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Ore-lead isotope pattern from the Iglesiente-Sulcis Area (SW Sardinia) and the problem of remobilization of metals

M. Boni[1] **and V. Koeppel**[2]

[1] Dipartimento di Scienze della Terra dell'Università degli Studi di Napoli, L. San Marcellino 10, I-80138 Napoli
[2] Institute for Crystallography and Petrography, Swiss Federal Institute of Technology, CH-8092 Zuerich

Abstract. In SW Sardinia syngenetic to syndiagenetic Pb-Zn ores occur in Cambrian carbonates, along the unconformity between the Cambrian and Ordovician, in Permo-Triassic karsts and in vein-type deposits related to late Hercynian granites, which also contact-metamorphosed some Cambrian deposits. In all types of deposits the lead-isotope ratios show similarly high μ ($={}^{238}U/{}^{204}Pb$) and high W ($={}^{232}Th/{}^{204}Pb$) values indicating a crustal origin for the lead. Most of the Cambrian ores contain isotopically similar or identical leads, whereas in the younger deposits the isotope ratios vary and suggest that especially the lead of Permo-Triassic ores may consist to a large extent of remobilized Cambrian, possibly also Ordovician, ore lead plus a Hercynian component.

The lead of three feldspar samples from Hercynian granites of the area also shows high μ and W values. Two of them are similar to the ore leads from a vein-type deposit and from contact-metamorphosed deposits. The third sample from the Capo Pecora granite contains a very unradiogenic lead that closely resembles many of the presumed Cambrian-Hercynian mixtures. Therefore, the possibility cannot be dismissed that at the time the Permo-Triassic ores were formed lead sources other than the already existing ores were present with the appropriate isotopic compositions.

Introduction

In the Iglesiente and Sulcis mining districts in SW Sardinia more than 30 major deposits of Pb–Zn and Ba are known, many of which have been exploited in the past and some are still being mined (Fig. 1). These are considered to be Mississippi-valley-type deposits. They are extremely variable in appearance, size and setting. They probably represent the products of several ore-forming processes (Cambrian, Ordovician, Permo-Triassic). Most of them lie within the Lower Cambrian Gonnesa formation which comprises shallow-water sediments deposited in different subenvironments of a carbonate platform. Because of their high degree of congruency with depositional structures, which indicates that the palaeogeography controlled the distributions of the mineralizations, the deposits are considered to be of syngenetic to syndiagenetic origin (Wilke et al. 1960; Boni, in prep.).

The aim of the present investigation was to see whether the lead-isotope ratios of the different ore types support the long-held view that large-scale remobilizations of existing ores did occur during the Ordovician and Permo-Triassic periods of mineralizations (Zuffardi and Salvadori 1964; Zuffardi 1965, 1969; Poll 1966), or whether different sources of metals were tapped during the different ore-forming periods.

Geological setting

The Precambrian to Cambrian sequence of SW Sardinia represents the evolution of a sedimentary platform over a thinning continental crust. Some 2,500 m of sediments were deposited at an average rate of about 40 m/my (Carannante et al. 1984). A Precambrian basement which is today, however, only poorly exposed was covered during the Late Precambrian and Early Cambrian by terrigenous deposits that passed upward into shallow-water carbonates. The final stage was that of a deepening open-shelf domain. Synsedimentary faulting was especially active at its margins (Bechstaedt et al. 1985). It dissected the carbonate platform and produced troughs and minor platform areas. At the end of the Cambrian, or during the Early to Middle Ordovician, an early Caledonian or late Assyntian orogenic phase, the Sardic phase (Stille 1939), moderately deformed the sediments which were then unconformably overlain by Ordovician conglomerates.

Cambrian sediments and ores

The Cambrian can be summarized from bottom to top as follows:

Nebida formation (Lower Cambrian)

This is a sandstone-siltstone, shallow-water complex (Matoppa member) which grades upward into a sequence of alternating beds of detrital and carbonate lithotypes (Punta Manna member) with a total thickness of 700–800 m (Cocozza 1979). Mineralizations are not common in the Nebida formation (Fig. 2). Barite layers occur in the upper carbonate beds close to the overlying dolomites or in some chert horizons (Gandin et al. 1974). In few areas layers of galena and sphalerite occur in the same carbonate intercalations.

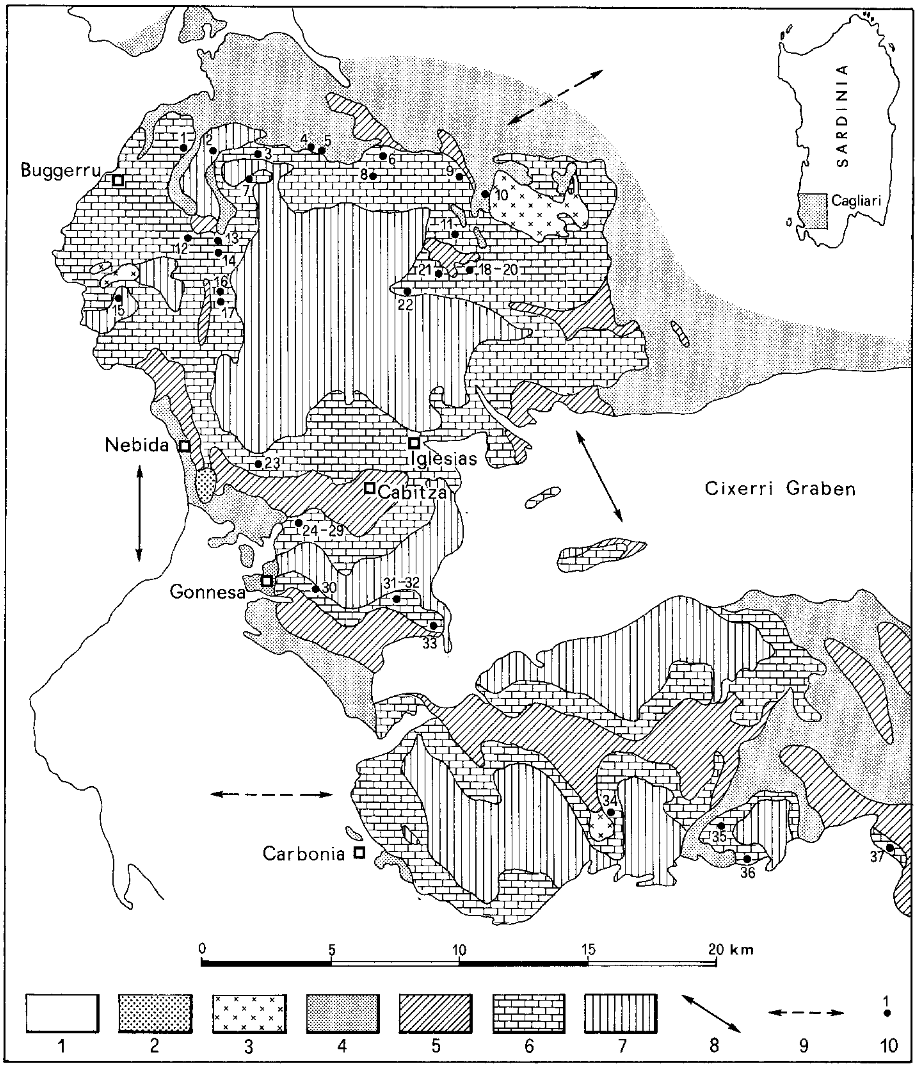

Fig. 1. Geological-structural map of the Iglesiente-N. Sulcis area. 1. Post-Hercynian sediments. 2. Permian porphyry. 3. Late Hercynian (Upper Carboniferous) granites. 4. Silurian and Ordovician slates, limestones and conglomerates. 5. Cabitza formation (Middle Cambrian). 6. Gonnesa formation (Lower Cambrian). 7. Nebida formation (Lower Cambrian). 8. Axial planes of the Sardic deformation. 9. Axial planes of the Hercynian deformation. 10. Sample localities. The numbers correspond to those in Fig. 2 and Table 1

Gonnesa formation (Lower Cambrian)

It comprises sediments related to carbonate-platform environments and is subdivided into two main dolomitic members, the Laminated Dolomite and the Massive Grey Dolomite, and a calcareous member, the "Ceroide" or wax-like limestone. The total thickness varies from 100–200 m in the Sulcis area to 500–600 m in the Iglesiente (Cocozza 1979).

Stratiform barite bodies with zebra structure (Gandin et al. 1974) are intercalated with dolomites (Fig. 2) especially in the Sulcis area. Sulfide-rich beds, varying from few centimeters to several meters in thickness, occur at various levels in the dolomitic succession, but generally not in sequences containing barite. The sulfides are massive pyrite and sphalerite with some galena. They often are disrupted, locally brecciated and normally deeply altered to a mixture of oxidation minerals and clays as a result of repeated cycles of weathering.

The mineralization in the Ceroide consists mainly of sphalerite, pyrite and galena. The Pb/Zn ratio steadily increases toward the top of the limestone. In some areas both galena and barite are enriched (Boni, in prep.). All types of ore-bodies are mainly strata-bound in spite of their apparent random distribution and their frequent relationship to main tectonic directions. Some of the Zn-rich (10%–15% Zn) mineralizations are related to black dolomitic shales which are locally interfingered with the Ceroide limestone and which (i.e., part of the Idina orebody in the S. Giovanni mine) possibly represent internal sediments.

The so-called Calcare blendoso, a peloidal mudstone typical of the S. Giovanni and Monteponi mines, consists instead mainly of broadly diffused strata-bound impregnations of yellow sphalerite (5%–6% Zn) with some pyrite and minor amounts of galena (Fig. 2). In places microcrystalline sphalerite peloids cemented by micrite and/or sparry calcite may be distinguished. The Calcare blendoso and the other carbonate lithotypes have undergone repeated diagenetic brecciation and are cemented by grey sphalerite. The breccia ore represents the most abundant of the strata-bound ore types in the upper part of the Gonnesa formation (Boni 1983).

Cabitza formation (Middle-Upper? Cambrian)

The nodular limestone is followed by a thick sequence of slate (Cabitza slate) which concludes the Cambrian sequence in the area. No mineralization is known from this formation.

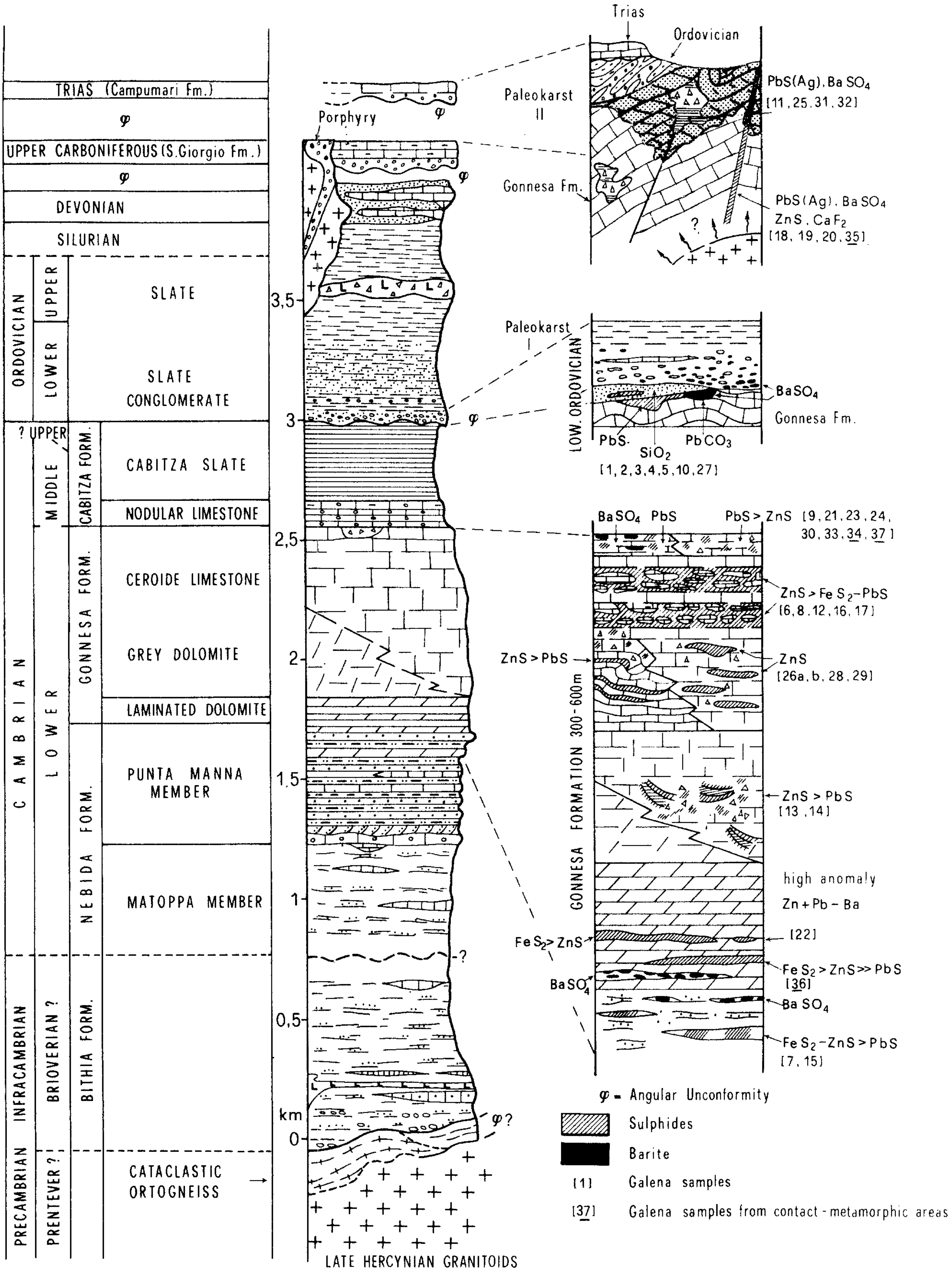

Fig. 2. General stratigraphic section of the Palaeozoic to Early Mesozoic in SW Sardinia showing a composite column with the location of the orebodies in their stratigraphic position. The numbers correspond to those in Fig. 1 and Table 1 (Boni, in prep.; Cocozza, 1979)

Ordovician sediments and ores

The Cambrian sequences were slightly deformed and partially eroded prior to the deposition of Ordovician sediments; the transgression is marked by a basal conglomerate, the so-called "puddinga", with a matrix rich in hematite (Cocozza et al. 1974). It locally contains detrital barite clasts derived from the underlying Cambrian mineralizations and more rarely detrital galena grains cemented by oxidized material (Benz 1964). This proves that at least some of the mineralizations in the Cambrian sediments are pre-Ordovician in age.

Where the transgression extended onto carbonate members of the Gonnesa formation, the contact zone is silicified and locally dolomitized and corresponds to the so-called quartzite horizon of the earlier authors (Benz 1964; Brusca and Dessau 1968).

Upper Palaeozoic

Scattered outcrops of Upper Palaeozoic sediments occur mainly at the margins of the Iglesiente-Sulcis region. They do not contain any appreciable mineralizations, except for the presumably Permo-Triassic sediments in karstic networks within Cambrian carbonates. These internal sediments do not show any evidence for compressive tectonics, and they thereby distinguish themselves from the Upper Cambrian to Lower Ordovician karst sediments.

Tectonics and magmatism

Two major tectonic lineations can be recognized in SW Sardinia. The older has an E-W axis and is related to the Sardic phase of deformation. The more recent one with axes roughly oriented N-S is related to the main phase of the Hercynian movements. Its intensity is everywhere greater than that of the sardic phase (Carmignani et al. 1982). The larger Hercynian folds overprint the Sardic ones and produce a variety of superimposed fold patterns in outcrops. These deformations have often been accompanied by recrystallization in the members of the Gonnesa formation. Dolomites reacted to the strain with boudinages and brecciation, whereas the limestones by flowing (Moore 1969). The Alpine tectonics were mostly distensive and resulted in an accentuation of the late Hercynian block faulting.

In the Palaeozoic of the Iglesiente-Sulcis area basic rocks occur either as metabasic clasts in the Upper Ordovician to Lower Silurian volcanoclastic sequence or as Upper Carboniferous to Lower Permian basaltic dikes. The Hercynian magmatic activity comprises two distinct acidic rock associations, a late- to post-tectonic suite of intrusives (Ghezzo and Orsini 1982) and a Permian series of extrusive rocks (Di Simplicio et al. 1975).

Some of the Cambrian and Ordovician ores were contact-metamorphosed by Hercynian intrusives, and they locally contain Cu, F and W minerals. It appears likely that these elements were introduced during contact metamorphism (Bone et al. 1981).

Paleokarst ores

The Iglesiente-Sulcis area was subjected to several karst cycles. Significant concentrations of economic minerals are linked to some of the karst cycles. The first cycle is related to the Sardic phase and the following emersion of the folded Cambrian series. The phenomena can be traced along the contact of Cambrian limestones and dolomites with Ordovician sediments where it is often marked by the aforementioned quartzite horizon. Mineralizations related to this cycle are not always of economic value. The ores consist predominantly of oxidation minerals like cerussite, hematite and "calamine" (secondary Zn minerals); varying barite contents are also present, some of economic value. In places barite is accompanied by galena and some pyrite plus sphalerite. Small networks of galena veinlets crosscutting secondarily dolomitized rocks may in places constitute the mineralization, e.g., Nanni Frau.

At the end of the Hercynian orogeny a long period of emergence and intensive erosion followed. Denudation of much of the Palaeozoic limestones and dolomites of the Gonnesa formation exposed them to weathering and produced extensive karst phenomena (Boni and Amstutz, 1982). This process also resulted in an intense dolomitization characterized by the presence of yellow ferroan dolomite. A deep-reaching network of fractures and cavities was formed and was subsequently filled both with fine detrital karst sediments and collapse breccias, cemented by calcite, quartz and barite and to a minor degree with sulfides. Argentiferous galena is the principal sulfide besides small amounts of pyrite, sphalerite, chalcocite and covellite. Whereas galena of Cambrian deposits contain approx. 300 ppm Ag, the concentration in these galenas may reach 8,000 ppm Ag which is located in inclusions of freibergite, argentite, polybasite, proustite, pyrargyrite and stephanite. Barite and sulfides occur mainly in the cement of collapse breccias. Fluorite is rare and only locally present.

Furthermore, vein-type deposits occur which follow Hercynian structures. Their mineral parageneses are similar to the karst ore types. They often have been considered to be the product of the same generation of ore-forming processes (Boni and Amstutz 1982). The Montevecchio (Pb–Zn–Cu) (Salvadori and Zuffardi 1973), the Mont'Ega (Ba–F–Pb) (Boni and Malafronte 1983) and some other Pb–F–Ba-bearing veins, however, are thought to be rather the products of hydrothermal activities related to late Hercynian granites.

In comparison to the pre-Ordovician karst cycle the late- to post-Hercynian karst network as well as the secondary dolomitization and vein formation are much more developed and may reach up to several 100 m in depth. This difference is considered to be the consequence of the more intensive Hercynian tectonics leading to a more pronounced horst and graben structure (Moore 1972; Cocozza et al. 1974).

Fluid inclusion studies

The main result of the fluid inclusion study of ore and gangue minerals of the Iglesiente-Sulcis mining district is the discovery that the pre- and post-Hercynian ores differ in the salinity and homogenization temperatures of the trapped fluids. The post-Hercynian fluids are considerably more saline (up to 24 equ. wt% NaCl). The homogenization temperatures vary between 60° and 130 °C (Boni, in press). The fluid inclusions of the pre-Hercynian mineralizations contain from 0 to 15 equ. wt% NaCl. Their homogenization temperatures range from 80° to 160 °C. The question remains, however, open as to the influence of the Hercynian tectonics on the composition of these inclusions.

Results of the lead isotope analyses

The results are listed in Table 1 and plotted in Fig. 3. In both diagrams (Fig. 3) the data points form clusters which are, however, not solely defined by any single type of deposit. The majority of galenas from stratiform to strata-bound deposits in Cambrian host rocks form a tight cluster ($^{206}Pb/^{204}Pb$: 17.80–17.91, $^{207}Pb/^{204}Pb$: 15.60–15.66, $^{208}Pb/^{204}Pb$: 37.80–38.05). The two exceptions within this group are a sample from Su Sollu (2) and a sample from the "Vena tetto" at the S. Giovanni mine (27) where detrital galena occurs in Ordovician transgression conglomerates. A sample from Campu Spina (Swainbank et al. 1982) also belongs to this group; it consisted of a galena boulder within the transgressive Ordovician conglomerate.

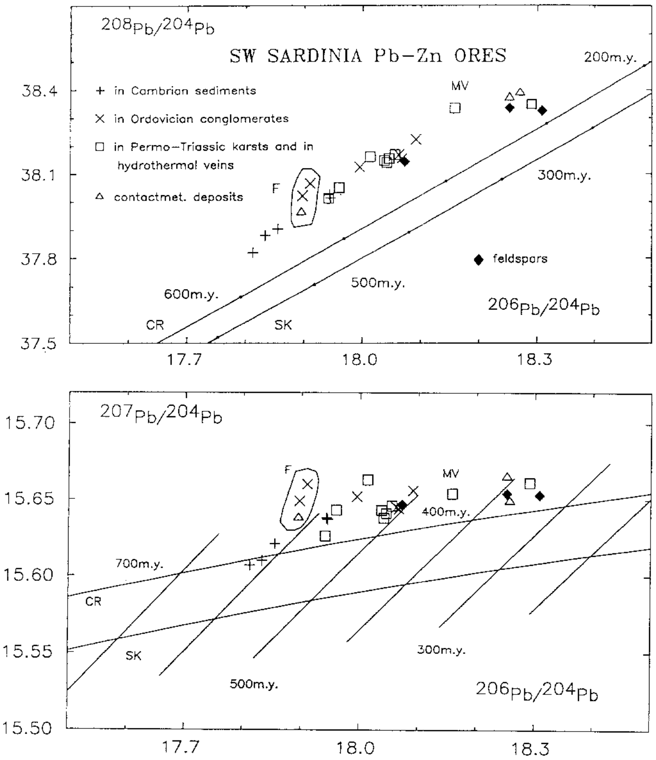

Fig. 3. $^{208}Pb/^{204}$**Pb**-$^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ evolution diagrams. SK and CR growth curves for average crustal leads according to Stacey and Kramers (1975) and Cumming and Richards (1975), respectively. F-data field of the majority of galenas from strata-bound deposits. MV: Montevecchio (Swainbank et al., 1982)

Most of the galena lead in Cambrian host rocks is isotopically very similar or even identical. Only the galenas from deposits in the upper Punta Manna member (15, 7), stratigraphically the lowest ore-bearing strata, contain a less radiogenic lead with lower μ and W values than the ore occurring in higher stratigraphic positions. For the latter there is a noticeable tendency of increasing μ and W values with decreasing stratigraphic age of the Cambrian sediments. However, the differences are small and barely outside the reproducibility of the NBS standard lead (Table 1 c).

The overall pattern is quite similar to that observed by Brevart et al. (1982) in deposits hosted in Cambrian sediments in the Montagne Noire ($^{206}Pb/^{204}Pb$: 17.76–17.94, $^{207}Pb/^{204}Pb$: 15.59–15.64, $^{208}Pb/^{204}Pb$: 37.77–38.06).

A second group consists of galenas from deposits located within the Ordovician transgression horizon and from Permo-Triassic vein and karst deposits ($^{206}Pb/^{204}Pb$: 17.94–18.09, $^{207}Pb/^{204}Pb$: 15.62–15.66, $^{208}Pb/^{204}Pb$: 38.00–38.23). In addition, some samples from the Idina orebody at the S. Giovanni mine (26) and from the Scalittas mine (12), both in Cambrian host rocks, belong to this group.

A third group comprises deposits that were contact metamorphosed by Hercynian granites and a hydrothermal vein-type deposit (Mont'Ega) that appears to be related to a Hercynian granite ($^{206}Pb/^{204}Pb$: 18.24–18.29, $^{207}Pb/^{204}Pb$ 15.66–15.70, $^{208}Pb/^{204}Pb$: 38.35–38.45). Swainbank et al. (1982) reported two identical galena analyses (Fig. 3) from the Montevecchio mine which also is considered to represent a hydrothermal vein-type deposit that follows a Hercynian structure (Salvadori and Zuffardi, 1973).

Table 1. Lead-isotope ratios of galenas, corrected for fractionation

Sample no.		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Mine, host rock
1		18.067	15.635	38.156	Nanni Frau O.
2		17.897	15.649	38.022	Su Sollu O.
3		17.995	15.652	38.124	Bau Mannu O.
4		18.076	15.646	38.175	Terra Niedda O.
5		18.048	15.644	38.163	Terra Niedda O.
6		17.896	15.640	37.986	Gutturu Pala C.
7		17.837	15.609	37.874	Candiazzus Sa Niva C.
7		17.828	15.610	37.890	
	mean	17.833	15.610	37.882	
7		17.858	15.622	37.898	
7		17.852	15.620	37.912	
	mean	17.855	15.621	37.905	
8		17.898	15.643	38.008	Canali Bingias C.
9		17.909	15.656	38.042	M. Serrau C.

Table 1. (cont.) Lead-isotope ratios of galenas, corrected for fractionation

Sample no.	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}P	Mine, host rock
10	18.091	15.656	38.224	Arenas O.
11	18.013	15.663	38.161	Serra di Baueddu (P-T) (?)
12	17.943	15.638	38.026	Scalittas C.
13	17.869	15.630	37.943	Pira Roma-S. Luigi C.
14	17.888	15.632	37.970	Pira Roma-S. Luigi C.
14	17.887	15.629	37.953	Pira Roma-S. Luigi C.
mean	17.887	15.630	37.961	
15	17.817	15.610	37.829	Canalgrande C.
15	17.805	15.609	37.829	
15	17.815	15.603	37.804	
mean	17.812	15.607	37.821	
16	17.878	15.640	37.990	Masua Marx C.
17	17.874	15.631	37.950	Masua Marx C.
18	18.041	15.638	38.141	Malacalzetta P-T vein-type
19	18.045	15.641	38.155	Malacalzetta P-T vein-type
20	18.055	15.646	38.169	Malacalzetta P-T vein-type
21	17.909	15.657	38.044	S'Ega S'Acqua C.
22	17.905	15.643	38.002	S. Benedetto C.
23	17.901	15.649	38.011	M. Bega C.
24	17.900	15.649	38.020	S. Giovanni Cont. Carolina C.
25	18.037	15.643	38.148	S. Giovanni Ricchi Ag P-T
26	17.880	15.641	37.990	S. Giovanni Idina C.
26	17.947	15.634	38.005	
26	17.942	15.641	38.026	
mean	17.945	15.637	38.015	
27	17.902	15.652	38.028	S. Giovanni Vena tetto O.
27	17.918	15.668	38.105	
mean	17.910	15.660	38.066	
28	17.894	15.640	37.974	S. Giovanni Massa Pozzo 4 C.
29	17.892	15.649	38.014	S. Giovanni Cont. W C.
29	17.883	15.638	37.967	
mean	17.887	15.643	37.991	
30	17.894	15.641	37.998	Sa Bagattu C.
31	17.964	15.642	38.067	Barega P-T
31	17.956	15.644	38.036	
mean	17.960	15.643	38.051	
32	17.941	15.626	38.013	Barega P-T
33	17.903	15.649	38.019	M. Arcau C.
34	17.897	15.639	37.977	M. S'Orcu C. metam.
34	17.892	15.636	37.952	
mean	17.895	15.638	37.965	
35	18.291	15.661	38.455	Mont'Ega P-T vein-type
36	18.257	15.649	38.342	M. Atzei-S.Croce C. metam.
37	18.243	15.659	38.353	Rosas-Sa Marchesa C. metam.
37	18.261	15.671	38.391	
mean	18.252	15.665	38.372	
C: Cambrian, O: Ordovician, P-T: Permo-Triassic karst				
Feldspar lead from Hercynian granites				
	18.255	15.653	38.335	Monte S'Orcu (close to No. 34)
	18.308	15.653	38.326	Tiny (close to No. 10)
	18.063	15.631	38.104	Capo Pecora (N of Buggerru)
Common lead standard SRM 981				
Jan. 1982–June 1983	16.889±5	15.427±6	36.493±25	(N=24)
July 1983–May 1984	16.896±6	15.435±7	36.525±22	(N=14)

All measurements were made on a MS 261 mass spectrometer with a single collector.

The following fractionation factors were used: ^{206}Pb/^{204}Pb: 1.0027, ^{207}Pb/^{204}Pb: 1.0041, ^{208}Pb/^{204}Pb: 1.0054.

The uncertainties for an individual measurement are 1% for the ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb ratios and 2% for the ^{208}Pb/^{204}Pb ratios

The lead exhibits isotopic features similar to that of galena-bearing deposits located in the Southern Alps and in Eastern Alpine nappe units (Koeppel 1983; Koeppel and Schroll 1983), i.e., high μ and W values of about 10 and 40, respectively. Similarly, the $^{207}Pb/^{206}Pb$ model ages are higher than the $^{208}Pb/^{204}Pb$ ages.

The stratigraphic position of the deposits in the Iglesiente and Sulcis area in Lower Cambrian sediments suggests an age of about 550 my. The $^{207}Pb/^{206}Pb$ model ages are 630 ± 10 my, and the $^{208}Pb/^{204}Pb$ model ages vary between 450 and 350 my according to the model by Stacey and Kramers (1975) and between 550 and 450 my following the model of Cumming and Richards (1975). The majority of the Ordovician deposits of the second group contain lead which yields reasonable $^{207}Pb/^{206}Pb$ model ages of 510 ± 10 my, whereas the $^{208}Pb/^{204}Pb$ model ages of 220–270 my and 330–370 my are low. A conspicuous discrepancy exists between the $^{207}Pb/^{206}Pb$ model ages of the third group (375–415 my) and their geologic age of 270 my or less. The $^{208}Pb/^{204}Pb$ ages according to the models proposed by Stacey and Kramers (1975) and also Cumming and Richards (1975) are again low (100–150 my and 210–270 my, respectively).

Discussion

The high μ and W values with respect to the values pertaining to the growth curves for average crustal leads observed in orogenic environments (Doe and Zartman 1979) points to a crustal origin of the lead. The similar μ and W values of all samples, except the ones in the Punta Manna member, indicate that the lead was derived from the same source or from sources with similar U/Pb and Th/Pb ratios. The discrepancy between the $^{207}Pb/^{206}Pb$ model ages and the geologic ages argues for source rocks that were at one stage depleted in U, after most of the ^{235}U had already decayed to ^{207}Pb. Thereby, the growth of especially the ^{206}Pb was retarded, and consequently the $^{207}Pb/^{206}Pb$ model ages are now too high. Such a uranium loss can occur during high-grade metamorphism (upper amphibolite to granulite facies) when upper crustal rocks are cratonized (Doe and Zartman 1979). Swainbank et al. (1982) also favor the view that the lead originated from crustal sources, possibly from lower crustal regions. As lower crustal rocks are virtually absent in SW Sardinia, this hypothesis cannot be tested. Uranium may also be lost during erosion and deposition of detrital material such as sandstones (Koeppel and Schroll 1983).

This study will be extended to include the Cambrian host rocks, the underlying clastic Nebida formation and the metamorphic Precambrian rocks (Minzoni 1980) to test whether they may have been possible source beds for lead. It is noteworthy that amphibolite- to granulite-facies metasediments in the Southern Alps and Eastern Alpine nappe units contain feldspar leads with high μ and W values similar to those in the ore of SW Sardinia (Koeppel and Schroll 1983). These sediments are of pre-Ordovician age and were probably deposited from the Late Proterozoic to Cambrian.

Probably the most interesting feature is that the lead of Permo-Triassic vein and karst deposits is in most cases isotopically similar to the lead from Ordovician ores. Some are even isotopically less evolved (Barega (31), Serra di Baueddu (11)). The only exception to this is the sample from Mont'Ega (35), a vein-type deposit probably related to a nearby Hercynian granite. The isotope pattern of most of the post-Cambrian ores could indicate that remobilization of lead from preexisting orebodies played an important role during the formation of many of the Hercynian deposits and possibly also during the Ordovician period of mineralization. This possibility has already been discussed by Zuffardi (1965, 1969) and Poll (1966) on the basis of lead isotope measurements of Cambrian and Hercynian ores. The Hercynian deposits of group 2 could contain 70% to 50% of lead remobilized from ores located in Cambrian host rocks of group 1, and 30% to 50% of a Hercynian lead component similar to the lead of group 3. If only lead from Ordovician deposits was remobilized, then an additional Hercynian component is not required.

To obtain an idea of the amount of lead possibly involved in remobilization processes the following rough estimate of the lead distribution within the 4 major types of ores may serve as a basis: in Cambrian host rocks: 2 × 10E6 t; in the transgressive Ordovician conglomerate: 5 × 10E5 t; in Permo-Triassic karsts: 3.5 × 10E5 t; related to Hercynian magmatism: 1.5 × 10E5 t.

Assuming that 60% of the lead in Permo-Triassic karsts consists of Cambrian ore lead then about 200,000 t of lead were remobilized. If the solutions contained 10 ppm of lead then a minimum of 2 × 10E10 t of water was needed for dissolution and redeposition of the lead. In comparison it is of interest to note that the annual ground water discharge in the Monteponi mine amounts to about 2 × 10E7 t (Civita et al. 1983). So even if dissolution and redeposition were far from being quantitative processes, the amount of water required for remobilization was certainly not prohibitive, provided that the hydrological conditions were similar as today.

Whether large-scale remobilization of lead during the late Hercynian period of mineralization really occurred remains an open question in view of the lead data from feldspars of Hercynian granites. Although more samples must be analyzed to evaluate the significance of the present results, it appears that the lead in the Hercynian granites is isotopically quite similar to the lead of the galenas from group 2 and 3. In spite of the granites being older (280 to 300 my, Del Moro et al. 1975; Cocozza et al. 1977) than the Permo-Triassic karsts, the possibility cannot be ruled out that sources of lead other than the Cambrian and Ordovician galena deposits were available to provide metals to the Permo-Triassic karst deposits.

Provided that the felspar lead of the granites represents the primary lead of the magma which had not been contaminated by wall-rock interaction or deuteric alteration processes, the results appear to indicate that the source of the magma must be sought in the same or similar rocks as the source of the ore leads.

The feldspar lead thus raises some doubts about the possibility that the Permo-Triassic ores owe their existence only to remobilization of large amounts of Cambrian and/or Ordovician ores. Nevertheless, in some instances the ore-lead data indicate that several periods of mineralizations coupled with remobilizations occurred within a restricted area. For example at the S. Giovanni mine, isotopic identities strongly support the view that remobilization of Cambrian ores occurred during the Ordovician transgression. It is noteworthy that the Idina orebody contains two types of lead, one with a normal Cambrian composition and one that is indicative for the Ordovician, or possibly even Permo-Triassic mineralization. At the present there is only weak sedimentological evidence that this orebody is the product of two different periods of mineralizations. Furthermore, the lead-isotope ratios support the long held view that the S. Giovanni-Ricchi Ag orebody belongs to the Permo-Triassic cycle of mineralization (Brusca and Dessau 1968).

The results on the contact-metamorphosed ores raise the question of whether all of them really originated in the Cambrian or not. In one case, M. S'Orcu (34), the lead is indistinguishable from that of other Cambrian deposits. However, at Mt. Atzei (36) and at Rosas-Sa Marchesa (37) the lead has the highest $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios and is similar to the lead of the vein-type deposit at Mont'Ega (35) as well as to the feldspar lead of two of the granites. It therefore seems possible, also in view of their different mineral paragenesis, that these deposits are of a more complex origin.

Conclusions

The lead of all deposits, except those in the Punte Manna member, was derived from the same source or from sources in which the U/Pb and Th/Pb ratios had evolved in a similar way. The source must be sought in crustal rocks, possibly in the lower crust, that formed in the Early Proterozoic or possibly in the Archean.

According to the high μ and W values and to the pattern of the $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{204}Pb$ model ages the lead belongs to the same isotopic province as the galena-bearing ores of the Southern Alps, Eastern Alpine nappe units and the Montagne Noire.

The lead-isotope data of galenas are compatible with the idea that during the Ordovician and Permo-Triassic periods of mineralizations lead from existing deposits was remobilized and redeposited together with varying amounts of a more radiogenic component. This could account for the isotopic heterogeneity of the lead in these deposits which contrasts with the homogeneity of the lead in the deposits hosted by the Gonnesa formation. It would also account for the low $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios in the later deposits. An estimate of the amounts of lead concentrated in the different deposits reveals that remobilization is feasible during a hydrological regime comparable to the present-day one.

The results from the S. Giovanni mine strongly support the view that remobilization of lead occurred during the Ordovician and the Permo-Triassic, perhaps even more extensively than expected with geological observations alone.

The results from so-called contact-metamorphic deposits indicate that those containing lead that is isotopically very similar to feldspar leads from Hercynian granites may have been severely altered by contact metasomatism.

The very unradiogenic feldspar lead from the Hercynian granite at Capo Pecora resembles many of the Ordovician leads and leads of Permo-Triassic deposits. Additional studies of leads from Hercynian magmatites are planned to further evaluate the possibility that lead sources with such low $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios existed during the late Hercynian.

A rock-lead study is planned on Cambrian and Precambrian sediments and metamorphic rocks to see whether they could have acted as possible source beds or not.

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Announcements

A symposium on sediment-hosted stratiform copper deposits. Ottawa, Canada, May 17–19, 1986

The Mineral Deposits Division of the Geological Association of Canada and the Mineralogical Association of Canada are organizing an international Symposium on Sediment-Hosted, Stratiform Copper Deposits as part of the Geological Association of Canada – Mineralogical Association of Canada – Canadian Geophysical Union Annual Meeting, Ottawa, 1986. Prospective authors, exhibitors and delegates should write to the following address requesting further information: "Sediment Hosted Stratiform Copper Deposits", c/o Professor A. J. Naldrett, Department of Geology, University of Toronto, Toronto, Ontario, Canada M5S 1A1

Gold '86. International Symposium on the Geology of Gold Deposits

Toronto, September 29–October 1, 1986. The Mineral Deposits Division of the Geological Association of Canada, the Toronto Geological Discussion Group, the Ontario Geological Survey – Ministry of Natural Resources and the Society of Economic Geologists will jointly host an International Symposium on the geology of gold deposits, in Toronto, Canada on September 29th to October 1st, 1986. For further information please write to: Gold '86, Selco Division of BP Canada Inc., 55 University Avenue, Suite 1700, Toronto, Canada, M5J 2H7

Geocongress '86

Johannesburg, 7th to 11th July, 1986. An International Earth Science Congress to commemorate the centenary of the discovery of the Witwatersrand Goldfield. Persons wishing to attend the congress should contact: The Symposium Secretariat, S. 339 CSIR, PO Box 395, Pretoria, Republic of South Africa 0001

International South European Symposium on Exploration Geochemistry

will be held in Athens (Greece) from 9 to 11 November 1986, sponsored by the Institute of Geology and Mineral Exploration (IGME) and the Association of Exploration Geochemists (AEG). Further informations by: The Organizing Committee, I.S.E.S.E.G., Institute of Geology and Mineral Exploration, 70, Messoghion str., 11527 Athens, Greece