts of ferromagnetic grains are reflected directly by a larger susceptibility value.

The differences between ARM and susceptibility are more evident when their anisotropy is examined (tables I and II).

As expected theoretically, the anisotropy degree (P') of AMS is lower than that of AAR for all fifteen samples. Indeed, since it is more difficult to give a remanent magnetization along an unfavorable axis than to induce a reversible magnetization along the same axis, the remanence is more anisotropic than susceptibility (Stephenson *et al.*, 1986). Stratigraphic plots and histograms of the anisotropy degree, both for susceptibility and remanence, are shown in figs. 2b-d.

The paleomagnetic analysis of the site (Sagnotti *et al.*, 1994a) has shown a primary component of magnetization (declination = 184.4°, inclination = − 52.6°; $\alpha_{95} = 3.7°$) that reflects the expected direction of the (reverse) geocentric axial dipole field at the locality, thus indicating that the observed anisotropy degree is too low to deflect significantly the primary magnetization vector.

The shape factor T (Jelinek, 1981), which is calculated from the natural logarithm of eigenvalues, is always larger for the AMS than for the AAR. The T value is zero for a neutral magnitude ellipsoid, + 1 for a rotational oblate magnitude ellipsoid and − 1 for a rotational

Table I. Anisotropy of magnetic susceptibility factors computed for each specimen.

Specimen	Height (cm)	Mean susc. ($\times 10^{-6}$ SI)	L	F	T	P'
LZ1911C	1	139	1.003	1.035	0.821	1.043
LZ1910C	67	145	1.004	1.034	0.810	1.042
LZ1908C	144	140	1.005	1.020	0.621	1.026
LZ1905C	259	126	1.001	1.021	0.891	1.025
LZ1901A	400	128	1.002	1.024	0.827	1.029
LZ1938C	419	143	1.006	1.021	0.535	1.029
LZ1928B	503	139	1.004	1.028	0.742	1.036
LZ1914C	555	157	1.002	1.027	0.849	1.033
LZ1918A	606	111	1.003	1.031	0.827	1.038
LZ1968B	711	110	1.007	1.024	0.526	1.033
LZ1915A	758	160	1.005	1.031	0.709	1.039
LZ1953B	773	332	1.002	1.026	0.877	1.031
LZ1948B	802	281	1.003	1.042	0.853	1.050
LZ1947A	805	209	1.003	1.038	0.834	1.046
LZ1943A	914	218	1.003	1.026	0.806	1.032

$L = k_{\max}/\mathrm{k}_{\mathrm{int}}$ (magnetic lineation); $F = k_{\mathrm{int}}/\mathrm{k}_{\min}$ (magnetic foliation); $P' = \exp\{2[(\eta_1 - \eta)^2 + (\eta_2 - \eta)^2 + (\eta_3 - \eta)^2]\}^{1/2}$ (corrected anisotropy degree), where $\eta_1 = \ln k_{\max}$, $\eta_2 = \ln k_{\mathrm{int}}$, $\eta_3 = \ln k_{\min}$, $\eta = (\eta_1 + \eta_2 + \eta_3)/3$; $T = 2(\eta_2 - \eta_3)/(\eta_1 - \eta_3) - 1$ (shape factor). Height is referred to the bottom of the stratigraphic sequence.

Table II. Anisotropy of anhysteretic remanent magnetization factors computed for each specimen.

Specimen	Height (cm)	Mean ARM ($\times 10^{-6}$ A/m)	RM (30 mT) ($\times 10^{-6}$ A/m	L	F	T	P'
LZ1911C	1	2978	48	1.023	1.046	0.333	1.071
LZ1910C	67	2973	130	1.019	1.050	0.433	1.072
LZ1908C	144	3456	69	1.007	1.034	0.660	1.043
LZ1905C	259	3921	189	1.008	1.027	0.521	1.037
LZ1901A	400	4031	148	1.013	1.024	0.289	1.038
LZ1938C	419	4500	701	1.026	1.034	0.137	1.061
LZ1928B	503	3606	1830	1.023	1.026	0.062	1.050
LZ1914C	555	3805	1543	1.022	1.066	0.487	1.093
LZ1918A	606	1722	31	1.027	1.029	0.044	1.057
LZ1968B	711	1704	3950	1.046	1.058	0.108	1.106
LZ1915A	758	4495	8235	1.018	1.147	0.775	1.185
LZ1953B	773	7418	17870	1.061	1.089	0.177	1.157
LZ1948B	802	18311	7845	1.037	1.245	0.713	1.318
LZ1947A	805	8731	6557	1.085	1.281	0.503	1.409
LZ1943A	914	7169	16000	1.038	1.088	0.387	1.132

$L = \mathrm{ARM}_{\max}/\mathrm{ARM}_{\mathrm{int}}$ (magnetic lineation); $F = \mathrm{ARM}_{\mathrm{int}}/\mathrm{ARM}_{\min}$ (magnetic foliation); $P' = \exp\{2[(\eta_1 - \eta)^2 + (\eta_2 - \eta)^2 + (\eta_3 - \eta)^2]\}^{1/2}$ (corrected anisotropy degree), where $\eta_1 = \ln \mathrm{ARM}_{\max}$, $\eta_2 = \ln \mathrm{ARM}_{\mathrm{int}}$, $\eta_3 = \ln \mathrm{ARM}_{\min}$, $\eta = (\eta_1 + \eta_2 + \eta_3)/3$; $T = 2(\eta_2 - \eta_3)/(\eta_1 - \eta_3) - 1$ (shape factor); RM (30 mT) = remanence left after demagnetization at 30 mT. Height is referred to the bottom of the stratigraphic sequence.

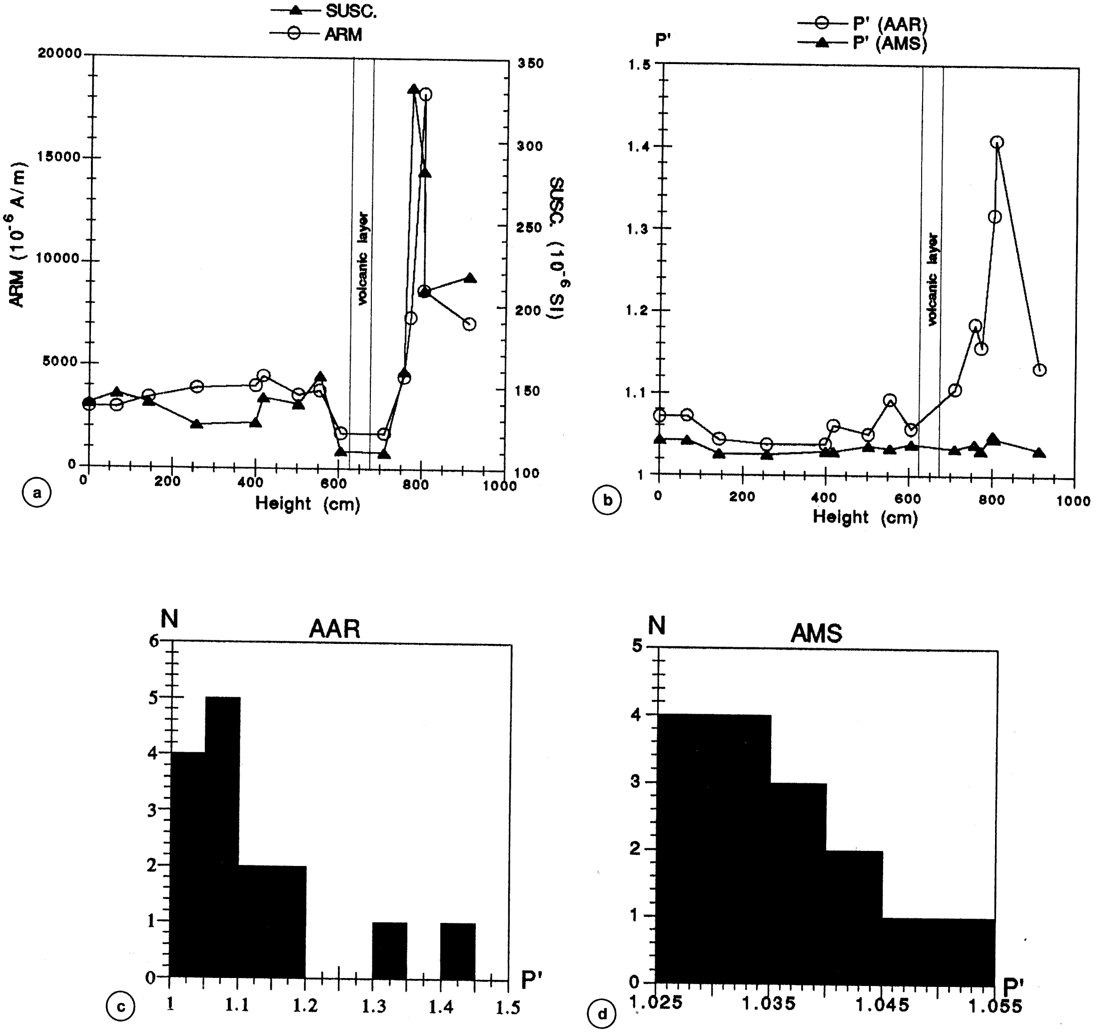

Fig. 2a-d. a) Plot of mean ARM and mean susceptibility vs. stratigraphic height (note the difference between the two vertical axis scales); b) plot of P' (both for AAR and AMS) vs. stratigraphic height. Histograms of P' for AAR (c) and AMS (d).

prolate magnitude ellipsoid. Therefore, even if all the samples are characterized by ellipsoid shapes in the field of oblateness ($0 < T < 1$) both for the susceptibility and the ARM, it is evident that the flattening of the anisotropy ellipsoid is greater when the paramagnetic contribution prevails. The ferromagnetic fraction shows mainly triaxial to weakly oblate ellipsoid shapes.

In order to better visualize the anisotropy ellipsoid shapes and their relationship with the anisotropy degree, the data from each specimen were plotted in T vs. P' (fig. 3a,b) and L vs. F (fig. 3c,d) diagrams. The AMS data are

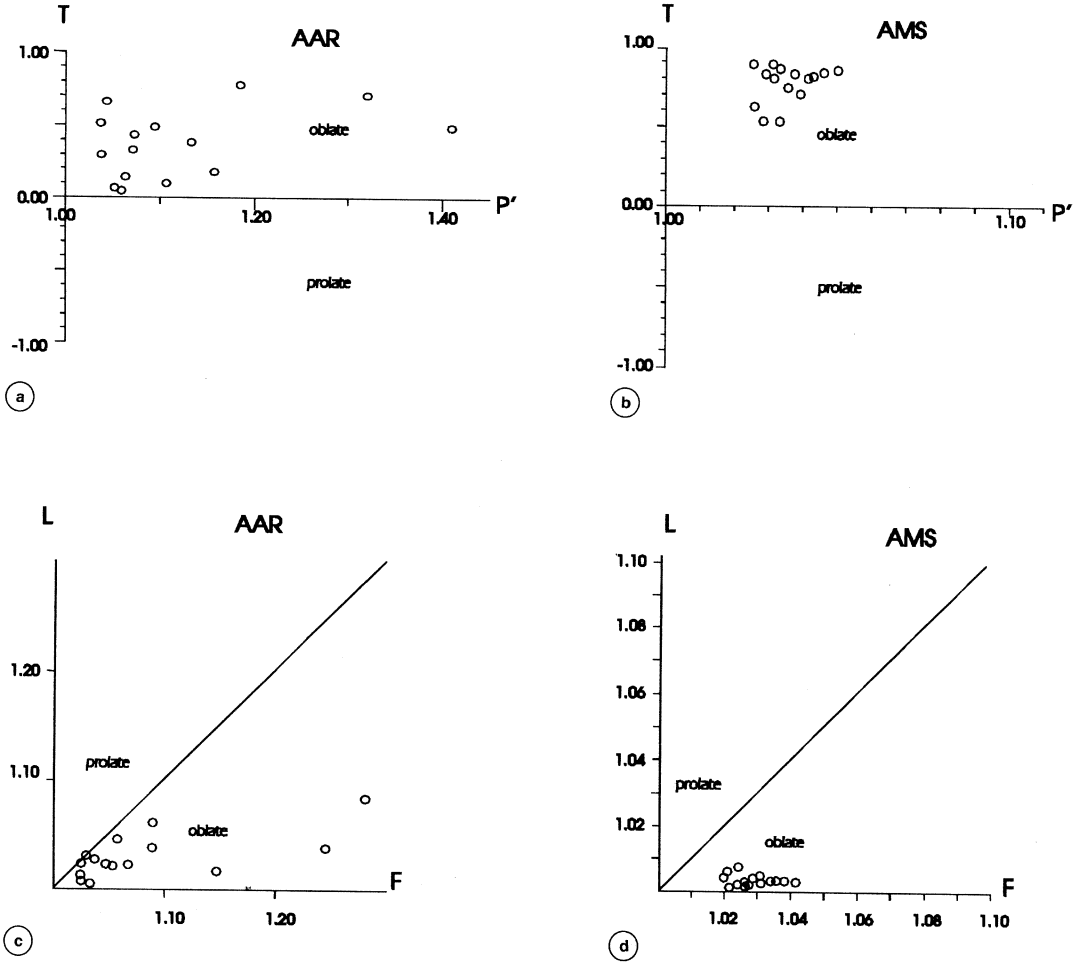

Fig. 3a-d. Plot of shape factor *T* vs. anisotropy degree *P′* for the AAR (a) and the AMS (b) data. Plot of *L* (magnetic lineation) vs. *F* (magnetic foliation) for the AAR (c) and AMS (d) data. Note the difference of scale between the AAR and AMS graphs.

well grouped, showing small variations of the anisotropy factors; the AAR plots are very different, showing a wider dispersion and three specimens (LZ1915A, LZ1948B, LZ1947A), all taken above the volcanic level, show values that are clearly away from the others. Since these anomalies are not evident in the AMS plots, they must be due to significant variations affecting only the ferromagnetic content.

Maximum, intermediate and minimum susceptibility directions for each specimen have been drawn on a Schmidt equal-area projection in fig. 4a; the minimum susceptibility axes are well grouped around the bedding pole, as expected for an undeformed or weakly deformed sediment with mostly depositional-compactional magnetic fabric (Hrouda, 1982). The maximum and intermediate susceptibility axes are slightly more scattered and in the bedding plane (dipping 6° to the WNW at this site). A previous study (Sagnotti *et al.*, 1994b) demonstrated that the mean maximum susceptibility axis (susceptibility lineation) at this site is horizontal and oriented N329° and strictly reflects the maximum extensional axis direction determined by structural analysis of joint planes and faults (fig. 4c). The same kind of projection has been used for the AAR results (fig. 4b). The minimum remanence axes are still grouped and parallel to the bedding pole; the other principal axes are in the bedding plane, but more scattered than the corresponding sus-

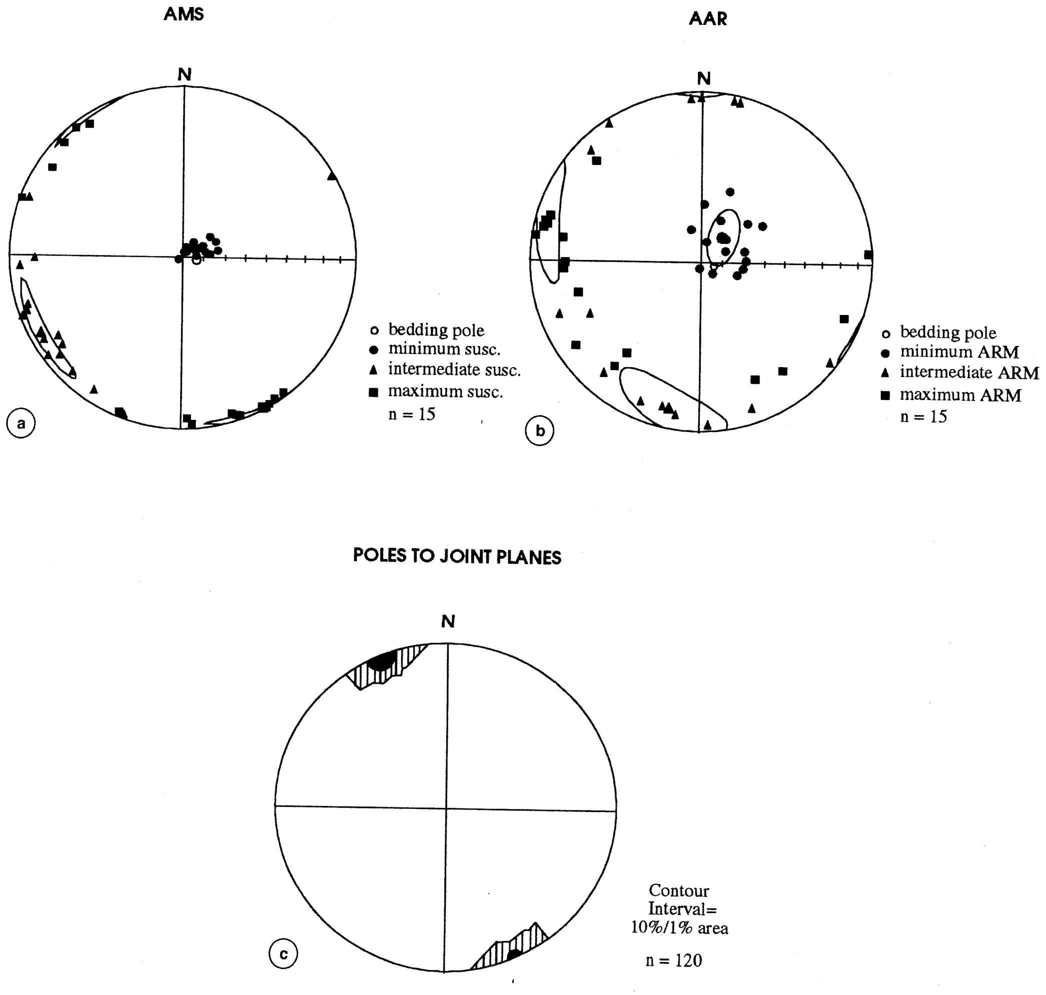

Fig. 4a-c. Schmidt equal-area projection of AMS (a) and AAR (b) principal axes, lower hemisphere. 95% confidence ellipses around the mean axes are also drawn. c) Contour plot of poles to joint planes at the Tini quarry.

ceptibility axes; the mean AAR maximum axis (AAR lineation) is oriented N284°.

The most interesting feature which emerges from a comparison between the two plots is that the AAR lineation deviates by 45° anticlockwise from the susceptibility lineation.

This difference proves the predominance of the paramagnetic matrix in the total AMS of these clays. Indeed, if the ferromagnetic fraction had prevailed, the AMS and AAR tensors should have been almost the same, since the AMS is influenced by all the magnetic fractions of the rock in proportion to their intrinsic susceptibility.

Both the AMS and AAR tensors show minimum axes perpendicular to the bedding plane, suggesting that the magnetic fabrics are mostly due to sedimentary-compactional processes. Moreover, the mean maximum AAR axis is not along the maximum extension direction. A possible explanation is that the ferromagnetic fraction of these clays was not influenced by the post-compactional stress, perhaps due to voids in the sediment structure which shielded the ferromagnetic grains from strain effects (Jackson, 1991). Thus, the mean maximum ARM direction may be related to the original fabric; in this case it would have been controlled by the currents acting at the water-sediment interface at the time of deposition.

4. Conclusions

We set up a routine laboratory technique to study the ARM and its anisotropy on standard paleomagnetic specimens, adapting the instrumentation avalaible at the paleomagnetic laboratory of the Istituto Nazionale di Geofisica. The first attempt to determine the AAR tensor of weakly deformed Upper Pliocene clays, whose bulk susceptibility is mainly dominated by the paramagnetic contribution, was successful.

The procedure necessary to give and measure ARM along different positions is relatively complex and time-consuming in comparison with the AMS measurements. Due to the intrinsic higher complexity of the measurement cycle, the AAR resolution is obviously affected by a higher degree of uncertainty with respect to the AMS. The main source of errors lies in restoring the remanent magnetization base level after each ARM acquiring process, especially when the remanence base level is so low that its measurement is affected by wide fluctuations.

The ARM measurements on the Valle Ricca upper Pliocene clays allowed the determination of well-defined anisotropy tensors. The comparison of AAR and AMS tensors on the same specimens is very interesting for structural and paleomagnetic studies. In particular, the simultaneous analyses of the anisotropy parameters and principal axes have shown that:

1) the degree of anisotropy is greater for the anhysteretic remanence than for the low-field susceptibility. The AMS ellipsoids are highly oblate; the ARM ellipsoids are slightly oblate to triaxial;

2) the miminum remanence and susceptibility directions are consistent and both parallel to the bedding pole of the stratigraphic sequence. This feature reflects the influence of the sedimentary and compactional processes on the total fabric of these sediments;

3) the maximum remanence direction is deviated 45° anticlockwise from the maximum susceptibility. This indicates a major difference between the ferromagnetic fractions and the paramagnetic matrix dominating the susceptibility of the rock. In particular, since it was observed that the maximum susceptibility direction is parallel to the extensional axis determined by structural analysis (Sagnotti *et al.*, 1994b), these results suggest that only the clayey matrix fabric was (slightly) affected by the stress that acted on this rock unit. This underlines that clayey sequences are particularly suitable for the empirical investigation of fabric to strain relationships of sediments at the very first stages of deformation.

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