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Palaeomagnetic and petromagnetic study of uranium-bearing polymetallic-fluorite mineralization in the Orlík-Kladsko crystalline complex (near Kletno, Lower Silesia, Poland)

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Palaeomagnetic measurements of polymetallic-uranium ore in the Old Uranium Kletno Mine were carried out. Thermal and alternating field (AF) demagnetizations of the rocks studied (fluorite and quartz veins, cataclased gneisses, calcareous-silicate rocks with epidote/grossular) enabled isolation of two well-defined magnetization components. A normal polarity palaeomagnetic direction was preserved in magnetite and coarse hematite, whereas reversed polarity is linked with fine hematite grains. Both statistically well-defined components do not differ within limits of error. The calculated mean palaeomagnetic pole was compared with the European apparent polar wander path. This comparison points unambiguously, within limits of statistical error, for an Early Cretaceous to Paleogene age of characteristic components of magnetization. Consequently this age limit constrains the time of uranium-bearing polymetallic-fluorite mineralisation.

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Key words: Poland, palaeomagnetism, Uranium, Sudetes.

INTRODUCTION

It has been demonstrated worldwide that palaeomagnetism can contribute greatly to estimation of the timing of mineralization, mainly for Mississippi-Valley Type Zn-Pb ores (e.g., Symons *et al.*, 1998; Symons and Arne, 2005; Boni *et al.*, 2005; Pannalal *et al.*, 2008) as well as for barite (Symons and Sangster, 1991) or sulphide ores (Gose and Kyle, 1993). In Poland, a few ore accumulations have been examined: Symons *et al.* (1995) estimated the time for a Zn-Pb precipitation event, while the age of the Lower Silesian copper mineralization, the so-called “Kupferschiefer”, was analysed by Jowett *et al.* (1987) and recalculated by Nawrocki (2000).

The palaeomagnetic method of age estimation of mineral deposits is, in short, based on the comparison of the palaeomagnetic pole position obtained with the reference apparent polar wander path (APWP) for the respective continent or terrane. Correct interpretation of the results depends on several important factors (Trench *et al.*, 1992) such as:

- reliability of the APWP for the continent;
- a distinct mineralization event lasting long enough to average the palaeosecular variation of the Earth’s magnetic field;
- a relatively isotropic magnetic fabric of the samples studied to avoid a biased acquisition of the palaeomagnetic vector;
- lack of any tectonic movement after acquisition of the palaeomagnetic record (or awareness of it so that the original position can be reconstructed);
- lack of post-acquisition alteration of magnetic phases leading to palaeomagnetic overprinting.

In the case when the last is evident, the estimated age of the remagnetization could be still used as the minimum age estimation for the mineralization studied.

Among hydrothermal parageneses, hematite, especially fine hematite aggregates dispersed in various hydrothermal minerals (e.g., fluorite, calcite, quartz), was found to be the most reliable material for the age determination of ore deposits (Hanuš and Krs, 1963; Krs, 1964; Evans *et al.*, 2001). Since hematite occurrence is inseparably connected with uranium ores in the Sudety Mts. (Bareja *et al.*, 1982) and since this type of mineralization has been successfully dated either in Australia (Indurm and Heinrich, 1993) or the Czech Republic (Krs and Stovichova, 1966), it led us to undertake preliminary palaeomagnetic studies of the Kletno polymetallic-uranium deposits.

GELOGICAL AND MINERALOGICAL SETTING

The research area is situated in the Orlík-Kladsko crystalline complex, in the Polish part of the Sudety Mountains, which defines the NE margin of the Bohemian Massif (Fig. 1A), and belongs to the European Variscan orogen composed of several microterranes amalgamated and finally integrated during the Carboniferous (Mazur *et al.*, 2006). The mosaic tectonic structure is additionally complicated by late Mesozoic and Neogene block movements. Numerous ore mineralization events took place during the complex geological history of the Bohemian Massif (Bernard, 1991). The Kletno ore deposits are located very near the border zone between the East and West Sudetes (Don *et al.*, 2003), along the NNW–SSE extended Kletno Fault, a part of the Staré Město–Kletno–Marcinków–Waliszów Zone (Fig. 1B), where gneiss is folded over crystalline schists and skarns and dips at 40–70° to the ENE. The main ore body

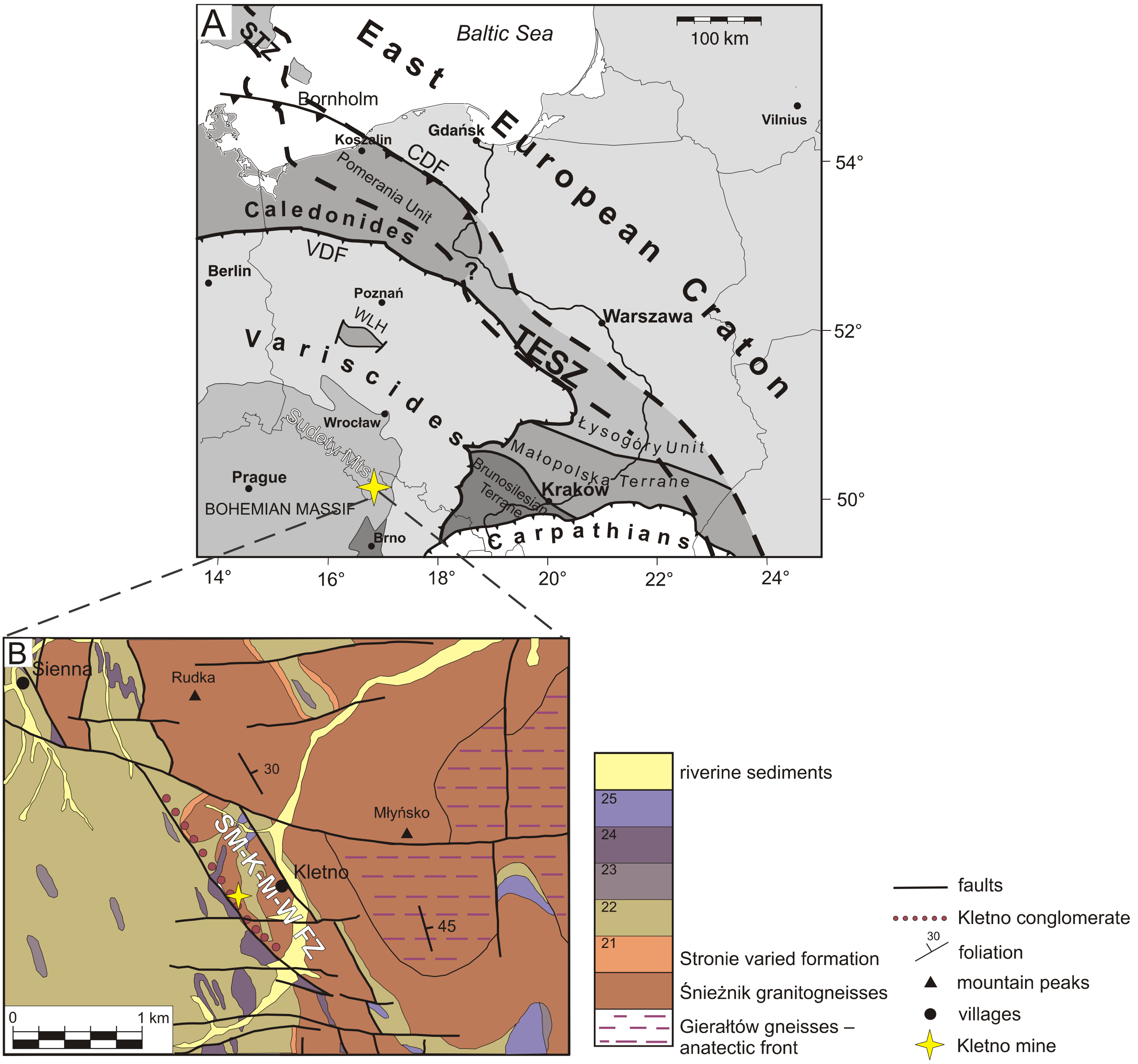

Fig. 1A – Location map of the Kletno mine within a tectonic sketch map of Poland (after Winchester and the PACE TMR Network Team 2002, modified); B – geological map of the Kletno fold area (after Don, 2001, modified)

TESZ – Trans-European Suture Zone, CDF – Caledonian Deformation Front; Stronie varied formation: 21 – light quartzites, 22 – mica schists, 23 – graphite schists, 24 – limestones, 25 – erlanes; SM-K-M-W FZ – Staré Město–Kletno–Marcinków–Waliszów Fault Zone (thickness up to 5 metres) occurs above the marble footwall under the hangingwall of the Śnieżnik gneisses. The detailed description of ore deposit structure and its genesis is given in Banaś (e.g., 1965, 1991). He distinguished three mineral associations: magnetite, polymetallic and quartz-fluorite-sulphide. According to Banaś (*op. cit.*) the magnetite vein mineralization is the oldest one, connected with regional metamorphism of Fe-deposits together with contact metamorphism of the Śnieżnik gneiss intrusion. On the other hand, the polymetallic and fluorite stages are thought to be a result of several low-temperature hydrothermal phases related to a deep-seated, post-magmatic or metamorphic source. Polymetallic-fluorite mineralization is spatially and genetically connected with the oxide uranium mineralization. Ore bodies occur as nests and small veins with pitchblende, sulphides, fluorite and quartz. The main uranium ore mineral is pitchblende, forming with fluorite the largest uranium accumulations. Down the dip the fluorite amount drops with increasing quartz and magnetite content. There are several hematite generations within the ore zone. Distinct parts of the magnetite ore were affected by martitization of variable intensity, up to complete pseudomorphoses of Fe_2O_3 after Fe_3O_4. As the process signs can be traced to a depth of *ca*. 50 m and some hydrated Fe oxides are associated with other secondary U, Cu, Pb minerals, it is thought to be mainly a supergene phenomenon related to tectonic uplift (Banaś, *op. cit.*). On the other hand, only a minor part of the mineral substance transfer has been ascribed to surface water circulation. The activity of hydrothermal solutions was probably of small importance in the magnetite oxidation process but could have resulted in martite formation during pitchblende precipitation. This view is in agreement with Bareja *et al.* (1982), who linked uranium-bearing zones with surrounding rock hematitization. Authomorphic crystals of specularite surround pitchblende in the form of needles in quartz, calcite, fluorite and also radial and rose aggregates as well as powdered hematite concentrations. Specularite is genetically connected with the hydrothermal oxide regime (UO_2, Fe_2O_3) present just before the main polymetallic crystallization stage. Significant dispersed cryptocrystalline hematite abundance has been noticed in polymetallic-fluorite assemblages and also as a thin layer between quartz and fluorite, therefore hematitization is thought to be genetically linked with quartz-fluorite-calcite bearing processes. Przeniosło and Sylwestrzak (1971) described large occurrences of a tiny hematite powder in a quartz rock lens and calculated that during quartz rock formation silica was supplied as well as some Fe_2O_3. Since hematite occurrence is strictly and indisputably connected with ore mineralization we assume that age estimations based on iron oxides is directly related to the time of mineralization.

ORE PLACEMENT STATE OF KNOWLEDGE

The timing of the ore events in the Kletno region has previously been estimated on the basis of general geological, structural and mineralogical evidence. Banaś (1965) postulated an Archaeon?/Caledonian? time of magnetite placement. On the other hand, this author proposed a late Variscan age for uranium-bearing polymetallic-fluorite mineralization, but also allowed a late Alpine age. Don *et al.* (2003) suggested a late Tertiary age for the uranium-fluorite mineralization in Kletno. He observed that one of the largest veins cuts the Staré Město–Kletno–Marcinków–Waliszów Falut Zone almost perpendicularly and shows no indications of tectonic activity or displacement on this fault.

Since the uranium-bearing polymetallic ore and also the fluorite association were distinguished in the Kletno mine, various Bohemian Massif mineral age estimations should be taken into account in our considerations. Tens of mineralization events were interacting in the same ore/place in the Bohemian Massif area (Bernard, 1991), therefore a huge age range is present in the literature. Fluorite mineralization in the Sudetes follows NW-extending zones of steep dip. Fluorite-barite associations' studies made in the Bohemian Massif area (Bernard *et al.*, 1976) link (e.g., on the basis of published fluid inclusion analyses) to the Triassic? renewal of tectonic activity along the system of NW–SE fissures with low-temperature hydrothermal fluid ascents, bearing elements, which under suitable conditions formed fluorite-barite-quartz fissure-fillings. Sudetic polymetallic (sulphide-uranium) mineralization together with fluorite and barite mineralization are thought to belong to one Permian-Triassic mineralization cycle, due to deeper crustal structure renewal (Jerzmański, 1976). In addition, Muszer (2004) suggested that the process which initiated metal migration was not related to regional metamorphic fluids and that old Variscan fault-dislocations and migration paths were used by younger metal-bearing fluids. Mikulski (2007) connected oxidative low temperature hydrothermal processes in the Western Sudetes with post-Variscan basin formations in upper Permian–Triassic or even Cretaceous time. Similar conclusions were expressed by Slobodník *et al.* (2008), who on the basis on Pb isotope data, indicated (Permian) Triassic–Jurassic and also Jurassic-Cretaceous mineralizing events in Moravia, while an Early Cretaceous age for the Mississippi-Valley Type (MVT) deposits in the Upper Silesia Basin is suggested in a model of Heijlen *et al.* (2003).

In the Kowary mineralization area (Mochnacka, 1966, 1967, 1982, 1991), where the magnetite and polymetallic-uranium ore structure and genesis is similar to that at Kletno, Pb/Pb and Pb/U pitchblende dating (Lis *et al.*, 1971) suggest 265 and 70 Ma absolute age estimation. Therefore Variscan Orogenesis as well as the Laramide Phase of Alpine Orogenesis was proposed for pitchblende formation and modification. Based on fluid inclusion and stable isotope data, the brine generation of the Zálesí uranium deposit (Czech Republic – Dolníček *et al*., 2009), 56 km NE from Kletno, has been linked to the Permian-Triassic tectono-sedimentary evolution of the Polish Basin (see Schmidt Mumm and Wolfgramm, 2004), while 160–200 Ma was proposed for the nearby Javorník mineralization by Legierski (1973). The Rožná uranium deposits, 150 km south from Kletno, are believed to be of post-Variscan age (late Stephanian/early Permian) on the base of K-Ar dating, and an Early to Mid Triassic hydrothermal event is thought to be responsible for uranium remobilization and quartz-carbonate-sulphide mineralization (Kříbek *et al*., 2009). On the other hand, 110–160 Ma was proposed as a Pb model age (Legierski, *op. cit.*). However, the most westward placed polymetallic-uranium ore in the Bohemian Massif (Joachimstahl) has been palaeomagnetically dated by Krs and Stovichova (1966), indicating a Mesozoic-Tertiary mineralization age, while Legierski (*op. cit.*) suggested 210–150 Ma. Among the Bohemian Massif metallogenic provinces, several ore-vein (quartz-hematite and hematite) have been analysed palaeomagnetically. The calculated poles corresponded to a late Paleozoic age (Central Bohemian pluton contact zone and Krusné hory). On the other hand, a Paleogene mineralization age for fluorite-barite and hematite has been suggested in western Bohemia (Hanuš and Krs, 1963; Krs, 1964 and literature therein).

SAMPLING AND LABORATORY METHODS

Fifteen independently oriented hand samples were collected from the Old Uranium Mine in Kletno, in the abandoned part of the uranium-bare, fluorite tunnel no. 18, that has been rendered accessible. The gallery is located in the highest, northwestern part of the mine, 773 m above sea level. Among the strongly tectonized rocks, with macroscopically visible hematite powder, we could distinguish: brecciated quartz veins with fluorite and calcite (K3–K5, K8, K14), as well as leucocratic schists (K1, K2, K12), calcareous-silicate rocks with epidote (K15), grossular and magnetite aggregates (K7, K13), partly cataclased gneisses (K6, K10) and silicate marbles (K9, K11).

From each hand specimen several cubic specimens (volume 8 cc) were obtained, giving a total number of 70 specimens. All palaeomagnetic and a part of the rock magnetic analyses were carried out in the palaeomagnetic laboratory of the Polish Geological Institute – National Research Institute in Warsaw, in a magnetically shielded space, reducing the ambient geomagnetic field by about 95% (manufactured by Magnetic Measurements, UK). In order to characterize the magnetic mineralogy, isothermal remanent magnetization (IRM) experiments were carried out. IRM acquisition curves were obtained using a *MMP1* pulse magnetizer (Magnetic Measurements, UK). IRM was imparted along three perpendicular axes in different DC fields (1.5 T, 0.4 T, and 0.1 T along *z*, *y*, and *x* axes, respectively) and was thermally demagnetized (in 14 steps, every 50°C up to 700°C) following the method of Lowrie (1990). Additional studies of magnetic properties, such as temperature (20–700°C) dependence of the isothermal remanence (TUS device), and hysteresis loops (*MicroMag 2900* Alternating Gradient Magnetometer, Princeton Measurements Corp.) were performed by T. Werner at the Institute of Geophysics of the Polish Academy of Sciences.

In addition to the rock magnetic experiments, several polished sections were prepared for reflected light microscope observations.

During the palaeomagnetic analyses, specimens were subjected to both thermal (using the non-magnetic oven MMTD, Magnetic Measurements, UK) and alternating field (up to 100 mT; AF, Molspin Ltd., UK) demagnetization experiments. After each demagnetization step, an intensity and a direction of remanent magnetization were measured using an *Agico JR-6A* spinner magnetometer (noise level 10^{-5}A/m). Characteristic components of a remanent magnetization were calculated by principal component analysis (Kirschvink, 1980) using the *PALMAG* package of Lewandowski *et al.* (1997) and, in a few samples, using a remagnetization circle method (McFadden and McElhinny, 1988). During thermal demagnetization experiments, magnetic susceptibility was measured with an *Agico KLY-2 Kappabridge* to monitor any mineral alteration due to increased temperature.

RESULTS

MAGNETIC MINERALOGY

Reflected light microscope analyses (Fig. 2) revealed irregular assemblages of crystalline hematite (specularite – Fig. 2C) or irregular patches and small veins of crystalline hematite interspersed with cryptocrystalline assemblages (Fig. 2A) as well as Ti-magnetite grains (only in samples K7, K13) replaced by hematite (martite) along fractures and grain boundaries (Fig. 2B).

Rock magnetic analyses distinguished two specific magnetic mineral assemblages. The first group revealed relatively low natural remanent magnetization (NRM) intensities, of between 2.5 and 27 mA/m, and a magnetic susceptibility range from 40 to 90 × 10^{-6} SI. A gradual rise of the isothermal remanent magnetization (IRM) acquisition curve with no saturation reached at 1.5 T indicates the dominance of a high coercivity mineral. This trend is typical for 85% of the samples (excluding calcareous-silicate rocks with grossular). Thermal demagnetization curves of three-axis IRM show a high coercivity component (blue triangles on Fig. 3A, C) with unblocking temperatures from 650 to 700°C, which are characteristic of hematite. Thermomagnetic curves for isothermal remanent magnetization (Fig. 4) and hysteresis loops (Fig. 5) show some differences among different lithologies. Cataclased gneiss (K6) contains abundant hematite but a hysteresis loop of typical “wasp-waisted” shape is observed. This is due to a mixture of SD and SP grains (Tauxe *et al*., 1996) or more likely to a mixture of two magnetic phases of a high and a low coercivity (Dunlop and Özdemir, 1997). The hysteresis curve as well as thermal treatment of SIRM from a heterogeneous quartz vein with fluorite and calcite (K14) reveal the presence of goethite?, magnetite and hematite. An epidote-bearing calcareous-silicate sample (K15) is strongly paramagnetic, but contains typical hematite with wider temperature spectra after heating. These analyses are in agreement with reflected light thin section observations (Fig. 2A, C), that confirm the presence of crystalline as well as of cryptocrystalline hematite assemblages.

The second set of specimens, composed of calcareous-silicate rocks with grossular (K7, K13), is characterized by higher NRM intensities from 40 to 500 mA/m and by very high magnetic susceptibility values from 1320 to 163 900 × 10^{-6} SI. IRM acquisition experiments are characterized by a rapid rise of the IRM curve in applied fields up to 0.2 T, which is indicative of a low coercivity mineral, most probably magnetite (Fig. 3B). The intensity of IRM gradually increased even above *ca*. 0.2 T

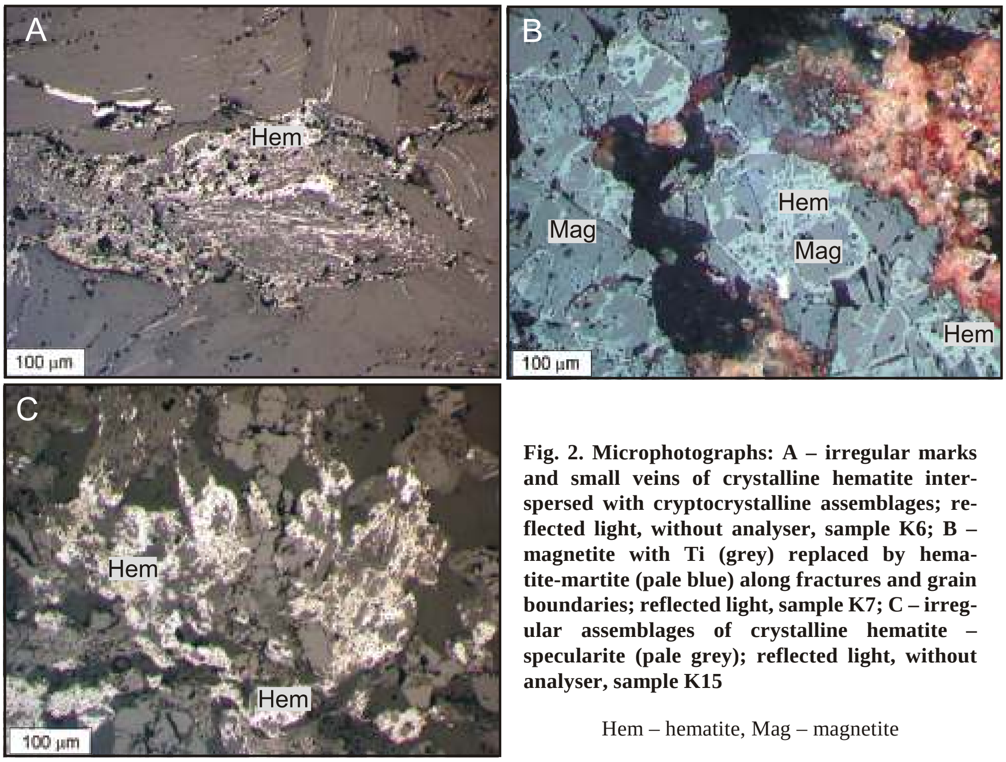

Fig. 2. Microphotographs: A – irregular marks and small veins of crystalline hematite interspersed with cryptocrystalline assemblages; reflected light, without analyser, sample K6; B – magnetite with Ti (grey) replaced by hematite-martite (pale blue) along fractures and grain boundaries; reflected light, sample K7; C – irregular assemblages of crystalline hematite – specularite (pale grey); reflected light, without analyser, sample K15

Hem – hematite, Mag – magnetite

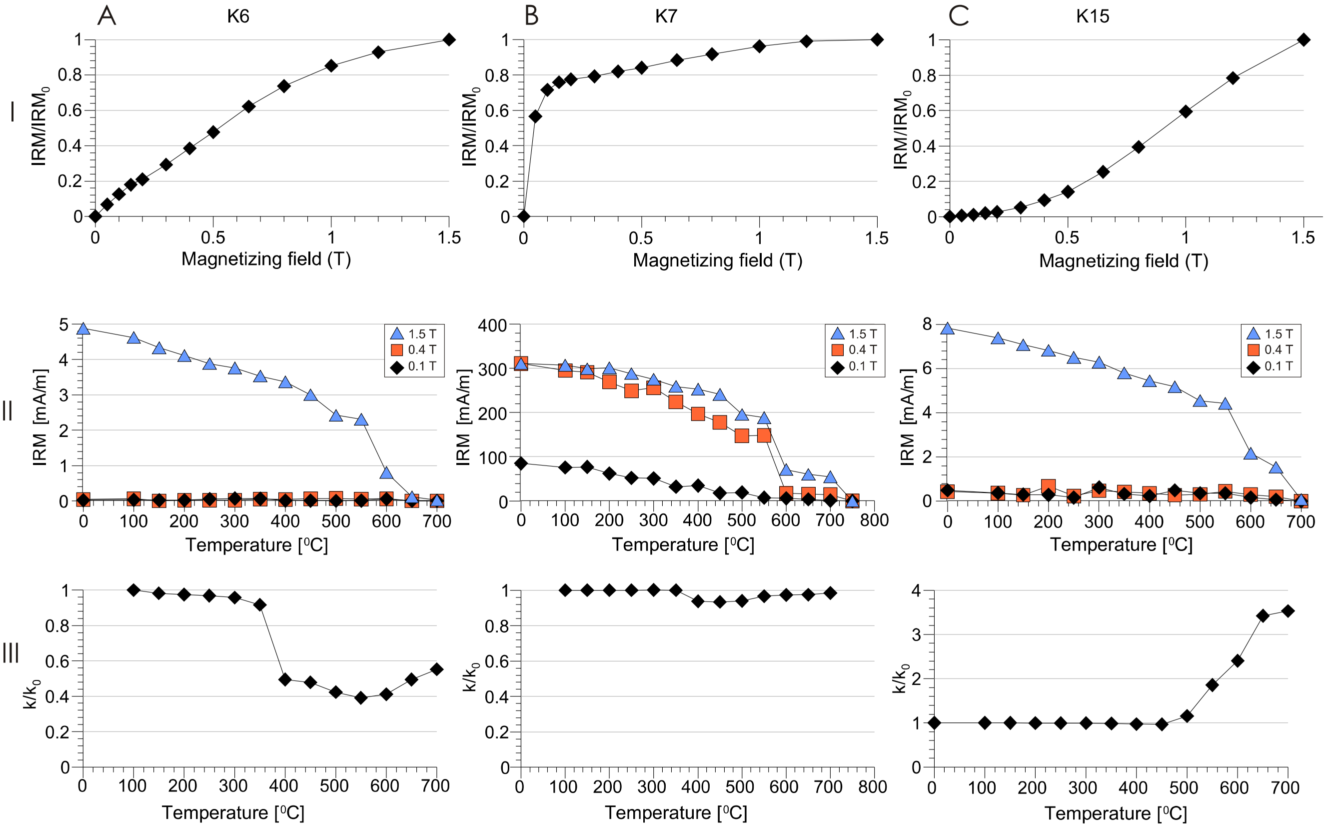

Fig. 3. Rock magnetic properties: (I) – stepwise acquisition of the isothermal remanent magnetization – IRM (II), thermal demagnetization of the three axes IRM, acquired in the fields of 1.5 T, 0.4 T and 0.1 T, (III) – magnetic susceptibility (k) changes during the thermal treatment

A – cataclased gneiss, **B** – calcareous silicate rock with grossular, **C** – calcareous silicate rock with epidote

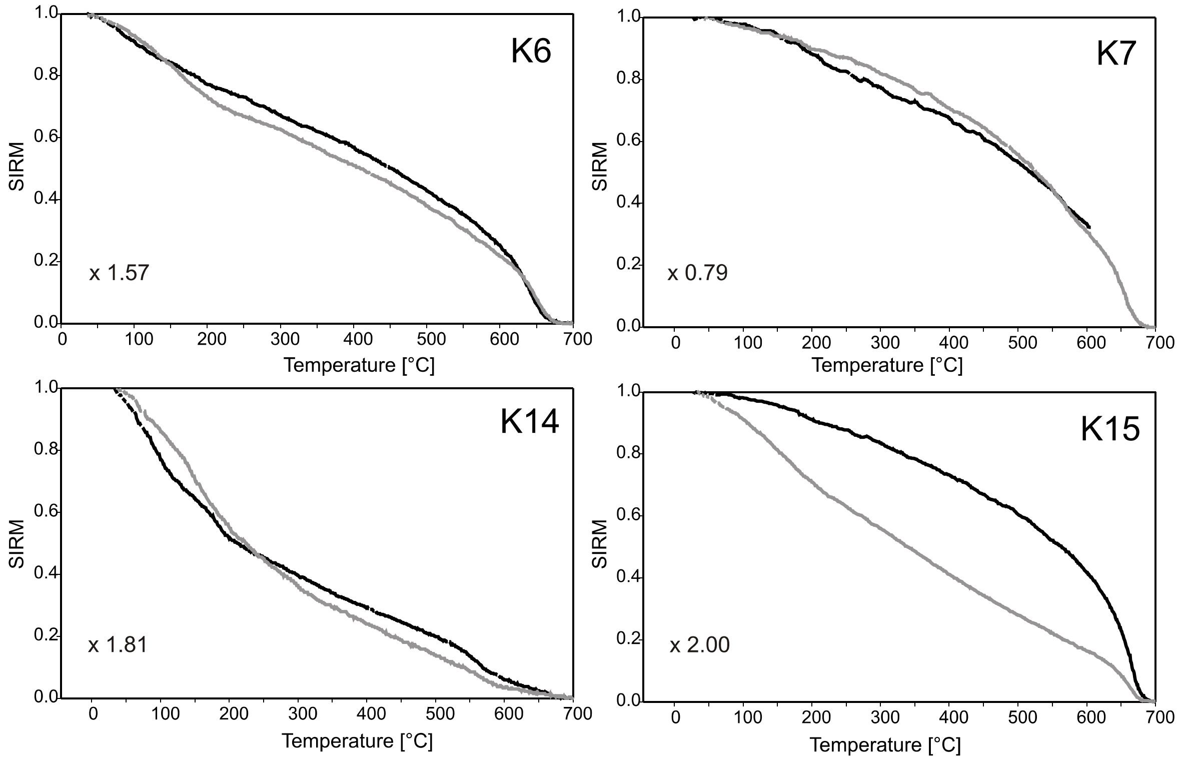

Fig. 4. Thermomagnetic curves for saturation isothermal remanent magnetization (SIRM; acquired in a 9 T field)

Black curve – fresh sample, grey – after one step of heating in air; curves normalized to its initial intensity and to the initial intensity of SIRM (at the room temperature) increased after heating to 700°C by 0.79 to 2.00 times; K6 – cataclased gneiss, K7 – calcareous-silicate rock with grossular, K14 – quartz vein with fluorite and calcite, K15 – calcareous-silicate rock with epidote

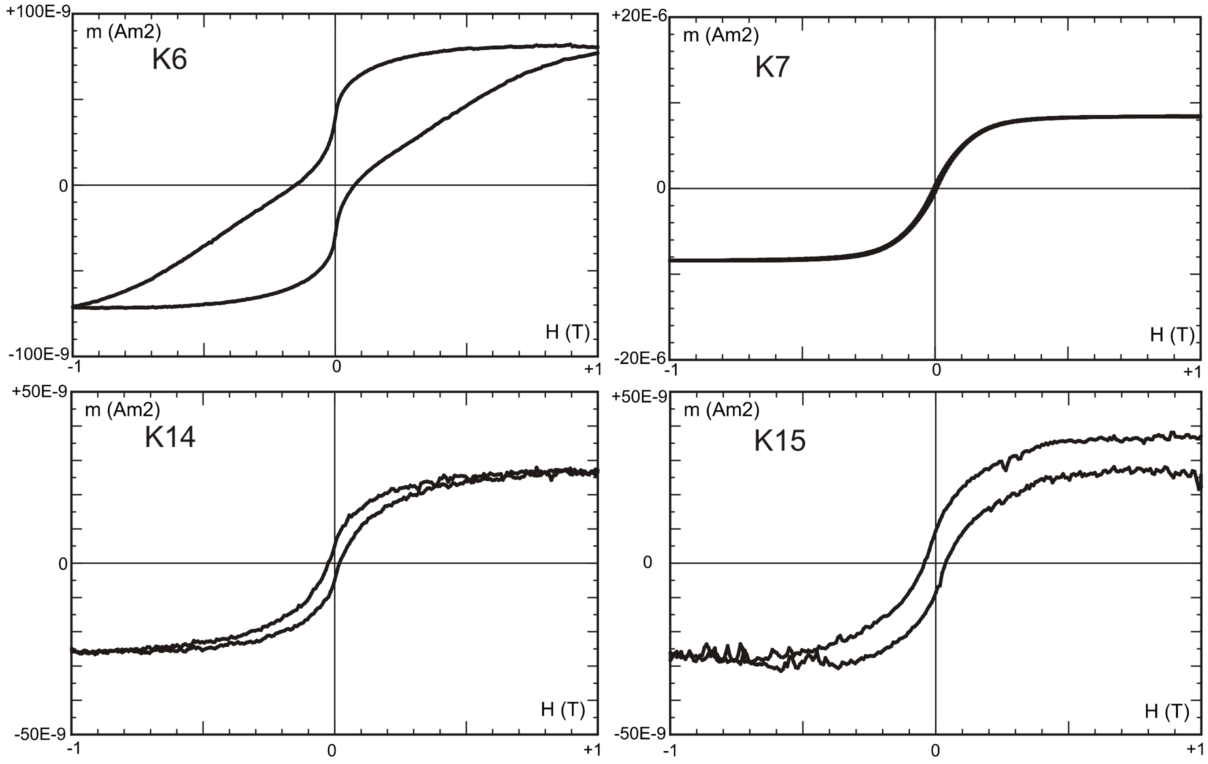

Fig. 5. Hysteresis loops from *MicroMag 2900* magnetometer after correction of paramagnetic contribution

K6 – cataclased gneiss, K7 – calcareous-silicate rock with grossular, K14 – quartz vein with fluorite and calcite, K15 – calcareous-silicate rock with epidote which indicates the presence of a high coercivity mineral as well. The triaxial IRM demagnetization pattern disclosed a dominance of hard (0.4–1.5 T, blue triangles in Fig. 3B) and medium (0.1–0.4 T, orange squares) components. Final demagnetization at a temperature of over 700°C implies the presence of hematite, but a rapid drop of intensity (medium component) in temperatures between 550–600°C is typical of magnetite (present also as a soft – black squares-component). Petromagnetic inhomogeneity in the grossular-bearing calcareous-silicate sample (K7 in Figs. 4 and 5) was corroborated in additional studies, where for a larger volume sample, the temperature dependence of SIRM points to hematite, while the hysteresis loop is typical of a low coercivity mineral. Microscope observations (Fig. 2B) reveal the presence of hematite along fractures and magnetite grain boundaries. A rapid susceptibility decrease during the thermal treatment at a temperature of about 400°C might be indicative of maghemite in some of the samples, whereas a susceptibility increase at temperatures above 500°C documents an oxidation process in paramagnetic minerals.

RESULTS OF DEMAGNETIZATION

From the total number of 51 specimens (from 11 hand samples) 65% were thermally demagnetized and the rest were selected for the AF procedure. Fifty five percent of samples preserved demagnetization in fields of up to 100 mT, therefore they were subjected to thermal treatment as well.

Considering the demagnetization behavior, samples can be divided into four groups (Fig. 6). To the first group belong two hand specimens (comprising 8 specimens) from cataclased gneiss (K6) and a brecciated quartz vein with fluorite and calcite (K8). They reveal a moderately steep negative inclination component, located between the second and third quarter of the hemisphere. An unblocking temperature of about 700°C (Fig. 6A) as well as AF demagnetization inability in a field of 100 mT, points to tiny hematite grains (which agrees with the observations of Kletetschka *et al*., 2000; Evans *et al*., 2001) as the main remanence carriers (see Figs. 3A and 5). A magnetic susceptibility drop (Fig. 3A) in a temperature of about 350°C indicates maghemite, that is oxidized to less susceptible hema-

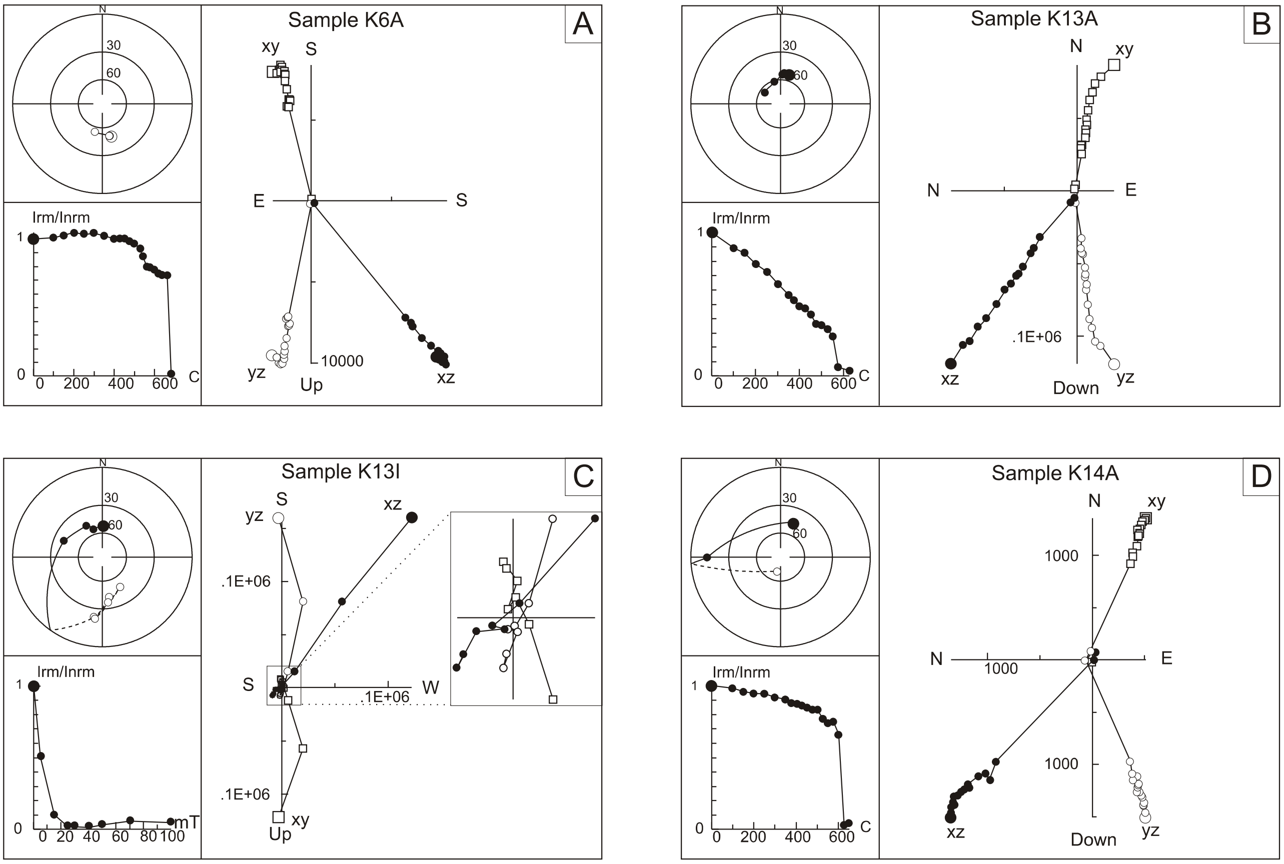

Fig. 6. Representative examples of orthogonal projections (Zijderveld diagrams) of demagnetization paths typical for A – cataclased gneiss and quartz vein; B, C – calcareous-silicate rock with grossular, D – brecciated quartz vein and epidote-bearing calcareous-silicate rock

Intensities of NRM: × 10^{-4} A/m

tite. However, there is no corresponding magnetization component isolated at this temperature.

Twelve specimens of a grossular-bearing calcareous-silicate rock with magnetite (K7, K13) belong to the second and third type of demagnetization pattern. Figure 6B shows a distinct positive inclination component directed to the NNW. A gradual drop in remanent magnetization intensity up to a temperature of 580°C is consistent with magnetite as a principal magnetic carrier (see also Figs. 3B and 5). The efficient alternating field method (Fig. 6C) confirms the dominance of a low coercivity mineral as a carrier of the positive inclination component. However, some of the samples (55%) from this group were not fully demagnetized in the field of 100 mT and revealed also a second, negative inclination component directed to the S. Hematite is suspected to be the magnetization carrier in this case (compare Figs. 2B, 3B and 4).

The last set of specimens contains a brecciated quartz vein (K14) and an epidote-bearing calcareous-silicate rock (K15), that showed a normal polarity component (Fig. 6D), gradually demagnetized up to the blocking temperatures of just above 600°C. It is presumably a coarse grained (Evans *et al.*, 2001) hematite component, since there is no proof of maghemite occurrence (see Figs. 2C and 3C–5). With its shallow inclination it is subparallel to the normal polarity magnetite components (Fig. 6B). Leucocratic schists (K1, K2, K12) as well as silicate marbles (K9, K11) did not reveal any interpretable component.

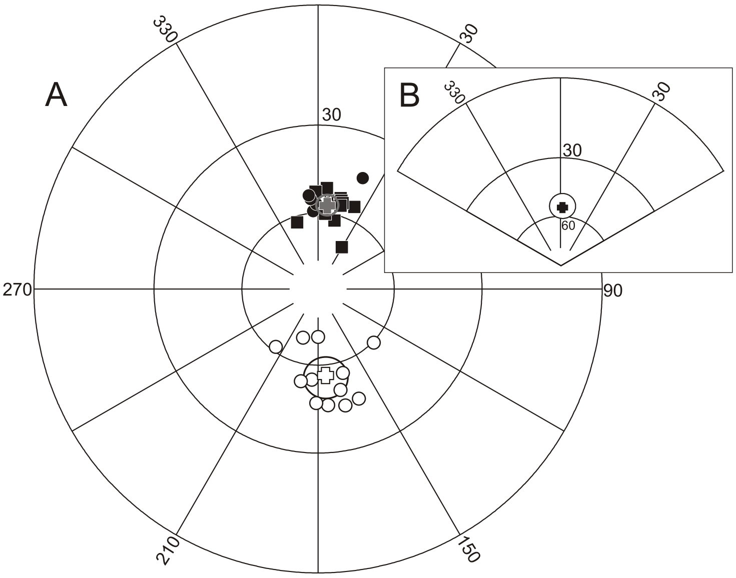

Fig. 7A – Stereographic projection of characteristic directions isolated from the rocks studied with mean directions (crosses) and α_{95} plotted; B – overall mean direction

Circles – hematite, squares – magnetite, black symbols – lower hemisphere projection (component A), white symbols – upper hemisphere projection (component B)

Putting together all the samples analysed, we can distinguish two distinct components of characteristic remanent magnetization (Fig. 7 and Table 1). The first component (denoted as A) is a high temperature, normal polarity component of moderately steep inclination (from 50 to 63°), directed NNW, which is presumably carried by magnetite as well as hematite. The second well-defined, high temperature and high coercivity component (denoted as B) with moderately negative inclination (from –44 to –71) towards the S was isolated in hematite samples. The presence of both normal and reversed polarity components points to a stable magnetization differing from the present-day field. A simple reversal test confirms that both normal and reversed polarity directions are antipodal within the limits of error (“C” category after McFadden and McElhinny, 1990).

DISCUSSION

Dual polarity components indicate an extended mineralization process. For the hematite grains, very resistant to remagnetization, the dual polarity palaeomagnetic component is probably coeval with hematite growth, but the same normal polarity direction preserved in magnetite might have been recorded after its crystallization. Magnetite grains are very sus-

Table 1

Characteristic palaeomagnetic directions isolated in the Kletno mine (lat. = 50.26°N, long. = 16.86°E)

Component	N	n	*D*	*I*	α_{95}	*k*	Plat	Plong	dp	dm	H/M
Normal - A	4	17	10	54	10.2	82.3	73	167	10	14	M + H
Reversed - B	4	12	174	–55	11.9	60.3	75	216	12	17	H
Overall mean (A + B)	8	29	2	55	7.1	62.1	75	189	7	10	M + H

N – number of hand samples used to calculate mean directions; n – number of specimens; *D* – declination; *I* – inclination; α_{95}, k – Fisher’s statistics parameters; Plat – palaeopole latitude; Plong – palaeopole longitude; dp – , dm – semi-axes of confidence oval: dp – in site-to-pole direction, dm – in perpendicular direction; H – hematite, M – magnetite ceptible to remagnetization and easily could have reset their primary signal due to a strong event connected with temperature and stress field changes. In this particular case it might be a hydrothermal fluid flow event as well as magnetite ore crumbling and tectonic movement processes, which led to magnetite remagnetization. Assuming that the main uranium precipitation event is coeval with hematite mineralization (Banaś, 1965), our results could be directly relevant to age estimation of the uranium ore.

For this purpose the palaeopole was calculated from the mean orientation combining normal and reversed polarity components. The palaeopole position obtained (Plat. 75°N, Plong. 189°E) was compared with the apparent polar wander path calculated for Europe for the last 200 Ma (Besse and Courtillout, 2003) in order to determine an oxide mineralization age (Fig. 8). The processes might have taken place in the Early Cretaceous, considering only the mean orientation of the palaeopole. However, the statistic error limit for this estimation is quite significant. The comparison of the mean values of the declination/inclination data (see Table 1) with the expected stable European declinations/inclinations calculated for the geographical coordinates of the Kletno mine (50.26°N, 16.86°E) leads to the conclusion that even Paleogene age is possible within a 95% limit of confidence. The oxide mineralization could have taken place no earlier than 148 Ma and not later than 36.5 Ma (Fig. 9). The mean in-

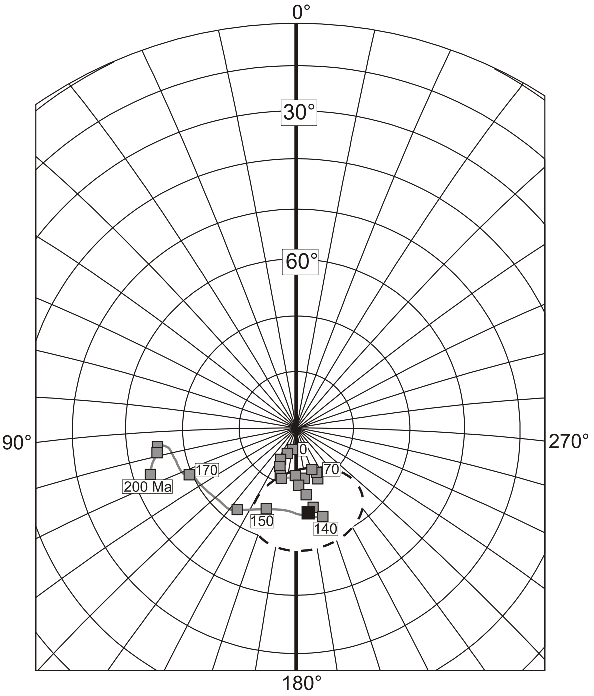

Fig. 8. Palaeomagnetic pole obtained from the rocks studied (with 95% confidence oval) plotted on the top of the apparent polar wander path of Europe (after Besse and Courtillot, 2003)

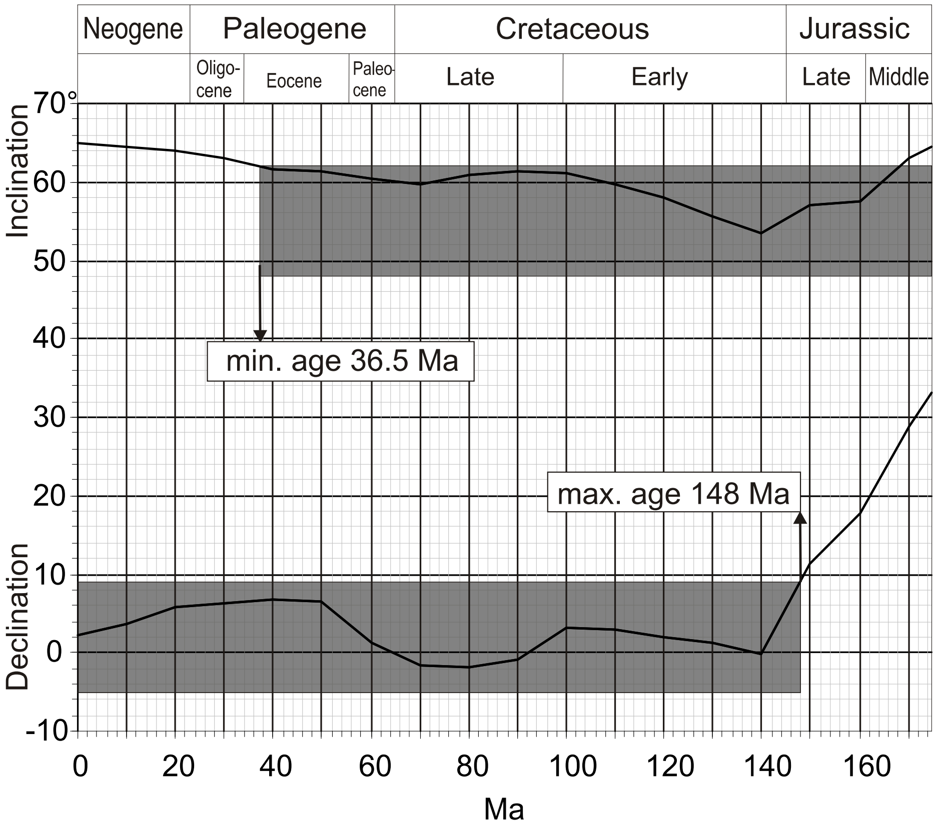

Fig. 9. Expected palaeodeclinations/palaeoinclinations calculated for the geographic coordinates of the Kletno mine (data after Besse and Courtillot, 2003) and declination/inclination of the characteristic component isolated from the Kletno mine rocks

The shaded area indicates error of age estimation related to the values of α_{95}

clination value of 55° (Table 1) may also be a sign of a Late Triassic mineralization age. On the other hand, that presumption would require a large counterclockwise rotation of about 40 degrees. The established regional tectonics (Don *et al.*, 2003), as well as the available palaeomagnetic data from the Sudetes (Nawrocki, 1998) allow us to exclude such significant Alpine tectonic rotations in this region.

The result of our work dispels the doubts concerning the previously suggested Variscan age (Banaś, 1965) of the uranium-fluorite veins, though additional sampling and more precise examination is planned to improve the statistics. However, the palaeomagnetic data did not let us construct a mineralization model.

The uranium-bearing polymetallic-fluorite ore is believed to be of hydrothermal origin (Banaś, 1965). In the Kletno region, fluid inclusion measurements (Zieliński, 1997) point to low-temperature solutions (120–240°C), while the low salinity suggests "post-ore" quartz and fluorite crystallization. Barbier (1974) suggested that continental weathering of granitoid rocks containing uranium might be a possible cause of the French vein uranium deposits. In oxidizing conditions (due to a lack of organic matter) uranium-rich concentrations might have been transported downwards along fractures by supergene fluids. Secondary replacement of "dispersed uranium" from granitoids and its precipitation in favourable conditions was proposed by Bareja *et al.* (1982) as a possible source of some uranium ore veins in the Sudetes. This scenario looks realistic, all the more as August and Wojewoda (2004) suggested that the Late Jurassic/Early Cretaceous should be considered as the most probable period of soil cover formation in the Sudetes. Deep continental weathering processes in Central and Northern Europe have been well documented by Migoń and Lidmar-Bergström (2001, 2002) since the Mesozoic up to the Cenozoic. The impact of intense weathering in the Kletno supergene ore zone is well documented (Banaś, 1965). In the time of a block uplift regime and subsequent stabilized land conditions, hydrothermal, metal-rich as well as supergene fluids could possibly have migrated using the same paths and thus generated specific mineral accumulations. Fluids of meteoric origin, descending during the Cretaceous basin inversion, were suggested as a possible source of the youngest hydrothermal vein system in the North Eastern German Basin (Schmidt Mumm and Wolfgramm, 2004).

CONCLUSIONS

– Strongly tectonized rocks (quartz and fluorite veins, leucocratic schists, calcareous-silicate rocks with epidote or grossular, cataclased gneisses and silicate marbles) from the Old Kletno Uranium Mine revealed two components of magnetization. The first one of normal polarity recorded in magnetite and coarse hematite and the second one with reversed polarity direction carried by fine grained hematite; these directions do not differ from each other within the error limits.

– Comparison of the palaeomagnetic data obtained with the apparent polar wander path for the European craton indicates an Early Cretaceous up to Paleogene age limit for the uranium mineralization.

– In order to constrain the age of uranium mineralization more precisely, additional palaeomagnetic sampling and improvement of the statistics of our data would be helpful.

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