# Variscan Skarn Ores in South-West Sardinia: their relationships with Cambro-Ordovician stratabound deposits

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Abstract. — In South-West Sardinia, in addition to the Lower Paleozoic stratabound sedimentary-diagenetic ore deposits, some mineralized skarn occurrences exist, associated with post-tectonic Variscan intrusions of leucogranites. Their metal content ranges from Fe-Zn-Pb-Ba (already present in the Lower Paleozoic associations) to F and Cu (with minor As, Mo, W and Bi). The metamorphic-metasomatic association consists of garnets, clinopyroxenes and wollastonite, often replaced by amphiboles, epidotes and, lastly, chlorites. Thermometamorphic evolution, calculated at pressures of about 1 Kb, may be subdivided into three stages: metamorphic (T > 550°C), metasomatic (T > 400°C), hydrothermal (T < 375°C). The mineralization is linked to the skarn lithotypes, which acted as a structural guide and a trap. We can distinguish in each area between metamorphic (along stratigraphic contacts) and vein skarns (Kerrick, 1977). Most of the ore minerals, consisting of several generations of pyrite, magnetite, pyrrhotite, sphalerite, chalcopyrite and galena, each showing about the same paragenetic order of deposition in all the studied areas, are related to the metasomatic and hydrothermal stages.

Ore genesis has been envisaged through a remobilization of metals contained in the Lower Paleozoic stratabound deposits, with a minor contribution of elements from the intruding magmatic bodies and/or intruded host rocks.

*Key words:* South-West Sardinia, Variscan, Skarn, Ore deposits.

## Introduction

In South-West Sardinia, in addition to the well-known stratabound ore deposits in the Lower Cambrian and Upper Ordovician sediments (Boni, 1985), other types of mineralization, smaller in size and therefore of lesser economic importance, have been exploited near major intrusive bodies of Variscan age (Fig. 1). The mineralizations consist of high temperature ores, ranging from skarn to hydrothermal deposits, containing Cu, F, As with minor amounts of W, in addition to Fe, Zn, Pb and Ba which are normally present in the mineralization of Cambrian and Ordovician age. The type of mineralization discussed is generally hosted in rocks which were affected by high-grade contact- metamorphism. Calc-silicate layers, typical of skarn elsewhere in the world, are present in these rocks, and they have recognizable sedimentary and/or diagenetic structures, as found in the older sediments and associated diagenetic ores. It is interesting to note that, with only few exceptions, this mineralization can be found in the same stratigraphic position as the Lower Paleozoic stratabound deposits.

On the other hand, the sedimentary facies hosting the non-metamorphic stratabound ores, and those affected by metamorphism, are quite different, so that any meaningful comparison between the ores is of necessity incomplete, whereas their affinity can be only casual. Furthermore, there are zones, like that of SE Sulcis, where the mineralization only

occurs where the host rocks were changed to skarn, whereas in the stratigraphically corresponding horizon no mineralization was developed. In other areas, such as the Fluminese region, the chief constraints of the ores and hosting skarns are tectonic, as well as the change of permeability between adjacent lithotypes.

The overall genetic framework of the high-temperature ores of SW Sardinia is therefore not simple, and is open to different interpretations. Some authors (e.g. CIAMPI, 1909; URAS, 1957; VIOLO & ZUCCHINI, 1965) consider the ores of complete epigenetic origin. Others (e.g. BENZ, 1964; URAS et al., 1965) have suggested that the skarn ores are products of metamorphism, which combines the elements of the pre-existing mineralization with new elements scavenged by hot fluids from the hosting sedimentary rocks, with perhaps an additional contribution from the nearby magmatic intrusives.

In our approach to the problem, we undertook a careful examination of the host rocks and the mineral paragenesis of the ores in various districts. These studies were complemented with sedimentological work and integrated with the accepted paleogeographic setting of the Lower Paleozoic terranes. The genetic models were then discussed in the light of the acquired data.

## Methods of study

The area of study was subdivided into three districts: Fluminese, Oridda and SE Sulcis (Fig. 1), each showing different characteristics.

Accurate mapping on a scale of 1:10.000 was carried out in the above-mentioned districts, in areas underlain by non-metamorphic and high-temperature metamorphic rocks. In places, the latter areas lie close to granitic outcrops. In others, the granitic rocks do not outcrop, and the distribution of skarns and hornfels are the only evidence for an intrusive body at depth. Where possibile, underground mapping was also carried out, e.g. in the Su Zurfuru mine. Stratigraphic sequences, in places

fragmentary, mineralized as well as unmineralized, were reconstructed, particular attention being focused on the sedimentological characteristics. These sequences have been tentatively compared and carefully sampled. Studies of both polished and thin sections and X-ray analyses were carried out. Fluid inclusion studies and microprobe analyses of the skarn minerals are planned for future work.

## Geological setting of the Lower Paleozoic terrane

Within the autochtonous Cambrian sequence of SW Sardinia (COCOZZA, 1979; BECHSTAEDT et al., 1985; 1988) (Fig. 2a) thick carbonates (Gonnesa Formation) developed on top of carbonate-clastic sediments (Nebida Formation), both being of Lower Cambrian age. The carbonate sequence is overlain by nodular limestones (Campo Pisano Formation), followed by deeper water clastics (Cabitza Formation), comprising the time-span from Middle Cambrian to Lower Ordovician. During the Lower Cambrian SW Sardinia was an epicontinental region. Deposition took place in shallow waters, bordered by an erosional area from the E to SE. With time a shallow ramp developed into a carbonate platform, due to its isolation from the source of the clastics. This isolation was caused by tensional tectonics, resulting in the formation of a basin between the platform and the (still exposed?) basement (BECHSTAEDT et al., 1988). Tensional tectonics were active from late Nebidan times onwards, as shown for instance by slump structures. Crustal stretching was especially active in Gonnesan times, as indicated not only by slope sediments with their breccias and mass movements, but also by ruptural events, which affected the platform, and its margins.

Numerous stratabound Pb-Zn and Ba deposits of Lower Cambrian age are known and have been partially exploited (BRUSCA & DESSAU, 1968). These deposits occur within the carbonate sequence of the Gonnesa Fm, and locally also within the upper parts of the Nebida Fm (Fig. 2b). They were defined by BONI (1985) as of Mississippi Valley type.
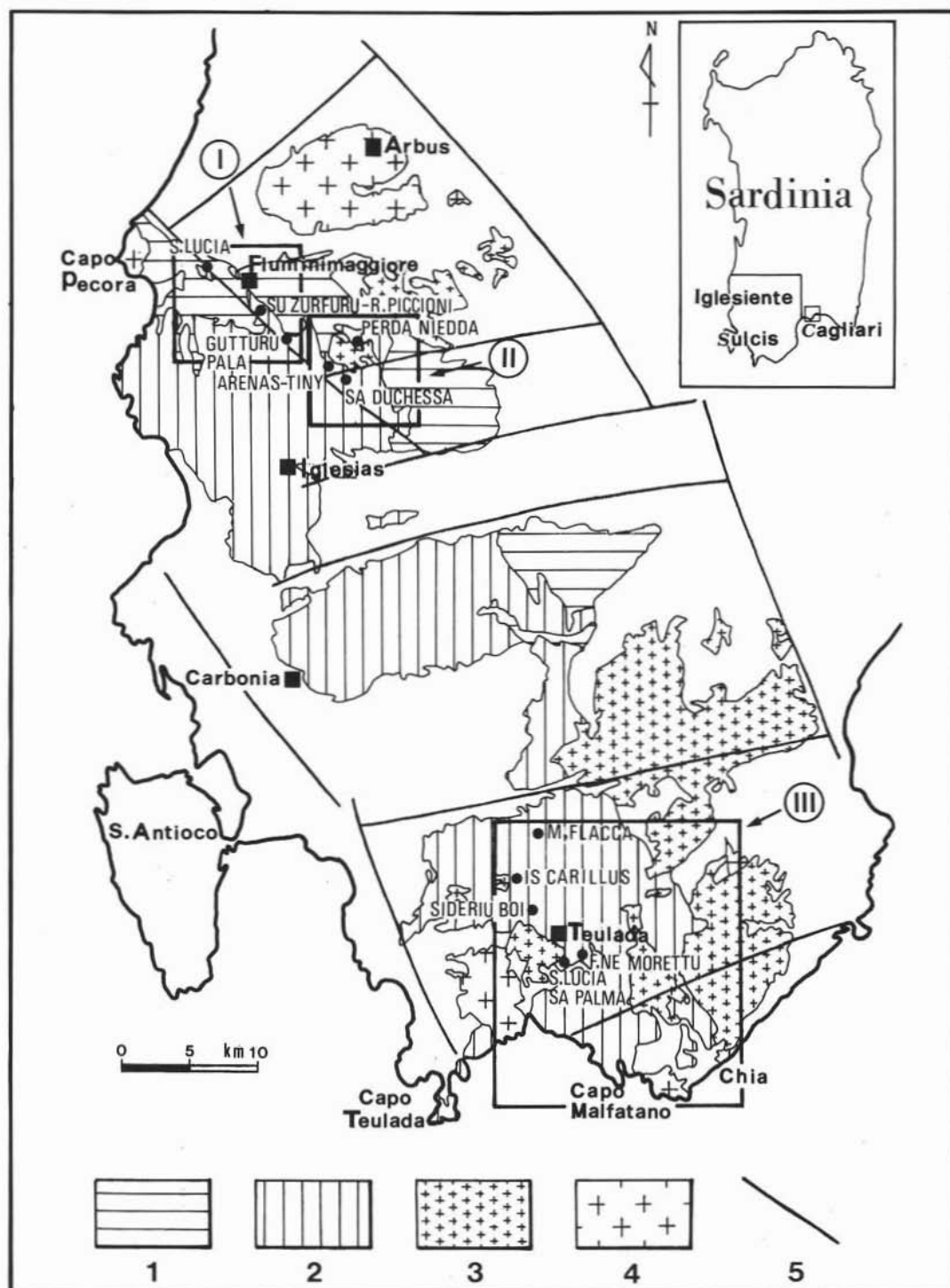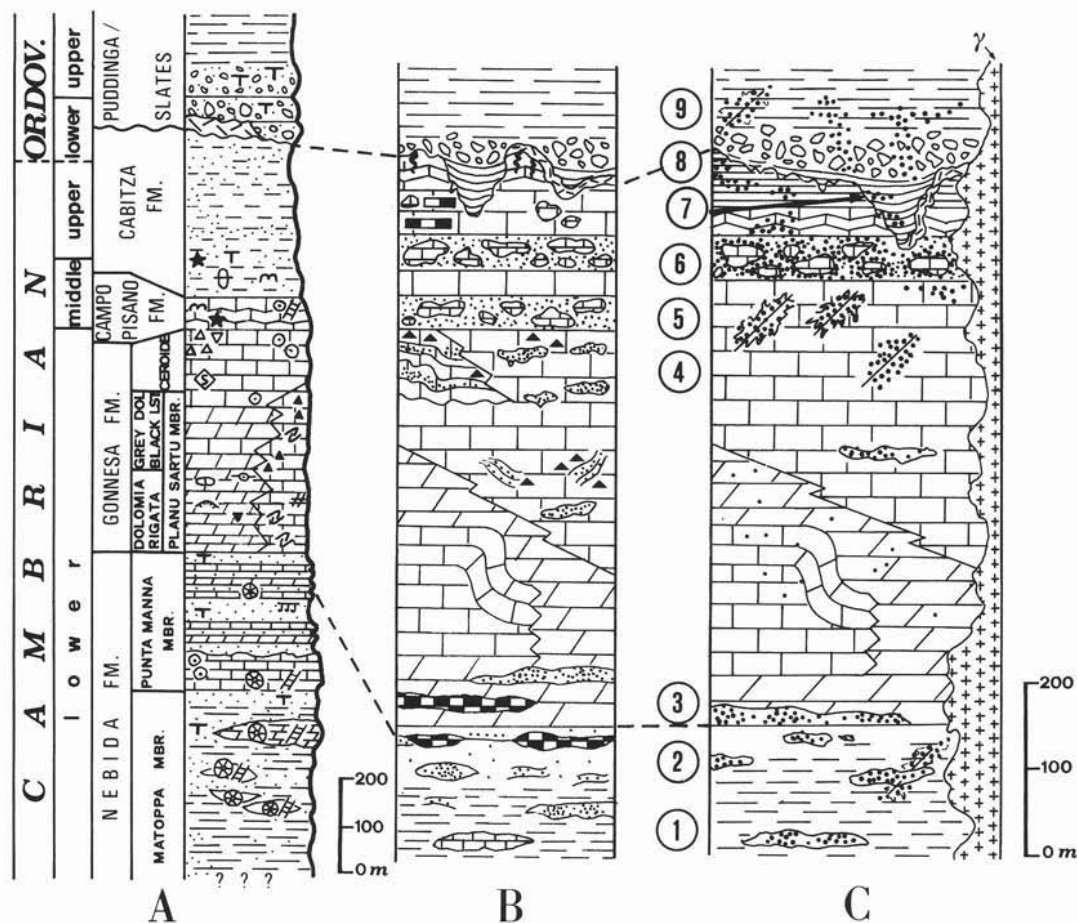
Fig. 1. — Geological map of SW Sardinia: in the squares are the investigated areas. 1) Upper Ordovician; 2) Cambrian Lower Ordovician; 3) Post-kynematic granites (leucogranites); 4) Synkynematic granites; 5) Main fault lines.

A. SEE TEXT AND BECHSTAEDT ET AL. (in press.)

B. SEE BONI (1985); ◼◻◼◻ BARITE; ░░░ Pb – Zn – Fe SULPHIDES.

C. ⊞⊞⊞γ LEUCOGRANITES; ▨ VEIN SKARN; ░░ METAMORPHIC AND VEIN SKARN; ① SKARN OCCURRENCES.

Fig. 2. — Idealized profiles of the Cambro-Ordovician in SW Sardinia. A) General profile with sedimentary facies; B) Enlarged profile of the mineralized interval with the location of the stratabound ores; C) Same profile with the location of the skarn ores: 1) Chia, 2) Mt. Flacca, Is Carillus, S. Lucia (Teulada), Filone Morettu, Sideriu Boi, 3) Sa Palma, 4) S. Lucia (Fluminimaggiore), 5) Su Zurfuru, 6) Gutturu Pala, Reigraxius, Barraxiutta, Perdu Carta, 7) Arenas p.p., Perda Niedda, Tiny, 8) Arenas p.p., 9) Roja Piccioni.

Recently, and at least for some of these ores, a complex genetic history is envisaged (BECHSTAEDT & BONI, in press). Only sparse mineralized occurrences are known in the uppermost carbonate levels of the Nebida Fm.

They consist of barite and layers of galena and sphalerite. Locally these deposits are associated with massive pyrite-marcasite, showing evidence of colloform structures and diagenetic brecciation. In Southern Sulcis

these mineral occurrences are also associated with the upper carbonate lenses, but are completely metamorphosed and also contain copper minerals. Some stratiform barite bodies and massive sulfides are found intercalated in the dolomite sequences of the lower Gonnesa Fm (Dolomia Rigata), whereas the mineralizations in the upper Gonnesa Fm (Ceroide limestone) are mainly stratabound.

The sulfides in the Ceroide limestone consist of sphalerite, pyrite and galena, the latter sulfide steadily increasing towards the top of the limestone. All types of orebodies occur in different horizons with a variable paragenesis depending on paleogeographic position (BECHSTAEDT and BONI, in press). Two main types of ores are known: yellow «blendoso» limestone, consisting of diffused impregnations of light-colored sphalerite in peloidal mudstone, and breccia ores, with sulfides cementing the breccia components. In Oridda, Fluminese and North Sulcis the last-mentioned ores were subjected to contact-metamorphism and contain abundant copper sulfides. The Cambrian and Lower Ordovician sediments and their contained mineralizations were deformed before Upper Ordovician deposition (Sardic phase, STILLE, 1939) (Fig. 2a, b). A short-level compression affected the area, leading to erosion and the development of fluviatile conditions and alluvial fans, followed again by shallow marine sequences (LASKE & BECHSTAEDT, 1987). The stratigraphic contact is mostly marked by conglomeratic deposits (the «puddinga»), but also by silica crust, concretionary iron oxide minerals and a karstic morphology (BONI, 1985). Ore deposits, although of lesser importance than those of Cambrian times, are linked to the contact between the Upper Ordovician and the deformed and eroded Cambrian - Lower Ordovician sediments (Fig. 2b). These deposits consist principally of veins and paleokarst fillings in the underlying Cambrian carbonates (BENZ, 1964; BONI, 1985). Here iron, barium and lead prevail over zinc. Silver is slightly more abundant than in the Cambrian ore bodies.

Both Cambrian and Ordovician ores were affected by early and late diagenetic processes, strong compressional tectonics (Variscan phases), magmatism (Variscan granites) and different stages of fluid circulations (BONI, 1985).

## Variscan tectonics and metamorphism in South-West Sardinia

The Variscan orogeny in Sardinia produced important deformations, followed by a significant late to post-tectonic magmatism (CARMIGNANI et al., 1982). A first distinction should be made between the Iglesiente and North - Sulcis areas, and Southern Sulcis. In the latter area the Variscan deformation and regional metamorphism were of a higher degree than in the other districts (MINZONI, 1981).

In Iglesiente and North - Sulcis, the most commonly accepted Variscan deformation history can be outlined as follows (CARMIGNANI et al., 1982).

First Variscan phase: slight folding with east-west axes, often superimposed on the Sardic phase trends.

Second Variscan phase: main deformation with north-south folding and very strong schistosity.

Third Variscan phase; slight deformation with variable fold-axis directions and block faulting.

The main structure of the Iglesiente is due to interference from a system of east-west trending folds («Sardic» or first Variscan?) with the north-south folds of the second main Variscan phase (CARMIGNANI et al., 1982).

Contrary to the more northern areas of the island, in South-West Sardinia the limit of burial diagenesis or anchimetamorphism was never exceeded, as stated by PALMERINI and PALMERINI-SITZIA (1978) on the basis of clay minerals content. GHEZZO & RICCI (1977), on the other hand, believe that in Iglesiente-Sulcis, as in South-East Sardinia, a metamorphic grade of lower greenschist facies was already present. During or after the late-Variscan tectono-metamorphic events, the Lower Paleozoic basement was affected by a complex sequence of successive multiple intrusive events spanning about 20 Ma (Fig. 1). The intrusive sequence is composed as follows (DI SIMPLICIO et al., 1975; BRALIA et

al., 1982; GHEZZO and ORSINI, 1982):

1) Deeply emplaced syn-tectonic and late-tectonic intrusions. No related significant skarn ores are known. They are found mostly in the central and northern areas of Sardinia.

2) Post-tectonic intrusions, present in South-West Sardinia, made up of pinkish biotite-bearing leucogranites, emplaced at about 289 ± 1 Ma (DEL MORO et al., 1975). The leucogranites, derived from homogeneous high-silica magmas, were produced in an extensional regime (GUASPARRI et al., 1984). The textural and structural features of leucogranitic intrusions indicate that the entire suite was emplaced at a shallow level in the crust as a consequence of the lower water content of the original magmas. The crystallization of leucogranites is thought to have occurred at pressure of 1 to less than 0,5 Kbar, corresponding to depths of 3,8 to less than 1,8 Km (GUASPARRI et al., 1984). This is in agreement with CONTI et al., (1972), who hypothesized a pressure of 0,5 Kb for the K-feldspar and cordierite hornfels facies in the metamorphic aureole immediately at the contact of the granite at Domus de Maria, in Southern Sulcis. However, RETTIGHIERI and TUCCI (1982) suggest a depth of at least 11 Km for the emplacement of the granite at Capo Spartivento, which belongs to the earlier emplaced monzo-granitic to gabbro-tonalitic late-tectonic plutonites. The leucogranites, to which the skarn ores discussed in this paper are mostly related, are usually pervasively altered by several pulses of hydrothermal activity. Sericite, chlorite and fluorite are often present. Retrograde boiling has been hypothesized (GUASPARRI et al., 1984) as well as sudden changes in temperature and pressure due also to extensive faulting accompanying the intrusions at shallow depths and in rocks with differentiated behaviour. The resulting contact aureoles in these conditions are ill-defined, and show evidence of telescoping. Leucogranites, and especially their fine-grained facies and porphyries, are recognized as the only products of the Variscan batholith directly connected with porphyry-type, mostly Mo-bearing mineralizations (GUASPARRI et al., 1984).

## South-East Sulcis

In SE Sulcis (area III in Fig. 1), the Lower Paleozoic terrane is characterized by the prevalence of the clastic sediments of the Nebida Fm, with minor outcrops of carbonatic rocks of the Gonnesa Fm (Lower Cambrian). The nodular limestones and slates of the Campo Pisano and Cabitza Fms are scarce. The change from silico-clastic sedimentation, which occurs on a homoclinal ramp, to the carbonates deposited in a rimmed shelf environment, is marked by mixed carbonatic-siliciclastic sequences, the so-called «Alternanze» (Nebida Fm, Punta Manna Member, BECHSTAEDT et al., 1985). The carbonate bodies of the «Alternanze» often show an irregular, lensoid form; the observed facies range from limestones to dolomites, mostly deposited in shallow water environments. Carbonate lenses belonging to the Punta Manna Member outcrop in the SE Sulcis area; especially interesting for the topic discussed in the present paper are the lenses of Mt. Flacca, Is Carillus, Sideriu Boi and those outcropping around Teulada (Morettu Vein, S. Lucia, Mt. Calcinaio - Guardia Manna Teulada; Fig. 1). Moreover, other carbonate lenses, (e.g. those outcropping near Chia and Capo Malfatano) have been related to the underlying Matoppa Member by MINZONI (1981). It should be noted, however, that in SE Sulcis the «basal carbonate», which in Northern Sulcis and Iglesiente represents the base of the Punta Manna Mbr, is not known. The carbonate lenses of the Punta Manna Mbr are locally isolated in the upper clastic sequences or grouped as multiple thin horizons in between the sandstones (Mt. Flacca, S. Lucia, Morettu Vein, Is Carillus, Sideriu Boi). A different situation can be observed on the eastern flank of Mt. Calcinaio and at Guardia Manna, where the lenses are numerous and barren. The carbonate intercalations show many different textures and facies: some of them have a prevailing algal-oolitic composition, whereas others contain oolites and archaeocyathans, and others are rich in algal filaments or have a prevailing flaser structure.

Many of these rocks host concentrations of mixed sulfides and/or magnetite-heamatite, in

places of small economic importance (TAMBURRINI and URAS, 1965; URAS et al., 1965; VIOLO and ZUCCHINI, 1965). At the same time, the carbonate intercalations were affected by metasomatism caused by high temperature fluids circulating in the metamorphic aureoles around the granitic intrusions. The granites outcrop as isolated apexes and are related to the late and post-kinematic phases of the Variscan orogeny. The granitic rocks produced during the latter phases are essentially leucogranites, to which the skarn ores are related. The carbonate lenses hosting the mineralization show also contact-metamorphism, whereas the contrary is not always true. It is important to point out that the protolith for all the metamorphosed and mineralized lenses consist of carbonates with «flaser» or wavy bedding structures (Morettu Vein, Is Carillus, S. Lucia, Sideriu Boi, Mt. Flacca).

The differences between the metamorphic-metasomatic parageneses found in the various lenses may be ascribed to: a) local variations in the original composition of the metamorphosed rocks; b) variable conditions of fracturing and of permeability to fluids of the host rocks; c) distance from the granite intrusions (EINAUDI et al., 1981; VIOLO and ZUCCHINI, 1965). At any rate, not considering the local differences in the mineralogical associations, we can distinguish between two main different, often superimposed, parageneses. Of these, one might replace the other, and both should correspond to different stages of the contact-metamorphic phenomenon. Where still recognizable, the primary paragenesis consists of: 1) garnet (mainly grossularite with less andradite) + wollastonite + pyroxenes (diopside - hedenbergite) (Sideriu Boi). Wollastonite may often be observed only as ghosts inside the andradite crystals, as already described at Sa Marchesa by VENERANDI-PIRRI (1981). This paragenesis corresponds to high - temperature metamorphic processes with minimum temp. 540°C (equilibrium temperature wollastonite - garnet with Pf = 1 Kb; UCHIDA and IIYAMA, 1982).

With decreasing temperature, this paragenesis is no longer stable and is therefore replaced almost completely by: 2) amphiboles (mainly tremolite and/or actinolite) + epidote (pistacite and minor clinozoisite) (S. Lucia, Mt. Flacca, Morettu Vein).

Finally, the hydrothermal circulation of fluids produced a widespread chloritization, in places so strong that it obliterated the preexisting parageneses (Is Carillus).

The metamorphic phenomenology may therefore be related to a 3-stage evolution of the system: metamorphic stage, metasomatic stage, hydrothermal stage, each of which developed with variable intensity and different modalities (Fig. 5). At Sideriu Boi, for instance, the prevailing association consists of grossularite garnet + wollastonite, at Morettu Vein amphiboles and epidotes prevail over garnets, all of them partially replaced by chlorites. At S. Lucia, layers with prevailing garnet + wollastonite alternate with layers containing prevailing epidotes (pistacite and clinozoisite). Lastly, at Mt. Flacca and Is Carillus garnets and wollastonite are often replaced by chlorite.

Most of the metamorphosed carbonate lenses host mixed sulfide and oxide mineralization, consisting of an association of pyrite, sphalerite, galena, chalcopyrite, pyrrhotite and/or magnetite/haematite. Local differences in the composition and in the metallic associations might be related to the variable importance of the single stages of metamorphic evolution. For instance, a greater enrichment in galena over sphalerite is noted in those areas where the last hydrothermal stages were more intense (Is Carillus, Mt. Flacca, Sa Perdaiola). In areas of well-developed higher temperature paragenesis, for example at Morettu Vein and S. Lucia, the metallic association is noted to be richer in sulfides and oxides deposited in the following sequence: 1) pyrite; 2) magnetite; 3) sphalerite with pyrrhotite and chalcopyrite inclusions; 4) galena and sulphosalts. In the areas where the highest temperature paragenesis has been less modified, the prevailing metallic mineral is haematite, with subordinate galena, sphalerite and chalcopyrite (Sideriu Boi; Fig. 3c).

Contact-metamorphic phenomena are not only limited to the body of the carbonate

lenses, but they are also found along the stratigraphic contact between the clastic sediments of the Nebida Fm and the carbonates (Dolomie Rigate/Planu Sartu Mbr) of the Gonnesa Fm. An interesting example may be observed at Mt. Sa Palma near Teulada, where the host rock, consisting of prevailing epidotes and chlorites with minor garnet, contains a small magnetite-haematite orebody, showing evidence of mushketovitization and then martitization (RAMDOHR, 1975) (Fig. 3a, b). Minor quantities of galena, sphalerite and pyrite also occur.

The carbonate lenses in the Matoppa Mbr were also subjected to contact-metamorphism, but in a less obvious way. The layers of metamorphic minerals, in the Capo Malfatano lenses are rare. The carbonate lenses, however, are completely marmorized. Metallic minerals are absent here. A similar situation can be observed in the lens near Chia, where the recrystallization of the carbonate body into iron gossan, probably originated from the oxydation of stratabound sulfides, has been observed.

From the discussion given above on the ore and gangue minerals of the metamorphic association and their geologic setting, it is possible to consider these metamorphic lithotypes as skarn sensu lato, as defined by BURT (1977), EINAUDI et al., (1981) and EINAUDI and BURT (1982). The structural setting and the development processes of the skarn bodies in the areas studied allow a further classification after KERRICK (1977) and EINAUDI and BURT (1982). The situations at Mt. Flacca, Is Carillus and Morettu Vein should be considered typical of vein skarn, emplaced through fault lines, along which metamorphic, metasomatic and lastly

hydrothermal fluids infiltrated. In places, quartz veins occur along these fault lines (e.g. Morettu Vein). The situation is different at Sa Perdaiola and in the small limestone quarry at the junction to the Teulada harbour. In both these areas, at the contact between granite and carbonate rocks, a metamorphic complex, described as a magmatic skarn in the sense of KERRICK (1977), was found (metamorphic minerals on the limestone side = Exoskarn, metamorphic minerals on the granite side = Endoskarn). The endoskarn is otherwise generally lacking or obliterated by the subsequent hydrotermal alteration (CONTI et al., 1970).

Even more different are the metamorphic complexes of Mt. Sa Palma and Sideriu Boi. The former, as already mentioned, is at the contact between the dolomitic limestone of Gonnesa Fm (Dolomite Rigate Mbr) and the sandstone of Nebida Fm (Punta Manna Mbr). Infiltration of hot fluids along the stratigraphic contact, which formed a preferential channelway, might have induced a bi-metasomatic exchange (KERRICK, 1977) between the constituents of both adjoining lithotypes. Therefore, this process probably produced a metamorphic skarn, as defined by KERRICK (1977).

At Sideriu Boi the geologic setting is more complex, because here the fluids penetrated along a fault line, and again at the contact between sandstone and carbonate rocks. Following KERRICK (1977) the latter should be considered a case between vein- and metamorphic skarn[1].

## Oridda

In Oridda (area II in Fig. 1) a post-tectonic leucogranitic body (DI SIMPLICIO et al., 1975; GHEZZO and ORSINI, 1982) intrudes the

[1] In the present paper the expression «metamorphic skarn» and «vein skarn», taken by KERRICK (1977), are in most cases purely descriptive, even if a variable amount of metasomatism is always taken into account.
Only locally the diffusion phenomenon is envisaged for the «metamorphic skarn», as e.g. in the «flaser lenses» of S. Lucia and Sideriu Boi in Southern Sulcis, where there is evidence of matter exchange between argillaceous and carbonatic lithotypes, with occasional $CO_2$ and $H_2O$ contribution.

About the «vein skarn», the infiltration mechanism is made clear by the abundance of fractures through which the fluids may have travelled and by the vein filling fractures.
Real hornfels, with non external contributions to their mineralogy, are rare and, in the well mineralized areas, difficult to be evidenced, thank to the interaction of the earlier metamorphosed lithotypes with the younger hydrothermal fluids and consequent retro-metamorphism.

Lower Paleozoic sequences consisting of Cambrian and Ordovician sediments.

The characteristic metamorphic and hydrothermal processes, developed around this body, caused the formation of hornfels, marbles and skarns (URAS and VIOLO, 1963a, b). In the areas where skarns prevail, the most common lithotypes are represented by the Ceroide limestone (Gonnesa Fm) and silico-clastic Ordovician sediments («quartz crusts», conglomerates and slates). The latter, near the contact with granites, are widely transformed into hornfels. In Oridda the contact between the slightly folded Cambrian-Lower Ordovician carbonates and the upper Ordovician clastics is unconformable. This contact is marked by an extended network of paleokarstic cavities, which acted as channelways for the metamorphic fluids and controlled the deposition of skarn minerals. Another important constraint for skarn formation are the NW-SE and NE-SW trending major tectonic lines. In the whole Oridda, however, and also far from known intrusions, a thermal low-grade metamorphism, mostly recognizable from the higher-temperature parageneses of the metallic minerals (e.g. Barrasciutta, Perdu Carta and Reigraxius), occurs everywhere. In the above-mentioned mines the ore bodies are stratabound and the host limestones are not recrystallized. However, among the ore minerals, near the usual sedimentary association (BONI, 1985) consisting of pyrite-sphalerite-galena, chalcopyrite (as inclusions in sphalerite), fluorite and arsenopyrite may also be recognized.

The most characteristic skarn outcrops occur in the areas of Perda Niedda (CIAMPI, 1909), Arenas-Tiny (BENZ, 1964) and Sa Duchessa (CARTA, 1942; URAS, 1957), where some small mixed sulfide ore bodies have been exploited. Three main types have been recognized: 1) skarn related to stratigraphic contacts, as e.g. between Gonnesa and Cabitza Fms (Sa Duchessa), and along the Cambro-Ordovician unconformity, recognizable at Perda Niedda, Arenas-Tiny and Punta Nebidedda (metamorphic skarn, KERRICK, 1977); 2) skarn in small veins in the marmorized Ceroide limestone, along main tectonic lines, as seen at Sa Duchessa p.p. (vein skarn, KERRICK, 1977); 3) skarn at the contact between granite and marble, as at Perda Niedda p.p. (magmatic skarn, KERRICK, 1977).

The skarns related to the paleokarstic cavities consist mostly of an association of andraditic garnet (often sufficiently abundant to form true garnetites, showing ghost of the original stratification, as at Tiny, Punta Nebidedda and Perda Niedda p.p.), wollastonite, tremolitic amphiboles, hedenbergite and minor diopside.

The subsequent lower - temperature hydrothermal stage is generally very well developed (especially at Perda Niedda), with abundant chlorite (replacing amphiboles, pyroxenes and garnets), sericite, fluorite, calcite and quartz (replacing wollastonite). The paragenetic sequence of the ore minerals at Perda Niedda is as following: pyrite → magnetite → chalcopyrite → sphalerite with chalcopyrite inclusions → galena and fluorite. Some inclusions of cobaltite and safflorite have been observed in the pyrite. Arsenopyrite and marcasite may also occur, as well as small needle-like inclusions of pyrrhotite in sphalerite (Fig. 4b).

The main ore minerals at Tiny chiefly consist of galena with less sphalerite and pyrite. These minerals generally fill the interstices between the metamorphic minerals (e.g. garnets), or may be observed in vein or cavity fillings in the marble. At Punta Nebidedda the general situation is similar as at Tiny. The mineralogic association of gangue minerals consists of andradite garnet, tremolite, epidotes and chlorite.

Both vein and metamorphic skarn have been observed at the Sa Duchessa mine, where the main ore, exploited in the past, consisted of calamine and copper carbonates enriched through supergene processes in relatively recent karstic cavities (CARTA, 1942; URAS, 1957). At Sa Duchessa, the protore consisted of stratabound pyrite-chalcopyrite bodies with minor sphalerite in the upper zone of a marmorized Ceroide limestone, at the contact with the Campo Pisano and/or Cabitza Fm (metamorphic skarn). In the mine area some poorly developed vein skarns also occur along
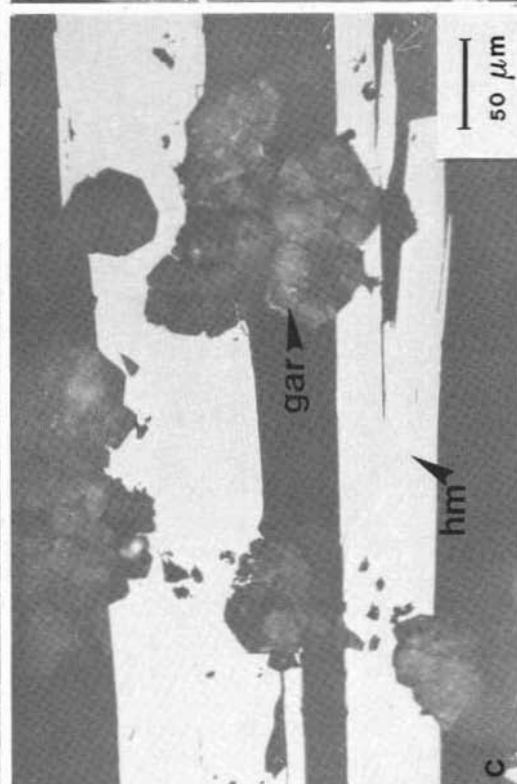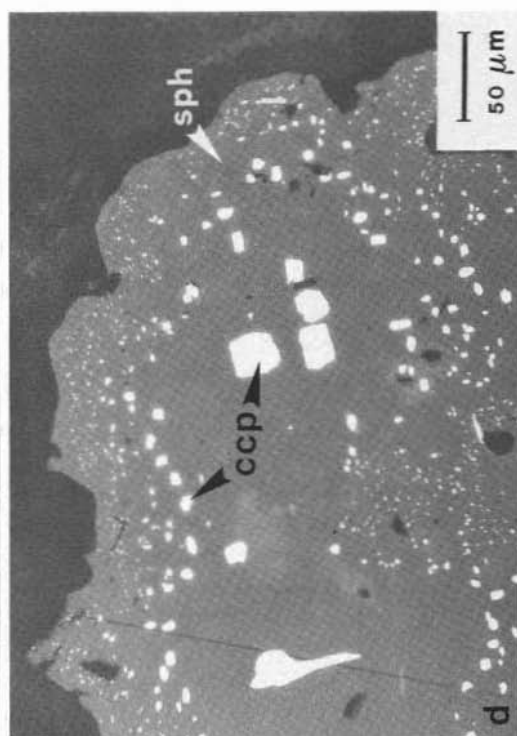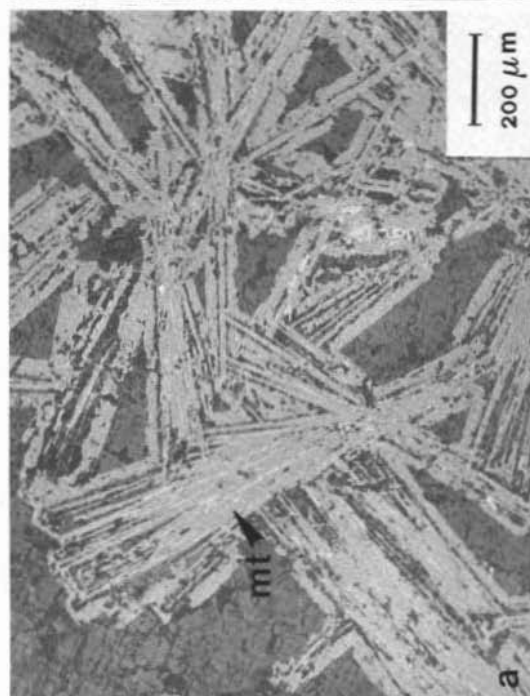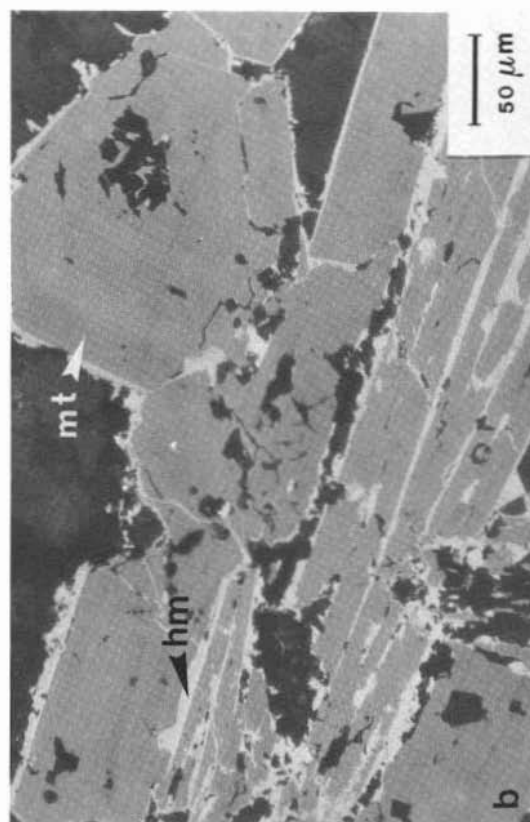
fracture lines. The small size of the vein skarns is probably responsible for the lack of mineralization. The mineralogical association of the barren vein skarns contains andradite garnet, tremolite, epidote (pistacite) and chlorites.

The genetic process is essentially the same for all three types of skarn mineralization, although they followed variable and diverse evolutionary paths. At Perda Niedda and Sa Duchessa skarn formation was followed by intense hydrothermal alteration, probably enhanced by the high permeability of the host rocks through which the fluids circulated. At Tiny and Punta Nebidedda, hydrothermal alteration is much less developed or even absent. Owing to this different evolution, the relationships between the metallic and non-metallic associations are also different in the various areas. At Perda Niedda and Sa Duchessa, the metallic paragenesis is often partly replaced by lower-temperature hydrothermal minerals, such as sericite, chlorite, calcite and quarz, as indicated by clear reaction rims. At Tiny and Punta Nebidedda, on the other hand, the prevailing ore mineral (galena) not only coexists with the higher-temperature skarn minerals such as wollastonite and andradite, but does not show any reaction rims. This could be explained by a very early segregation of galena together with the skarn minerals.

From the discussed parageneses, it could be inferred than in Oridda the most likely interval for mineralization begins below 500°C and ranges between the segregation of the higher - temperature minerals (garnet + wollastonite + pyroxenes) and the hydrothermal alteration stage (chlorite + epidote + sericite). With decreasing temperature, the andraditic garnet might have

reacted releasing iron, which may have formed magnetite, followed by the deposition of sulfides, and lastly by the last hydrothermal mineral phases (> 200°C).

## Fluminese

The part of the Fluminese area studied here (area I in Fig. 1) mainly contains the lithologic units belonging to the middle-upper stratigraphic partition of the Lower Paleozoic. In places, these show evidence of intense thermometamorphic and hydrothermal phenomena related to the granite intrusions. In the area investigated no igneous rocks occur, although locally (e.g. Su Zurfuru) there is evidence of probable granitic apexes at shallow depths (PRETTI and URAS, 1972). The tectonic grain of the Paleozoic sequences is characterized by a series of anticlines and synclines, with axes running NW-SE, detached in turn by several faults. The oldest outcropping sequences are represented by the carbonate lithotypes of the Gonnesa Fm (Lower Cambrian), followed stratigraphically by the nodular limestone of the Campo Pisano Fm and the clastics of the Cabitza Fm (Middle-Upper Cambrian - Lower Ordovician). These lithotypes are unconformably covered by Upper Ordovician clastic sequences (microconglomerates and arenaceous slates; LASKE and BECHSTAEDT, 1987). The carbonates outcrop along an almost continous line (E-W) from Mt. Gennargentu to Punta Manna de Pubusinu and also as a few isolated blocks (S. Lucia, Punta Pala Su Sciusciu, Giovanni Longu), aligned NW-SE. They mainly consists of dolomites and limestones with rimmed shelf and shelf margin facies (cherty limestone, slumpings) with frequent breccia horizons. To these breccia horizons are related the sedimentary stratabound Pb-Zn ores exploited at Gutturu Pala (BONI, 1985). Some small mineralizations are also related to the inter-Ordovician unconformity. Here, unlike the Oridda area, haematite concentrations occur in a small network of veins. In the Fluminese, the unconformable contact is between two clastic lithotypes (Cabitza Fm and Upper Ordovician). In this area, therefore, the

Fig. 3. — a) Magnetite crystals pseudomorphs on haematite (mushketovite), showing also later martitization. Sa Palma, pol. sect., N. II, air; b) Zoned magnetite crystals on haematite (mushketovite). Later haematite can be seen along crystallographic directions (martite). Sa Palma, pol. sect., N II, oil imm; c) Haematite bladed crystals, partly replaced by garnets. Sideriu Boi, pol. sect., N II, oil imm; d) Sphalerite with chalcopyrite inclusions of different dimensions. S. Lucia (Teulada), pol. sect., N. II, oil imm.
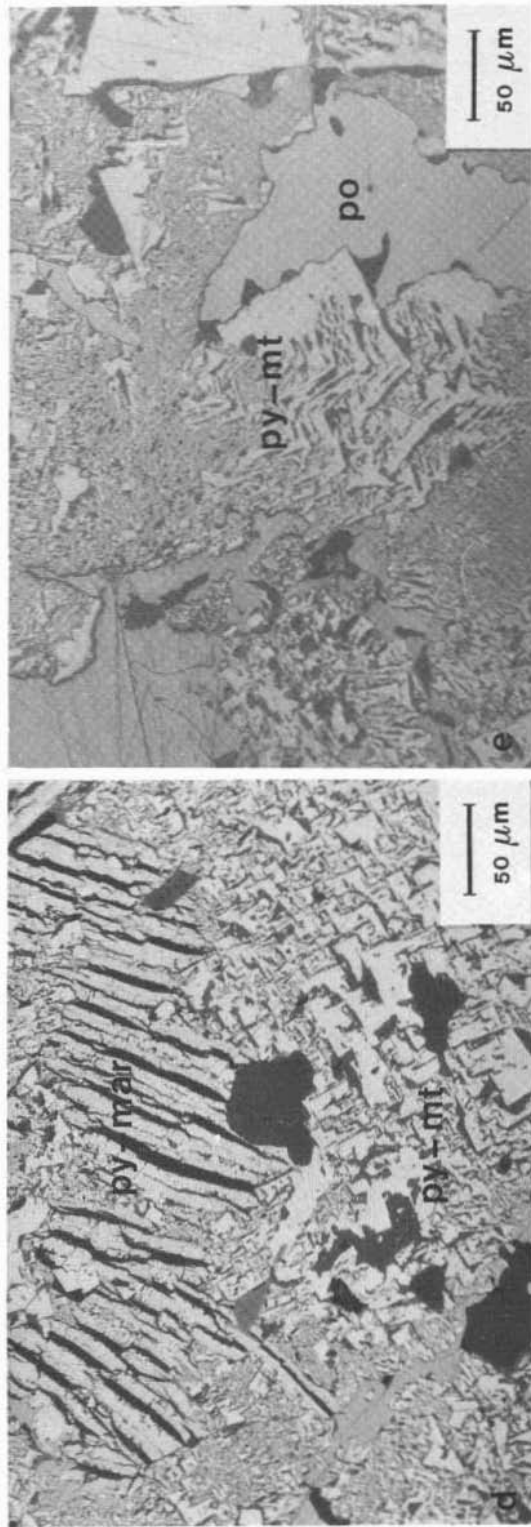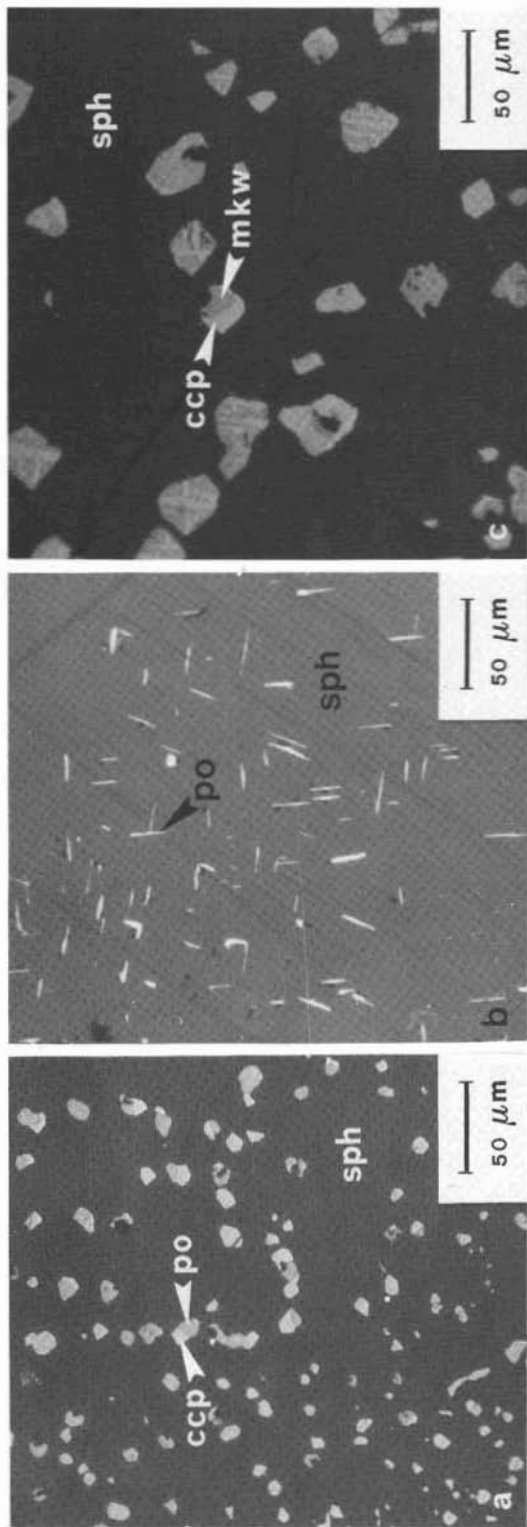
mineralized paleokarstic cavities related elsewhere to the underlying Cambrian carbonates are not present. The emplacement of the late- and post-Variscan leucogranites caused an intense circulation of high-temperature fluids with formation of tactites (hornfels and skarns) and hydrothermal veins. In some cases the activity of the fluids acted on pre-existing metallic concentrations, resulting in a wide range of a) metamorphosed ore bodies; b) skarn mineralization and c) mineralized veins.

The mineralized veins (F-Ba-Pb-Ag) occur only at S. Lucia (Fluminimaggiore; BAKOS and VALERA, 1972), whereas at Roja Piccioni only some small skarn veins occur. In the Su Zurfuru - Giovanni Longu area the mineralized veins and skarn ores are overprinted on small pre-existing sedimentary ores, also showing evidences of contact-metamorphism (BALASSONE et al., in press). In the Gutturu Pala mine, as in Barrasciutta, Perdu Carta and Reigraxius (Oridda), higher-temperature effects are slight and have been observed only in the ore minerals, as shown by chalcopyrite inclusions (often altered to covellite) in the sphalerite and rare neoformations of magnetite on pyrite.

The most interesting characters of skarns in the whole Fluminese district, however, are seen in the old Su Zurfuru mine (F-Ba), owing to a new exploration program which has allowed the discovery of skarn-related ore occurrences, rich in Pb-Zn and Cu. The Su Zurfuru mine is situated on the northern side of the Giovanni Longu hill, where the clastic lithotypes belonging to both the Cabitza Fm and the Upper Ordovician predominate. The Gonnesa Fm here consists only of isolated limestone blocks with a red matrix-breccia,

some of them embedded in the slate and/or Ordovician conglomerate. Some of the blocks contain black chert nodules and slumped layers; in places the matrix-breccias have elongated clasts of white-grey Ceroide.

Owing to strong tectonism in the area and to contact-metamorphism, it is difficult to distinguish between Cambrian-Lower Ordovician and Upper Ordovician slates. The latter may be recognized with some degree of certainty, even if they contain the microconglomerate facies, also called «puddinga» (LASKE and BECHSTAEDT, 1987), at their base. From the tectonic point of view, the Su Zurfuru mine appears to be associated with the NW-SE trending Su Zurfuru fault. This is one of 2 important structural lines which intersect the E-W trending Sa Broccia anticline (BALASSONE et al., in press).

The metamorphic effects are very different depending on the various lithotypes. Thermal metamorphism of the slates and microconglomerates produced hornfels, in places also showing metasomatic effects, evidenced by large crystals of garnets, fluorite, armenite (BALASSONE et al., in press) and pyrite. Marmorization of the carbonates is the more conspicuous effect, accompanied, especially in the breccia matrix, by neoformed calc-silicates such as clinopyroxenes (hedenbergite), sporadic garnet, amphiboles, quartz and chlorite. Metallic minerals are very rare. The emplacement of the skarn bodies follows some important directions, such as stratigraphic contacts and tectonic directions. Consequently these bodies have generally elongated shapes, although where both conditions are accomplished, the skarn body may also extend laterally to a considerable extent, reaching massive forms.

The Su Zurfuru mine contains a combination of both metamorphic and vein skarn (KERRICK, 1977). The former is massive and occurs along the contact between marble and metamorphosed slates. The latter occurs entirely in the marble and is related to fault zones. It may be hypothesized, however, that both of them form a single skarn body along the marble-slate stratigraphic (?) contact (metamorphic skarn), from which several apophyses originate (vein skarn), probably

Fig. 4. — a) Chalcopyrite + pyrrhotite inclusions in sphalerite. Su Zurfuru W, pol. sect., N II, oli imm; b) Pyrrhotite platelets aligned along sphalerite crystallographic directions. Perda Niedda, pol. sect., N II, oil imm; c) Oriented under-unmixing of mackinawite in chalcopyrite, both in a sphalerite matrix. Su Zurfuru W, pol. sect., N. II, oil imm; d) Pyrrhotite being replaced by intergrowths of pyrite-marcasite (upper part of the photograph) and pyrite-magnetite (lower part). Su Zurfuru W, pol. sect., N. II, oil imm; e) Pyrrhotite being replaced by intergrowths of pyrite-magnetite. Su Zurfuru W, pol. sect., N II, oil imm.

along small joints, acting as channelways for the fluids, in the marmorized limestones. The massive skarn has a mineralogic association consisting of andradite garnet, wollastonite, clinopyroxenes, actinolite and epidotes. These early minerals seem to have been replaced at least partly by lower temperature phases, such as chlorite, generally replacing pyroxenes and amphiboles, quartz and calcite (often showing reaction rims with wollastonite) and fluorite. The ore minerals in the massive skarn consist of pyrite, sphalerite (with pyrrhotite and chalcopyrite inclusions), galena, pyrrhotite, magnetite, marcasite and haematite. There are also minerals of supergene origin, such as covellite and bornite. The most frequently observed parageneses are: pyrite I → magnetite + pyrrhotite → pyrite II + sphalerite (with pyrrhotite and chalcopyrite inclusions) → galena. Some mackinawite sub-exsolutions in the chalcopyrite inclusions have been observed. They may be compared with those described at Sa Marchesa by VENERANDI-PIRRI (1971). According to RAMDOHR (1975), they represent exsolution products from the high-temperature chalcopyrites. Their occurrence may indicate temperatures around 250-200°C (Fig. 4c). In places, some pyrite-marcasite intergrowths replacing pyrrhotite were found, as well as a few haematite patches replacing magnetite and pyrite I. Most of the ore minerals are contained in a fibrous network of wollastonite, pyroxenes and amphiboles.

The so-called vein skarn (or apophyses) consist of sub-rounded bodies with zoned structure. In fact, the outer rims of these bodies, in contact with the host marble, show an aureole of idiomorphic elongated hedenbergite macrocrystals (up to 10 cm in length) in places largerly replaced by chlorite. These crystals are associated with minor quartz and calcite, and with traces of sulfides (mostly chalcopyrite and galena). The inner part of the apophyses consist of the same pyroxenes, but the hedenbergite crystals are smaller and with an ipidiomorphic habitus, whereas calcite and quartz are more abundant. The ore concentrations consist of pyrrhotite, chalcopyrite, sphalerite, pyrite, magnetite, marcasite and galena, and are much higher in the inner zones. The mutual relations between the minerals are as follows: pyrite I → pyrrhotite →sphalerite (with chalcopyrite and pyrrhotite inclusions) → magnetite + calcsilicate → pyrite II + chalcopyrite → galena. In places, it is possibile to observe triple junctions between pyrite I, pyrrhotite and sphalerite (with the above-mentioned inclusions), which is interpreted as evidence of the almost synchronous deposition of these minerals. Pyrite-marcasite (VENERANDI-PIRRI, 1971; RAMDOHR, 1975) and pyrite-magnetite intergrowths, both developed after pyrrhotite, are very common (Fig. 4d, e).

## Conclusions

From the evidence presented in this work, the following points can be made with regard to the skarn ores of SE Sardinia:

1) The general coincidence (with only a few exceptions) of the stratigraphic position of the Cambrian and Ordovician stratabound ores with the skarn mineralizations (BONI, 1985).

2) The additional elements (As, F, W, Cu) in the skarns, compared with the Lower Paleozoic sedimentary ores (Fe, Zn, Pb, Ba).

3) The gradual change in ore parageneses between sedimentary-diagenetic low-temperature minerals and high-temperature associations, towards the metamorphic aureoles around the intrusive bodies.

4) The association of skarn ores with the upper Nebida Fm in SE Sulcis, the upper Gonnesa Fm and the Upper Ordovician unconformity in Oridda and Fluminese (with the puzzling exception of Su Zurfuru).

5) The association of the skarn mineralized bodies with the post-tectonic leucogranites, already known in literature for their small «porphyry copper» potential (GUASPARRI et al., 1984).

As far as skarn genesis is concerned, these processes are mostly controlled by an intense thermal rise and movement of fluids (probably $H_2O$ and $CO_2$) in the areas affected by granite intrusions. The differences in the lithologic composition of the protoliths, the differences in permeability (along fractures or contacts between diverse lithologies) and the
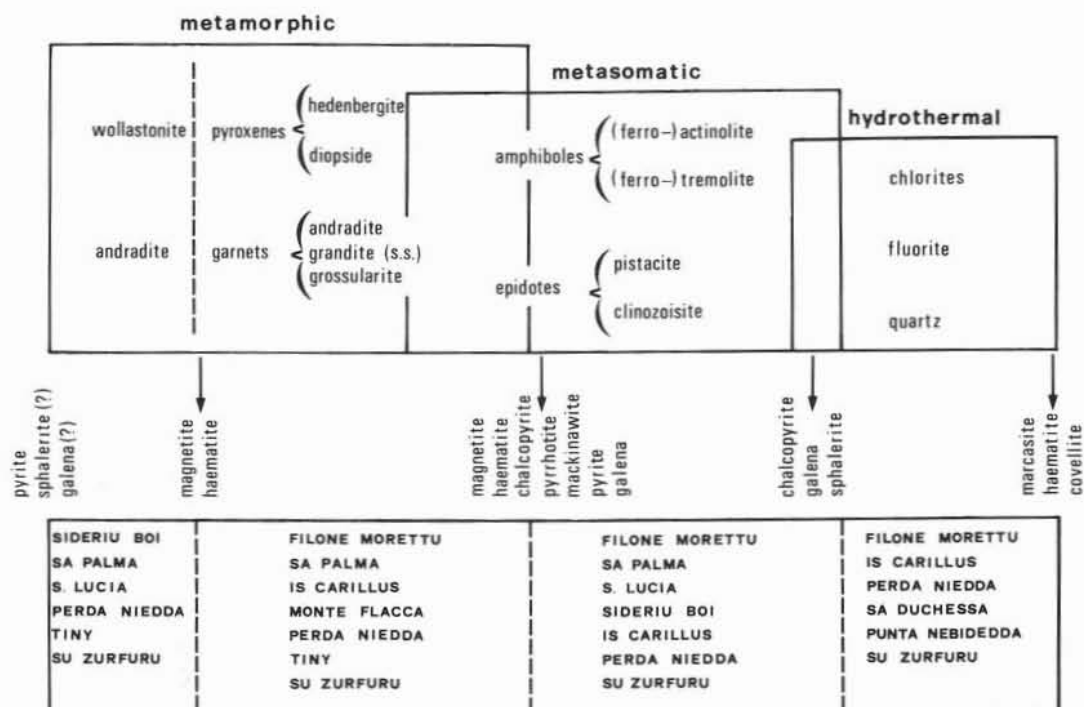
Fig. 5. — Different stages of the skarn and ore minerals formation.

variable distances from the granite intrusions, have generated a wide series of metamorphic lithotypes, including all possible stages between calc-silicatic hornfels and skarn sensu stricto.

In SE Sulcis, the sedimentary protoliths have a mixed carbonatic-silty-clayey composition («lenses» of the Nebida Fm). Those mostly involved in the formation of skarn minerals are the lenses with flaser structure, with a low clay content. Metamorphism and mineralization in the upper Nebida Fm in SE Sulcis may have developed with either small or no external contribution. The protolith, therefore, even where deeply modified in its mineralogy, might have retained its original chemical composition. The metamorphic lithotypes derived from the latter process should be classified as calc-silicate hornfels rather then real skarn. In SE Sulcis these situations seem to be common, with only few exceptions classificable as metamorphic skarn.

In Oridda and Fluminese, even though in places essentially similar situations as in Sulcis

occur, the skarn s.s., of both vein and metamorphic types, are much more frequent in the Gonnesa Fm and at the inter-Ordovician unconformity. In these skarn evidence of metasomatic exchanges is also provided by the coarser grain size of the minerals (especially garnets and pyroxenes). Moreover, it is of special interest to draw the attention to the high iron content of these skarns s.s., contained in hedenbergite pyroxenes and andraditic garnets, compared with the hornfels of SE Sulcis, whose garnet are predominantly of the grossularitic type.

It is possible, however, summarizing the several observed parageneses in the areas studied, to distinguish 3 main mineralogic associations (UCHIDA and IIYAMA, 1982), which reflect 3 different evolutionary stages at pressure of about 1 kb (Fig. 5, 6):

1) Metamorphic stage (T > 550°C), characterized by garnet + wollastonite and garnet + pyroxenes (2 generations of garnets, the second being anomalously birefringent and zoned: VERKAEREN and BARTHOLOMÉ, 1979).

2) Metasomatic stage (T > 400°C),

characterized by epidotes and amphiboles (actinolite > tremolite).

3) Hydrothermal stage (T < 375°C) characterized by chlorite, fluorite, quartz and calcite.
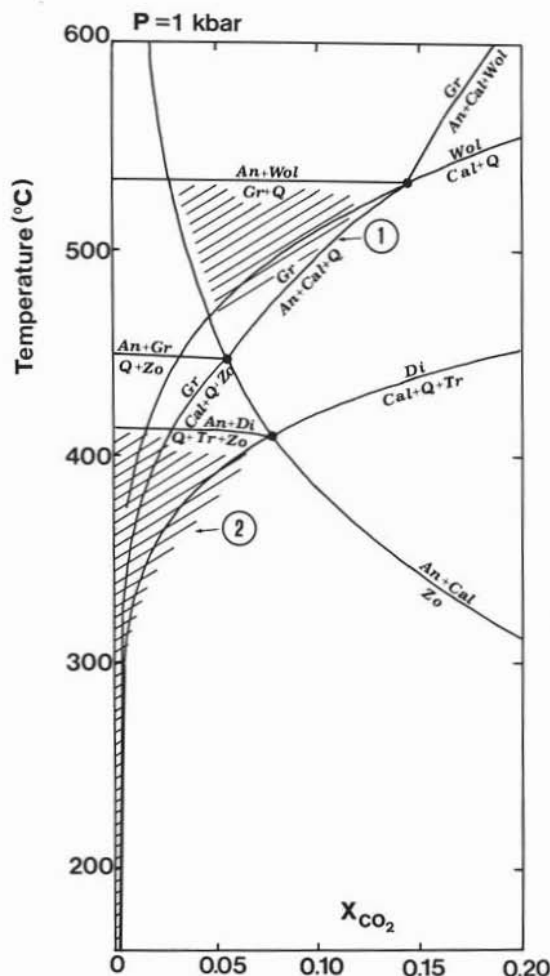
The metallic associations are similar in all the studied areas. There are, however, variable percentages of the elements, which in turn reflect both the content of the original stratabound Lower Paleozoic concentrations (BONI, 1985) and the association characteristic of the metamorphic stages related to the mineralization. To the first, higher-temperature metamorphic stage, only small pyrite and haematite - magnetite (mushketovite) concentrations are related, both coexisting with the garnets (Fig. 5). To the metasomatic and hydrothermal stages most of the ore minerals are related, comprising several generations of pyrite, magnetite, pyrrhotite, sphalerite, chalcopyrite and galena, each showing about the same paragenetic order of segregation. The ore minerals appear to have been deposited chiefly together with the amphiboles and epidotes; they were then partly replaced by chlorite minerals. The temperature for the main phase of the deposition should therefore range between 400 and 200°C (EINAUDI and BURT, 1982), with minor deposition of lower-temperature sulfides coexisting with chlorites (Fig. 5). Critical points for the sulfides are the coexistence of chalcopyrite (stable below 325°C, SUGAKI et al., 1975) and the presence of mackinawite exolutions in chalcopyrite (200-250°C, RAMDOHR, 1975). PADALINO and VALERA (1977) observed fluid inclusion homogenization temperature ranging from 370°C to 100°C in the various generations of fluorite crystals in the Oridda area.

The mineralizing process, however, was facilitated by the deposition of the higher-temperature metamorphic minerals such as garnet, wollastonite and pyroxenes, along the stratigraphic contacts and structural directions. They caused an increase in permeability in comparison with the former lithotypes, thus opening the way to major fluid circulation and at the same time acting as a trap for the metal-bearing solutions.

Finally, to the last hydrothermal phases, with temperature of about 100°C or less (BONI, 1985), are related the multiple generations of vein fillings, containing Ag-bearing galena, fluorite and barite, with quartz, calcite and dolomite as gangue minerals.



Fig. 6. — T-$X_{CO_2}$ diagram in the system CaO-MgO-$Al_2O_3$-$SiO_2$-$H_2O$-$CO_2$. $P_{tot}$ = 1 kb. This figure was constructed on the assumptions that $Al_2O_3$ and MgO are inert components, that CaO is a mobile component, that $SiO_2$ is an excess component and that $H_2O$ and $CO_2$ are percfectly mobile components. Based on the diagram of UCHIDA and IIYMA (1982) . 1) metamorphic stage associations; 2) metasomatic stage associations. Abbreviations:  An = anortite,  Tr = tremolite, Di = diopside,  Gr = grossularite,  Zo = zoisite, Wol = wollastonite,  Cal = calcite,  Q = quartz. The application of this diagram to our parageneses is only approximate.

It is reasonably certain that, at least for some of the investigated areas, the origin of the metals in the skarn mineralization is from the Cambro-Ordovician stratabound ores. Indeed, in places it is possible to observe a gradual transition between non-metamorphic and metamorphic paragenesis. The first indication of a rise in temperature is the appearance of chalcopyrite inclusions (chalcopyrite «disease», cf. CRAIG and VAUGHAN, 1981) in sphalerite, followed by the replacement of pyrite by magnetite. However, there is no conclusive explanation for the source of Cu in the skarns, since this metal is absent from the Lower Paleozoic mineralizations of SW Sardinia.

Whether large-scale remobilization of lead during the late Variscan period of mineralization really occurred remains an open question in view of the lead data from feldspars of the leucogranites (BONI and KOEPPEL, 1985). They are isotopically quite similar to the lead of galenas from both contact-metamorphosed and some of the vein filling ores. The feldspar lead thus raises some doubts that the late Variscan ores owe their existence only to remobilization of large amounts of Lower Paleozoic ores. It therefore seems possible that at least some of these deposits, in spite of their «stratabound» appearance, are of more complex origin.

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