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Irreversible Changes of Anisotropy of Magnetic Susceptibility of Rocks due to Uniaxial Pressure

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Abstract. The irreversible changes of anisotropy of magnetic susceptibility of basalt rocks due to uniaxial pressure up to 250 MPa have been investigated. As a result of the irreversible pressure changes of the domain structure of ferrimagnetic minerals, the degree of anisotropy as well as the shape of the ellipsoid of susceptibility in rocks with initial isothermal remanent magnetic saturation polarization changes systematically. The qualitative behaviour of the changes of the degree of anisotropy is determined by the superposition of shape and domain effects. The magnitude of the pressure-induced changes of anisotropy of susceptibility depends on the stability of the domain structure which can be characterized by the coercive force of the rocks, and on the orientation of the saturated remanence with respect to the uniaxial pressure.

Key words: Rock magnetism – Anisotropy of magnetic susceptibility – Effect of pressure on magnetic properties

Introduction

A knowledge of the physical essence of the changes of the magnetic properties of rocks and minerals due to applied pressure provides a base for interpreting the tectonomagnetic changes observed in seismically active regions, as well as for interpreting certain local anomalies of the geomagnetic field. In experimental and theoretical work, besides the study of the pressure changes of various types of remanent magnetic polarization, attention has also been given to the changes of the magnetic susceptibility of rocks, particularly those due to the effect of directional uniaxial pressure (Kapica,1955; Nagata, 1966; Ohnaka et al., 1968) and to a lesser extent also to the effect of hydrostatic pressure (Nullman et al., 1978).

Uniaxial pressure on ferrimagnetic minerals is responsible for an additional uniaxial anisotropy with the effective anisotropy constant $\sim\frac{3}{2}\lambda\tau$, where λ is the magnetostriction coefficient and τ the stress (Kneller, 1962). The anisotropy constant depends on whether compressive stress or tensile stress is involved, and on the nature of the magnetostriction of the ferrimagnetic minerals. The theoretical interpretation of the changes of susceptibility of rocks due to uniaxial pressure, which is founded on the mechanism of rotation of the vector of spontaneous magnetization in separate domains (Stacey, 1962; Nagata, 1966), agrees well with experimental results obtained from specimens which have been subjected to pressures of the order of tens of MPa. In order to explain the pressure changes of susceptibility of samples in their initial undeformed state, however, we must also take into account the mechanism of irreversible discplacements of domain walls due to external stress (Kinoshita, 1968). Thus, the changes of magnetic susceptibility in rocks, subjected to pressure in the Earth's crust, may be considerably different from those observed on repeatedly deformed specimens.

Most measurements of the pressure changes of susceptibility were carried out parallel ($\chi^{\parallel}$) and perpendicular ($\chi^{\perp}$) to the uniaxial pressure. In view of the different magnitudes of the irreversible changes of directional susceptibilities $\chi^{\parallel}$ and $\chi^{\perp}$ after the stress has stopped acting on the samples (Kapica, 1955; Nagata, 1970), we may also assume irreversible anisotropy changes of magnetic susceptibility of rocks as a result of external pressure. However, no systematic study has been conducted in this respect. From the author's earlier paper (Kapička, 1981) it follows that re-ordering of the domain structure of ferrimagnetic minerals due to the magnetic field results in relatively large irreversible changes of anisotropy of magnetic susceptibility of rocks. The nature of these changes is closely associated with the degree of anisotropy and with the orientation of the ellipsoid of susceptibility due to the shape effect, and the ambient magnetic field relative to each other.

In order to throw light on the question of the extent to which irreversible changes of the domain structure, caused by applied mechanical stress, affect the anisotropy of magnetic susceptibility, changes of anisotropy of basaltic rocks due to uniaxial pressure are studied systematically in the present paper.

Experimental Procedure

The measurements were carried out on Tertiary basaltic rocks from the Bohemian massif, some of whose mechanical and magneto-mechanical properties had already been investigated (Kapička, 1978). Their ferrimagnetic fraction consisted of titanomagnetites with various degrees of oxidation. The basalts studied had different degrees of anisotropy of magnetic susceptibility due to the shape effect (ranging from isotropic to specimens with the degree of anisotropy of $\sim 4\%$) as well as considerably different values of the coercive force (Table 1). The cubic specimens, $2 \times 2 \times 2$ cm, were cut so that their surfaces were perpendicular to the directions of maximum, intermediate and minimum susceptibili-

Table 1. Degree of anisotropy P, coercive force H_c and grain size of the magnetic fraction for specimens in natural state

Specimen no.	P	H_c [10^2 A m^{-1}]	Grain size of magnetic fraction [mm]
211	1.019	60	0.015–0.05
219	1.038	62	0.07 –0.2
231	1.042	23	0.01 –0.07
235	isotropic	227	0.007–0.015

ty in their natural state. The opposite pressure surfaces were ground plane-parallel with an accuracy of 0.02 mm. The specimens were deformed by uniaxial pressure in a hydraulic press with end-pieces of the same cross-section as the sample. Paper inserts were placed between the specimen and the platens. The pressure range was 0–250 MPa, which is in the region of elastic deformation of basalts. The increment of the applied stress was constant ~ 8 MPa s^{-1}. The magnetic saturation of the specimens (J_{rs}) was carried out in a field of $\sim 40 \times 10^4$ A m^{-1}. The magnetic susceptibility was always measured before and after applying the pressure with a KLY-1 AC bridge (Jelínek, 1973) in a weak magnetic field of 80 A/m. The susceptibility anisotropy and its parameters were determined from measurements of fifteen directional susceptibilities with the aid of the Aniso program (Jelínek, 1972). The usual parameters were used to decribe the anisotropy: the degree of anisotropy was characterized by the parameter $P = \chi_1/\chi_3$, the shape of the susceptibility ellipsoid by the parameters $F = \chi_2/\chi_3$ and $L = \chi_1/\chi_2$, $\chi_1 \geqq \chi_2 \geqq \chi_3$ being the maximum, intermediate and minimum susceptibility of the specimens. To determine whether the differences observed between the directional susceptibilities are substantial as compared to the observation errors, i.e. whether the specimens are anisotropic or isotropic, the F-test (Jelínek, 1972) was used. The changes in the shape of the ellipsoid due to pressure were represented with the aid of an $L - F$ diagram in which the line passing through the origin at an angle of 45° separates the points referring to oblate ellipsoids of susceptibility from those referring to prolate ellipsoids. The changes in the orientation of the major axes of the susceptibility ellipsoid were illustrated with the aid of stereographic projection.

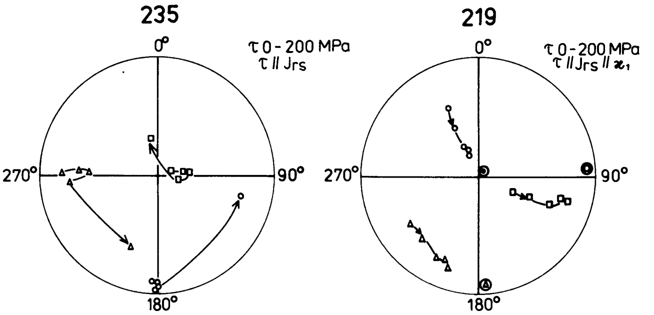

Fig. 2. Changes of orientation of the axes of maximum (△), intermediate (□) and minimum (○) susceptibility due to 50-MPa incremental pressure changes, J_{rs} orientation $-180°$. The orientation of the major axes of the ellipsoid under natural conditions (specimen 219) is encircled. Equal-area projection, lower hemisphere

Experimental Results

The irreversible changes of the degree of anisotropy P due to stress τ for specimens 211, 219, 231 and 235 with initial isothermal remanent magnetic saturation polarization (J_{rs}) are shown in Fig. 1. Due to the ordering of the domain structure by the magnetic field, the degree of anisotropy of the specimens with J_{rs} differs from that of the specimens in the natural state, when it is only determined by the shape effect. In each case, the uniaxial stress was applied parallel with J_{rs}. The basalts could be divided into three groups according to the behaviour of $P = f(\tau)$: (*a*) Those which do not display systematic changes of the degree of anisotropy over the whole range of stresses, regardless of the orientation of J_{rs} and of the original susceptibility ellipsoid with respect to one another (231); (*b*) Specimens 219 and 211 in which the systematic changes of the degree of anisotropy depend on the orientation of the ellipsoid and on J_{rs} with increasing stress (decrease of P with increasing τ if J_{rs} is parallel to χ_3, and an increase if J_{rs} is parallel to χ_1). The absolute values of the changes of P are $\sim 3\%$; (*c*) Isotropic specimens in the natural state (235) in which

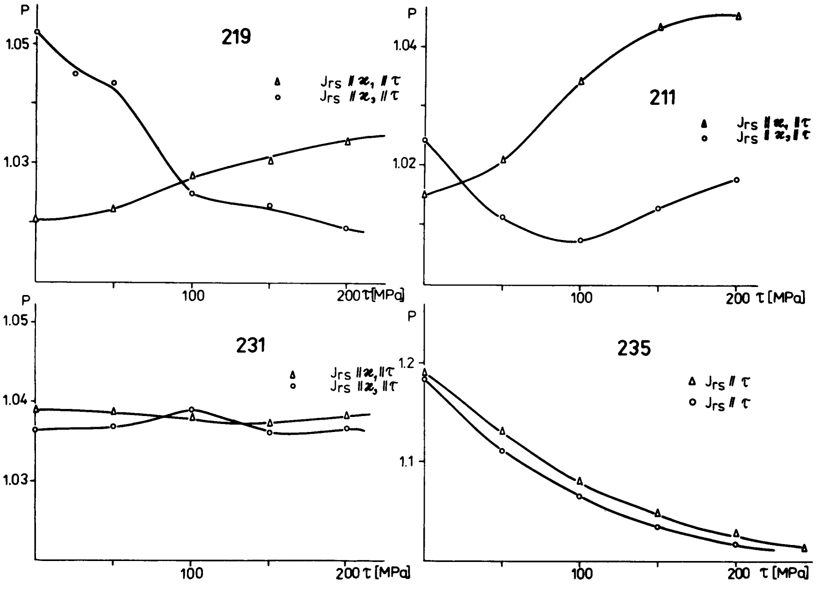

Fig. 1. Irreversible changes of the degree of anisotropy P due to uniaxial pressure τ for specimens with isothermal remanent magnetic saturation polarization in directions χ_1 and χ_3

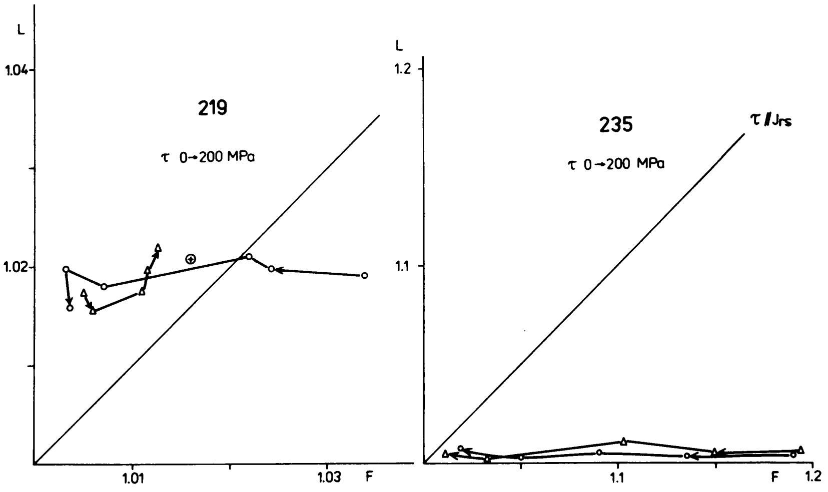

Fig. 3. Irreversible changes of the shape of the susceptibility ellipsoid due to pressure with J_{rs} in the direction of χ_1 (▵), χ_3 (○). ⊕ – specimen 219 in original condition

the degree of anisotropy P due to the domain effect decreases with increasing stress for any direction of saturation. The absolute changes of P are $\sim 18\%$. In all cases the changes of the degree of anisotropy are reversible in the sense that approximately the same anisotropic condition results from repeated saturation in the same direction.

Figure 2 shows the changes of orientation of the principal axes of susceptibility for specimens 235 and 219 as a function of stress. The (*a*) group of specimens displayed no change of orientation of the susceptibility ellipsoid over the whole range of stresses. The (*b*) and (*c*) type specimens display a quite similar tendency of changes: the direction of the minimum susceptibility is gradually changed by the increasing stress (in increments of 50 MPa) from that of the initial saturation remanent magnetic polarization until it is perpendicular to J_{rs}, the tendency of the changes of χ_1 being the opposite. The degree to which the orientation of the major axes of the ellipsoid changes, depends on the degree of anisotropy of the basalts due to the shape effect and it is largest for the isotropic specimens in the natural state.

The changes of the shape of the susceptibility ellipsoid due to uniaxial pressure for the specimens representing type (*b*) and (*c*) basalts are illustrated in the $L-F$ diagram in Fig. 3. The specimens of group (*b*) have qualitatively different changes of shape of the susceptibility ellipsoid with increasing stress for directions of the initial J_{rs} (and τ) parallel with χ_3 and χ_1. In the first case, the oblate ellipsoid changes to the prolate, in the second, the ellipsoid remains prolate for all stresses τ. But the changes of shape of the ellipsoid of specimen 235, which was isotropic before acquiring J_{rs}, are always characterized by a decrease of the parameter F which is analogous to the case of J_{rs} parallel to χ_3 of the anisotropic specimen 219. However, the isotropic condition is not achieved even for the highest values of τ, i.e. the curve of the gradual changes as a whole is located in the field of oblate ellipsoids.

The magnitude of the irreversible pressure changes of anisotropy depends on the orientation of the uniaxial stress τ and of the direction of the initial J_{rs} of the specimens with respect to one another. Figure 4 shows the changes of the degree of anisotropy $P=f(\tau)$ when the pressure is applied parallel and perpendicular to J_{rs}. Whereas the J_{rs}-direction was the same in both cases (e.g., parallel to χ_3 with specimen 219), the stress was applied along the direction of χ_3, on the one hand, and along the direction of χ_1, on the other. From the figure we can see that repeated magnetic saturation of the same specimen in the same direction, following deformation by pressure τ_{max} $\sim$250 MPa, generates the same degree of anisotropy (see degrees of anisotropy for $\tau=0$ denoted as ● and ⊙). Whereas considerable changes in the degree of anisotropy take place by applying τ parallel to J_{rs} (a decrease of P by 3–16%), if the pressure is applied perpendicularly the initial degree of anisotropy remains practically constant, relatively small changes being observed only for high stress values.

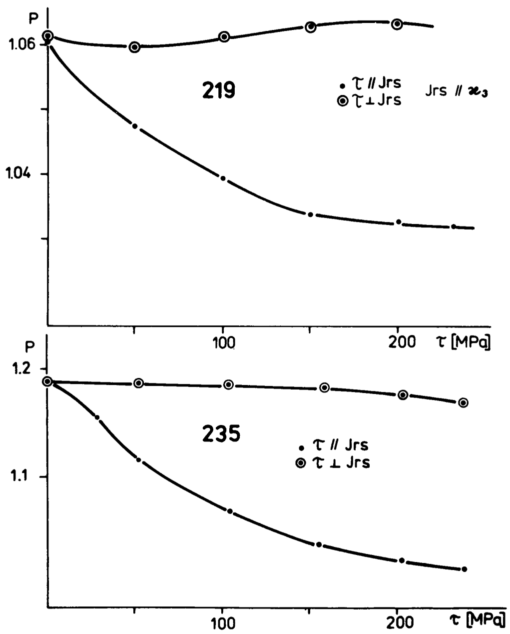

Fig. 4. Irreversible changes of the degree of anisotropy P due to pressure τ for parallel and perpendicular orientation of J_{rs} and τ

The pressure changes of anisotropy of magnetic susceptibility were compared with the changes due to the re-ordering of the domain structure of ferrimagnetic minerals by an AC magnetic field. An example of the functions $P=f(\tau)$ and $P=f(\tilde{H})$ for one basalt with its initial J_{rs} in the direction of χ_3 is shown in Fig. 5. The gradual change to the "antiparallel" domain structure was achieved by applying the AC field $\tilde{H}$ to the sample in stationary position ($\tilde{H}$

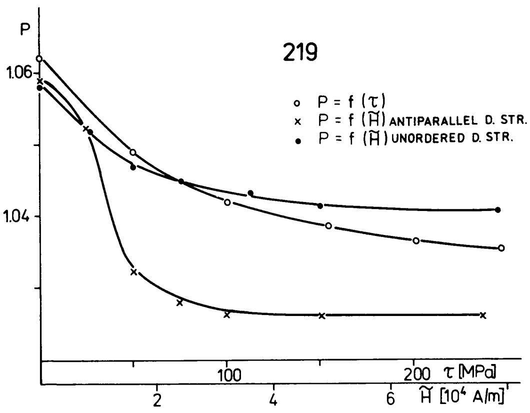

Fig. 5. Comparison of changes of the degree of anisotropy P due to pressure τ with the changes due to the re-ordering of the domain structure of the specimens caused by field $\tilde{H}$

parallel to J_{rs}), the change to the "unordered" domain structure by applying the AC field to the specimen rotating about three mutually perpendicular axes. The pressure changes of the domain structure, resulting in a change of the degree of anisotropy, are more of the nature of an "unordered" structure although deviations may be observed under stresses exceeding 150 MPa. If uniaxial pressure is applied, stabilization of the degree of anisotropy, which already occurs at AC magnetic field intensities of about 3–4×10^4 A m^{-1}, is not observed for stresses τ up to 250 MPa.

Discussion

The results presented above indicate that the anisotropy of magnetic susceptibility of basaltic rocks containing cation-deficient titanomagnetites, depends not only on the shape effect, i.e. on the degree to which the ferrimagnetic grains in the rock are ordered, but also on the domain structure of these minerals. If p is the concentration of the ferrimagnetic minerals, the directional susceptibility is then given by [Janák, 1977]

$$\chi=\frac{p\,\chi_i}{[1+(1-p)N\chi_i]}, \qquad (1)$$

where χ_i is the intrinsic susceptibility of the ferrimagnetic mineral and N the effective value of the demagnetization factor. If we restrict ourselves to the elastic deformation in which irreversible changes of shape and orientation of ferrimagnetic grains do not occur in basalts, the observed changes of the directional susceptibilities and of the susceptibility anisotropy are caused by changes of the intrinsic susceptibility of ferrimagnetic grains.

The domain effect contributes to the overall anisotropy in that the minimum of directional susceptibility is associated with the direction of preferred orientation of the domains (i.e. the domains with magnetization in the J_{rs}-direction prevail) (Fig. 2). If we assume that the reversible susceptibility is due to the mechanism of reversible motion of domain walls (e.g. Kneller, 1962) the observed effect is caused by the 180° domain walls being in much more stable potential gaps after magnetic saturation, which decreases their mobility. The real domain structure of ferrimagnetic grains even in the case of saturation remanence, however, is not formed just by the simple structure of the 180°-walls in the direction of J_{rs} as a result of minimization of the overall energy; indeed closure domains with 71°-walls are formed in the first place (Bhathal and Stacey, 1969). The directional susceptibility perpendicular to the ordered domain structure is then determined by the mobility of these walls rather than by the rotation of the vector of spontaneous magnetization in the main domains.

Irreversible changes of the domain structure and, consequently, also irreversible changes of the susceptibility anisotropy occur as a result of external pressure. The qualitative differences in the functions $P=f(\tau)$ for various directions of J_{rs} in the specimens (Fig. 1) are due to the superposition of the shape and domain effects (Kapička, 1981).

The magnitude of the irreversible pressure changes of the susceptibility anisotropy varies from basalt to basalt and depends on the stability of their domain structure with respect to the weak AC field in which the susceptibility is being measured. The contribution of the domain effect is substantial in specimens with a hihger coercive force which is indicative of a considerable concentration of potential barriers restricting the mobility of domain walls (groups *a* and *b*). These basalts display a much larger stability of the domain walls in saturated condition than after pressure has been applied, when the domain walls are located in other potential gaps, energetically more advantageous. Specimen 235 with a conspicuously higher coercive force contains a considerably non-stoichiometric titanomagnetite characterized by a high degree of oxidation (Kropáček and Kapička, 1979). In specimens with small coercive force (group *c*) the stability of the domain structure in saturated state even after re-ordering by mechanical stress is practically the same and, therefore, the domain effect has a negligible influence on the susceptibility anisotropy.

The pressure changes of susceptibility anisotropy also depend substantially on the direction in which the uniaxial pressure is acting relative to the J_{rs} in the specimens. When τ was perpendicular to J_{rs}, practically no changes of the degree of anisotropy were observed even for quite large stresses τ (Fig. 4). Although the stress distribution close to the pressure surfaces of the specimens may be affected by the contact between the specimen and the press platens, we may assume that the stress acting in the direction of the applied uniaxial pressure is dominant in the sample as a whole. The various orientations of the stress and of the direction of the preferred ordering of the domains in the initial saturated state are responsible for the directional dependence of the pressure changes determined experimentally.

If we consider the stress field round the dislocations to represent a substantial part of the potential barriers limiting the motion of domain walls (Kinoshita, 1968; Carmichael, 1968), we find that the dislocation slip in certain crystallographic planes is caused by the applied stress. In cubic crystals with a spinel structure (magnetite, titanomagnetite) the slip planes are planes $\{111\}$ with the slip direction $[110]$. The interaction energy of the stress field of the dislocation with the domain wall depends on the orientation of the slip plane and domain wall with respect to one another, and if an edge dislocation is involved, the appropriate relation reads (Vicena, 1955):

$$\Delta E=\tfrac{3}{4}\delta\lambda\, Gb\frac{1+\gamma}{1-\gamma}\sin\omega, \qquad (2)$$

where δ is the width of the domain wall, λ is the magnetostriction coefficient, G the modulus of rigidity, γ Poisson's ratio, b Burgers vector and ω the angle between the slip plane of the dislocation and the perpendicular to the domain wall. For basaltic rocks containing titanomagnetites without crystallographic texture, homogeneously distributed throughout a non-magnetic matrix, one may assume that:

a the slip planes $\{111\}$ are uniformly distributed in all directions;

b the component of the shear stress in the slip plane and slip direction, which is decisive for the motion of the dislocation, is largest if the applied stress is parallel to the slip plane.

The magnitude of the interaction energy of the dislocation with a 180°-system of domain walls in magnetically saturated condition depends on the angle ω characterizing the position of the dislocation slip plane in and domain walls with respect to one another. The stress applied perpendicular to the domain walls causes the dislocations which do not form effective potential barriers, fixing the positions of these walls, to move in the first place. Dislocations with non-zero interaction energy ΔE may only be re-ordered by stress oriented in another direction, the most effective being the stress parallel to the ordered domain structure.

The differences in the magnitude of the changes of degree of rock anisotropy due to uniaxial pressure and to the magnetic field are caused by slightly different mechanisms of both effects. The applied field affects the position of the domain walls directly. Assuming a constant distribution of potential barriers, the applied stress however affects it indirectly via the changed dislocation configuration and the changes in the distribution of the internal stress fields associated with it. If the applied stress is sufficiently large, the resultant domain pattern has the nature of a disordered structure because it is controlled by the distribution of the easy directions of magnetization [111] which can be considered as uniform in specimens without marked texture. The observed behaviour of the changes of the degree of anisotropy due to pressure, which is analogous to the changes of P due to the effect of the AC field on rotating specimens, i.e. to the change from directional ordering of domains to a disordered condition, also corresponds to this.

The investigation of irreversible changes of anisotropy of magnetic susceptibility due to pressure has proved that the contribution of the domain effect to the overall anisotropy in some rocks is substantial. In interpreting the pressure changes of susceptibility, or of its anisotropy, this effect should be considered together with the mechanism of rotation of the vector of spontaneous magnetization (e.g. Nagata, 1970) due to the applied stress.

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