Società Italiana Mineralogia e Petrologia - Milano, 1974, Vol. XXX (1): pp.251-303

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CORRELATION BETWEEN SEDIMENTATION ENVIRONMENT AND ORE - PROSPECTING (***)

SEDIMENTOLOGICAL AND ORE-GENESIS STUDIES OF THE CAMBRIAN «ARENARIE» AND «DOLOMIE RIGATE» FORMATIONS (SARDINIA - ITALY): DEPOSITION AND CONCENTRATION OF BARITE IN AN EVAPORITIC ENVIRONMENT

RIASSUNTO. — Lo studio paleogeografico degli ambienti di sedimentazione delle «arenarie» e delle «dolomie rigate» cambriche del Sulcis Settentrionale (Sardegna) ha permesso agli Autori di individuare un orizzonte, localizzato in genere al passaggio «arenarie»-«dolomie rigate», con frequenti concentrazioni lentiformi di barite. Le litofacies che accompagnano questo orizzonte baritico sono rappresentate da arenarie a cemento dolomitico e dolomie di ambiente da intercotidale a sopracotidale. La deposizione del solfato è avvenuta in un ambiente evaporitico, probabilmente sopracotidale: l'orizzonte evaporitico è ora caratterizzato dalla presenza di lenti di barite a tessitura «zebrata», «chicken-wire» o massiva, di dolomie laminate di probabile precipitazione chimica ed infine modelli di minerali evaporitici (halite, anidrite ecc.) ora costituiti da barite, calcedonio, quarzo, dolomite.

Intensi fenomeni di silicizzazione diagenetica hanno interessato la fascia di contatto tra le arenarie e le dolomie («quarzite di contatto») e parte delle dolomie rigate stesse (selci) provocando la sostituzione dell'orizzonte solfatico. Infatti, sia nelle dolomie che nell'orizzonte evaporitico è possibile trovare ooliti, dolomie a lamine, dolomie con stratificazione incrociata, barite zebrata o chicken-wire ora completamente silicizzate. I minerali prodotti dalla silicizzazione sono rappresentati da megaquarzo, calcedonio ad allungamento negativo e calcedonio ad allun-

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(***) Lavoro eseguito con i contributi del C.N.R.: contratto di ricerca n° 7300069.05, intestato al Prof. Carmelo Maxia, e contributo del Centro Studi Geominerari e Mineralurgici del C.N.R.

gamento positivo; la presenza di questo ultimo minerale è ritenuta caratteristica di ambienti ad elevata salinità.

Lo studio dettagliato delle litofacies ha permesso la ricostruzione di un ambiente di tipo « piana cotidale », inondata periodicamente da maree e più sporadicamente da uragani. Piccoli bacini, separati da deboli rilievi, sottoposti ad intensa evaporazione permettevano l'evoluzione del chimismo delle acque verso una elevata salinità ed un elevato pH. Apporti dal paleocontinente di acque dolci, verosimilmente ricche di SiO_2, Ba e altri metalli, diluendo queste acque ad alta salinità, instauravano un ambiente « schizohalino » con neoformazione di dolomite. Contemporaneamente, o poco dopo, la silice e il bario sostituivano l'orizzonte evaporitico dando luogo alla « quarzite di contatto », alla selce e ai banchi baritici suscettibili, questi ultimi, di coltivazione.

Gli Autori concludono ritenendo tutto l'orizzonte di contatto « arenarie » - « dolomie rigate » del Sulcis settentrionale fortemente indiziato per mineralizzazioni di barite, qualora ricorrano gli stessi caratteri sedimentologici descritti in questa nota.

1. - Introduction.

The increasing interest in and detailed studies on modern evaporitic environments has lead to the recognition of many examples of such types of deposition in ancient geological sequences (Wood and Wolfe, 1969; Bosellini and Hardie, 1973).

When some barite depositions in the carbonatic facies of the Cambrian sequence in Sardinia (Italy) were first studied it was believed that there had been found an evaporitic environment of barite, dolomites and silica deposits, that had been more or less intensely transformed and masked by complicated phenomena of diagenesis, metagenesis and metasomatism (Gandin et al., 1973).

As these rocks are Cambrian in age it would be rash to make close comparisons with modern marine basins in work to achieve an exact paleogeographical interpretation of the evolution of the sediments.

Many factors have been taken into consideration in the course of the field and laboratory analyses; however this work is based on the following irrefutable data:

i) the presence in the rocks of the area of a sulphate (namely barite);
ii) the presence of unfossiliferous bedded dolomite, described everywhere as typical supratidal environment;
iii) the presence of algal flora typical of very shallow marine waters.

Many other factors, of course, have been used to give the most complete scheme possible of paleogeographic environments during Cambrian dolomite deposition in the Northern-Sulcis (Sardinia); among them there are:

— the close correlation between the barite layers and some dolomitic facies;

— the presence of barite pseudomorphing anhydrite;

— the cubic models of halite completely replaced by silica and barite;

— the frequent pinching out of barite layers, testifying the presence of small supratidal basins;

— the large diffusion of dolomite with algal mats, voids filled by calcite and barite, intraclasts, oncoids, peloids, ooids, etc.

At this point the reason for the presence of so much barite, since it is rather unknown in the modern sabkha or evaporitic basins, and for the absence of gypsum or anhydrite (Wood and Wolfe, 1969) might be raised.

The answer to this question is based soley on supposition. Without a doubt the middle Cambrian represents, not only in Italy but also in Spain and Morocco where are the closest outcrops of the same age, a period of supply of particular metals from the paleocontinent to the marine basins. Large quantities of lead, zinc, iron and barium have been weathered and carried out to sea where they have been precipitated according to various physico-chemical parameters.

These events are not unfrequent in the geological past; for instance the Middle Trias of Alpine facies is characterized, along several thousand kilometers, as is well known, by lead-zinc mineralization with local concentrations of copper, barite, iron etc.

A very important consequence of this study supports our idea about the genesis of barite in an evaporitic environment; a great amount of barite was discovered by following the above mentioned genetic markers. Thus it can be shown that detailed paleogeographical and sedimentological research over a relatively large area, made in the Cambrian dolomite of Italy for the first time, can form the basis for prospecting for sedimentary mineralization.

2. - Stratigraphic Scheme and Tectonic Setting.

The stratigraphy of Low-Middle Cambrian of Sardinia is well known from several papers (TARICCO, 1929; MAXIA, 1934; MINUCCI, 1935 a, 1935 b; PRETTI and TAMBURRINI, 1967, 1968; BRUSCA and DESSAU, 1968; COCOZZA, 1969; MCMOORE, 1969; ULZEGA, 1970; PADALINO et al., 1971; LEONE, 1973); unfortunately many of these papers outline the Cambrian geology for rather small areas and a general synthesis is still lacking.

In this paper the stratigraphy and tectonics of the region are briefly sketched in order to place the barite and « quarzite » layers in a general geological setting.

The area investigated includes almost the whole northern Sulcis area (fig. 1) which is the most southern part of Cambrian outcrops.

To the north, west and south the Cambrian outcrops disappear under the Cenozoic and Quaternary formations of the Cixerri Valley and the Sulcis Coal basin, while eastwards the Cambrian is partially covered by the Silurian transgression or metamorphosed by Hercynian granite intrusion. The oldest member, the base of which is not seen, is made of sandstones and siltstones; its age is Low-Middle Georgian.

These sandstones show prevalent angular to sub-rounded quartz fragments in sericitic cement; near the contact with overlying dolomites the cement is made up essentially of carbonate minerals.

Frequent sedimentary structures such as cross and current bedding, small slumpings, ripple-marks, mud-cracks are visible in this member (ANGELUCCI, 1970).

Lenses of dolomite and oolitic limestone appear in the higher part of the sandstones; in this part the cement is carbonatic and thin beds of barite may be present.

The « Metallifero » complex overlies the sandstones and siltstones; the age is Upper Georgian — Lower Acadian. This member which hosts the most important lead-zinc-barite mineralization of Sardinia, is made up by several types of carbonate facies; bedded dolomite with cherts and barite, is prevalent at the bottom (at least in the Sulcis district), whilst grey, massive dolomite and limestone are at the top.

The bedded dolomite — the « dolomia rigata » of Italian authors — includes detritic constituents at the base; these components decrease sharply upward.

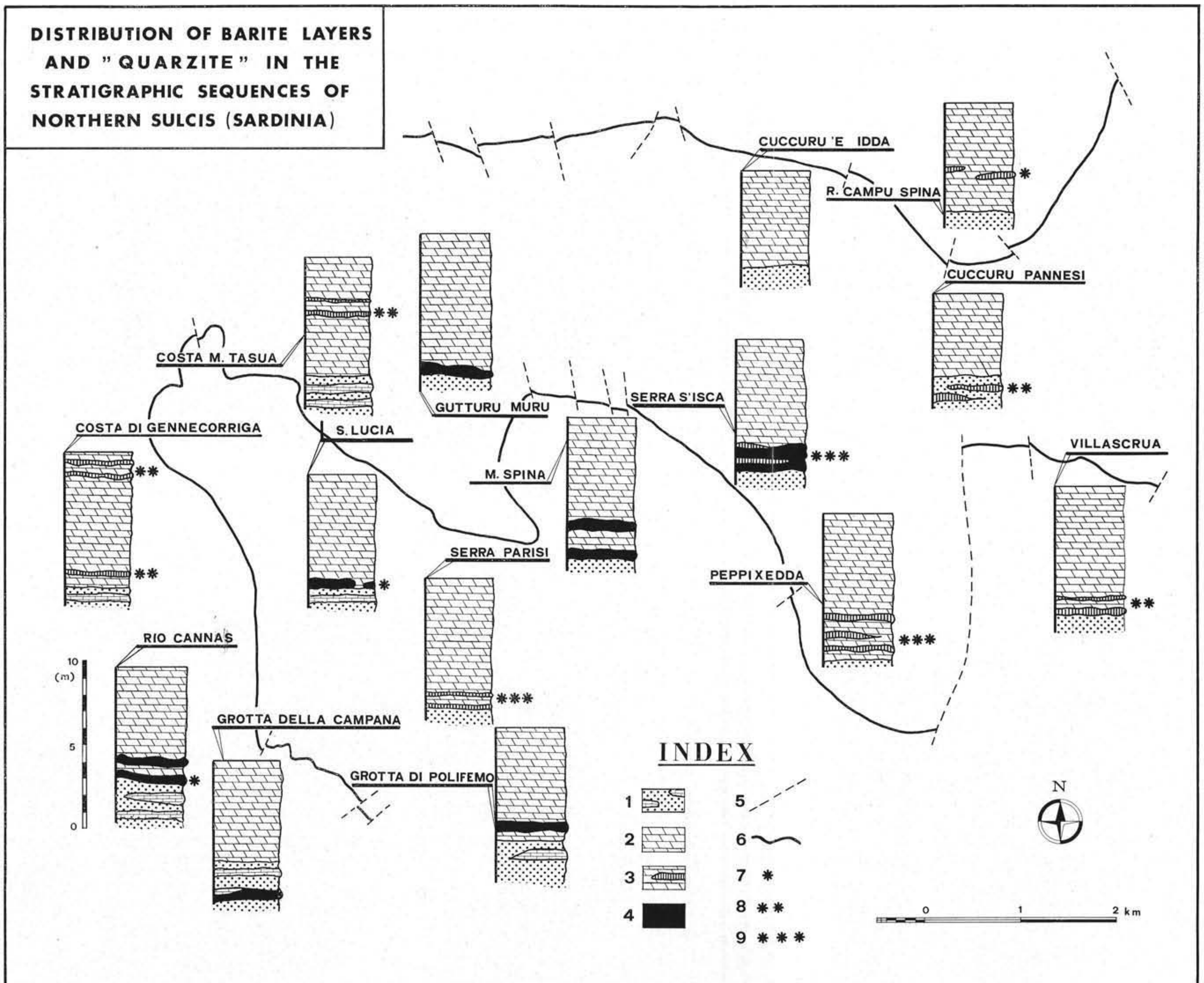


Fig. 11. — Index:

1) « arenarie » member.
2) « dolomie rigate » member.
3) barite layers.
4) « quarzite » horizon.
5) main faults.
6) boundary between « arenarie » and « dolomie rigate » members.
7) barite traces.
8) important barite traces.
9) barite exploitations.

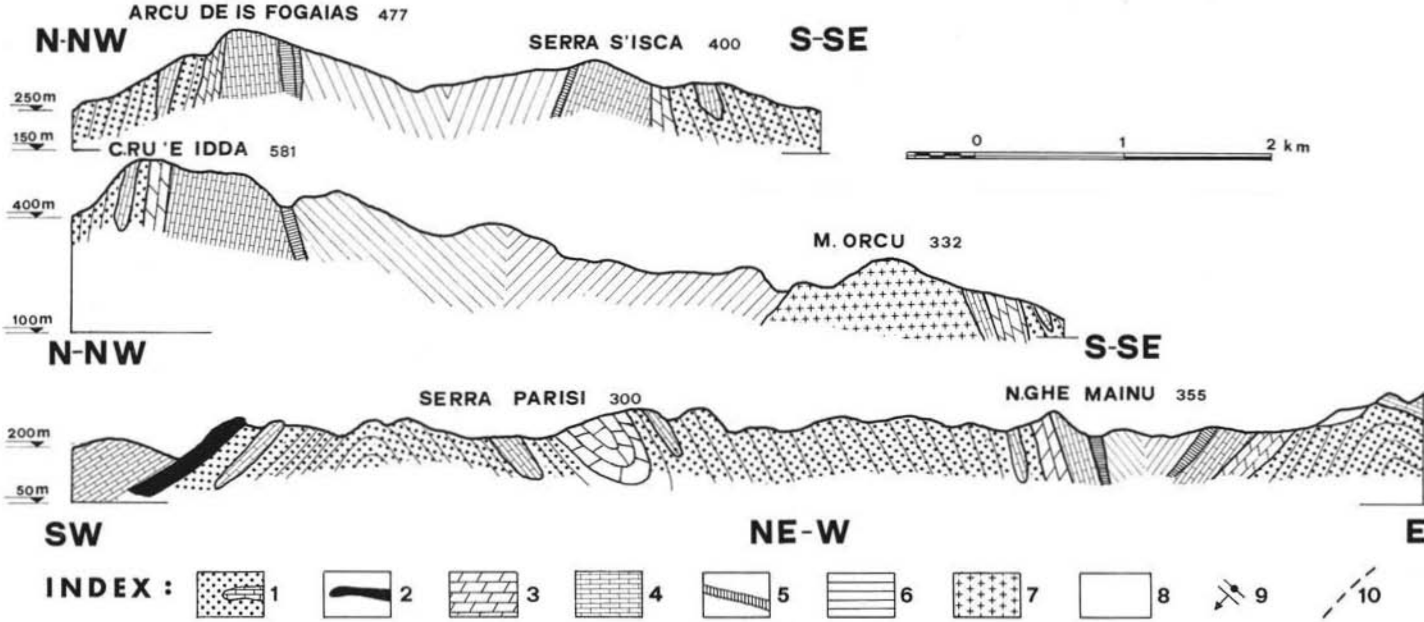


Fig. 2. — Cross-sections illustrating the main structures of northern Sulcis area; index:

1) « arenarie » member; sandstones and siltstones with interbedded dolomite and limestone bands.
2) « quarzite »; horizons of microcrystalline quartz and chalcedony with impurities of barite, carbonates, galena, pirite and iron oxides.
3) « dolomie rigate » member; homogeneous and laminated dolomite with chert levels. Frequent barite layers and nodules.
4) « dolomia grigia e calcare ceroide » member: massive, grey dolomite and fine-grained limestone with nodules and veinlets of galena and barite.
5) « calcescisti »; shaly limestone.
6) « scisti di Cabitza » member; slates and sandstones.
7) granite and differentiated facies.
8) post-Cambrian sediments.
9) strike and dips of strata (50°-70°).
10) main faults.

Large masses of silica (quartz and chalcedony) occur frequently along the contact between the sandstones and the bedded dolomite, replacing both the sandstones with carbonate cement and the dolomite with quartz clasts.

Barite and iron oxides are rather widespread in such chert and, as residual minerals, they mark extensive replacement.

The bedded dolomite as well as the chert nodules are the fundamental topic of this research and the various facies will be described in detail in the next chapter.

The « Metallifero » complex thickness, the sedimentary structures of dolomites and limestones and the metal content are variable through the Cambrian outcrops.

In the Northern area (Iglesiente district) the thickness of dolomites and limestone is about 700-800 meters; the basal dolomite hosts predominantly zinc-iron mineralization; the limestone is massive.

In the Southern area (Sulcis district) the thickness is strongly reduced, 80-100 meters; the basal dolomites prevalently contain barite; the limestone often shows thin bedding and intraformational breccias.

A thin horizon — 1/5 meters — of nodular shaly limestone (locally named « calcescisti ») overlies the « Metallifero » complex and marks the passage to Cabitza slates. This nodular limestone is very rich in fossils such as trilobites, hyolites, brachiopods and echinoderms.

The « scisti di Cabitza », siltstones with interbedded thin horizons of sandstones, are Middle-Upper Acadian and close the cycle of Middle Cambrian sedimentation.

Thin dykes of « diabase » cut the sandstones and dolomites; this rock is greatly modified now and formed by a mass of sericite, quartz, calcite, ankerite and iron oxides (as showed by X-ray analyses); however the ghost structures of plagioclase phenocrysts show clearly an intersertal texture (fig. 3).

Few kilometers eastwards the Ordovician unconformity covers the Cambrian sequence giving rise, along the transgression surface, to silicification phenomena (BENZ, 1964; POLL, 1966; PADALINO et al., 1972).

The tectonics of the Sulcis shows a very complex example of superimposed distinct phases of deformation; three orogenesis produced the present structural pattern; the Caledonian; the Hercynian, terminating in batholitic emplacement; and the Alpine limited to rifting and to the rejuvenation of old folds.

It seems that the folding in the Cambrian rocks can be ascribed to the early Caledonian phase — Sardic phase — followed by two strong and one weak Hercynian phases (Mc MOORE, 1969).

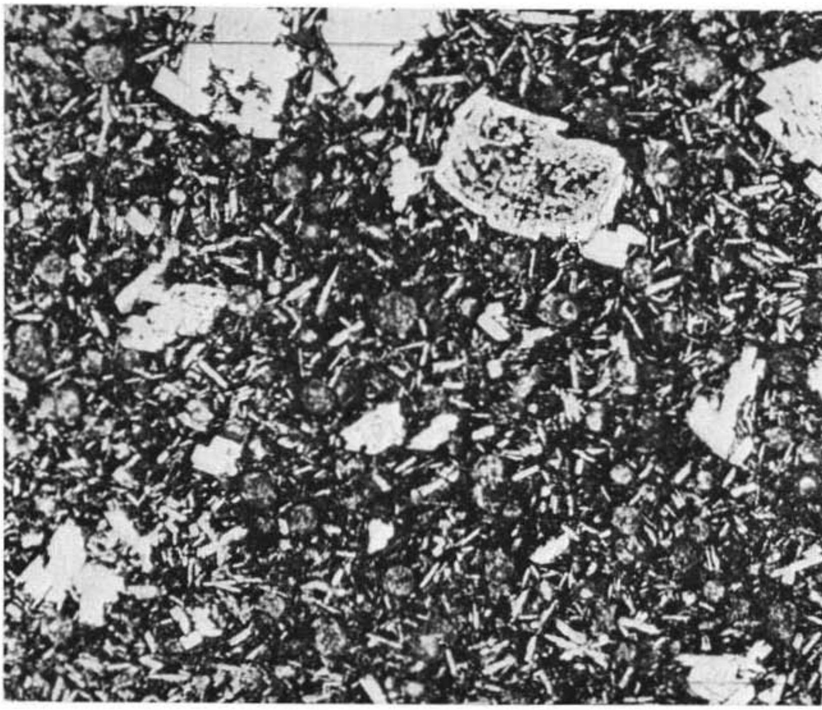


Fig. 3. — Diabase dike; well-formed plagioclase phenocrystals in an intersertal texture matrix. The rock is completely altered and only a ghost-structure is recognizable. Thin section; nicols //; × 10.

As is visible on the geological map and cross-sections, a system of folds with E-W trend is present; this trend is attributable to the Caledonian and first Hercynian phases.

The second Hercynian phase of deformation produced folds the axial surfaces of which trend N-S or N 30-40° W and which have extensively modified the preexisting structures (fig. 2).

The final (fourth) deformation phase has been identified in Sulcis by POLL (1966) as crenulation clevage and it seems less intense then the preceding ones.

Many authors have studied and described in recent years the tectonics and general structures of the Iglesiente-Sulcis district (VARDABASSO, 1956; ARTHAUD, 1963; POLL, 1964; VALERA, 1967; MC MOORE, 1969) and though they attached a different degree of importance to the influence of structure on mineralization, the fundamental tectonic outlines are sufficiently detailed.

3. - Lithofacies of Sandstone and Laminated Dolomite Members (Low-Middle Cambrian).

3.1. - SANDSTONE (« ARENARIE ») MEMBER.

The base of Middle Cambrian sequence is made up by sandstones of Low-Middle Georgian, as has been described in the preceding chapter.

Only the high part of « arenarie » member, the so called « alternanze » of Italian Authors was investigated. In fact the top of « arenarie » frequently shows dolomite layers and oolitic limestone lenses, sometimes very rich in *Acheocyathinae*.

The X-ray analyses of the sandstones showed mostly quartz and sericite, but the microscopic analyses of the mineralogical composition is a little more complex:

i) sub-angular quartz grains with weak blastic phenomena;
ii) small crystals of acid plagioclases;
iii) rare muscovite and biotite;
iv) small crystals of rutile, tourmaline and apatite as accessories.

The cement is essentially made of sericite or carbonate minerals near the contact with the dolomitic member.

The interbedded clayey levels show about the same chemical composition but only fine microcrystalline quartz and sericite are recognizable under the microscope. On the other hand the carbonate lenses are very rich in quartz fragments as are the first dolomite layers of « dolomia rigata » member; in such cases in fact fragments of sandstone or individual angular quartz are cemented by a dolomitic matrix.

This transitional horizon is present almost everywhere but sometimes it is completely silicified, thus giving rise to the so-called «quarzite » in which the dolomitic cement has been replaced by fine microcrystalline quartz and/or chalcedony.

Barite too may be present in the cement of sandstone or dolomite; but it is localized in the narrow horizon of contact.

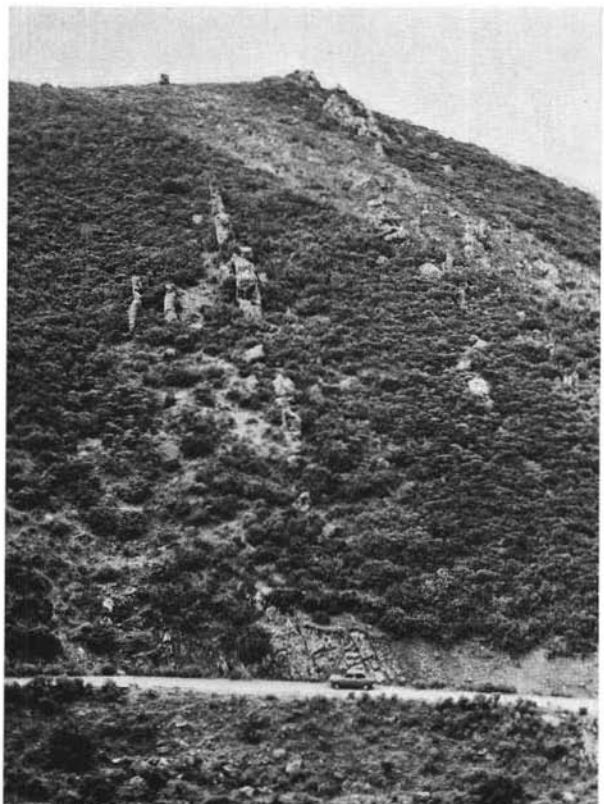


Fig. 4. — « Quarzite »; outcrops of « quarzite » along the contact between sandstones (at left side) and dolomites (at right side).

3.2. - Laminated Dolomite (« Dolomie rigate ») Member.

The « dolomie rigate » are present throughout the whole area and their thickness is rather variable from about 50 m up to 200 m; the changes in thickness are due both to stratigraphic and tectonic causes.

In the South-West and central part of the area the contact with the underlying sandstone is marked by the thick horizons of « quarzite » that shall be described later in the chapter devoted to silicification phenomena (fig. 4).

The more characteristic facies of « dolomia rigata » is a thin bedding with nodules of chert; but frequently the bedding, along with the chert, disappears and the dolomite is made up by dark fine grained dolomite.

All the lithofacies recognized on the field and by the microscopic studies and some of the more common sedimentary elements in such sediments, are hereafter described in detail. Then an attempt has been made to arrange the obtained data in an environmental scheme.

3.2.a) - *Dolomitic micrites.*

They are not very frequent in the dolomitic sequences. The matrix is formed of euhedral, more rarely anhedral grains with sizes ranging from 2.6 μ to 5 μ (with frequent 7 μ-8 μ grains).

In some cases laminae formed of ony one layer of tiny rounded clasts are found. In other cases they contain small rounded peloids and frequent cubic or polygonal pseudomorphs of halite crystals arranged in thin levels (fig. 5 *a*) or scattered at random in the matrix (fig. 6 *a*).

Fig. 5.

a) laminated dolomicrite with thin levels of halite cubic molds. Thin section; nicols //; × 4.

b) clear, homogeneous, laminated dolomite. The laminae show a weak grade-bedding; note the iron oxide concentration along the styolite seam. Thin section; nicols //; × 7.

c) « cloud-like » laminated dolomite. The dark micritic laminae are cracked by evaporitic nodule growth later replaced by chalcedony (white). Thin section; nicols //; × 4.

d) « quarzite » horizon; microcrystalline quartz laminae, appearing graded, with linear voids filled by megaquartz. To be remarked is the similarity with the homogeneous laminated dolomite (fig. 5 *b*). Thin section; nicols +; × 7.

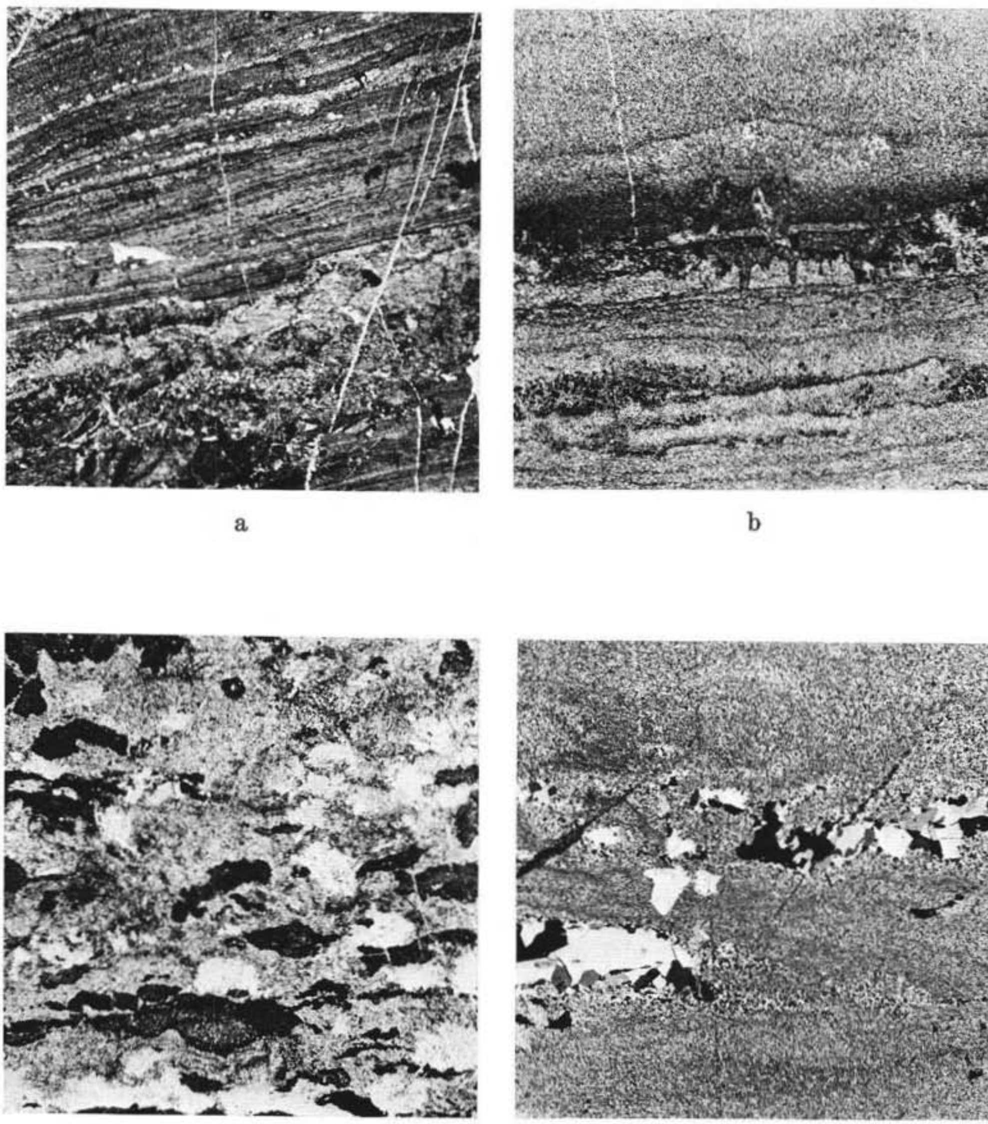


Fig. 5.

3.2.b) - *Laminated dolomitic microsparites and sparites.*

Numerous types of laminated dolomites have been grouped. The most common exhibit clear, homogeneous laminae (WOOD and WOLFE, 1969) or dark algal-mat lamination; while peculiar types made of « cloud-like » bands or of thin laminae, formed by radial, c-elongated dolomitic crystals (marine crusts of PURSER and LOREAU, 1973), are rather infrequent but interesting from a genetic point of view.

The first group is made of homogeneous fine-grained (size range of grains: 5 μ-30 μ) laminae alternating with coarse ones (size range of grains: 13 μ-38 μ). Sometimes a graded bedding texture seems to be present, but perhaps neomorphism has preserved the primary granulometry (fig. 5 *b*). Barite, filling the interstices between dolomitic grains like a cement, is often found in the coarse laminae.

The laminae ascribed to the algal-mat growth show a more or less wavy structure, sometimes with well evident *Renalcis* forms (fig. 6 *b*), often masked by recrystallisation.

The term « cloud-like » laminae has been attributed to structures given by discontinuous dark micritic (or fine microsparitic) laminae. They contain frequently halite pseudomorphs, and are alternated with clear, irregular, nodular layers constituted partially of dolomitic granular matrix, and partially of chalcedony with radially ar-

Fig. 6.

a) dolomicrite with peloids and halite molds. Thin section; nicols //; × 7.

b) irregularly dark laminated dolomite. Algal mat with *Renalcis* sp. in a void filled by sparry dolomite. A thin rim (clear) of acicular carbonatic crystals is bordering the algal and void walls. Thin section; nicols //; × 7.

c) dolomicrosparite with oncoids, intraclasts and peloids. Thin section; nicols //; × 7.

d) dolomicrosparite with peloids (« grumuleuse » structure) including a Trilobite fragment. Thin section; nicols //; × 100.

e) dolomicrosparite with peloids (« grumuleuse » structure) including an Echinoderm fragment with a micritized rim. Thin section; nicols //; × 100.

f) chert with alternated intraclastic and oolitic beds; the matrix is made up by microcrystalline quartz and length-slow chalcedony. Thin section; nicols //; × 4.

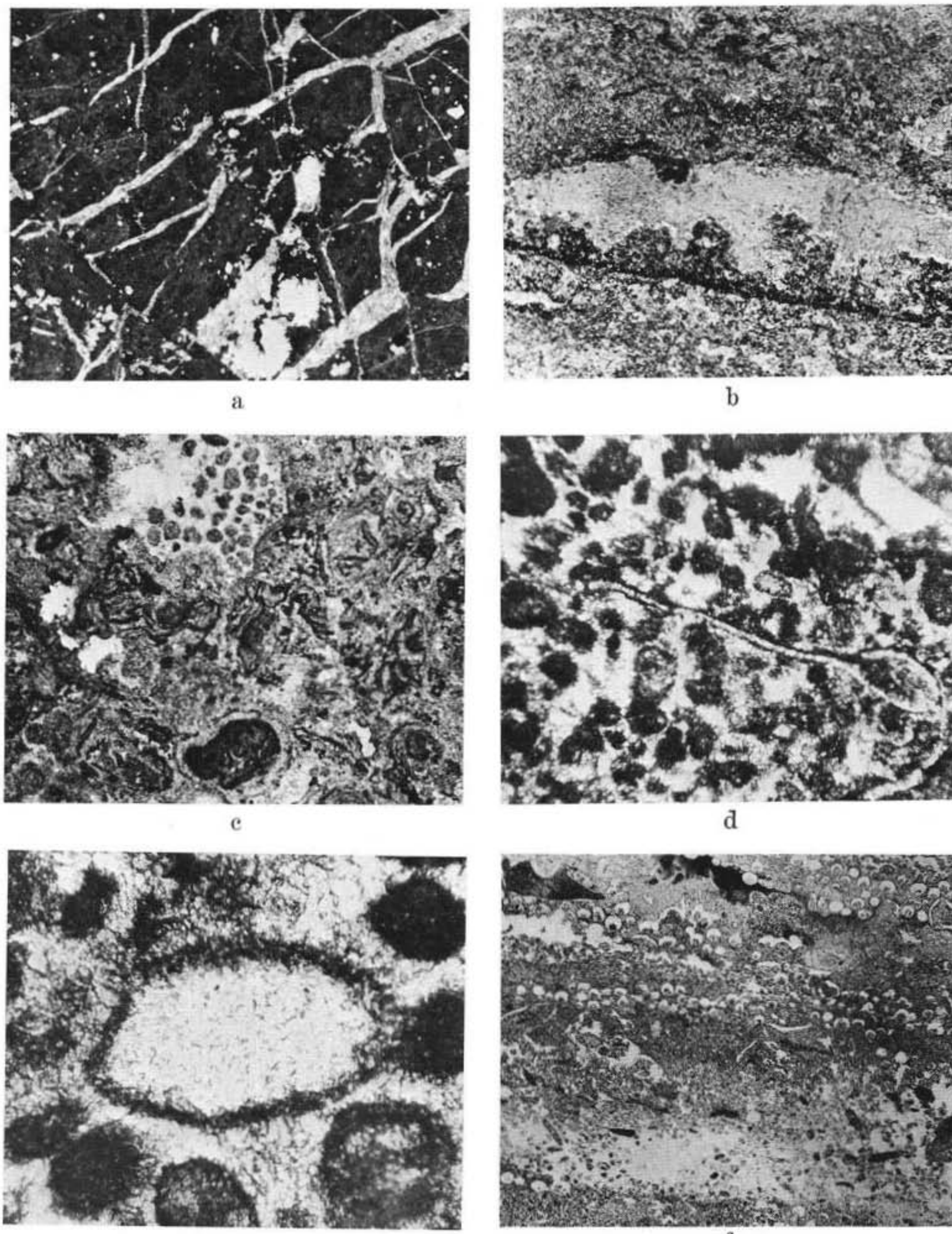


Fig. 6.

ranged fibers (fig. 5 *c*). Instead of chalcedony, in other cases, calcite, filling the voids with geopetal structure, is present.

The marine crust type lamination is formed by radial c-elongated dolomitic crystals; each row of them forms a lamina (36 μ in thickness). Pockets filled by peloids or concentric ooids alternate with such laminae (fig. 7 *a*). In some homogeneous microsparitic layers nodules of barite (fig. 13 *b*) are often present; cracking features, perhaps connected to evaporitic nodule growth, are also frequent in the overlying beds (fig. 8 *a*).

Quite different, though also constituted of crystal rows, are laminae each of which shows one layer of carbonate crystals (45 μ thickness) elongated normally to the bedding. They appear to have grown in mutual competition thus forming a crowded texture (fig. 10 *a*) very similar to the one illustrated by ARTHURTON (1973, *fig.* 2 *a*, 2 *c* and 2 *e*) for layered halite fabric. Laminae are commonly bent and sometimes cracked. Interlaminary voids and very frequent cubic or polygonal pseudomorphs (60 μ) of halite are present.

In the « quarziti » and some cherts can be found laminated textures due to the different sizes of microquartz crystals (fig. 5 *d*).

3.2.c) - *Microsparitic dolomites with intraclasts, oncoids, and peloids.*

The cement of these rocks is of two quite different types rarely associated: the first is formed by euhedral or polygonal dolomitic crystals (22μ-28μ), while the second is constituted by a felt of elongated needle-shaped crystals (fig. 10 *b*) (length 60μ-80μ; width 13μ $\sim$).

Irregular or rounded bird's eye type voids are frequent in the first type of cement. Alloclasts are represented by a few lumps, intraclasts, frequent irregular oncoids (fig. 6 *c*) and very common peloids with irregular shapes typical of the « grumuleuse » structure (BATHURST, 1971). Fossils, locally abundant, are represented by trilobite (fig. 6 *a*) and brachiopod fragments and well rounded micritized echinoderm particles (fig. 6 *e*).

Ooids are scarcely represented in dolomites, while they are very frequent and abundant in cherts.

This type of microfacies is probably also represented by oolitic cherts (fig. 7 *b* and 7 *c*). Here the allochems are only ooids and peloids, often well sorted, sometimes giving a graded texture. In such cherts secondary dolomite remains with frequent isolated empty or limpid dolomitic crystals are abundant.

3.3. - Sedimentary Elements of Microfacies.

The more common sedimentary elements found in the described litofacies are:

3.3.a) - *Ooids.*

i) Ooids with radial structure are generally of small size (520 μ-175 μ) (fig. 7 *b* and 7 *d*). The nucleii cannot be easily recognized because of the strong recrystallization; it seems however in some cases to be of micritic matter. The cortex has almost the some thickness as the radius of nucleus; it is composed of bundles of radial clear crystals alternating with dark ones which cross the whole cortex. Sometimes it is possible to recognize the ghosts of the former concentric envelopes now covered by the radial arrangement of acicular carbonate crystals. Some X-ray analyses on the carbonatic samples containing such types of ooids exhibit a small quantity of clay minerals (illite and montmorillonite types) that were not found in carbonate samples containing the other type of ooids.

The shape is generally uniformly rounded, sometimes elongated and with a lobate outline.

This type of ooid is found in some carbonate lenses interbedded to the « arenarie » and in some cherts of dolomites. The difference between the two groups is due to the different average size (400 μ in carbonatic lenses; 200 μ in cherts) and to the different diagenesis that masked the early structures much more in the cherts.

They are very similar in morphology to those described and illustrated by Eardley (1938) for the Great Salt Lake.

Eardley observes that the radial structure of these ooids is due to bundles of calcite crystals produced by an early recrystallization that takes place at the same time as the aragonite-calcite inversion of envelopes with microgranular structure.

The envelopes in a first stage consisted of concentric layers of aragonite and calcite crystal with occluded clay.

When the recrystallization takes place the clay is segregated in the region between bundles of radiating calcite crystals and so the ooids exhibit a pseudo-interference figure of the uniaxial type and a characteristic lobate outline.

Geographically such types of ooids are found only along some coastlines of the Salt Lake at a depth varying between 1 and 4 m (RUSNAK, 1960). Its salinity is seasonally very high in an environment with a rather high energy due to wave agitation.

ii) Ooids with concentric structure (size range $400\,\mu$-$115\,\mu$) (fig. 7 *a*). The nucleus generally is of a larger size than the cortex and has a microsparitic texture, perhaps formerly micritic. The cortex has a variable thickness and is formed by one or more concentric envelopes; each one consists of radially disposed crystals intersected by a very thin dark and opaque layer. Shape is generally rounded, sometimes elongated, but often the outer envelopes of the cortex are broken or corroded.

These ooids are found in pockets of marine-crust type dolomite. The sizes are variable and the absence of sorting may testify the *in situ* growth without persistant transportation.

This type of ooid can be compared in structure to that described by LOREAU and PURSER (1973), found in well protected environments of lagoons or intertidal flats of the Persian Gulf. The main difference is due to the bigger sizes and to the minor regularity of recent forms compared to the Cambrian ones.

Fig. 7.

a) concentric ooids with radial envelopes; they are interbedded in « marine crusts » formed also by radial, crystalline laminae: detail of fig. 8 *a*. Thin section; nicols //; × 30.

b) concentric ooids with ghosts of radial envelopes in chert. Thin section; nicols //; × 20.

c) half-moon ooids, strongly recrystallized and replaced by silica. Thin section; nicols //; × 20.

d) radial ooids, similar to Salt Lake ones in calcareous lenses of « arenarie » member. A strong recrystallization of nucleii is evident. Thin section; nicols //; × 20.

e) half-moon ooids (detail of fig. 7 *c*); an asymmetric nucleus made of euhedral dolomite crystals, perhaps with a little residual micrite (black), is visible. Thin section; nicols //; × 100.

f) as above with crossed nicols; the carbonatic nucleus is surrounded by microcrystalline quartz and length-fast chalcedony. Thin section; nicols +; × 100.

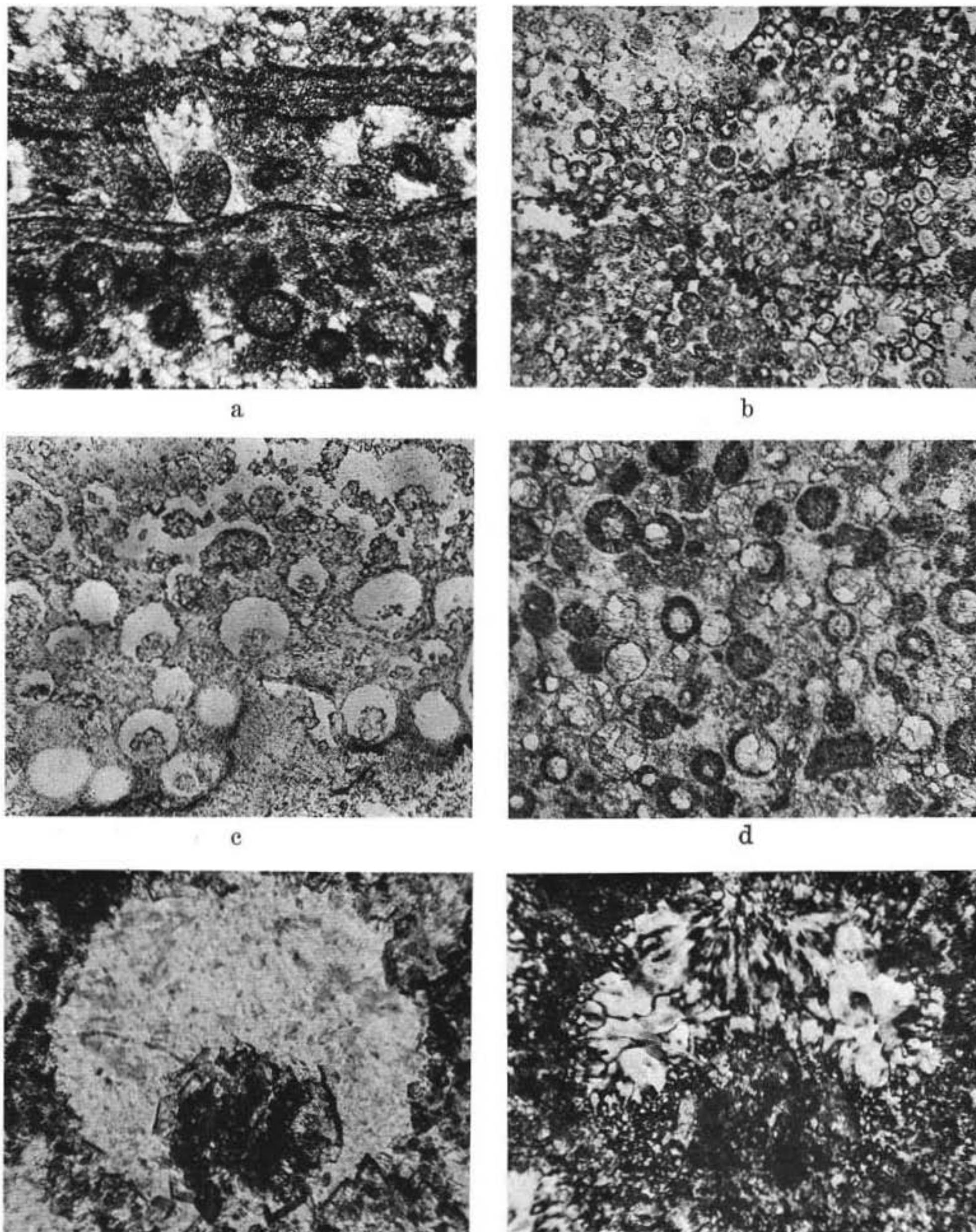


Fig. 7.

The environment in which these types of ooids are formed is localized near the limit between the inter- and supratidal zone « an environment which is more humid than wet » (LOREAU and PURSER, 1973).

It is very interesting to observe in this connection that such types of ooids have been found by PURSER and LOREAU (1973) in a well protected site associated with an aragonitic crust formed by laminae of 50 μ average thickness, very similar in structure to the ooid envelopes.

In some of the Cambrian samples small concentric ooids and coated grains with radial envelopes — in pockets and thin beds alternating with radially structured laminae — very closely recall aragonitic crusts found in the Persian Gulf supratidal flat. These crusts develop in a hot, arid supratidal environment where there is a hard substrate.

iii) The ooids of some cherts interbedded to the dolomites may seem different. Their texture has been very much modified by the diagenetic recrystallization and also by the silicification (fig. 6 *f*). However in some cases it is possible to recognize the typical concentric disposition of the envelopes but it is impossible to find the early disposition of the carbonatic crystals.

The sizes of these ooids seem bigger (600 μ-300 μ), than the others just described. The numerous forms showing the characteristic half-moon structure (fig. 7 *c*, 7 *e* and 7 *f*) seem to indicate a diagenesis similar to that suggested by CAROZZI (1963), that is a dissolution of the outer envelopes, but not necessarily the presence of sulphate envelopes, and a later filling of the voids by silica.

3.3.b) - *Fossils.*

Generally remains of animal organisms are very rare, less rare are those of algae, but these are often more difficult to recognize.

Animal remains are represented by rare fragments of trilobites (fig. 6 *d*), brachiopods and by frequent fragments of echinoderms well rounded and with evident micrite envelopes (fig. 6 *e*). One can find them generally associated in microsparitic facies, with peloids, some of which are possibly of algal origin, in the upper carbonatic levels interbedded to the « arenarie » or immediately at the base of the « dolomie rigate ». Algal remains are represented by algal mats produced by the activity of green-blue algae. Generally neomorphism tends to destroy the shape of colonies. Only rarely one can recognize small colonies of *Renalcis* sp. (fig. 6 *b*) or little bodies referred to as reproductive cells (Johnson, 1966) among peloids of algal origin. Very frequent are oncoids and « intraclasts » of which the origin is certainly partly ascribed to algal activity (fig. 6 *c*) (Gandin et al., 1973).

3.3.c) - *Voids and nodules.*

i) Bird's eye type, with a geopetal structure is present in laminated or intramicrosparitic dark dolomites. The filling is generally formed by first a calcitic (or dolomitic) rim, followed by sparry calcite and/or barite (fig. 8 *b*).

a *b*

Fig. 8.

a) laminated dolomite with nodules and beds of sulphate (barite: clear grey) and quartz (white). Some dolomitic laminae are broken by sulphate and quartz growth.

b) dark dolomicrosparite with intraclasts and voids. The voids are filled by calcite and barite.

When the rock is silicified (particularly the laminated type) the void filling carbonates too are replaced by silica (quartz). The voids of intramicrosparitic and irregularly laminated dolomite (algal mats) are rounded and more rarely arranged perpendicularly to the bedding. For the dolomites with flat laminae (also silicified) voids are generally linear (fig. 5 *d*). Sometimes there are also cracks of prism-crack type.

ii) Voids with sparry or siliceous filling without rims are sometimes associated with bird's eye structures whether in intramicrosparitic dolomites or in irregularly laminated dolomites. They generally have an irregular or a rounded shape; the filling is formed by sparry calcite (or dolomite), frequently by sparry or fibrous barite, and finally by silica with the megaquartz habit.

iii) Nodules with mosaic dolomitic (calcitic), microquartz or chalcedony filling can be recognized as void like structures, also associated with the other two types, in irregularly laminated microsparitic dolomites or in silicified rocks. The shape of these « voids » is sometimes well rounded, generally irregular; in this case it recalls a chicken-wire and chicken-mesh structure.

The filling is sometimes formed by a more or less regular mosaic of crystals (dolomite or quartz), sometimes by carbonatic needle-like felted crystals and sometimes by spherulitic chalcedony (fig. 16 *a*). In some cases one can observe that the outline of such « voids » is very similar to the outline of anhydrite crystals (MILNER, 1962). It is possible to assume that sulphate crystals or nodules have been replaced by carbonate, barite or silica matter.

The described structures of voids and nodules are summarized in Table I.

3.3.d) - *Intraclasts and intraformational breccias.*

Peloids, oncoids, lumps and irregular fragments of algal mats have been grouped as intraclasts of organic origin.

Among peloids some (size 60 μ ~) are similar to fragments or parts of algae which form algal mats (GANDIN et al., 1973), others (size 200 μ ~) well rounded made of micrite could be ascribed to the activity of organisms (foecal pellets ?).

The oncoid group also includes those irregular bodies which have more or less concentric coats produced partly, at least, by algal activity.

In some thin sections of « quarziti » and dolomites intraclasts derive from cracked laminae or crusts. Sometimes continuous laminae become discontinuous and finally become clasts. Cracked or bent laminae, which leave funnel-like voids, become filled by laminae or crustal fragments and sometimes barite (fig. 8 *a*).

TABLE I. — *Bird's eye Structures, « Voids » and Nodules.*

Morphology	Type of host rock	Rim	Filling	Sizes (in mm)
Rounded or irregular	Dark intramicrosparite	euhedral dolomite or calcite	calcite and minor dolomite and/or barite	3.5 × 2.3 0.6 × 0.3
« Sheet-crack » type	Dark and light irregularly laminated dolomite	as above	calcite	3.0 × 0.6 0.6 × 0.1
« Sheet-crack » type	« quarzite »	euhedral megaquartz	microquartz or absent	4.6 × 0.4 2.6 × 0.4
« Prism-crack » type	« quarzite »	as above	as above	3.0 × 0.2 4.0 × 0.1
Rounded or irregular	Dark intramicrosparite or laminated dolomite	absent	spathic calcite and/or barite and megaquartz	5.2 × 3.0 0.6 × 0.6
Rounded and irregular « Chicken-wire », « Chicken-mesh » types	Dolomicrosparite, cherts and « quarzite »	absent	granular dolomite, megaquartz and chalcedony	5.0 × 3.0 0.6 × 0.5

Monogenic intraformational breccias are not very frequent; thin beds seldom have dolomitic angular clasts cemented by microsparitic dolomite. The evaporitic layers also show thin brecciated levels but the origin in this case is different. The former is due to sharp variations of energy during the sedimentation which cause the cracking of sediment-water interface. The latter, on the contrary, may be due to the crystallization forces of sulphates that bend and break the overlying dolomitic laminae.

3.3.e) - *Evaporitic mineral molds.*

Molds of evaporitic minerals are very frequent both in dolomites and in the « quarzite » and cherts and they may be summarized as follows:

i) Cubic or polygonal molds of halite crystals are found mainly in micritic (fig. 9) or sparitic and « cloud-like » laminated dolomites. They are replaced by carbonates and very fine chalcedony giving a statistic isotropy (see LASER microanalyses). Their sizes range from 30 to 85 μ.

ii) Prisms of ex anhydrite are found mainly in the « quarzite » and in the cherts and only subordinately in the intramicrosparites.

In the first case they have been completely replaced by pseudomorph quartz and/or barite (fig. 13 *e*), while in the second case the prismatic molds are made of mosaic calcite or dolomite.

iii) Needle-like carbonatic crystals, very similar to those illustrated by FOLK and PITTMAN (1971), are rather frequent as cement or « void » filling and dispersed in some cherts (fig. 10 *f*). They may perhaps be the result of the replacement of gypsum nodule crystals.

3.3.f) - *Dolomite crystals.*

Euhedral crystals of dolomite occur chiefly in the chert nodules and, though more seldom, in the « quarzite ». Of course, the dolomite crystals, sometimes of poikilitic type, are frequently present in the dolomitic beds, but in the siliceous horizons they are isolated and can be grouped in different types:

i) euhedral clear unzoned crystals of small size (about 0.3 mm in length);

ii) euhedral clear zoned crystals sizes of which may range up to 1 mm of length (fig. 10 *c*);

iii) dolomitic ghost-crystals partially or completely replaced by microcrystalline quartz (fig. 10 *d* and 10 *e*) and chalcedony.

There is a gradual transition between the two last types, and particularly from the anhedral to the corroded or empty form remains.

Fig. 9. — Clear dolomicrite; detail of fig. 6 *a*. Cubic molds of halite, replaced by chalcedony and barite. Thin section; nicols //; × 200.

It would appear important to point out at least three facts:

— the corroded and empty remains are more frequent among the zoned crystals;

— this type of crystal is absent in the chert host-rocks (i.e. laminated and dark dolomites) which exhibit a different dolomitization;

— the silicification interrupted early dolomitization of sediments, probably in a schizohaline environment (Folk and Land, 1972), replacing preferentially the impur e core of crystals not yet dolomitizated (Dietrich et al., 1963);

— the dot-like remains (fig. 10 *e*) may be indicative of evaporite replacement by silica, according to the Folk and Pittman (1971) illustration.

3.3.g) - *Stylolites.*

Stylolitic structures are rather frequent in the laminated dolomites (fig. 5 *b*) and their amplitude and thickness are very variable.

In the field undulated surfaces of erosion, frequently marked by a ferruginous seam, are visible in the laminated dolomite; these structures may decrease progressively to the microscopic sizes, always maintaining the dark, ferruginous seam.

At the microscopic scale the more common patterns — according to the Amstutz and Park classification (Amstutz and Park, 1967) — are of wave-like and/or sutured type but also rectangular types may be present; along the same stylolitic seam gradual transition from one type to another may coexist.

As regards the bedding the horizontal stylolites are the most common type; the interconnected-network stylolites are rarely present and in this case they are parallel to the bedding.

About 40 thin sections of dolomite and chert facies containing stylolite structures have been examined and classified in Table II.

From the this table four facts stand out immediately:

i) the stylolites in the laminated clear dolomite are very poor in Fe, as well as the host rock;

Fig. 10.

a) bent laminae of dolomite crystals showing an unusual habit. The crowed texture is rather similar to that of a layered halite texture. Thin section; nicols //; × 100.

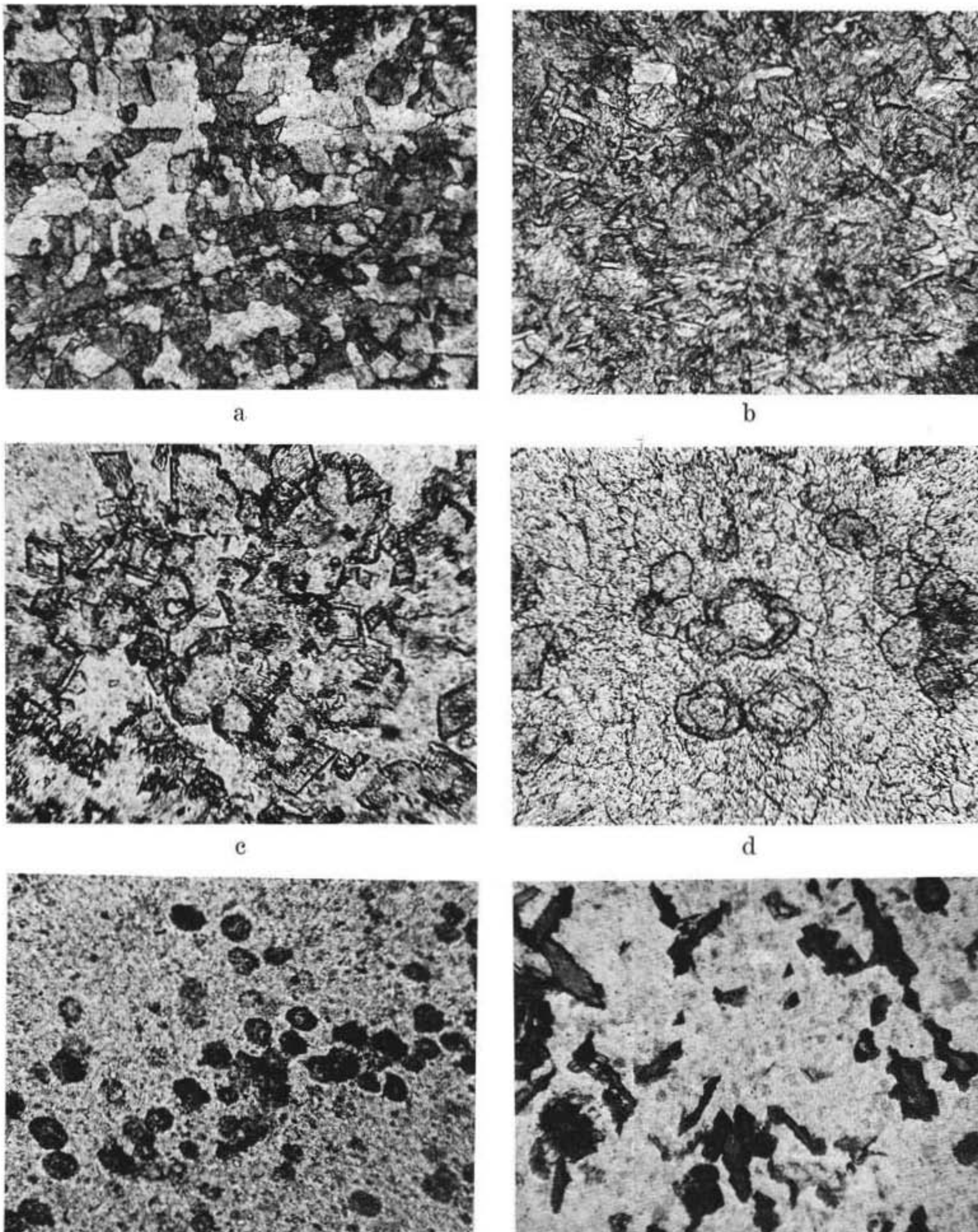
b) unusual habit of dolomite; needle-like crystals arranged as a felt in dolointramicrosparite. Thin section; nicols //; × 250.

c) dolomitization interrupted by silicification in chert; the euhedral crystals are mostly zoned but unzoned and limpid ones (at right) are also present. Thin section; nicols //; × 30.

d) ghosts of dolomitic euhedral zoned crystals in the microcrystalline quartz matrix of chert. Thin section; nicols //; × 250.

e) tiny dark « peloids » loosely distributed in chert, probably indicating a replacement of evaporites by silica. Thin section; nicols //; × 250.

f) needle-like dolomite crystals, perhaps pseudomorph on fibrous gypsum; the matrix is made of microcrystalline quartz and chalcedony. Thin section; nicols //; × 150.



a b c d e f

Fig. 10.

ii) the largest amplitude is present in the stylolites of laminated dolomicrosparite, while the weakest in the stylolites of homogeneous dolomicrite;

iii) the portions of rock dissolved during the stylolite formation seem to be higher in the laminated dolomites than in the oolitic. In the first case in fact, some stylolite fingers show residual laminated dolomite that is absent in the bedding, testifying the dissolution of at least one bed a few millimeters thick. In the case of oolitic dolomites, on the other hand, the oolites themselves indicate the amount of dissolved rock, which is less than one millimeter.

iv) the silicified dolomites, even though maintaining the stylolite structures, frequently show variable sizes and deformations of the seams (fig. 17).

The stylolite seams very frequently exhibit not only ferruginous bands but also perfect euhedral crystals of clear dolomite; these seams in fact represent loci of various mineralogical dissolution and recrystallization processes (AMSTUTZ and PARK, 1967; PARK and SCHOT, 1968) and the maximum of geochemical element variety is concentrated here (see 6.5. and Table IV).

3.4. - INTERPRETATION OF THE LITHOFACIES.

It is always rather difficult to interpret the environmental deposition of a geological sequence, especially when intense phenomena of neomorphism, dissolution and recirculation has altered the original textures.

These difficulties are particularly marked in ancient sediments of evaporitic type; in fact in the early diagenetic stages the sediments are subjected to different hydrological regimes with sharp variations of salinity, pH, temperature etc..

Nevertheless, an attempt has been made to develop an ideal scheme in which to arrange the Cambrian dolomites of the Sulcis area. The more common dolomite, the homogeneous laminated dolomite, is similar to those described as supratidal lagunar environment, for instance, small basins periodically flooded by fresh and marine waters; intense evaporation, modifying the water salinity, causes the chemical precipitation of the carbonates. This precipitation is hastened during dry seasons and slowed down by dilution of fresh and marine waters;

TABLE II. — *Relationships between Stylolite Type and Host Rock.*

Rock type	Stylolite type	Stylolite sizes in mm amplitude	length	Observations
Laminated dolosparite with oncoids	wave-like and sutured	0.05-0.7	0.2 -1	Small content of iron along the seam
Laminated dolomicrosparite	wave-like and sutured	0.1 -0.2	0.3	As above
Laminated dolomicrosparite	up-down peak and sutured	0.4 -0.6	0.08-0.1	
Homogeneous dolomicrosparite	wave-like	0.04-0.2	0.08-0.6	Variables sizes along the same styolitic seam
Homogeneous dolomicrite	wave-like	0.02-0.04	0.08-0.1	Large oxidized Fe bands. Halite models in the host-rock
Silicified sandy dolomite (« quarzite »)	wave-like	—	—	Intensely deformed
Silicified dolomicrosparite (« quarzite »)	wave-like and sutured	0.08-0.1	0.1 -0.5	Small content of iron along the seam
Contact dolomicrosparite-chert	sutured	0.4	0.4	Variable size of seam
Idem as the preceding one	sutured	0.1	0.2	

the result of this process is a laminated sediment with dark fine and clear coarse grained beds.

The intertidal environments, closely connected with the above mentioned lagoons, show also laminated dolomites, but in this case the rather irregular lamination is due to the presence of *Renalcis* type algae, giving rise to a more or less continuous algal mat.

The cracking of these algal mats produced clasts, part of which have been reworked and transported in different environments, thus forming the intraclast dolomites.

A problem is the interpretation of oolite facies genesis. Two main groups of ooids, of rather different origin, have been distinguished. The first one, recognized in the calcareous lenses of « arenarie » and in some chert levels, can be ascribed to a Salt Lake type (EARDLEY, 1938); this testifies an hyperhaline environment with rather high energy during the sandstone sedimentation.

The second group of ooids, similar to Persian Gulf lagoon type (LOREAU and PURSER, 1973), occurs in dolomites which could be the product of evaporitic crusts; these ooids may in fact grow in situ among these carbonatic crusts, in humid cavities subjected to intense evaporation.

The described environments, along with the particular hydrogeological regimes due to the mixing of fresh and marine waters, well explain the development of small evaporitic basins with sulphates and, though more seldom, halite precipitation. These environments may explain also related phenomena as well as the early dolomitization of carbonatic sediments, the forming of clear euhedral dolomite, connected to a « schizohaline » salinity (FOLK and LAND, 1972), and finally the silicification caused by protracted subaerial conditions and a more intense supply of silica from the continent.

4. - Barite mineralization.

4.1. - DISTRIBUTION OF BARITE LAYERS IN THE STRATIGRAPHIC SEQUENCE.

At first sight, the barite layers occur in a relatively narrow horizon; this horizon is included between the top of the « arenarie » member and the base of the « Metallifero » member (and namely of laminated dolomite).

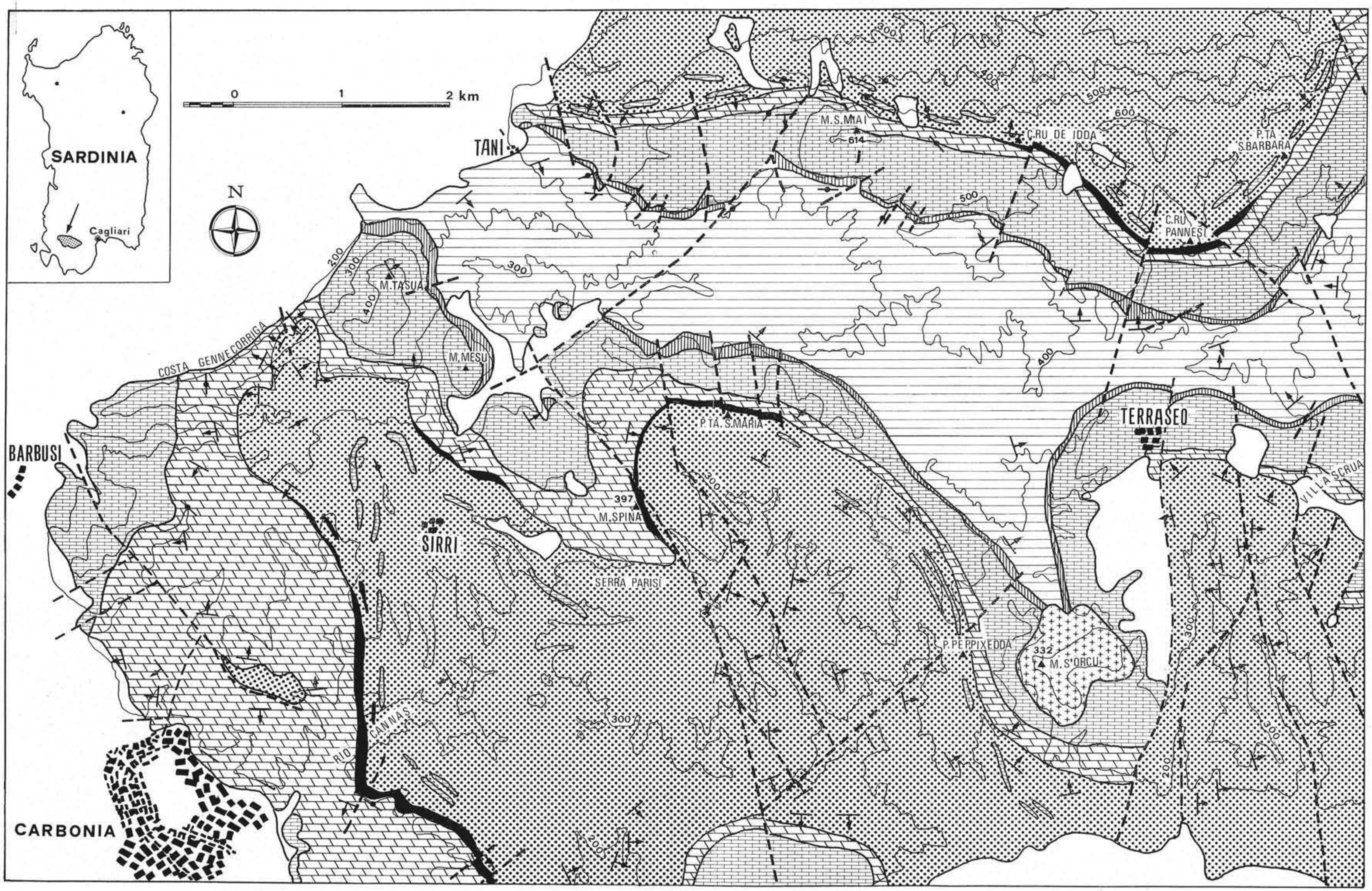


Fig. 1. — Geological map of Cambrian outcrops; index as fig. 2.

Entering into details, the occurrences of barite layers are rather different and this difference seems to be closely related to the geographic position of the outcrops.

In the Northern area (i.e. Cuccuru Pannesi and Campo Spina) the barite is present almost exclusively in the highest part of sandstones — or so called « alternanze » — where the sandstones exhibit limestone and dolomite interbedded lenses.

Only thin layers of barite mixed to dolomite occur in the laminated dolomite with chert nodules.

Southwards the barite mineralization increases greatly and many open casts for exploitation are present in different areas but always along the sandstones-dolomite boundary.

Fig. 11 shows the stratigraphic variations of the barite occurrence in different sequences. In the extreme eastern zone (Costa Tasua, Costa di Genna Corriga) the first barite layer (Genna Corriga) is localized in the dolomite, just above the contact with the underlying sandstones (about 1 m); other two barite layers outcrop 15-20 m above.

The thickness of this stratified barite is about 0.50 m and the content in $BaSO_4$ is sharply variable. In fact large masses of dolomite or thin nodules of chert, distributed at random along the baritic horizons, reduce the sulphate content.

Going east and southward thick « quarzite » horizons appear overlapping with the barite layers.

The petrographic characteristics of such masses of quartz and chalcedony will be described in 5.1.

Frequent nodules and veinlets of barite and iron oxides are present in this « quarzite » that assumes a typical reddish colour; where the rocks are less altered the colour is grey or dark grey and small crystals of pyrite are not unfrequent.

From the mining point of view the central part of the investigated area is the most interesting; in fact where «quarzite» disappears, thick and continuous layers of barite are present; in this area many small open casts have exploited several tons of barium sulphate in these last years (i.e. Serra Parisi, Serra S' Isca, Peppixedda, Villascrua, etc.).

As it is possible to note from the above mentioned figure 11 the stratiform exploitable barite is always localized along the contact sandstones-dolomites and only traces of sulphate as nodules, veinlets, birdeyes, filled up by barite and calcite, occur in the higher part of dolomite sequences.

Southward the « quarzite » assumes the maximum development; here in fact a continuous, thick horizon made of quartz and chalcedony marks the contact between sandstones and dolomites; even if this horizon (i.e. Grotta della Campana) is sometimes localized in the sandstones, nevertheless the distance of the «quarzite» from the contact is always very short, no more than 5-10 meters.

The development of « quarzite » marks the reduction of barite which is generally present only in small voids and/or veinlets in the quartz; but in such cases the traces of barite in the overlying dolomites are more abundant even if not interesting from an economic point of view.

4.1.a) - *Local scale.*

The barite outcrops show, on the field, several structures supposed to be connected with the different paleoenvironments during the diagenesis.

Nevertheless, in this chapter, are described the macro meso and microstructures of barite without any interpretation however, since these are mentioned in the general conclusions.

On the macroscopic scale the barite horizons may be characterized by at least three main structures:

i) « Zebral » barite.
ii) « Chicken-wire » barite.
iii) Massive barite.

The « zebral » barite occurs mainly at the bottom of mineralized sequences; in fact in the northern zone this type is present in the sandstone (i.e. Cuccuru Pannesi) and in the central area along and/or near the contact sandstones-dolomites (i.e. Villascrua, Peppixedda, Serra S' Isca, etc.).

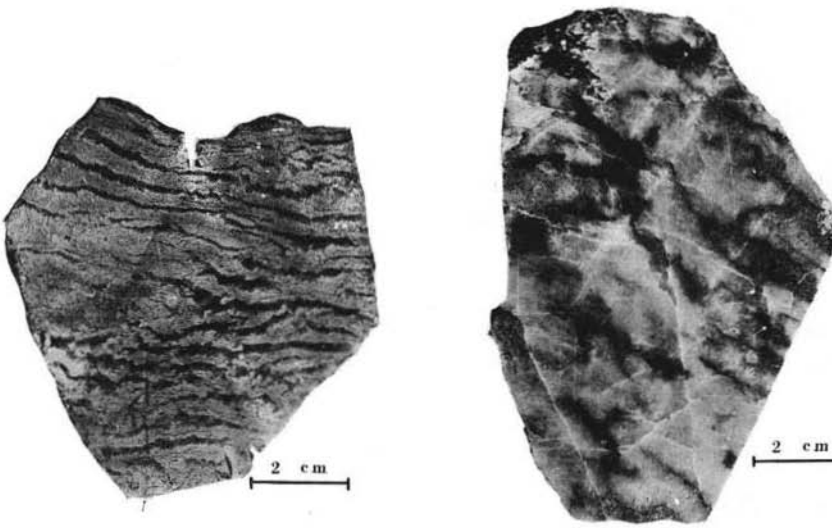
The only exception is the Genna Corriga sequence where the first barite layer exhibits a massive structure with rare starlets of galena and the upper ones tend to assume a « zebral » or « chicken-wire » structure.

When the barite layers are more than one (generally two or, but more seldom, three) they show both structures, namely the « zebral » and massive ones.

The « chicken-wire » structure may be present in the upper mineralized horizons and they may taper into massive barite beds with reduced thickness.

4.1.b) - *Handspecimen scale.*

As it has been previously remarked the barite shows a rather large range of structures.



a *b*

Fig. 12.

a) « zebral » barite; thin alternation of fibrous-radiated (dark) and fine-grained (clear) barite.

b) « chicken-wire » barite; nodules of barite (white) with a weak dolomite matrix (dark).

The « zebral » barite (fig. 12 *a*) may be made up by:

i) a thin alternation of fibrous-radiated and microcrystalline mosaic barite;

ii) thin beds of white barite and dark dolomite;

iii) thin alternations of barite and quartz.

The « massive » barite generally does not show any particular structure; but sometimes it may assume a rough « zebral » structure when the thickness is strongly reduced and it appears as thin bands of barite alternated with dolomite.

The « chicken-wire » barite (fig. 12 *b*) may be present both in the « zebral » barite and in the massive one. In the first case the parallel bedding changes to a progressive undulation of rhythms leading to the characteristic nodular structure. In the second case the « chicken-wire » structure may be recognized by the presence of a barite nodule parting due to a weak carbonate matrix.

4.1.c) - *Microscopic scale.*

On the microscopic scale the barite shows the widest variety of structures.

Figure 13 points out the different barite habits which occur in the same and/or different matrix.

As described previously, the « zebral » barite may be of different mineralogical compositions:

i) alternations of well shaped fibrous-radiated and microgranular barite (fig. 13 *a*). This type of mineralization, which is the best from a mining point of view, outcrops in the Serra Parisi open-cast;

ii) dolomicrosparite with oncoids including well crystallized fibrous-radiated barite (fig. 13 *b*);

Fig. 13.

a) well-shaped fibrous-radiated barite alternated to microgranular, mosaic barite. Thin section; nicols +; × 20.

b) nodules of fibrous-radiated barite in dolomicrosparite with crusts and ooids. Thin section; nicols +; × 20.

c) alternations of fibrous-radiated barite and mosaic quartz. Thin section; nicols +; × 20.

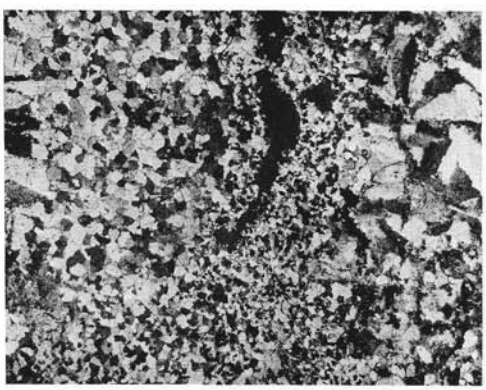
d) mosaic barite. Thin section; nicols +; × 150.

e) « quarzite » horizon; euhedral prisms of barite pseudomorph anhydrite. The matrix is made up by microcrystalline quartz and chalcedony. Thin section; nicols //; × 250.

f) « quarzite » horizon; anhedral barite surrounded by well-crystallized quartz; the matrix is fine, microcrystalline quartz and chalcedony. Thin section; nicols //; × 250.


a


b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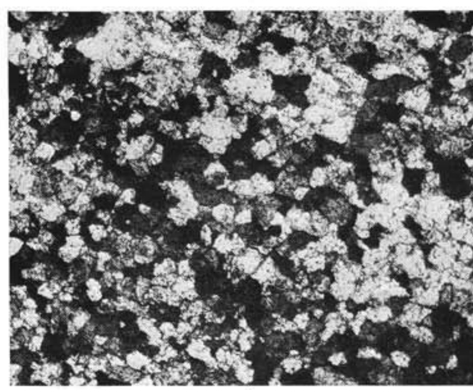
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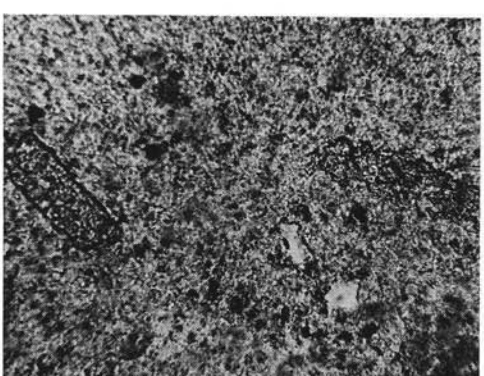
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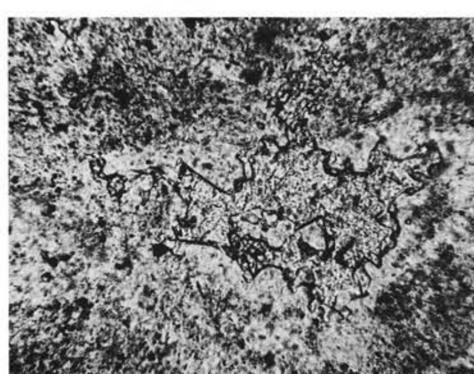

f

Fig. 13.

iii) thin alternations of fibrous-radiated barite and microcrystalline quartz (fig. 13 *c*). Such a structure is very similar to the first one apart from the presence of quartz instead of microgranular barite.

The massive barite may exhibit different habits in connection with the content and type of matrix:

i) large, euhedral poikilotopic barite with inclusions of euhedral crystals of dolomite;

ii) mosaic barite with small quantities of microcrystalline quartz and chalcedony (fig. 13 *d*).

Such a type of mineralization shows a high barium sulphate content and it is localized just along the contact with the underlying sandstones (i.e. Serra S'Isca open cast).

The « quarzite » contains some traces of different shaped barite:

i) euhedral prisms dispersed into microcrystalline quartz (fig. 13 *e*). The shape of these prisms suggests the presence of anhydrite subsequently replaced by pseudomorph barium sulphate;

ii) anhedral barite surrounded by megaquartz into microcrystalline quartz and chalcedony matrix (fig. 13 *f*). In this case a phenomenon rather similar to void filling appears to occur.

Later many different microscopic barite structures shall be arranged in a general outline, taking into account the complex phenomena of diagenetic recirculation and replacement.

5. - Silicification and Remobilization Phenomena.

The presence of large masses of silica (quartz and chalcedony), the genesis of which has been under discussion for a long time, has been frequently outlined during the field and laboratory analyses.

Detailed studies have lead to the recognition of at least two main groups: the « quarzite » and chert levels (fig. 14).

5.1. - « Quarzite ».

The stratigraphic column (fig. 20) shows the presence of such « quarzite » just at the top of the « arenarie » member (« alternanze » of Italian authors); but the maximum development is localized along the « arenarie »-« dolomie rigate » boundary.

The « quarzite » horizon may laterally disappear or interfinger with barite layers; in the transition zone, the occurrence of « zebral quarzite » (fig. 15 *b*) exactly simulating the zebral barite, is rather infrequent, but extremely significant.

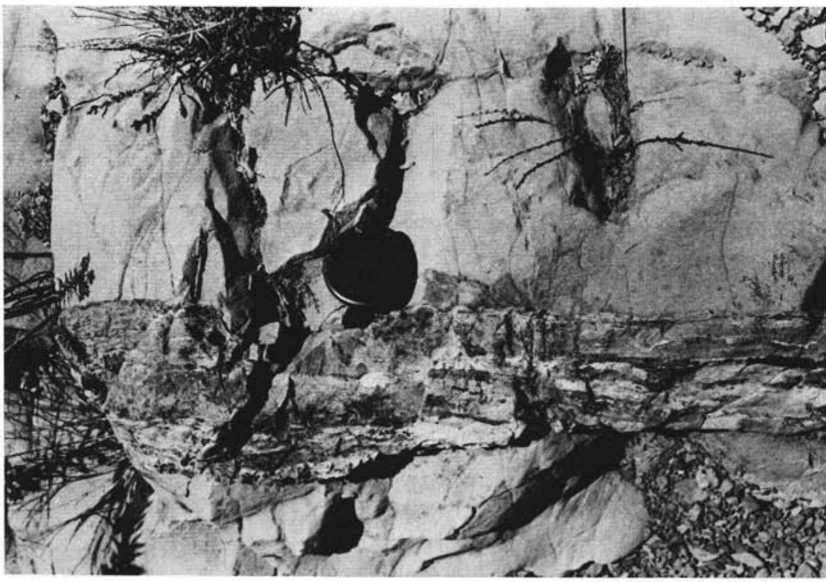


Fig. 14. — Chert level in clear, homogeneous laminated dolomite.

When the « quarzite » is absent the contact between sandstone and dolomites is marked by the presence of arenaceous dolomites as described in 3.1.

In the field the « quarzite », near the contact with the sandstone, appears schistose-like with clay and iron oxide impurities; going towards the dolomites the appearance is massive, clear and with the same lamination of dolomites (fig. 15 *a*).

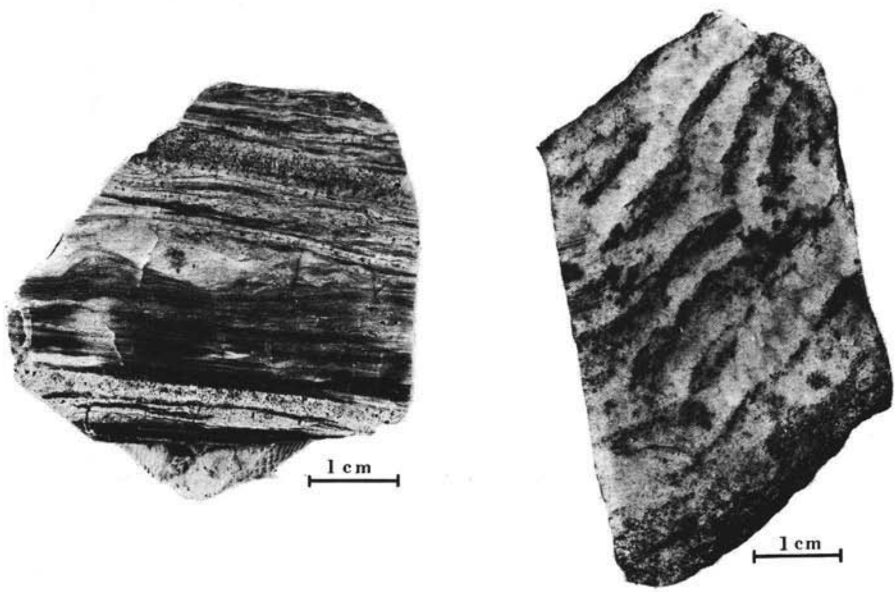
On the microscopic scale further observations may be noted:

i) the presence of detritic constituents in the lower « quarzite » levels. The texture of this type is very similar to that of dolomitic sandstone belonging to the transition horizon.

The quartz clasts show a weak growth edge (fig. 16 *a*) while the matrix is made of microcrystalline quartz, nodules of barite and less frequently chalcedony;

ii) the absence of a detritic constituent in the higher « quarzite » which appears laminated by alternation of micro- and mega-quartz laminae. Sheet-crack and prism-crack type voids filled by euhedral quartz are rather frequent;

iii) the « quarzite » interbedded with barite lenses contains a great amount of length-slow chalcedony nodules (fig. 16 *b*).



a *b*

Fig. 15.

a) « quarzite » horizon; structure simulating the laminated dolomite made of microcrystalline quartz with voids and sheet-cracks.

b) « quarzite » horizon; structure simulating the « zebral » barite, made of fibrous radiated and microcrystalline quartz.

5.2. - Cherts.

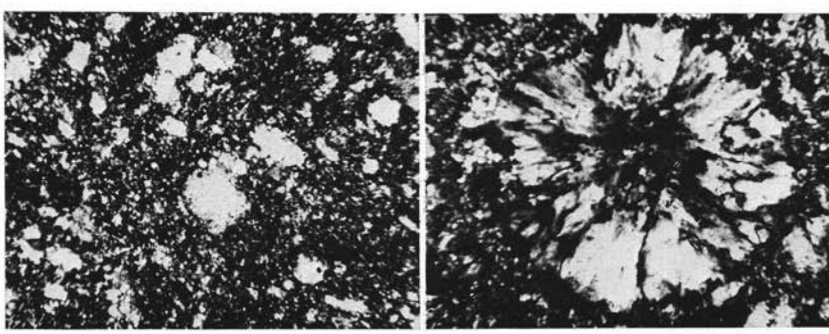
Chert is distributed through the whole dolomitic sequence; lenses and thin beds are the most common features (fig. 14). Despite being so widespread the chert levels are almost exclusively associated with the clear laminated homogeneous dolomites.

However, one can find chert interfingering with barite lenses; in such cases the thickness of chert is rather high, up to one meter. When the sulphate is absent its thickness may be reduced to few centimeters. Microscopic observations gave the following data:

i) the presence of a continuous oolitic level with ghost structures of cross-bedding. Sometimes the ooids are of half-moon type (fig. 6 *f* and 7 *c*); these ooids show an asymmetrical nucleus of euhedral dolomite, and a rim of microcrystalline quartz surrounded by length-fast chalcedony (fig. 7 *e* and 7 *g*);

ii) the chert with barite are made up by microcrystalline quartz and length-slow chalcedony;

iii) very small inclusions of barite crystals are visible, at high magnification, in the quartz of these chert levels. Sphalerite is also found in such cherts, but its presence is rather infrequent.



a *b*

Fig. 16.

a) « quarzite » horizon; fragments of quartz with a weak growth edge in a matrix of microcrystalline quartz and barite. Thin section; nicols //; × 150.

b) « quarzite » and barite horizon; nodules of length-slow chalcedony in a matrix of microcrystalline quartz, chalcedony and barite. Thin section; nicols +; × 150.

5.3. - Remobilization.

The described silicification phenomena produced, during the diagenetic stages, the partial dissolution of evaporitic and carbonatic minerals. As described previously in 4.1 the reworked barite, filling voids and diagenetic veinlets, is more abundant in the dolomites lying on « quarzite » horizons. One may hypothesize a progressive and partial replacement of evaporitic seams by silica and a subsequent removal of barium cations, thus modifying the chemistry of basin waters. This process may be recognized in the « quarzite » interfingering with barite levels, where small veinlets of barite, starting from the residual not-replaced barite, cut the microcrystalline quartz matrix and the stylolites (fig. 17).

Fig. 17. — « Quarzite » horizon; small veinlets of barite (grey) cutting a stylolitic seam (black). The matrix (clear) is made of microcrystalline quartz, chalcedony and residual nuclei of barite. Thin section; nicols //; × 120.

Remobilization of carbonate minerals is mostly developed in « shrunken oolites » of cherts. In this case the concentric carbonate envelopes have been dissolved and the holes filled by microcrystalline quartz and later length-fast chalcedony. This paragenetic sequence: microcrystalline quartz — length-fast chalcedony should be the result of a variation from very high to high silica concentration, according to Folk and Pittman (1971).

5.4. - Possible Scheme for the Interpretation of the Origin, Removal and Precipitation of Silica.

At least three factors are required to explain the silicification phenomena in the investigated area, as well as in the whole Sardinian Cambrian sequence:

i) origin of the silica;

ii) removal of silica;

iii) environment of silica deposition.

Regarding the first of these, two possible origins for the silica could be speculated upon: the silica may be due to submarine volcanic emanations or secondly due to silicate hydrolysis of continental rocks.

This second hypothesis seems the more likely and in accordance with the field observations.

In fact the thickness of the « arenarie » member, of which the base is unknown, is so great as to conceive a paleocontinent of granite-type rocks, subjected to weathering for a long time. Large masses of rock could be dissolved and carried away into solution and/or suspension; in this way silicate hydrolysis may lead to silica and aluminium removal.

Furthermore the hydrolysis phenomena may produce the cation freeing as Ba, Pb, Zn, Fe, perhaps distributed at the geochemical level in the lattices of the main rock constituents.

The absence, in the « quarzite » and cherts, of siliceous organic remains may confirm once again the inorganic origin of such deposits.

The mode of silica removal is one of the most debated geochemical and geological problems. An understanding of the silica behaviour in the fresh and marine waters must consider the different ways in which the silica is transported in natural waters, by true solutions and by adsorption on clay particles. Both these types certainly occurred during the silica removal towards Cambrian sedimentation basins. At the beginning, the presence of clay particles or small, detrital components can be hypothesized; these might play an important role for adsorption phenomena. Their presence is testified not only by the detrital quartz in the « quarzite » but also by the occurrence of small quantities of Al revealed by X-ray and Laser analyses (see 6.5).

On the other hand the evaporitic environment with high pH (perhaps more than 9) and relative high temperature could produce an increase in the silica solubility (OKAMOTO e Al., 1957).

The described pattern allows an easy explanation of the precipitation of silica. The fresh waters, probably flowing on the paleoreliefs, carried into the basins the silica in colloidal and true solution forms. The mixing with marine waters and the weak presence of Al cations caused the deposition of colloidal SiO_2 (KRAUSKOPF, 1959, 1967).

The behaviour of silica in true solution, entering in an evaporitic basin, depends on the alkalinity of the waters; the solubility increases abruptly because of ionization of H_4SiO_4. In this way a chemical precipitation of length-slow and/or fast chalcedony might occur. This type of deposition is more frequent in the top of the « quarzite » horizon and in the chert levels, where the detrital components are almost absent.

The circulation of silica rich waters, during the early diagenetic stages, caused the dissolution of microsparite and micrite, interrupting the dolomitization process but preserving the euhedral zoned dolomite crystals (DIETRICH et al., 1963).

This phenomenon may be produced by small pH changes of the order of 8.5-9; thus when the pH decreases the carbonate solubility increases and viceversa and the simultaneous dissolution of carbonates and deposition of silica takes place (KRAUSKOPF, 1959).

6. - Geochemistry.

During the field work samples for geochemical purposes were collected, specifically avoiding the mineralized and altered outcrops.

More than one hundred rock samples have been analysed for Ba, Pb and Zn.

The barite layers were neglected, information being required only on the geochemical behaviour of Ba, Pb and Zn in the different members.

In this chapter, the geochemical results shall be compared with previously published data from the Iglesiente area.

6.1. - Experimental.

The rock samples — about 50-100 grammes of the freshest rock possible — were ground mechanically in an agata mortar. The powders were treated differently for Ba and Pb-Zn; the former by sodium carbonate fusion and the latter by aqua regia dissolution.

After filtering, water-leaching and acidification (HCl) the obtained solutions were analysed by a Perkin-Elmer mod. 303 atomic absorption spectrophotometer with a digital concentration readout accessory (DCR-1).

The samples showing very high concentrations and the low-mineralized facies have been verified and analysed both by X-ray and by the usual chemical methods.

6.2. - Results.

The results obtained on about 100 samples are given in fig. 18 *a* and 18 *b*. Two facts are, at first, available from Ba diagram:

i) the very high Ba concentration throughout the whole sequence i.e. in the « arenarie » including carbonatic lenses, in the « quarzite » and in the « dolomie rigate » including the chert levels;

ii) the hghest Ba concentration is localized in the « quarzite »; this agrees with the preceding observation regarding the evaporitic origin of this horizon. On the other hand, Zn is more concentrated in the « dolomie rigate », but its content is very low, at least by comparison with other parts of the Iglesiente-Sulcis area, where the « dolomie rigate » show a mean higher than 1000 ppm of Zn (Violo and Zuffardi, 1971).

Lead has not been included on the general diagram of the means because the values are highly variable and generally lower than instrument sensitivity which is, in this case, about 20 ppm.

As can be seen from the geological map the sequence studied shows a sandstone-dolomite contact with interbedded thick layers of « quarzite »; nevertheless this « quarzite » is absent over a large part of the area. During the geochemical investigations a strong difference was noted in the Ba values; thus the data coming from sequences with and without « quarzite » were differentiated in two mean-diagrams.

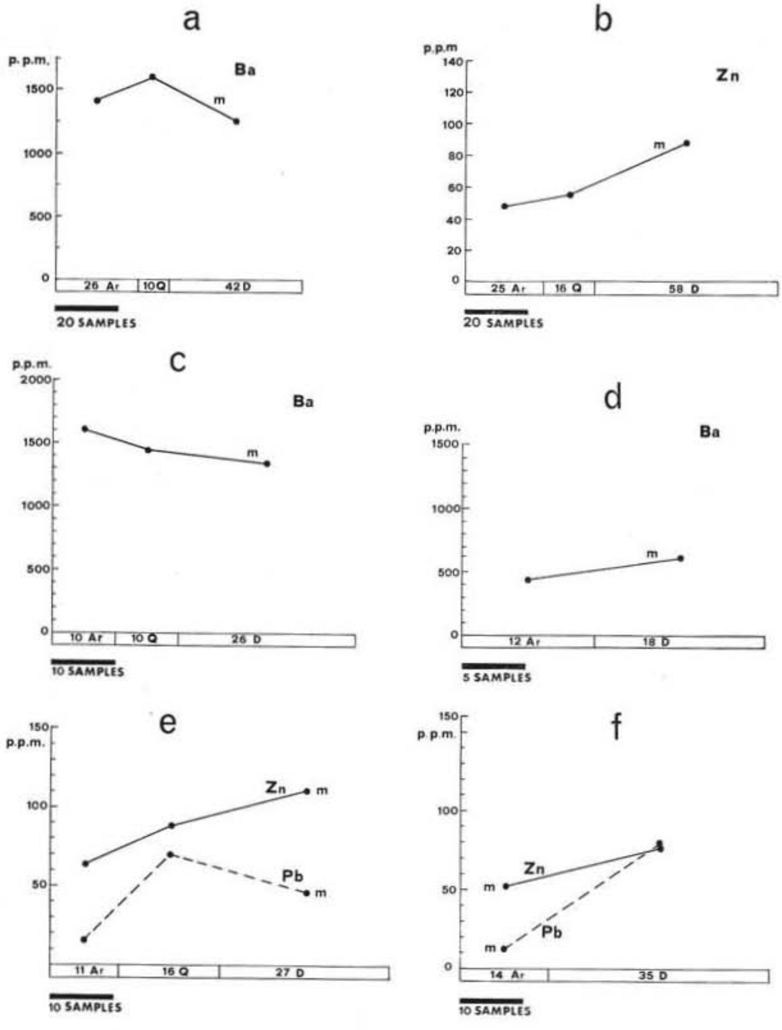


Fig. 18.

a) and *b*) diagrams representing the mean (m) distributions in the « arenarie » (Ar), « quarzite » (Q) and « dolomie rigate » (D) members of Ba (a) and Zn (b).

c) and *d*) diagrams representing the Ba mean (m) distributions in the sequences with (c) and without (d) « quarzite » horizon.

e) and *f*) diagrams representing the Pb-Zn mean (m) distributions in the sequences with (e) and without (f) « quarzite » horizon.

Diagram *c* of fig. 18 outlines the variation of the Ba mean in the general sequence « arenarie »-« quarzite »-« dolomie rigate ». A comparison with the preceding diagram (fig. 18 *a*) shows, in the latter diagram, that the Ba content in the « arenarie » is higher than in the « quarzite » and « dolomie rigate ».

Diagram *d* of fig. 18 shows instead the Ba mean in the sequence « arenarie »-« dolomie rigate »; in this case the Ba content in the « arenarie » is lower than the general Ba mean in all the sandstones.

The Ba mean of « dolomie rigate » does not show any significant variation.

Diagram *e* points out the Zn and Pb mean variations in the general sequence « arenarie »-« quarzite »-« dolomie rigate ». Zinc — see also the next diagram (fig. 18 *f*) — always shows an affinity with the dolomites while the Pb is more concentrated in the «quarzite» horizon.

The last diagram (fig. 18 *f*) made of the Pb-Zn mean of « arenarie »-« dolomie rigate » general sequence confirms once again the relative trend of Pb-Zn to the biostatic rock and namely dolomites.

6.3. - Correlation coefficient.

An attempt to calculate the *r* — correlation coefficient — of the couples Ba-Zn, Ba-Pb and Pb-Zn in the different members was made.

The formula used was.

$$r_{xy} = \frac{\dfrac{\Sigma(x-\bar{x})(y-\bar{y})}{n-1}}{\left[\dfrac{\Sigma(x-\bar{x})^2}{n-1}\cdot\dfrac{\Sigma(y-\bar{y})^2}{n-2}\right]^{1/2}}$$

(from Koch and Link, 1971).

Four facts appear to be rather meaningful:

i) the positive correlation between Ba and Zn in the « arenarie »;

ii) the positive correlation between Ba and Pb in the « quarzite »; the coefficent is high enough to be significant in spite of the reduced number of pairs;

iii) the independence of Pb and Zn in the « quarzite »;

iv) the positive correlation between Pb and Zn in the « dolomie rigate »; in this case the low correlation coefficent — 0.27 — is significant because of the relative high number of pairs.

The other correlation coefficents are not significant because the low values of the r_{xy} and/or the pairs give a large band of indetermination (LIORZOU, 1957).

The following Table III gives the obtained results:

TABLE III.

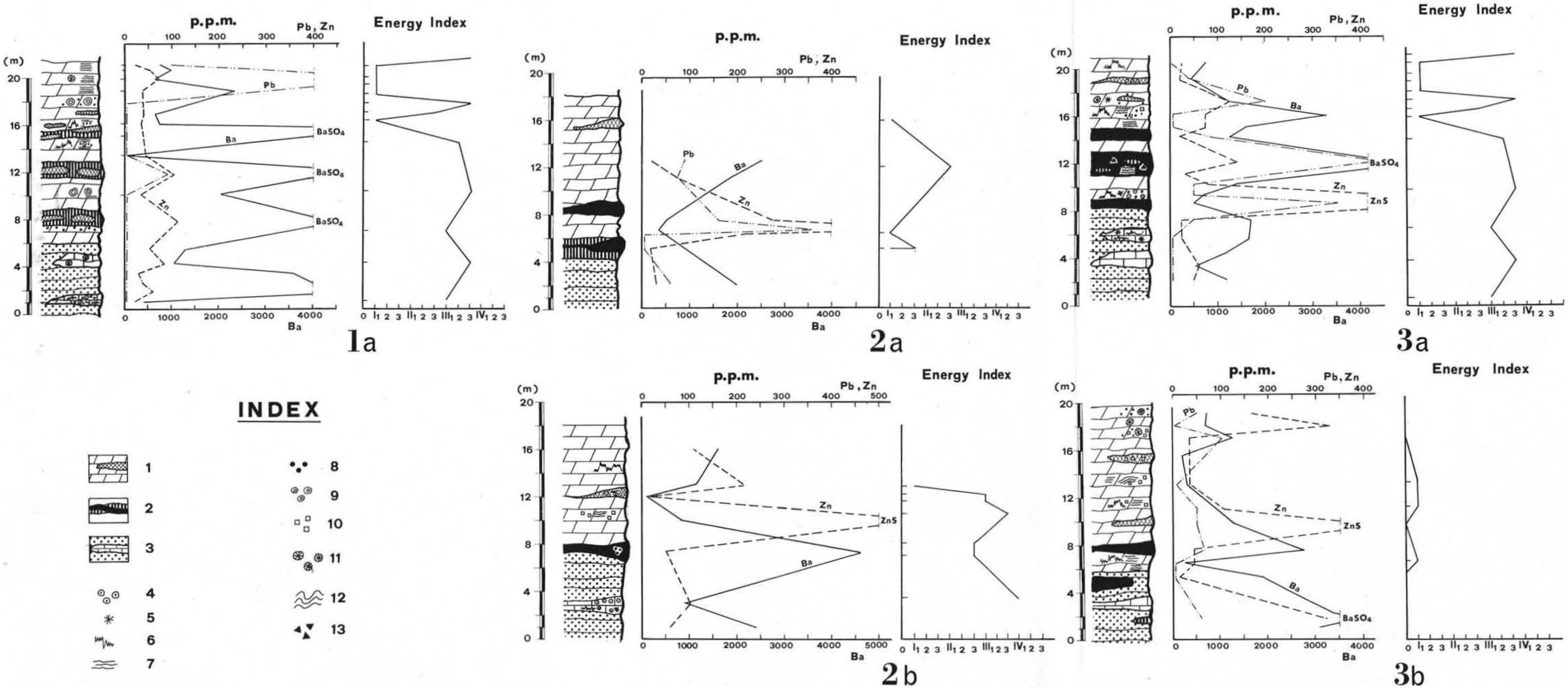
Type of rock	xy	r_{xy}	n° pairs
« arenarie »	Ba - Zn	0.92	18
	Ba - Pb	0.31	18
	Pb - Zn	0.36	20
« quarzite »	Ba - Zn	— 0.11	11
	Ba - Pb	0.85	12
	Pb - Zn	0	16
« dolomie rigate »	Ba - Zn	— 0.16	43
	Ba - Pb	— 0.14	42
	Pb - Zn	0.27	52

6.4. - DISTRIBUTION OF Ba-Pb-Zn IN THE STRATIGRAPHIC SEQUENCES.

The distribution of Ba, Pb and Zn contents in the stratigraphic sequences shows some anomalies connected probably with the paleogeographic environment during the sedimentation and with the reworking by diagenesis.

The north-western area (fig. 19-1a) is characterized by the presence of three barite levels; the sandstones show, in this part, the highest Ba geochemical contents of the whole area. In contrast the lead-zinc contents are relatively low, apart from an anomaly for lead localized at the top of the sequence, and connected, as will be described later, with the presence of voids and diagenetic veinlets.

The sequences of the central part of the area (fig. 19-2a and 2b) are instead characterized by the presence of zinc anomalies delineated by the occurrence of sphalerite. Lead is always low or absent, or at least lower than instrument sensitivity. The positive Pb-Zn anomalies seem not to be connected with barite layers.



Index:

1) « dolomie rigate » with chert nodules.
2) « quarzite » (black) and barite (striped).
3) « arenarie » with dolomite and limestone bands.
4) ooids.
5) fossils.
6) stylolites.
7) homogeneous clear laminae.
8) peloids.
9) oncoids.
10) molds of evaporitic minerals.
11) voids.
12) undulated laminae.
13) intraformational breccias and clastic dolomite.

1a: north-western part 2a, 2b: central part 3a, 3b: south-western part

Fig. 19. — Distribution of Ba, Pb, Zn contents and diagrams of energy index in some sequences of northern Sulcis:

In the south-western part of the area (fig. 19, 3a and 3b) the occurrence of thick « quarzite » along the sandstone-dolomite boundary marks a strong Ba positive anomaly. This is pointed out by small nodules of barite giving a high dispersion to the geochemical data. A relative coincidence among Pb, Zn and Ba anomalies is observable in this case.

6.5. - Result of the Microanalyses by Laser LMA1.

An attempt to analyze some sedimentary features by Laser Microspectral Analyzer LMA1 was made.

The application of this instrument permits the analysis of small areas on polished and thin sections and observing them before and after the analysis. The availability of a binocular optical microscope of 500 × magnification enables the laser beam to be directed to the respective point with high accuracy and the depth and the diameter of the respective craters to be measured (Smirnov and Alii, 1972).

The crater dimensions are variable, having diameters from 20 μ to 100 μ and almost equal depths; the microvolume evaporates between two carbon electrodes (point-to-point distance 10 mm) and the dispersion and recording of the spectra is effected by means of the Plane-Grating Spectrograph PGS2.

The following Table IV gives the obtained results:

Table IV.

Type of rock and/or structure	Main components	Micro-elements always present	Micro-elements frequently present	Micro-elements rarely present
1) Clear homogeneous laminated dolomite	Ca, Mg	Ba, Sr, Mn^{-}	Al, Si	Pb^{-}, Fe^{-}
2) Dark laminated or homogeneous dolomite	Ca, Mg	Ba, Sr, Al, Si, Mn	Fe, Pb, Ti^{-}	Zn
3) « quarzite »	Si, Al, Ba	Ca, Mg	Ba, Sr, Mn	Fe, Ti, As, Cd, Cu^{-}
4) « quarzite » breccia				
i) fragment with metallic minerals	Si, Fe	Al, Mg, Ca, Mn, Fe	Ti, Cu^{-}, Sb	W, Bi
ii) white fragment	Ba	Ca, Mg, Si, Al, Sr		Mn^{-}

(*Table IV*)

Type of rock and/or structure	Main components	Micro-elements always present	Micro-elements frequently present	Micro-elements rarely present
iii) reddish fragment	Ba	Ca, Mg, Si, Al, Sr	Fe, Mn	Ni⁻
iv) matrix	Si, Al	Mg, Ca	Ti, Cd⁻	
v) reddish matrix	Ba	Al, Si, Mg, Ca, Sr	Mn, Fe	
5) Carbonatic breccias	Ba, Ca, Mg	Sr, Mn	Pb	
6) « zebral » barite				
i) fibrous-radiated barite	Ba	Sr, Ca, Mg⁻	Al⁻, Si⁻	
ii) microgranular barite	Ba	Sr, Ca, Mg, Al, Si	Ti, Fe, Mn⁻	
7) Chert and dark inclusion	Si	Mg, Ca	Sr, Al, Ba	Ti, Ag
8) Dark dolomite inclusions	Si	Mg, Ca	Sr, Al, Ba⁻	Ti, Ag
9) Voids				
i) white	Ca, Mg	Si, Mn	Ba, Sr, Al	Zn, Fe⁻, Na⁻
ii) pink	Ca, Mg, Ba	Ba, Sr, Si, Al, Mn	Pb, Fe, Ti, Zn⁻	Ni, Cu, K⁻
10) Stylolites	Ca, Mg	Fe, Mn, Al, Si, Sr	Ba, Ti, Pb, Bi, Zn, Cd	Cu, Ni, Ag, As, Co⁻, Sn, Cr
11) Metallic minerals in dolomite	Fe, Zn	Ca, Mg⁻, Zn	Al, Ba, Sr, Mn, Ti, Pb	Ni, Cd, Cu, Si
12) Metallic minerals in « quarzite »	Fe	Si, Cu	Ba, Al, Ca, Mg, Pb, Zn	As, Sr, Mn, Bi, Sb, Ti, W
13) Clear veinlets in dolomite	Ca, Mg	Pb, Fe, Mn, Al	Ba⁻, Sr	Zn
14) Halite models (cubes)	Ca, Si, Ba	Sr, Mn	Zn⁻	

— About 200 microspectral analyses.

— When an element is present in two sectors this means that the element may occur as the main component in some analyses and as microelements in some others.

— The sign ⁻ means that the elements are present in very small quantities.

Table IV shows a wide variety of macro and microelement compositions; in fact the microanalyses, by selecting particular microzones, permitted the detection of elements that are not visible in the conventional geochemical analyses. The results obtained, however are only of a preliminary nature.

In summarizing, the following results may be outlined:

i) the dark dolomite is generally richer in metals than the clear one;

ii) the Al-Si elements are very common in almost every spectrum, testifying the presence of small quantities of clay (see also the X-ray analyses);

iii) even if in traces, the Mn is rather common not only in the voids and stylolites but also in the carbonatic facies and « quarzite »;

iv) the wide presence of Ba even when the barite is not visible microscopically;

v) the « zebral » barite, confirming the microscopic observations, is made up by alternated beds of pure well-crystallized and microgranular barite with clay impurities;

vi) the voids, filled mostly by calcite and/or dolomite and barite, show a very interesting composition of microelements; K and Na denote the differentiation of connate waters during diagenesis toward alkaline environments. The Pb always appears later in sedimentary paragenesis (AMSTUTZ et al., 1964) and its presence in the bird's eye structures is in accordance with its behaviour. These recirculation phenomena are visible also in the short veinlets in the dolomite;

vii) the widest variety of metals is found in the stylolite seams: these are marked generally by a continuous, ferruginous band in which cubes of ex-pirite, now completely oxidized into limonite, may occur. Elements such As, Ag, Co, Sn, Cr are present in very small quantities, while Ca and Mg are evidently the products of the influence of the enclosing host rock;

viii) the cubic models of halite have been completely replaced by chalcedony, barite and carbonates with a little clay.

Some of the samples showing a high metal content were investigated by X-ray [1]; these samples revealed, apart from sphalerite and barite, the presence of weak peaks due to clay minerals at low angles.

Thus the available data seem to be in good agreement with the preceding sedimentological studies; the complex phenomena of element removal, recirculation, dissolution and replacement are confirmed, at least on the geochemical scale, by the above mentioned results.

7. - Paleoenvironmental Scheme and Conclusion.

The data obtained during the field and laboratory works need to be arranged in a general scheme taking into account the present day carbonate and evaporitic environments.

On the regional scale, the « quarzite » horizons interfinger with barite layers; the zones of transition show residual nodules and thin beds of barite included in microcrystalline quartz and chalcedony masses. Locally, « zebral » structure, simulating « zebral » barite but made up almost exclusively of quartz, occurs in the « quarzite ».

An understanding of silicification phenomena has been outlined previously; thus the most important sedimentological problem is the supply, removal and deposition of sulphates and salts. To resolve such a problem a sketch of the morphology of the sedimentary platform must be outlined.

The thickeness of the carbonate member varies considerably in the different parts of the area and this could be due both to stratigraphic and tectonic causes. These thickness changes and heteropic passages (fig. 20) testify to the presence of reliefs and basins on a flattened landscape, probably subjected to periodic tidal and hurricane floods.

Evaporitic conditions might occur in the marginal tidal flats, periodically supplied by marine water. These conditions gave rise to the diagenetic intrasedimentary growth of sulphates above the water table (Bosellini and Hardie, 1973). Such growth was favoured by the presence of porous levels as, for instance, carbonate sands.

Halite also may precipitate in the small basins settled on the flat; the unfrequent occurrence of clorides may be imputed to a weak development of evaporation. Experiments indicate that halite can preci-

(1) Instrument: Jeol DX-GO-S, Cu tube, Ni filter.

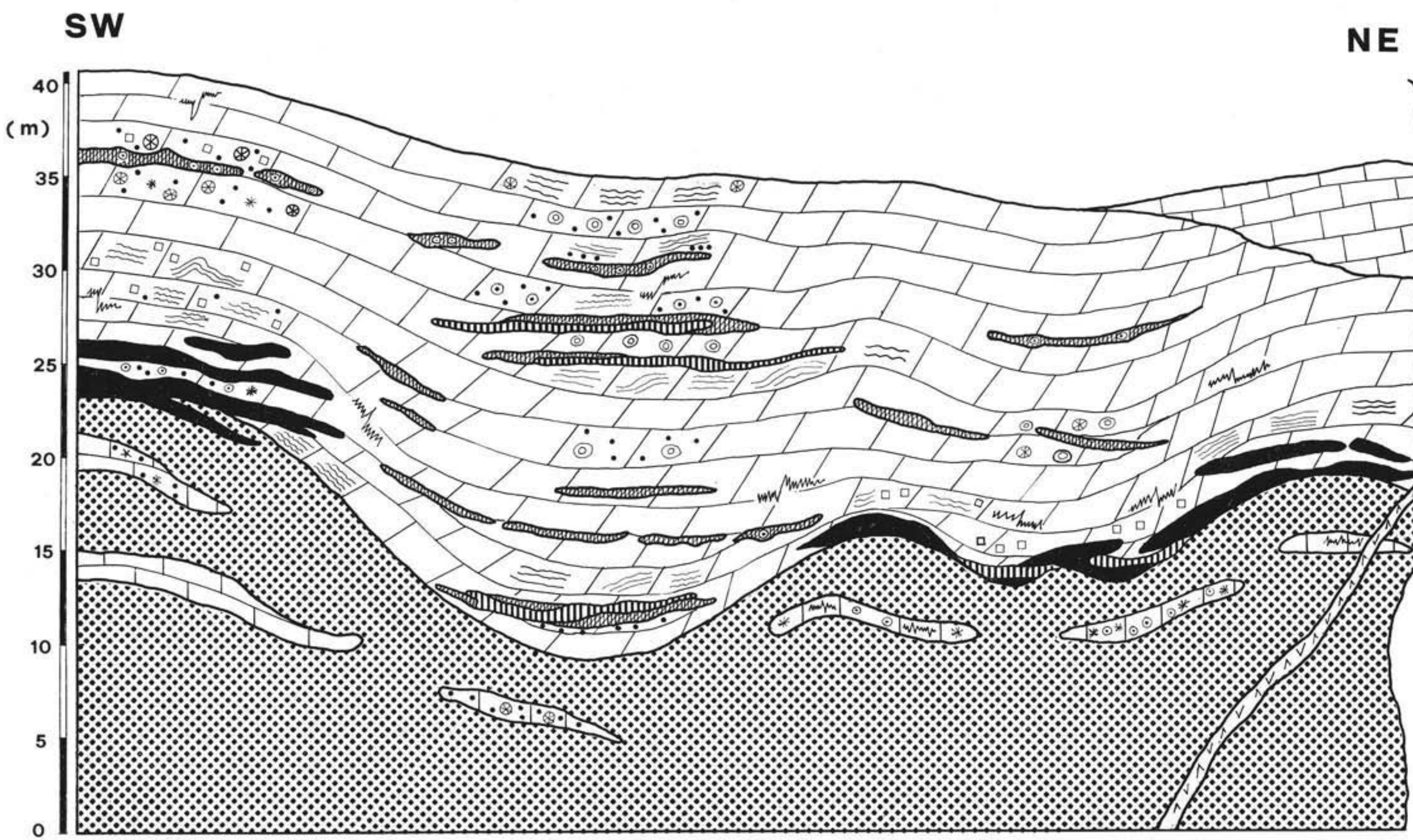


Fig. 20. — Scheme of the general stratigraphic sequence: index as fig. 19; the uppermost limestone (at the top, right side) and the diabase dyke (at the bottom, right side) are represented.

pitate by mixing brines of differing stages of evaporation; these brines must be of different composition and specific gravity and precipitation may occur without a further water loss by evaporation and from unsaturated waters (RAUP, 1970).

The continental supply of fresh water, probably rich in SiO_2, Ba, and smaller amounts of Al, Pb, Zn, Fe, Mn, etc. greatly modifies the preceding physical-chemical parameters.

The mode of silica removal has been suggested in 5-1; the colloidal and true solution silica might occur, producing a different mobilization. In fact the colloidal silica, along with a little Al and Mn, may be floculated right at the beginning of mixing with marine water and probably in a deltaic environment. It is possible a little Ba, adsorbed to clay particles, could be involved in the general floculation.

The silica and the Ba carried in true solutions show a higher mobility and may remain in the water of sediments. This fact may allow the replacement by Ba of evaporites made of Ca-sulphates with different grain-sizes, or of alternate sulphate-dolomite beds. The replacement is obviously selective, in the sense that Ba prefers the sulphate beds. The result of such a replacement, depending on the amount of Ba, could originate the alternation of fibrous-radiated barite and dolomite or fibrous-radiated and mosaic barite.

The silica supply, near the reliefs, might replace more easily the carbonates thus giving alternately barite and chalcedony. On the reliefs or where a lot of silica was available the replacement of sulphates and carbonates produced the « zebral quartzite ».

The frequent presence of length-slow chalcedony may agree with the vanished evaporite according to FOLK and PITTMAN (1971).

An attempt to interpret the energy index of sedimentary environments has been made following CATALOV (1971) (fig. 19). Almost every type of lithofacies recognized in the Sulcis sequences may be correlated with those of CATALOV's paper; only the homogenous laminated dolomite has been interpreted by the writers as indicative of very low or low energy (O-I_1). The sandstones and the interbedded carbonatic lenses show a middle-high energy index.

A middle-high energy index was also present during the deposition of the « quarzite »-barite horizon, apart from local reductions; this is in good agreement with the hypothesis of high porosity, favouring sulphate growth and later barite and silica replacement.

The minimum energy index is attributed to micritic and homogeneous laminated dolomites frequently containing halite molds.

The described paleoenvironmental scheme lead to a very important conclusion: detailed sedimentological studies are fundamental in the prospecting of sedimentary ore deposits.

Acknowledgements.

The Authors are indebted to Prof. R. ASSERETO of Milano University and Prof. R. FOLK of Austin University for the constructive discussion during a field trip in Sardinia.

They are very grateful also to Dr. C. GARBARINO of Cagliari University for his assistance during X-ray analyses and for computer using in statistical calculations.

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