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Paleomagnetic dating of non-sulfide Zn-Pb ores in SW Sardinia (Italy): a first attempt

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Abstract
A first paleomagnetic investigation aimed at constraining the age of the non-sulfide Zn-Pb ore deposits in the Iglesiente district (SW Sardinia, Italy) was carried out. In these ores, the oxidation of primary sulfides, hosted in Cambrian carbonate rocks, was related to several paleoweathering episodes spanning from the Mesozoic onward. Paleomagnetic analyses were performed on 43 cores from 4 different localities, containing: a) non-oxidized primary sulfides and host rock, b) oxidized Fe-rich hydrothermal dolomites and (c) supergene oxidation ore («Calamine»). Reliable data were obtained from 18 samples; the others show uninterpretable results due to low magnetic intensity or to scattered demagnetization trajectories. Three of them show a scattered Characteristic Remanent Magnetization (ChRM), likely carried by the original (*i.e.* Paleozoic) magnetic iron sulfides. The remaining 15 samples show a well defined and coherent ChRM, carried by high-coercivity minerals, acquired after the last phase of counterclockwise rotation of Sardinia (that is after 16 Myr), in a time interval long enough to span at least one reversal of the geomagnetic field. Hematite is the main magnetic carrier in the limestone, whereas weathered hydrothermal dolomite contains goethite or a mixture of both. The results suggest that paleomagnetism can be used to constrain the timing of oxidation in supergene-enriched ores.

Key words *paleomagnetism – Sardinia – non-sulfide ores – calamine*

1. Introduction

Non-sulfide ores, mainly the supergene-formed types, are rapidly becoming an important source of metallic zinc as well as lead (Large, 2001; Boni, 2003; Hitzman *et al.*, 2003). However, time constraints for the deposition of these ores are still unclear, due to multiple oxidation events through time, which control their silicates/carbonates paragenesis. Because the timing and evolution of weathering profiles might have important implications for the exploration of non-sulfide deposits, it is a priority to obtain a reliable estimate for the age of the oxidation phenomena, either by use of radiogenic isotope systems, or by other unconventional methods.

In this paper, we report on a first attempt made to use paleomagnetism for constraining the age of the non-sulfide Zn-Pb ore in the Iglesiente-Sulcis district (SW Sardinia, Italy), where the oxidation of primary sulfides has been related to paleoweathering episodes dating back to Cenozoic and even Mesozoic times (Boni *et al.*, 2003).

2. Paleomagnetism and ores

In the last twenty years, a major effort has been made in dating stratabound, disseminated and massive sulfide ore deposits, as well as their

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host rocks with paleomagnetic methods (Symons *et al.*, 1996, 2002; Symons and Stratakos, 2000; Leach *et al.*, 2001; Bradley and Leach, 2003). These authors claim, though not without debate (Kesler *et al.*, 2004), that a Characteristic Remanent Magnetization (ChRM), acquired during the ore minerals forming processes, can be recognized in most ore deposits.

In these studies, magnetic susceptibility, demagnetization of the natural remanent magnetization, acquisition of artificial remanences and other magnetic measurements were performed on several thousand specimens of mainly Mississippi Valley Type (MVT) mineralization and gangue, in order to identify their magnetic carriers. Thermal demagnetization and specific rock magnetic analyses show that the ChRM in most deposits, as well as in monomineralic specimens, is carried by single or pseudosingle domain pyrrhotite and/or magnetite. Almost all the paleomagnetic studies used several stability tests (conglomerate, fold, contact and reversals test) to constrain the acquisition age of ore remanence (Symons *et al.*, 1996). The main conclusion is that the paleomagnetic ages of most sulfide deposits seem to be coeval with the later stages of major orogenic events in the same region.

Few investigations have been undertaken so far to date non-sulfide deposits, with the exception of few economic laterites and bauxites (mainly aimed to broader geodynamic and/or paleoclimatic studies) and of Proterozoic manganese deposits (Evans *et al.*, 2001).

3. Geological setting of SW Sardinia and the non-sulfide zinc-lead deposits

3.1. *Geological setting*

The Iglesiente-Sulcis area in SW Sardinia (fig. 1) is one of the oldest mining districts in the world, where exploitation started in pre-Roman times, initially for silver-lead-copper and later for zinc and barium deposits. Due to increasing economic difficulties, the last producing mine in the area was closed in 1998.

SW Sardinia is dominated by Paleozoic lithotypes, of sedimentary as well as igneous origin, followed by Cenozoic and Quaternary volcanics and sedimentary rocks. Among the Paleozoic rocks, Cambro-Ordovician lithologies (limestones and dolomites of the Gonnesa Group) predominate (Bechstädt and Boni, 1994). The Cambrian sediments are the preferential host for both primary and secondary (oxidated) Zn-Pb ores. Most of the primary ores are stratabound (Sedex + MVT): they consist of Zn-Pb sulfides locally associated with barite, with hydrothermal alteration limited to local dolomitization and silicification (Boni, 1985; Bechstädt and Boni, 1994; Boni *et al.*, 1996).

A strongly pervasive hydrothermal dolomitization («Geodic Dolomite»: Boni *et al.*, 2000) of possible Permo-Triassic Age affected large volumes of the Cambrian carbonate rocks across the whole district (more than 500 km^2). These dolomites are Fe-rich, both replacive and saddle-shaped, frequently with zebra structures. The Late Variscan uplifts in Sardinia were followed by the inset of small porphyry stocks and several pulses of extensional tectonics, which caused repeated circulation of hydrothermal fluids during the Mesozoic (Boni *et al.*, 1992, 2002), accompanied by deep karstification of the Cambrian carbonate rocks, which continued during the Cenozoic. The development of karstic networks in the Cambrian limestone, was favored in all periods by the aggressive character of the circulating waters and by the high sulfide content of the carbonate rocks undergoing dissolution.

A phase of widespread tensional tectonics in the Middle Oligocene produced a large rift system locally accompanied by the deposition of continental sediments. This was followed by a major episode of Oligocene-Miocene volcanism, correlated to a drift-related ~50° counterclockwise rotation of the Corsica-Sardinia microplate (Gattacceca, 2001). The spreading in the Liguro-Provençal Basin and the rotation of Corsica-Sardinia, ended no earlier than 16 Myr (Early Langhian; see Speranza *et al.*, 2002) in response to the retreat of a westward dipping subducting slab (*i.e.* Faccenna *et al.*, 2004).

During Miocene and Pliocene, SW Sardinia was subjected to several emersion-erosion phases, alternating with marine transgressions, dramatic climatic changes (Messinian evaporites) and volcanic episodes of calc-alkaline to alkaline basalts. A last Plio-Pleistocene tensional

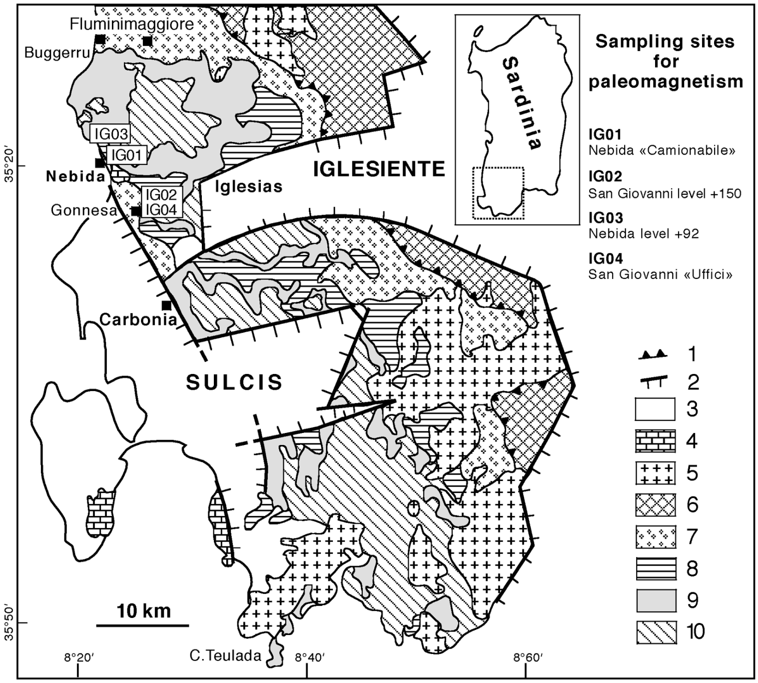

Fig. 1. Geological sketch map of the Iglesiente mining district, with the location of the sampled sites (modified from Boni *et al.,* 2003). Abbreviations: 1 – overthrust; 2 – normal fault; 3 – Cenozoic; 4 – Mesozoic; 5 – Variscan granites; 6 – Palaeozoic (allochthonous); 7 – Ordovician to Devonian succession; 8 – Iglesias Group (Middle Cambrian-Lower Ordovician); 9 – Gonnesa Group (Lower Cambrian); 10 – Nebida Group (Lower Cambrian).

tectonic phase was responsible for the differentiated uplift of the Paleozoic basement, which was fragmented into a series of stepped fault blocks in both the Iglesiente and Sulcis areas.

3.2. *Non-sulfide deposits*

The «Calamine»-type ore is considered to be the result of supergene oxidation of primary carbonate-hosted sulfide mineralization, with subsequent remobilisation of zinc and partly of lead, followed by redeposition of secondary oxidized minerals either *in situ* as *gossans*, or as reaction products within the hosting carbonates. In the latter case, they not only replace substantial areas of the fractured and karstified carbonate rocks, but fill as internal sediments their dissolution vugs and karst cavities, producing secondary enrichments also at greater distances from the primary sulfide bodies (Large, 2001; Hitzman *et al.*, 2003).

Historically, the «Calamines», consisting of a mixture of zinc carbonates and hydroxy-carbonates and silicates (with minor Pb), capping in the whole area the primary sulfide bodies, were the principal source of zinc of the Iglesiente-Sulcis district (Moore, 1972; Boni *et al.*, 2003). The most important mines (fig. 1), where non-sulfide ores have been exploited for several hundred of meters in depth from the present surface, were: San Giovanni, Monteponi and Campo Pisano in the Iglesias valley, as well as the Nebida-Masua mineralized complex along the western coast. Smithsonite, hydrozincite, and hemimorphite were the principal zinc-bearing economic minerals. Cerussite, anglesite and the rare mineral phosgenite were also common, generally associated with nodules and lenses of residual galena and a range of fairly exotic species (Billows, 1941; Moore, 1972; Stara *et al.*, 1996; Aversa *et al.*, 2002). A complex assemblage of iron and manganese oxy-hydroxides characteristic for its red-brown staining (goethite, lepidocrocite, hematite) and residual clay minerals accompany the non-sulfide ore.

An interesting parallel effect of the oxidation of the sulfide ore, is the supergene alteration of the ferriferous hydrothermal dolomites («Geodic Dolomite»), which are the host rock of most sulfide deposits in the Iglesiente district. In fact, these dolomites, are not only Fe-rich (some of them approach ankerite composition), but contain small pyrite grains. When affected by supergene processes, the «Geodic Dolomite» turns reddish-brown, its disseminated pyrites alter to goethite and hematite and a patchy de-dolomitization process starts locally. These effects in the dolomite host rocks can be followed deep down, at least until the same levels in the mines where the «Calamine» mineralization has been exploited (*e.g.,* level −100 of the Monteponi mine). We emphasize that we consider the weathering of the «Geodic Dolomite» not related to recent surficial weathering only, but contemporary with the formation of «Calamine» ore.

When investigating the timing of the non-sulfide deposits in a given area, one must consider the ages of the various stages of tectonic uplift and peneplanation. To document the major constraints on the oxidation and preservation of the deposits, it is also necessary to relate them to climatic oscillations both at a global and local scale. What makes this task difficult in SW Sardinia, is the lack of precise geological constraints on the development of the numerous karstification phases that are closely related to formation of the «Calamine» ores. Karstic dissolution related to uplift of the Paleozoic carbonates, occurred repeatedly: 1) during Permo-Mesozoic, 2) several times during Cenozoic, and 3) after the Plio-Pleistocene block tectonics until the Present.

However, the most reliable time span we can envisage from the limited geological constraints, in which both tectonic and climatic conditions were favorable for the formation of the non-sulfide deposits ranges from Middle Eocene to Plio-Pleistocene. The latter was the time when the differentiated uplift of distinct sectors of the Paleozoic basement displaced at very different levels the base of the weathering profiles in the various areas of the Iglesiente-Sulcis.

Our aim was to use paleomagnetism to provide constraints on the age(s) of the oxidation process, evaluating the characteristic remanent magnetization carried by various iron minerals, like hematite, goethite and, in case, of the remaining as well as of newly formed magnetic iron sulfides. Sardinia has been the subject of several paleomagnetic studies since the 1960's and a reliable dataset of paleomagnetic results is available (see van der Voo, 1993; Speranza, 1999; Speranza *et al.*, 2002 and references therein), referring to a wide age range (Paleozoic to Present), to provide a suitable reference for comparison with the new data.

4. Sampling strategy

Samples were collected using a portable gasoline-powered drill and were oriented *in situ* with a compass mounted on an inclinometer. 43 oriented cores were collected from 4 sites in the surroundings of Iglesias, either on outcrops (sites IG01 and IG04) or inside two abandoned mines (sites IG02 and IG03).

Site IG01 - Weathered «Geodic Dolomite» along the «Strada Camionabile» (Nebida) – The sampling took place shortly east of the village of Nebida, in a small valley cut in the carbonates (39°20′N-8°27′E), where patchy outcrops of hydrothermal dolomite («Geodic Dolomite») on the Cambrian limestone are clearly exposed. The contacts with non-dolomitized host rock are sharp, locally marked by a slight silicification. Vertical schistosity planes mostly control the dolomite bands; the control is rarely made by fractures. The crystals are typically saddle-shaped, lining concretionary voids and small horizontal cavities.

The weathered hydrothermal dolomite is brown-reddish due to its high Fe-oxide content.

Locally, the dolomitization affect**s** a post-Variscan breccia, whose carbonate clasts show schistosity and traces of primary sulfide crystals, that have also undergone weathering and oxidation processes. However, some of the breccia clasts have not been dolomitized and still consist of white Cambrian limestone.

21 cores were sampled at this site, in varying lithologies: 6 samples represent the Cambrian limestone, with oxidized sulfides, 9 samples were collected from the weathered «Geodic Dolomite» and 6 samples were drilled in the carbonate clasts, with traces of primary sulfides crystals, composing a brecciated patch.

Site IG02 - «Zona Ossidati Piombiferi», level +150, San Giovanni mine (Iglesias) – The sampling was performed underground in the oxidation area of Idina-Sant'Anna of the San Giovanni mine (39°15′N- 8°27′E). These are the upper levels of the mine and contain only local remnants of sulfides (galena), prevailing Fe-oxides-hydroxydes, clay-infillings and limited concentrations of Zn- and Pb-carbonates. It is probable that in this area of the mine, the primary orebodies consisted not only of the stratabound Zn-rich Pre-Variscan mineralizations, but also of the Post-Variscan (Ag)-galena bodies in paleokarst breccias. Host rocks are the Cambrian limestones and the weathered hydrothermal dolomites.

7 cores were sampled at this site: 5 of them represent the mineralized dolomite breccias, 1 was drilled in a clast of Cambrian limestone and 1 in the weathered hydrothermal dolomite.

Site IG03 - Zona «Calaminari», level +92, Nebida mine (Nebida) – The sampling has been performed underground at the +92 level of the Nebida mine (39°25′N-8°25′E). In this level, situated well above the present water table, there are almost no sulfides left, whereas in the lower levels, a continuous transition to Zn-Pb sulfides takes place. The direction of the oxidized ore bodies, which replace the primary sulfides as well as part of the carbonate host rocks, is N-S, which is the general tectonic trend of the whole area. The carbonate host rock is heavily dolomitized («Geodic Dolomite» replacing hydrothermally Cambrian limestone), but also karstified and altered to a mixture of de-carbonated material, Zn-carbonates and hydrocarbonates, Zn-silicates, Pb-carbonates and sulfates, and Fe oxides/hydroxides. Beyond the described occurrences of non-sulfide mineralization at the level +92, allochthonous concentrations of ferruginous, «earthy» smithsonite and hemimorphite-rich clays, fill a maze of interconnecting karst cavities and open conduits in this, as well as in the other upper levels of the mine.

9 cores were sampled at this site, all in the dolomite hosting the non-sulfide Zn ores.

Site IG04 – San Giovanni mine (Iglesias) – In this site, behind the old building of the mine direction (39°15′-8°27′), only the white limestone belonging to the upper stratigraphic part of the Lower Cambrian succession (Gonnesa Group) was sampled. In this outcrop the limestone is strongly deformed by Variscan tectonics (penetrative schistosity and recrystallization), not dolomitized neither mineralized. In this site 6 cores were sampled.

5. Methods

In the laboratory two to three standard cylindrical specimens of 2.54 cm in diameter and 2.20 cm length were cut from each sample. Natural Remanent Magnetization (NRM) was measured on a 2G Enterprises DC SQUID cryogenic magnetometer operating in a magnetically shielded room at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome, Italy. A Pyrox oven located in the shielded room was used for thermal demagnetization. Alternating Field (AF) demagnetization was performed with three orthogonal coils installed inline with the cryogenic magnetometer. We first analysed the behaviour of 10 couples of pilot «sister» specimens (*i.e.* standard paleomagnetic cylinders cut from the same core). Of each couple, one specimen was subjected to stepwise AF demagnetization up to 100 mT, the other to thermal demagnetization up to 650ºC. On the basis of the pilot study results, the remaining specimens followed an hybrid AF and thermal demagnetization protocol. In this case, stepwise AF demagnetization was first applied and consisted in 9 steps at increments of 5 mT in the interval 5 to 30 mT and then increments of 10 mT up to 60 mT. Samples were subsequently demagnetized at 60°C, 80°C, 100°C, 120°C, 200ºC, 300°C, 400°C, 500°C, 580°C, 610°C and 640°C. Magnetic susceptibility was measured after each heating step in order to monitor alteration and/or neoformation of magnetic minerals during the thermal treatment. The AF followed by thermal demagnetization protocol was designed as the most efficient demagnetization treatment, which could also provide information on magnetic mineralogy, so that the ChRM components carried by high-coercivity minerals having low (goethite) and high (hematite) unblocking temperatures could be easily identified. Low-coercivity minerals like magnetite and magnetic iron sulfides (pyrrhotite, greigite), instead, would have been mostly demagnetized below 60 mT upon the AF routine. Orthogonal vector demagnetization plots (Zijderveld, 1967) were used to represent demagnetization data, and principal component analysis (Kirschvink, 1980) was used to identify the characteristic remanent magnetization. The mean directions were calculated using Fisher (1953) statistics. The reversal test of McFadden and McElhinny (1990) was applied to assess the antipodality of the normal and reverse means.

6. Results

The AF demagnetization behaviour indicated that for most samples the main magnetic carriers are high-coercivity minerals only (*i.e.*, the NRM intensity shows very low to null decrease in AF up to 100-150 mT). For such samples, therefore, magnetic components were retrieved after thermal demagnetization (figs. 2a-c to 5a-c). The measurements of magnetic susceptibility after

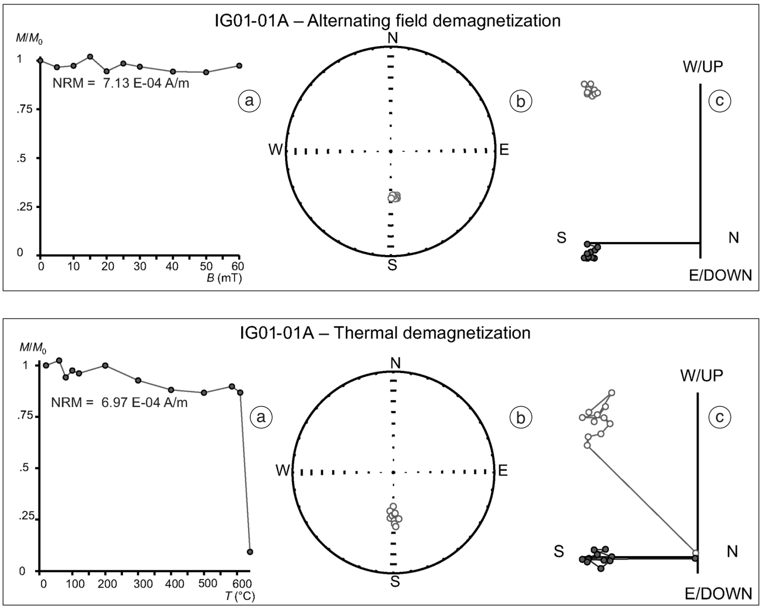

Fig. 2a-c. Stepwise demagnetization data for sample IG01-01A (non-dolomitized brecciated limestone, Nebida «Camionabile»). From left to right: a) normalized intensity plot, the intensity of the Natural Remanent Magnetization (NRM) at the beginning of the treatment is also indicated; b) equal area projection in geographic coordinates (open circles – upper hemisphere, reverse polarity); c) orthogonal vector diagrams in geographic coordinates (open circles – vertical projection; full circles – horizontal projection). The AF demagnetization treatment (upper diagrams) essentially did not affect the NRM of the sample, whereas the sharp drop in NRM intensity during the thermal treatment between 610°C and 640°C (lower diagrams) indicate that the characteristic component of the NRM is of reverse polarity and is carried by hematite.

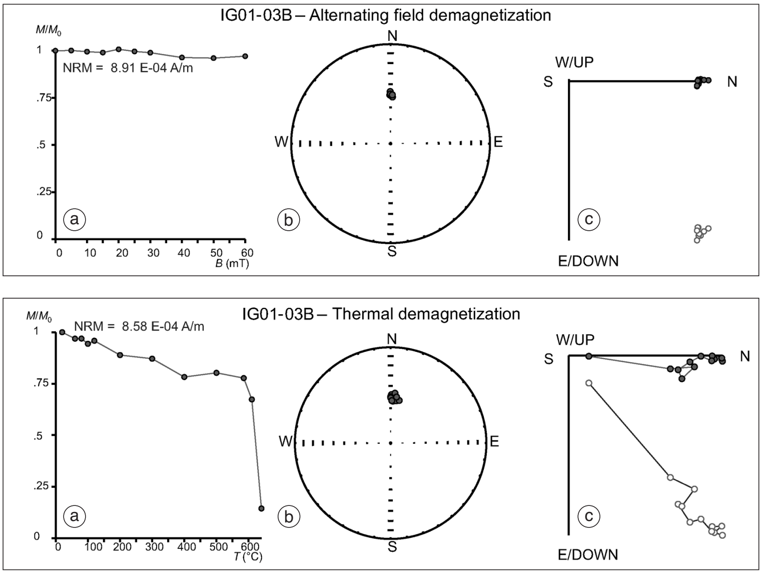

Fig. 3a-c. Stepwise demagnetization data for sample IG01-03B (non-dolomitized brecciated limestone, Nebida «Camionabile»). Plots and symbols as in fig. 2a-c (full circles in the equal area projection (b) indicate projection on the lower hemisphere, normal polarity). The sample shows essentially the same behavior of sample IG01-01 (see fig. 2a-c), but its characteristic component of the NRM is of normal polarity.

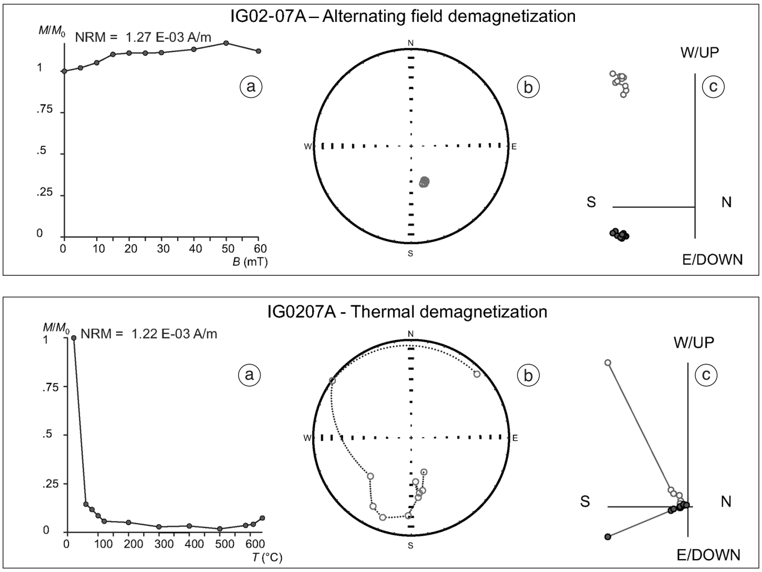

Fig. 4a-c. Stepwise demagnetization data for sample IG02-07A (San Giovanni mine, level +150). Plots and symbols as in fig. 2a-c. The NRM of the sample is essentially not affected by AF treatment and shows a sharp drop in intensity just after the first heating step (60°C) and is almost fully demagnetized at 120°C, indicating that the characteristic component of the NRM is of reverse polarity and is carried by goethite.

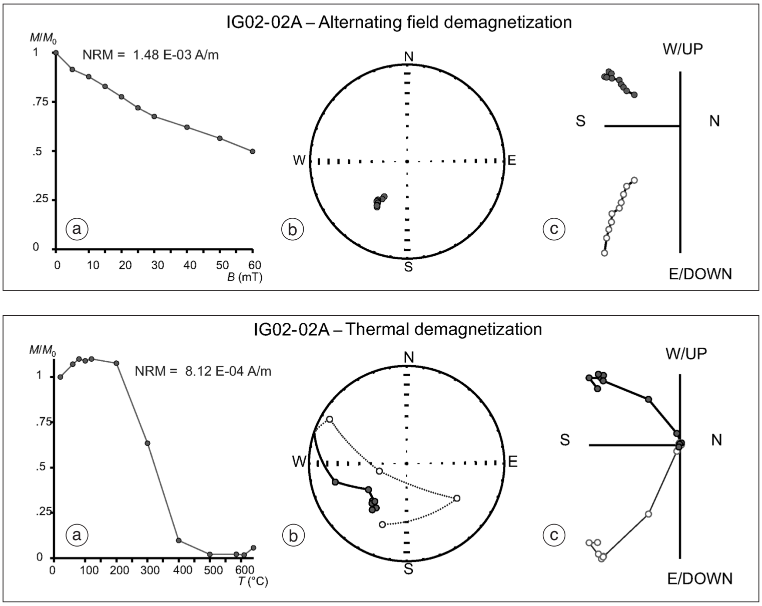

Fig. 5a-c. Stepwise demagnetization data for sample IG02-02A (San Giovanni mine, level +150). Plots and symbols as in fig. 2a-c. The NRM of the sample is reduced at *ca.* 50% of its initial value after AF treatment in peak field up to 100 mT. The following thermal treatment pointed out a sharp drop in intensity between 300°C and 400°C, after which the sample is essentially demagnetized, indicating that the characteristic component of the NRM is likely carried by intermediate-coercivity magnetic iron sulfides (pyrrhotite ?). The direction of the characteristic remanence is however aberrant.

each heating step indicate that neoformation of magnetic minerals occurs above 500°C. In any case, no significant change in paleomagnetic direction was detected in association to such thermal alteration.

Reliable paleomagnetic data were obtained from 18 samples out of a total of 43 (table I). No tectonic correction was applied to the paleomagnetic data. The white-coloured, non-mineralized limestones (samples 13-18 taken in the carbonate clasts with traces of primary sulfides crystals at site IG01-Nebida and all samples from site IG04-San Giovanni), show very low NRM intensities (of the order of a few 10^{-5} A/m) and irregular behaviour during progressive demagnetization. No reliable paleomagnetic data could be obtained from these samples.

The weathered hydrothermal dolomites sampled at Nebida, site IG01, are generally reddish and show demagnetization behaviours indicating that their main magnetic carriers are high-coercivity minerals only (the NRM intensity shows very low to null decrease in AF up to 150 mT). The behaviour during thermal demagnetization indicates that dolomite samples contain a mixture of goethite (indicated by a significant loss of the NRM intensity at 80-120°C; *i.e.* Dekkers, 1988, 1989) and prevailing hematite (as indicated by complete demagnetization at temperatures of 640-680°C; *i.e.* Dunlop, 1971). The prevalence of hematite is evident in the non-dolomitized limestones containing weathered crystals of former pyrite, sampled in the same locality (*i.e.* IG01-01 and IG01-03, figs. 2a-c and 3a-c). The narrow range shown by the unblocking temperature of hematite is possibly related to its pseudomorphic nature on precursor pyrite crystals.

The mineralized limestones lacking sulfides sampled in both mines (sites IG02 and IG03) are also characterized by high-coercivity magnetic carriers, with a very low to null NRM intensity loss up to 150 mT AF. Their behaviour during thermal demagnetization indicates that their main magnetic minerals are hematite (that is, most of the remanence is lost between 580°C and 640°C) and/or goethite (*i.e.* sample IG02-07, fig. 4a-c). Generally, however, it has been observed that the prevailing magnetic carrier is goethite at site IG02 (San Giovanni mine) and hematite at site IG03 (Nebida mine) (table I).

Three samples among those cored at the site IG02 (San Giovanni mine, level +150) show a Characteristic Remanent Magnetization (ChRM) likely carried by magnetic iron sulfides (thermal demagnetization achieved at 200-350°C; *i.e.* sample IG02-02, fig. 5a-c), whose directions were not coherent among the 3 samples (fig. 6 and table I). The «anomalous» paleomagnetic directions observed in such sulfides-dominated samples are likely due to their acquisition before tilting of the host-rocks (*i.e.* magnetic iron-sulfides are of Paleozoic Age). Structural complexity of the area and lack of precise elements to define a simple tectonic correction to apply to the data prevent further speculation about paleomagnetic data from those three samples.

Paleomagnetic data from all the remaining 15 samples, indicate that the high-coercivity minerals provided a well defined and coherent ChRM that was acquired after the rotation of Sardinia (that is after 16 Myr) and in a time interval long enough to span at least one reversal of the geomagnetic field. In fact, 10 samples display a normal polarity ChRM and 5 specimens a reverse polarity ChRM (fig. 6). Assuming that, by chance, the oxidation event started just be-

Table I. Summary of reliable paleomagnetic data.

Specimen	Lithology	Decl ChRM (°)	Incl ChRM (°)	MAD (°)	Mag. Min.
IG01-01	Cambrian limestone	179.6	−53.9	4.9	Hematite
IG01-02	Cambrian limestone	12.9	44.5	3.1	Hematite
IG01-03	Cambrian limestone	3.1	50.5	2.8	Hematite
IG01-04	Cambrian limestone	17.6	47.5	4.0	Hematite
IG01-05	Cambrian limestone	356.8	50.7	5.8	Hematite
IG01-07	Weathered dolomite	347.7	48.2	7.0	Magnetite
IG01-09	Weathered dolomite	182.9	−67.9	3.2	Hematite
IG01-12	Weathered dolomite	3.4	52.0	8.5	Goethite + hematite
IG01-20	Weathered dolomite	352.4	51.1	5.3	Goethite + hematite
IG01-21	Weathered dolomite	8.7	33.1	4.4	Goethite
IG02-01*	Mineralized dolomite breccia	160.9	−26.1	5.9	? Fe-sulfides
IG02-02*	Mineralized dolomite breccia	222.1	47.3	3.3	? Fe-sulfides
IG02-03	Mineralized dolomite breccia	169.7	−58.8	2.7	Goethite
IG02-04	Mineralized dolomite breccia	169.6	−46.4	6.3	Goethite
IG02-06*	Cambrian limestone	228.8	50.6	6.0	? Fe-sulfides
IG02-07	Weathered dolomite	170.2	−44.5	4.3	Goethite
IG03-02	Weathered dolomite	0.9	52.3	6.8	Hematite
IG03-06	Weathered dolomite	357.0	41.4	7.1	Hematite
Mean (*N*=15)		359.7	49.9	$\alpha_{95}=4.7$	

Decl – declination; Incl – inclination; ChRM – Characteristic Remanent Magnetization; MAD – Maximum Angular Deviation from principal component analysis (Kirschvink, 1980); Mag. Min. – main magnetic minerals carrying the ChRM (see text); * – discarded samples, whose ChRM is likely carried by magnetic iron sulfides; α_{95} – half-angle of the 95% confidence circle about the mean direction (Fisher, 1953).

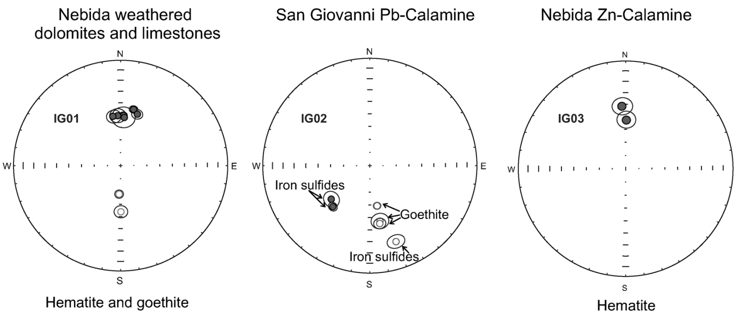

Fig. 6. Equal area projection in geographic coordinates (open circles – upper hemisphere, reverse polarity; full circles – lower hemisphere, normal polarity,) of reliable paleomagnetic data for sites IG01, IG02 and IG03. Ellipses around individual directions indicate the maximum angular dispersion on the mean paleomagnetic direction computed by principal component analysis (Kirschvink, 1980) on the demagnetization data. At site IG01 the Characteristic Remanent Magnetization (ChRM) are carried by hematite and goethite and define two antipodal clusters of normal and reverse polarity along the N-S axis. At site IG02 the ChRM are carried either by goethite (3 samples) or magnetic iron sulfides (3 samples). The first group defines a cluster of reverse polarity close to the N-S directions, the ChRM of the second group are dispersed and far from the N-S direction. At site IG03 only two reliable ChRM were obtained, which are similar and of normal polarity close to the N-S axis.

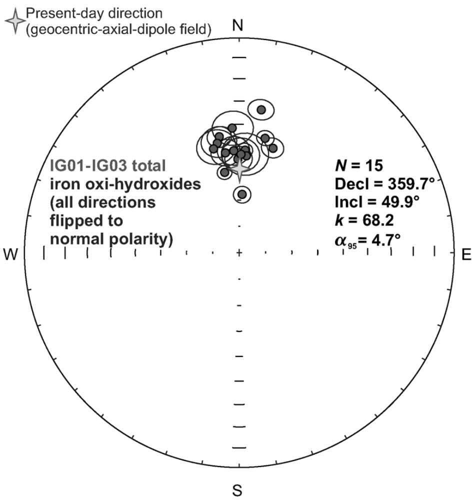

Fig. 7. Equal area projection and statistical parameters (Fisher, 1953) of all the reliable paleomagnetic data carried by high-coercivity oxi-hydroxides for sites IG01-IG03. Geographic coordinates, all data flipped to normal polarity. Ellipses around the individual directions indicate maximum angular dispersion on the mean paleomagnetic direction computed by principal component analysis (Kirschvink, 1980) on the demagnetization data. The star indicates the direction of the geocentric axial dipole field in the study area.

fore a reversal and ended soon after it, a lower limit of the order of 5-10 kyr can be placed for the duration of such oxidation event. No upper limit can be set in view of the paleomagnetic data.

The mean value calculated on such high-coercivity ChRM, after transforming all polarities to normal is: declination = 359.7°, inclination = 49.9°, α_{95} = 4.7°, k = 68.2, N = 15 (fig. 7 and table I). The data pass the reversal test of McFadden and McElhinny (1990), with a classification of «*B*» (*i.e.* the observed angle between the mean of the normal polarity set and the mean of the reverse polarity set is 8.9° and the critical angle for the reversal test is of 9.3°).

Such ChRM was recognized as carried by hematite (or a mixture between goethite and prevailing hematite) in 10 samples, by only goethite in 4 samples (3 of which with reverse polarity, all from the San Giovanni mine, site IG02, where hematite was not recognized as a main magnetic carrier) and by magnetite in 1 sample (from the reddish dolomites at site IG01).

7. Conclusions

Despite the limited dataset due to the scarcity of accessible «exposures» or mining sites, some interesting conclusions can be drawn from the paleomagnetic data obtained in this study.

First of all, in both the non-sulfide ore bodies and in their host rocks consisting of deeply weathered ferroan dolomites, a complex magnetic mineralogy could be detected. The most common magnetic carrier is hematite, followed by goethite; in a few samples it was even possible to detect primary (?) iron sulfides.

These different magnetic mineralogical phases could be related to distinct weathering episodes, which took place repeatedly during the geological evolution of the area. However, the last measurable oxidation event happened for sure after the rotation of the Corsica-Sardinia continental block (Early Miocene, *ca.* 16 Myr), as indicated by the clustering of the paleomagnetic directions on the present-day geocentric axial dipole field.

Because some of the measured samples show inverse polarity, the last oxidation episode must have started before *ca.* 780 kyr (age of the Brunhes-Matuyama boundary; see Tauxe *et al.*, 1996). However, it could have been possible that the last oxidation episode lasted much longer in time and encompassed one or more polarity reversals of the geomagnetic field.

Based on geological reasoning only, we can argue that the most probable age for the bulk of supergene non-sulfide Zn-Pb ore in SW Sardinia, as well as for the weathering and «reddening» of the hydrothermal «Geodic Dolomite» host rocks, was comprised in a time span between Middle Eocene and Plio-Pleistocene (Boni *et al.*, 2003). By paleomagnetic methods, we could not narrow this interval, but only confirm that at least part of the oxidation episodes were younger than the Early Miocene (Early Langhian) and likely extending back quite far from the Present. The observed reactivation of the alteration profiles in the whole mining district, which caused the replacement of earlier-deposited supergene mineral phases by others adapted to new hydro-geochemical conditions, could also have caused the precipitation of several generations of magnetic minerals presently coexisting in the same oxidized lithotype. Furthermore, the recognition that the goethite-dominated samples from site IG02 show reverse polarity implies that the host-rocks were not significantly heated (the 120°C Neél temperature of goethite drops radically in goethites substituted with diamagnetic elements, see Mathé *et al.*, 1999) during at least the last 780 kyr.

Even though a precise age determination could not be reached for the genesis of non-sulfide Zn-Pb ores in the Iglesiente district, the paleomagnetic method, together with radiogenic isotope systems and fission tracks, could be a powerful tool to establish the timing of the weathering profiles (Théveniaut *et al.*, 2002) associated to non-sulfides in other mineralized areas with a less complex geological history than SW Sardinia.

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