Ore Geology Reviews, 7 (1993) 413–431
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Paleogeographic and diagenetic context of a baritic mineralization enclosed within Frasnian peri-reefal formations: Case history of the Chaudfontaine mineralization (Belgium)

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(Received September 30, 1991; revised version accepted August 24, 1992)

ABSTRACT

Dejonghe, L. and Boulvain, F., 1993. Paleogeographic and diagenetic context of a baritic mineralization enclosed within Frasnian peri-reefal formations: Case history of the Chaudfontaine mineralization (Belgium). *Ore Geol. Rev.*, 7: 413–431.

The Chaudfontaine ore deposit, which is composed mainly of barite, is hosted in the Frasnian shale and carbonate formations of Belgium. A detailed description of the sedimentary structures involving barite crystals shows that many of these crystals have developed under gravity control. Two populations of barite were formed: crystals which grew in brine above the sediment-water interface, and crystals which developed in the sediment during early diagenesis. Each population has specific size, habits and structures, and the size and abundance of the crystals may be expressed as a function of the degree of barium supersaturation. Morphological similarities were found between Chaudfontaine barite and gypsum from evaporites. The formation of the ore deposit is then replaced in its sedimentological and palaeogeographical context: a sea-level drop affecting a semi-restricted marine basin. A predominantly burial diagenesis is responsible for the good preservation of the ore deposit.

Introduction

This paper treats a dominantly baritic mineralization located within the clayey-carbonate sediments of the Belgian Frasnian. This work will show that the formation of a barite layer may be due to a process similar to that which governs the formation of the more "classic" evaporite deposits (Dejonghe, 1990), such as those of gypsum or halite, and integrated within a particular sedimentologic context. Although the description of the mineralization and of the accompanying sedimentary structures are emphasized, the paleo-eustatic, paleogeographic and diagenetic environments will also be treated, as well as their respective influences on the characteristics of the mineralization and/or the surrounding sediments.

Location and geologic context

The Chaudfontaine mineralization (Dejonghe, 1979, 1985) is situated in the Verviers Synclinorium (Graulich et al., 1984; Graulich and Dejonghe, 1986), a structural unit of the Variscan domain in eastern Belgium (Fig. 1). The surrounding country rocks, Lower Devonian to Upper Carboniferous, are exclusively of sedimentary nature (limestones, shales, sandstones).

The mineralization is principally composed of barite, with accessory pyrite, sphalerite and

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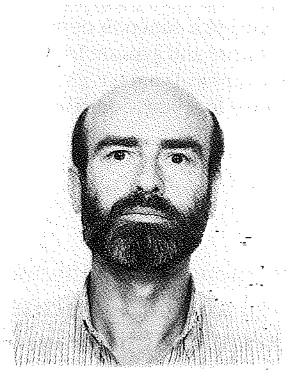
galena. Small inclusions of chalcopyrite and bravoite have also been noted (Dejonghe et al., 1978, 1985).

The mineralized body does not crop out, but has been cut by three cores (Geological Survey of Belgium reference numbers 134E303, 134E310 and 134E396) forming a right-angle triangle whose short sides are 180 m and 375 m long. The mineralization occupies the two flanks of a faulted anticline, at depths of 80 to 210 m (Fig. 2). The maximum thickness of the mineralization is 10.75 m. The mineralized layers alternate with barren layers. In all three cores, the mineralization occurs at the same stratigraphic level, i.e., at the summit of the Frasnian (Fig. 2). More precisely, following the terminology of Coen-Aubert and Lacroix (1979), it is situated at the top of the "second *Phillipsastrea* biostrome" of the Aisemont Formation overgrowing a micritic bioherm ("red marble bioherm").

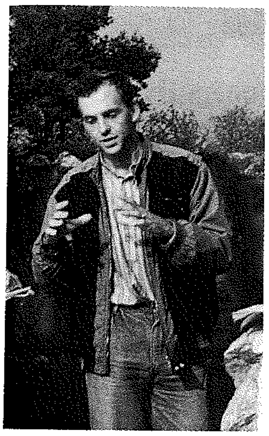
The paleogeography of the Frasnian formations of the Verviers Synclinorium has been studied in detail by Cnudde et al. (1986) and Dejonghe and Mamet (1989). For their part, Boulvain (1990) and Boulvain and Coen-Aubert (1991) have documented the paleogeographic evolution of the Frasnian ramp as a function of the eustatic fluctuations in the Dinant and Namur synclinoria.

Paleogeographic context

During the Frasnian period, the sedimentary basin (comprising the present-day Dinant, Namur and Verviers synclinoria) was



Léon Dejonghe graduated as Mining Engineer from the Polytechnic Faculty of Mons (1969), as Geological Engineer from the Brussels University (1971) and obtained a Doctorat d'Etat dès Sciences Naturelles from the University Pierre et Marie Curie of Paris in 1985. He works for the Geological Survey of Belgium since 1971 where he is now Chief Geologist-Director. He is also part-time Professor at the Brussels University for the course of metallogeny. His main reseach interests are in the metallogenesis of sediment-hosted stratiform mineral deposits, geochemical prospection, tectonics and geological mapping of Paleozoic formations. He is author or co-author of 66 papers. In 1991, he was awarded the "Agathon DE POTTER Price" from the Royal Belgian Academy of Sciences.



Frédéric Boulvain graduated from the Brussels University (Lic. Sc. géologiques, 1981) and the University of Paris XI (DEA mineralogy-geochemistry, 1985). He obtained in 1990 a Doctorat en Sciences from the Brussels University after five years research on Frasnian mudmounds of Belgium (EEC sectorial grant). He is now geologist at the Geological Survey of Belgium. His main research interests are in carbonate sedimentology and diagenesis.

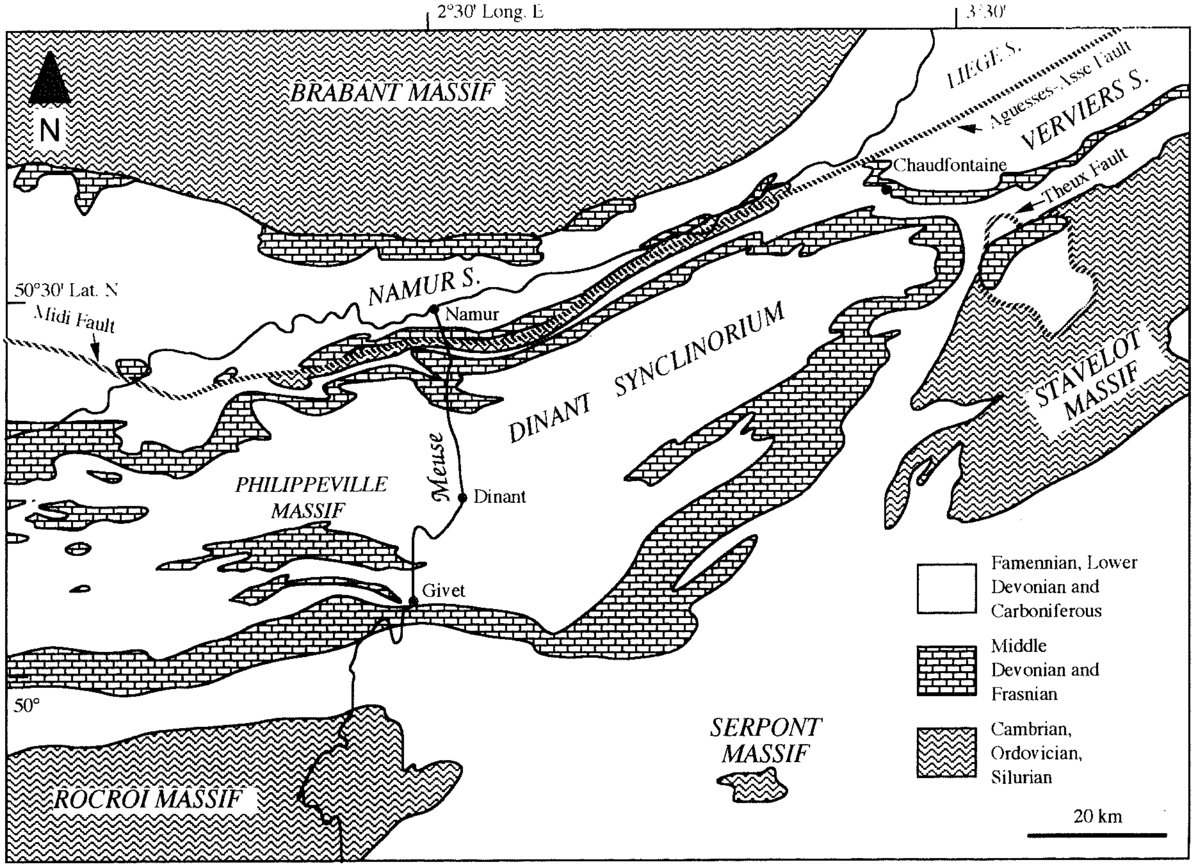


Fig. 1. Tectonic units of the Palaeozoic of Belgium.

bounded, to the north, by the southern extremity of the Caledonian continent (now known as the Brabant Massif) which was experiencing peneplanation, and to the south by the emerging mid-european ridge.

The Frasnian occurs in a general context of eustatic rise (Johnson et al., 1985). In the region under consideration, a drowned carbonate platform was followed, at the end of the Frasnian, by a mixed ramp with clay-carbonate sedimentation (Boulvain, 1990). During the stable period which succeeded this eustatic rise, a number of red micritic bioherms began to develop in the argillaceous limestones containing brachiopods, sponges, bryozoa and crinoids (Fig. 3A). Their location was possibly influenced by hypothetic active faults. The argillaceous limestones cover a vast area on the carbonate ramp, however, the bioherms are found principally in the southern part of the sedimentation basin (Philippeville Massif, situated in the central part of the Dinant Synclinorium, Fig. 1).

These lenticular edifices, several dozens of meters in thickness and several hundreds of meters in horizontal extent, show a vertical sedimentary differentiation: the organic community is dominated, at the lower levels, by deposition of sponges and carbonate and iron oxidizing bacteria (*Siderocapsaceae* and filamentous bacteria of the *Sphaerotilus-Leptothrix* group). It then becomes richer in crinoids, corals, *Sphaerocodium* and *Renalcis*, towards the middle and upper levels of the edifices.

In the Verviers Synclinorium, the shallower depth due to the proximity of the Brabant Massif is demonstrated by the increasing amount of corals in the argillaceous lime-

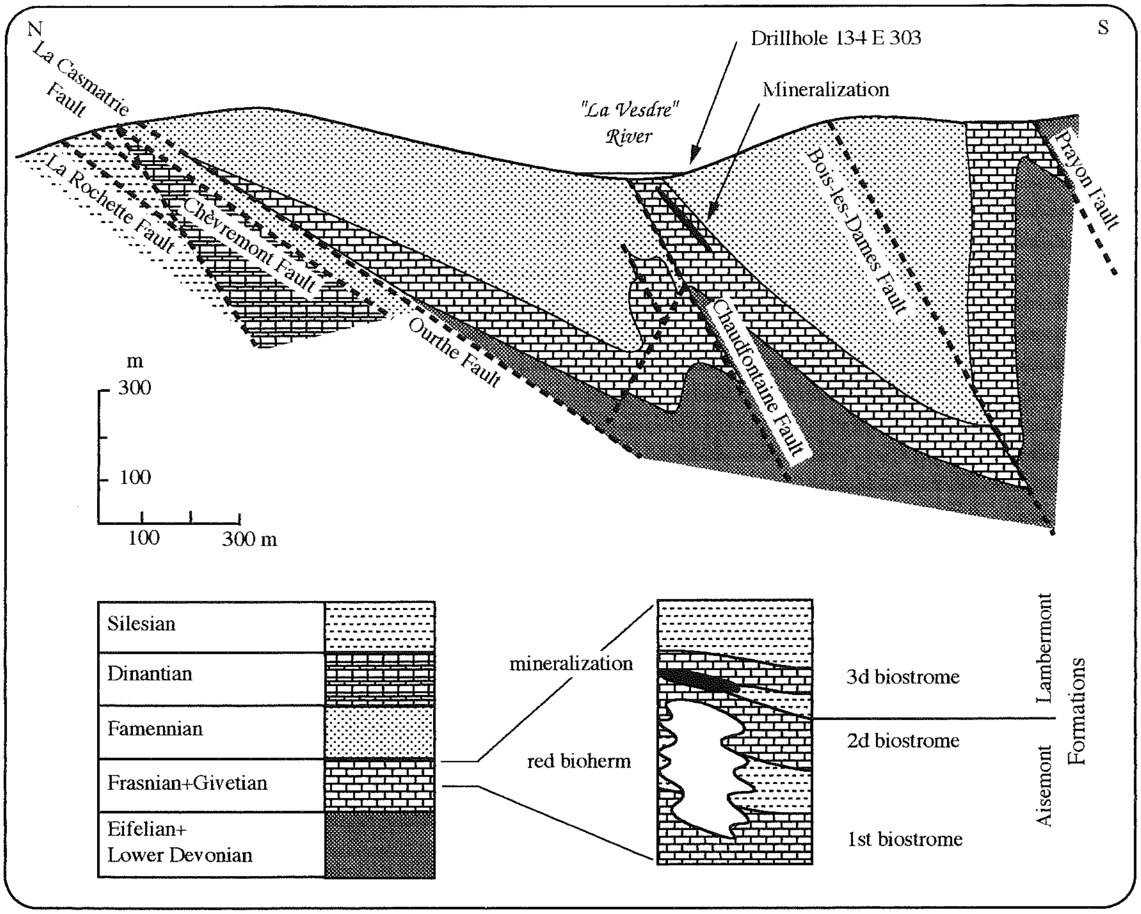


Fig. 2. N–S cross-section including one of the three mineralized drill holes (drill hole 134E303). The Chaudfontaine fault cuts an anticline. In this section, the mineralization only exists on the northern flank of this anticline. In other sections, the mineralization occurs on both flanks.

stones. It is within these argillaceous limestones ("first *Phillipsastrea* biostrome") that the Chaudfontaine bioherm will begin to grow (Fig. 3A).

A second eustatic rise induced a displacement towards the north of the different facies belts (Fig. 3B). The surviving bioherms are henceforth surrounded by fine-grained argillites, instead of a continuous calcareous bed and, due to the different speeds of sedimentation, a certain relief developes. During the stable period which succeeded the eustatic rise, an ecologic evolution with progressive diversification of the communities can again be seen in all of the edifices. The lower levels, rich in sponges and iron-oxidizing and carbonate-depositing bacteria, are overlain by a middle layer containing crinoids, corals and algae. This vertical differentiation is, this time, superimposed on a horizontal zonation due to the relief of the edifices.

This period of eustatic stability comes to an end with a lowering of the sea level of 10 to 20 m (Boulvain, 1990), and is characterized (Fig. 3C), depending on the position within the sedimentary basin, by the following phenomena:

— the appearance of cryptalgal facies at the top of the micritic bioherms. In the Philippeville Massif, facies which initially characterized the central part of the edifices, spread over their slopes;

— to the north of the area of sedimentation

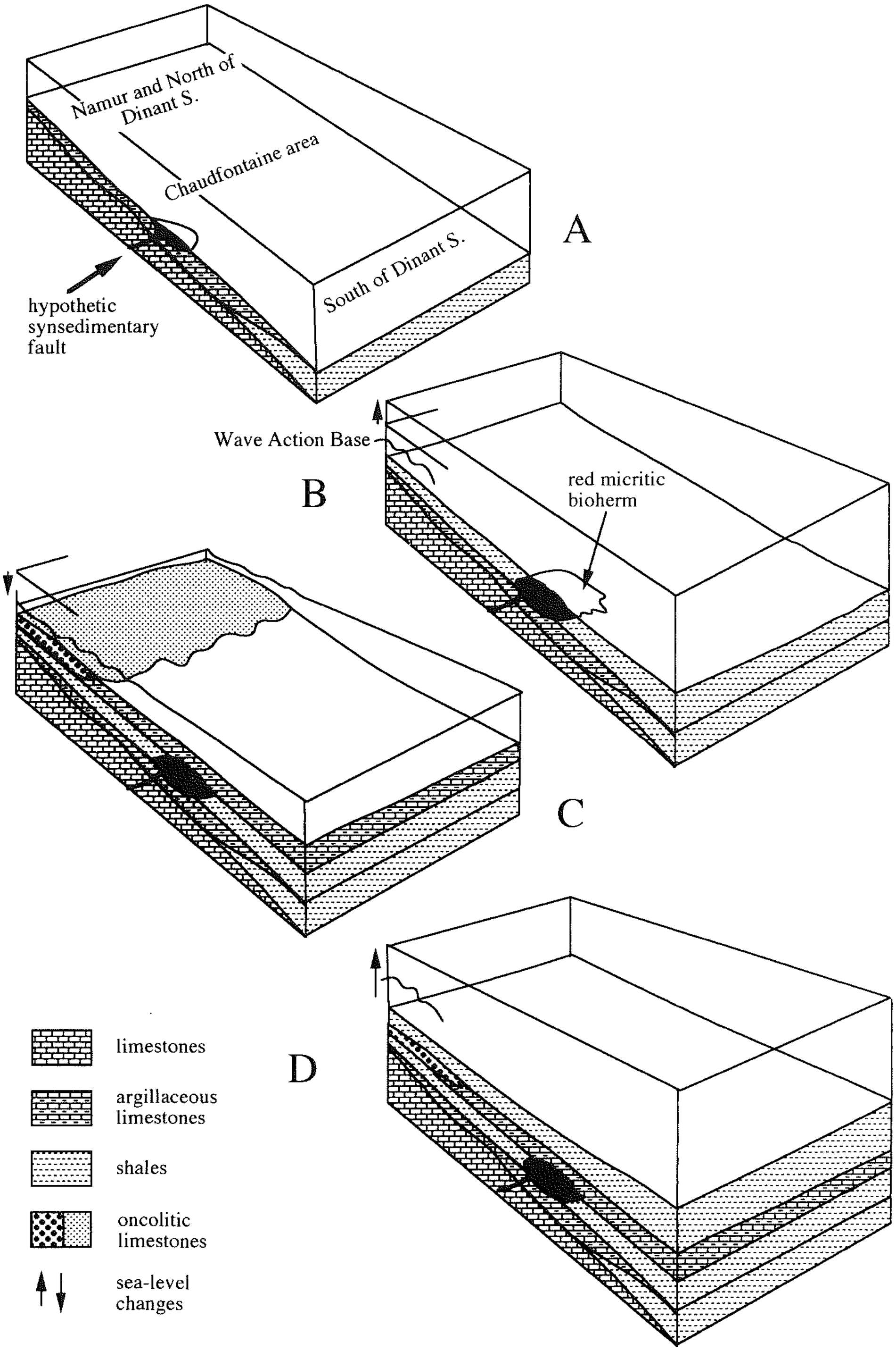


Fig. 3. Schematic reconstruction of the Upper Frasnian ramp paleogeography in the East of Belgium. Explanations in the text.

(the internal zone of the ramp), formation of oncolitic shoals overlying the brachiopod-containing argillaceous limestones. In some places, cryptalgal laminites indicate an inter- to supratidal environment;

— in the Verviers Synclinorium, overlying the Chaudfontaine red marble bioherm, the development of a continuous biostromal bed of variable thickness ("second *Phillipsastrea* biostrome"), locally rich in oncoliths. Evaporite pseudomorphs are also present;

Finally, a third eustatic rise, of great amplitude (Fig. 3D), ends the biohermal regime, for the whole basin and argillaceous sedimentation dominates with, after a brief coral episode, non-bioturbated fine-grained argillites.

The Chaudfontaine mineralization

Barite occurs in various forms: (1) as isolated and scattered lamellar or tabular crystals; (2) as aggregates of either non-orientated crystals (often with 120° junctions) or roughly parallel lamellar crystals cemented in a cherty rock; (3) as rare radiating aggregates of lamellar crystals; the rosette structure is still rarer; (4) as massive aggregates, often of large elongated subhedral crystals; (5) as aggregates of anhedral crystals of extremely varied shapes and sizes.

The barite is white, sometimes with a faint greyish or pinkish tinge and occurs in numerous sedimentary structures which are described in detail in the following chapter. Many structures are controled by gravity (hence giving rise to geopetal fabrics). Some structures, such as slumps and load casts, involve pre-existing barite crystals in hydroplastic sediments. However, barite is never found to fill fractures or karst cavities.

The ore matrix is complex and consists of a mixture of black chert and argillaceous limestone with a varying proportion of dolomite. The cherty component is often predominant and will be referred to as "silicite" after Teodorovich (1958). Sedimentary breccias, sometimes mineralized, are also abundant. These breccias are neither associated to shear zones, nor to collapse structures. They occur sometimes in connection with slumps. The contacts between mineralized beds and barren intercalations are always parallel to the bedding. They may be very sharp, but gradual variations in the shape and size of barite crystals also occur.

The hanging wall of the ore body is a light grey nodular limestone with an abundant argillaceous matrix, interbedded with irregular layers of green and red shale. At the footwall, grey and black limestones (0.20–20 m thick and occasionally brecciated) cap red bioherms with thin red and green shaly layers.

Sedimentary structures of the Chaudfontaine deposit

Thirteen sedimentary structures involving barite crystals have been described and illustrated by Dejonghe (1990) from the Chaudfontaine deposit. These structures are, among others:

- rhythmic layering of barite, sphalerite and barren sediments;
- conform (parallel to bedding) discontinuity surfaces between baritic and barren layers;
- barite crystal floors;
- baritic sediment filling in barite crystal floors with screen fabrics (Fig. 4);
- levelling of irregular relief by layers rich in barite crystals;
- redeposited baritic clasts in sedimentary breccias;
- redeposited barite crystals;
- synsedimentary minifaults creating accomodation for barite crystals.

Most of these structures involve sedimentary redeposition of barite crystals in a periodically agitated environment.

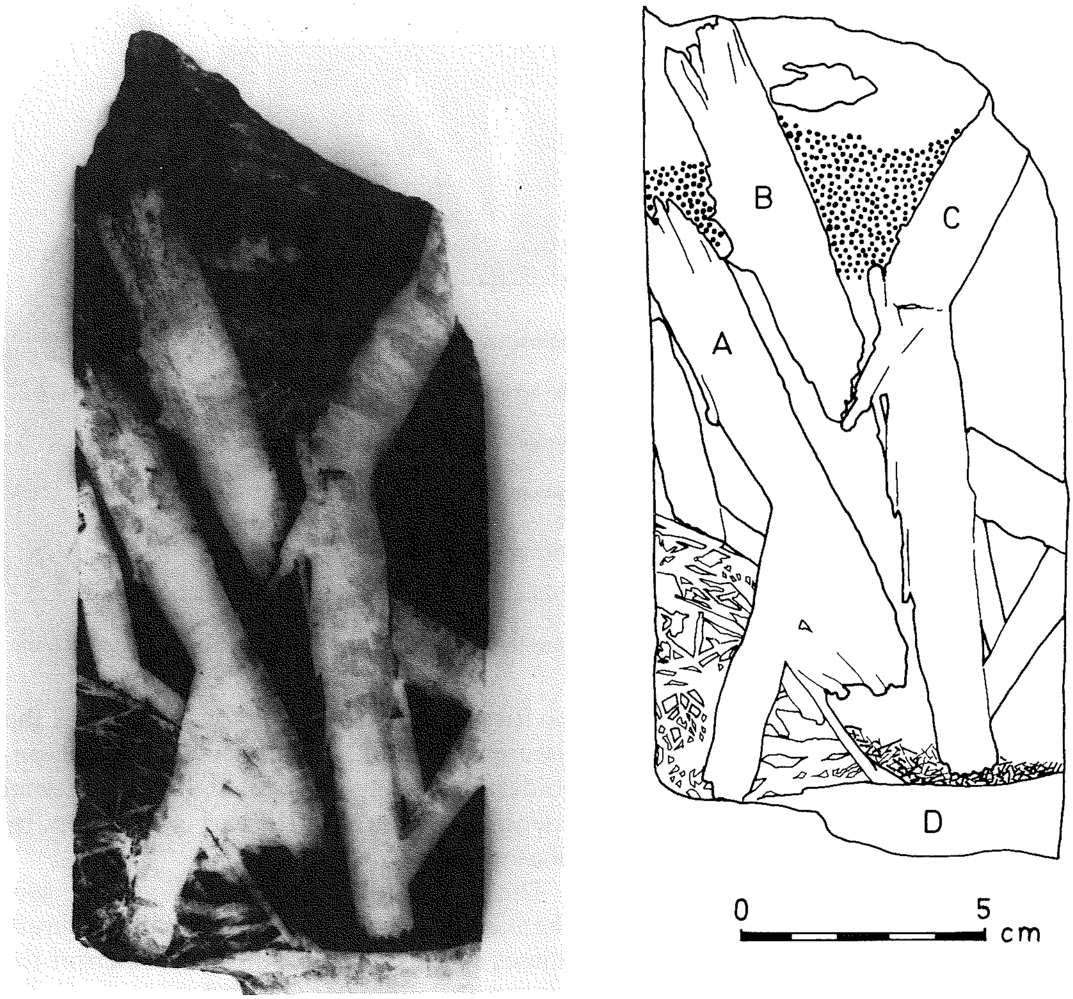


Fig. 4. Chaudfontaine drill hole 134E396: longitudinal section of a core between depths of 195.05 and 195.25 m. *A*, *B* and *C* are decimeter-size crystals forming "V"-shaped cavities which are filled, at the bottom (stippled area), with an aggregate of barite and sulfides (mainly pyrite). The aggregate is totaly absent from the silicite on the right of crystal *C*. There is an accumulation of millimeter-size barite crystals on top of crystal *D*.

Diagenesis

The diagenetic evolution of the Upper Frasnian micritic bioherms and the sediments, stratigraphically equivalent, on the carbonate ramp have been studied by Boulvain (1989, 1990) and Boulvain et al. (1992). More specific information on the Chaudfontaine mineralization and the surrounding country rocks based on the isotopic studies of S, C, O, Sr, Pb are furnished by Dejonghe et al. (1989).

All the micritic bioherms are characterized by the same diagenetic sequence made of at most five phases of cementation which are, sucessively (Fig. 5):

(1) A radiaxial low-magnesian calcite in mm- to-cm size crystals, containing micronic inclusions of organic material and inframicronic inclusions of dolomite. These crystals are predominantly non-cathode luminescent with small bright orange luminescent spots. Its mean isotopic composition is δ^{13}C

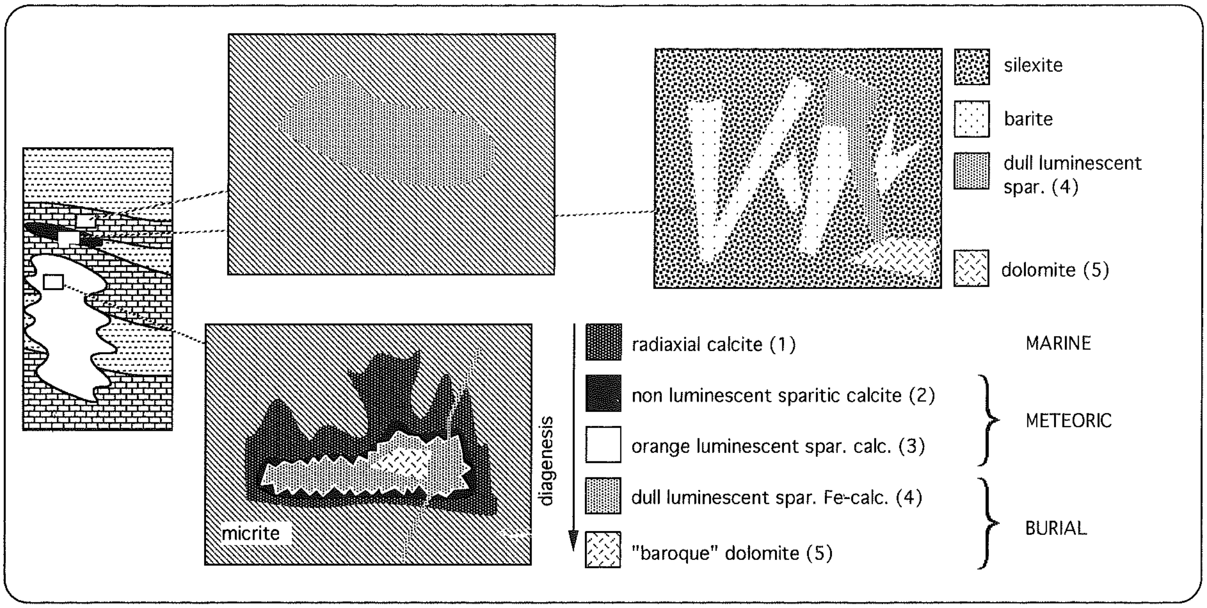


Fig. 5. Diagenetic evolution (cementation) of Upper Frasnian limestones and argillaceous limestones of Chaudfontaine.

PDB = 1.69‰ (var = 1.4, $n=8$); δ^{16}O PDB = −8.02‰ (var = 1.1, $n=8$);

(2) A sparitic non-luminescent low-magnesian calcite in automorphic equant crystals, infra-mm to mm in size. The mean isotopic composition is δ^{13}C PDB = 2.87‰ (var = 1.1, $n=8$); δ^{16}O PDB = −7.7‰ (var = 0.6, $n=8$);

(3) A sparitic low-magnesian calcite forming a syntaxic border on the preceeding cement (2) with a bright orange luminescence and sometimes with a zonation of alternating luminescent and non-luminescent bands. The luminescence is linked to a mean MnO content of 1.2% (var = 0.3, $n=16$);

(4) A xenomorphic low-magnesian sparitic calcite in equant crystals, mm to cm in size, with a dull orange luminescence. This calcite only contains a small amount of manganese, but 1% of FeO (var = 0.01, $n=13$). The mean isotopic composition is δ^{13}C PDB = 2.24‰ (var = 1.5, $n=13$); δ^{16}O PDB = −10.86‰ (var = 1.0, $n=13$);

(5) A "baroque" or "saddle-shape" ferriferous dolomite.

The bioherm cavities are characterized by the succession of phases (1), 2, 3, 4, (5). The cavities in the surrounding sediments and the fissures in general, by phases 4, (5). The oncoidal grainstones deposited in the internal zones, to the north of the carbonate ramp, by phases 2, 4, (5).

The petrographic observations and the geochemical and isotopic analyses of the different phases of the diagenetic sequences permit the reconstitution of the post-sedimentary evolution of the Frasnian carbonate ramp (Boulvain et al., 1992).

The radiaxial calcite (1) is a secondary cement resulting from the restabilization of an early marine cement by fluids precipitating the automorphic calcite (2) (Kendall and Tucker, 1973; Kendall, 1977; Kerans et al., 1986). This second phase is a meteoritic sparitic calcite formed during the post-Frasnian marine regression. This cement has been abundantly precipitated in the internal area of the ramp, entirely obstructing the porosity. In the micritic bioherms, furthest from the recharge zones of the meteoritic aquifer, only a minor volume of sparite (2) has been precipitated, immediately followed by the manganiferous sparite (3), indicating the beginning of the closing off of the aquifer (Meyer, 1978; Frykman, 1986; Miller, 1986). Finally, during burial, the ferriferous calcite (4) completely blocked the residual porosity of the micritic bioherms and the entier porosity of the surrounding sediments. This cement is contemporary with the opening of a fracture network and the development of pressure-solution phenomena. The "baroque" dolomite (5) is cogenetic with, or slightly later than the ferriferous calcite.

In the Chaudfontaine mineralization, the carbonates associated with the barite occur principally in two forms:
— as white spathic calcite in mosaics of multicentimetric crystals or in the form of laths with the same habit as the barite crystals (core 134E396, between 195.5 and 195.7 m). These laths are included in a silicite;
— as "baroque" ferriferous dolomite.

The spathic calcite corresponds to phase 4 of the diagenetic sequence and the ferriferous dolomite to phase 5. The barite crystals are believed to be approximately contemporaneous with phase 1, and locally replaced by phase 4 during diagenesis.

Relationships of the mineralization to sulfate evaporites

Several pieces of evidence testifying to the relationship between the Chaudfontaine mineralization and the sulfate evaporites have been presented by Dejonghe (1986, 1990). The most important of these are, the high salinity of the fluid inclusions within the barite crystals (mean: 16.5% equivalent NaCl, with a maximum of 23% equivalent NaCl for the core 134E396, Dejonghe et al., 1982a,b); the presence of anhydrite and gypsum crystal pseudomorphs; the presence of anhydrite at an equivalent stratigraphic level in the Soumagne core, 8 km to the east of the Chaudfountaine core; the association of the mineralization with certain silicic forms (microquartz and petaloïd megaquartz) frequently linked to evaporites (Arbey, 1980) and finally the isotopic composition $\delta^{34}S$/Canyon Diablo of the barite ($26.1<\delta^{34}S<30.5‰$) which corresponds to the known value for Upper Devonian sulfates of marine origine. To these arguments we can add a generally restricted sedimentologic context at the end of the Frasnian, as a result of the eustatic drop indicated above.

In contrast to S, the Sr and probably the Ba are not of marine origin: the $^{87}Sr/^{86}Sr$ ratio of barite (clustering around 0.7112) is significantly above the seawater ratio of the Frasnian (around 0.7087; Dejonghe et al., 1989).

In summary, the Chaudfontaine mineralization was trapped in small shallow pools situated at the top of an Upper Frasnian biostromal formation. These pools were temporarily isolated from the open sea and evolved under evaporitic conditions. Sulfate solutions were thus present in substantial amounts. In such environments, proliferation of organisms is great, as is their mortality. Thus bacterial reduction could play an important role. If metals were available, very favourable conditions for their precipitation would have existed. Precipitation could have occurred during the mixing of two different solutions; one carrying the sulphur, the other carrying the metals. The possibility of two solutions is supported by isotopic data indicating that the sulphur is of marine origin whereas, the Sr and Ba are of non-marine origin. Therefore, Dejonghe (1985, 1986) and Dejonghe et al. (1989) made the hypothesis that metalliferous brines reached the site of deposition along active fault drains, which could also be responsible for the location of the bioherms.

Structural nature of the barite growth processes growth of millimetric barite crystals

At least four, millimetric barite crystallization processes are possible as illustrated in Fig. 6:

Hypothesis 1: barite nuclei appear in the brine (chemical nucleation), and are deposited at the water/sediment interface (mechan-

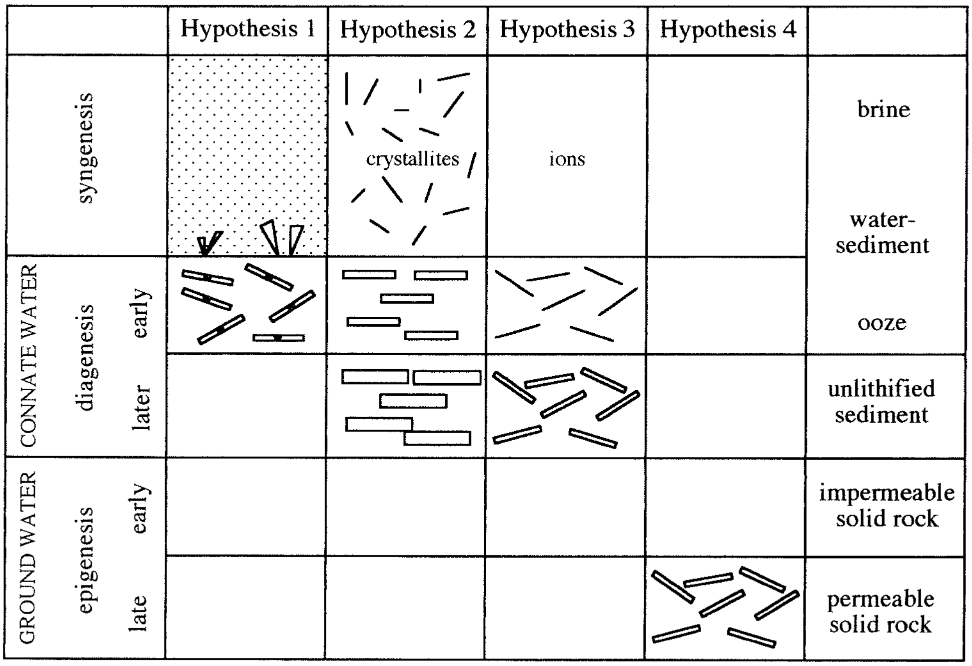


Fig. 6. Diagram of hypotheses concerning the time and process of crystallisation.

ical sedimentation). Here, or in the uppermost unconsolidated sediment, the crystals continue to grow, until their present size. The overlying brine and/or connate water feed the growth (the crystallization takes place partly syngenetically and partly during incipient diagenesis).

Hypothesis 2: lamellar barite crystallites appear and grow in the brine, reaching millimetric sizes, before being deposited at the water/sediment interface (syngenetic crystallization). They may subsequently continue to grow in the unconsolidated sediment during diagenesis.

Hypothesis 3: an ooze, rich in Ba ions is deposited. Barite starts to crystallize during early diagenesis and growth may continue during later diagenesis.

Hypothesis 4: strata with high porosity allow groundwater to migrate laterally. An influx of Ba-rich epigenetic water causes barite to crystallize in the pores of consolidated sediment (epigenetic crystallization).

The last hypothesis may be rejected outright, as it can not explain the geopetal fabrics; the first three are, *a priori*, all plausible.

Hypothesis 2 is more open to criticism than the remaining two. Dejonghe (1985) and Cnudde et al. (1986) have stressed that the paleogeographic environment of the Chaudfontaine area at the end of the Frasnian was one of very shallow water. Studies on fluid inclusions (Dejonghe et al., 1982a; Dejonghe, 1985) have shown that the viscosity of the brines, in which the barite precipitated, is not very high. These two conditions do not favour the continuous growth of nuclei and crystallites because their free fall through the brine would have been very brief. However, in extremely still water, laminae of barite may occur and grow while floating at the surface of a brine, as observed by Orgeval in the Bou Grine mine in Tunisia (Orgeval, pers. commun.). In this case, the lamellae would subsequently have acquired a preferred orientation parallel to the bedding on deposition at the sediment/water interface.

A strong argument in favour of diagenetic growth is the fact that in the rhythmites, the millimeter-size barite crystals lack preferred orientation. Barite laminae crystallizing in brine would have been deposited parallel to the bedding. However, we must also take into account the morphology of the rhythmites: there are sharp limits between the alternating barite-rich and barren layers (Dejonghe, 1990). This argues in favour of hypothesis 1: only barite nuclei previously deposited at the sedimentary interface can explain such sharp limits. It is unlikely that such clearly distinct barite-rich strata could have arisen from lithologically undifferentiated sediment through diagenetic growth without pre-existing nuclei.

Many authors have claimed that diagenetic growth of barite or other stratiform ore deposits occur in superficial, freshly deposited sediment (Macquar, 1978; Amstutz and Fontboté, 1982). The ore forming process must be, therefore, a surface-linked process.

It should be remembered that, at Chaudfontaine, mineralized and barren sediment alternate on a centimeter to meter scale. The sharp contacts between barren and strongly mineralized layers clearly seem to reveal that sedimentation frequently ceased. Such contrasting lithologies on either side of discontinuities are indicative of major changes in the influx into the sedimentary basin, following gaps.

Therefore, the Chaudfontaine deposit rhythmites are strata formed by mechanical deposition (sensu Schulz, 1976, pp. 296–297) of nuclei, crystallites or millimeter-size crystals fed from a brine, and which possibly continued to grow during early diagenesis. The space rhythm is time-linked: the fluctuating supply of sediment of various lithologies combined with varying physico-chemical conditions gave rise to rhythmically alternating mineralized and barren layers.

Growth of decimeter-size barite crystals

The following observations concerning the position and habit of decimeter-size barite crystals indicate that they were static during their growth, whereas the nuclei of millimeter-size barite crystals were deposited dynamically:

(1) Decimeter-size barite crystals are often sub-vertical, whereas millimeter-size barite crystals lack preferred orientation (Fig. 4);

(2) Euhedral decimeter-size barite crystals ends (crests), although exceedingly rare, are always found towards the stratigraphic top of sub-vertical crystals;

(3) When thickening occurs, decimeter-size barite crystals always thicken towards the stratigraphic top (Fig. 4);

(4) Decimeter-size barite crystal aggregates occur in a fibroradiating pattern with the "open-book-like" fabric always turned towards the stratigraphic top; this fabric never occurs in millimeter-size barite crystals;

(5) When millimeter- and decimeter-size barite crystals are involved in geopetal fabrics, millimeter-size crystals always fill the "V"-shaped cavities between the crystals (Fig. 4);

Thus, the decimeter-size barite crystals were fixed at the sedimentary interface during their growth. They were chemically fed by the brines and made up beds with decimeter-sized crystals (free growth) which were later, in places, covered with layers rich in millimeter-size barite crystals.

Physico-chemical parameters of barite precipitation and growth

Several parameters control the precipitation of barite: pH, Eh, temperature, pressure, chemical composition, water turbulence, bacterial activity, etc. In fact, the behaviour of trace elements in aquatic systems is highly complex due to the large number of possible interactions with ill-defined, dissolved and particulate components. In the system Ba–S–O–H–C, the Eh–pH diagram for barium species at 25°C and 100 kPa shows that below pH of 1.2, $BaSO_4$ dissolves to form Ba^{2+}, and $BaSO_4$ is replaced by $BaCO_3$ at a pH of about 11.6 (Brookins, 1988). However, the course of the $BaSO_4$ solubility is hardly changed by the presence of NaCl in the system. A very strong, quantitative increase in the solubility is seen even at low NaCl concentrations (see, e.g., the investigations of Strübel, 1967). The marine geochemistry of barium has been discused elsewhere (Chow and Goldberg, 1960; Hanor, 1969; Wogelmuth and Broecker, 1970; Church, 1970; Church and Wogelmuth, 1972; etc.), but note that direct precipitation may take place when external factors change. Mixing with other water is one of the main causes suggested for precipitation, and has been invoked at Chaudfontaine (Dejonghe, 1985, 1986; Dejonghe et al., 1989). However, we believe that at Chaudfontaine, the main factor responsible for the occurrence of two different populations of barite crystals was the varying degree of barium supersaturation.

Growth of decimetric barite crystals

Slight supersaturation gave rise to scarce nucleation. The few barite nuclei deposited at the sedimentary surface, therefore, grew in their preferred crystallographic directions. In the case of inclined crystals, free growth in the brine was only hindered when crystals touched each other. Sub-vertical crystals grew without hindrance, hence the preferred development of aggregates of sub-vertical crystals. The weak degree of barium supersaturation must have lasted for long periods, in order to have allowed crystals to have grown to decimeter sizes. Still water is another prerequisite for the growth of large barite plates with a high resistence to currents as these would otherwise have been broken. These conditions explain why decimeter-size barite crystals are relatively isolated, preferentially sub-vertical, and scarce among aggregates, why they thicken towards the stratigraphic top and why their fan-like fabric opens out towards the stratigraphic top.

Growth of millimeter-size barite crystals

Strong Ba supersaturation gave rise to abundant nucleation: numerous barite nuclei were deposited at the sedimentary surface and grew practically simultaneously in the ooze. The richness in millimeter-size barite crystals of some layers indicates, that although the effect of dilution of barite was slight, it was not nonexistent. The growth of millimeter-size barite crystals was limited by the crystals being rapidly covered with fresh (either barren or mineralized) sediment, and, hence removed from the mineralizing action of the brine. Their further growth depended on the mineral content of the connate water. The lack of preferred orientation is the result of this very early diagenetic growth.

The diagram in Fig. 7 shows the sequence of phenomena giving rise to decimeter-size barite crystal floors associated with rhythmites rich in millimeter-size barite crystals. Figure 8 illustrates this model; the sequence of events observed is as follows.

(1) Heterogeneously mineralized sediment (*C*) is deposited. The discontinuity surface at the top of the sediment (*a–a′–a″*) forms a ridge. (Such ridges often occur in slumped formations.) A small fault (f) with a throw of a few mm affects the black layer (*a–a′*).

(2) Above the discontinuity surface (*a–a′–a″*), a sediment rich in millimeter-size barite crystals is deposited, filling in a mini-trough left of, and due to mini-fault *f*; to the right of the ridge, the layer wedges out. These two features prove that both the ridge and fault existed before the millimeter-size crystal-rich sediment was deposited.

(3) A floor of centimeter-size barite crystals grows at the sediment/water interface in still water. A giant decimeter-size barite crystal (*A*), over 20 cm long, grows preferentially at the top of the ridge. The cylindrical exterior of the core shows that crystal *A* is welded to other decimeter-size barite crystals in various positions.

(4) A 10-cm-thick bed of silicite is depos-

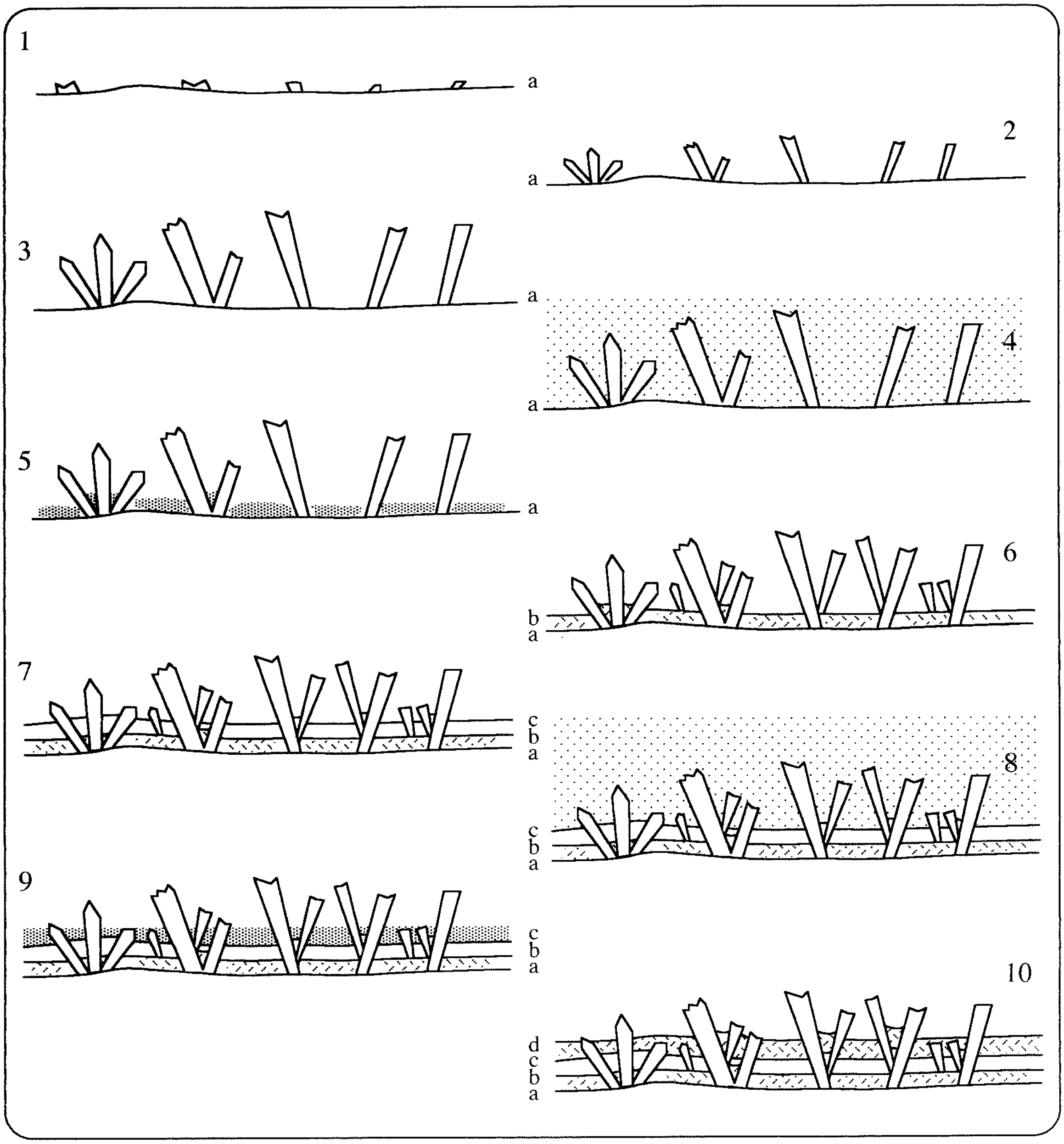


Fig. 7. Diagram of the development of decimeter-size barite crystal floors associated with millimeter-size barite crystal-bearing rhythmites. *a*, *b*, *c*, and *d* are water/sediment interfaces and the stippling at stages 4 and 8 represents nucleation in the brine.

ited, wich did not cover completely the decimeter-size barite crystal *A*; layer *b–b′–b″* is 2 cm thick and very rich in millimeter-size barite crystals; a few lamellar millimeter-size barite crystals are sandwiched between black and brown laminae.

(5) Following this series of relatively barren deposits, mineralized sedimentation starts again, initially in the form of millimeter-size barite crystals and subsequently forming spathic barite (*B″*).

(6) More sediment is probably deposited

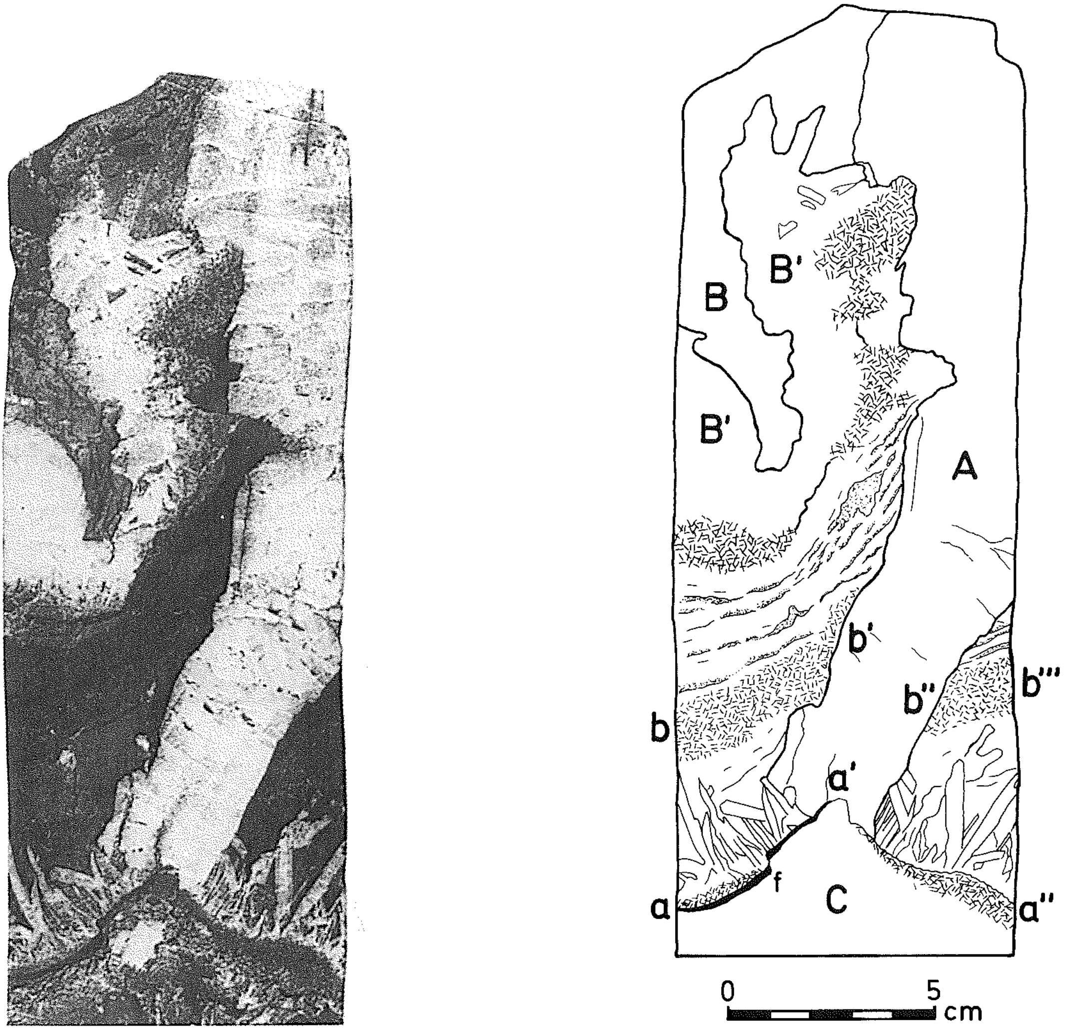


Fig. 8. Chaudfontaine drill hole 134E396: longitudinal section of a core between depths of 206.32 and 206.55 m. *C* is an aggregate of lamellar to anhedral millimeter-size barite crystals and silicite. *a–a′–a″* is a ridge-shaped sedimentary surface affected by a small synsedimentary fault *f*. The right side of the ridge and the small depression due to the minifault are covered with sediment that is very rich in millimeter-size barite crystals. Above the ridge, a floor of centimeter-size barite crystal and a barite megacrystal (*A*) of more then 20 cm long has developed. *b–b′–b–b′* is a layer of silicite with frayed carbonate clasts and a few lamellar millimeter-size barite crystal parallel to the bedding. *B′* is massive pure barite whose core (*b*) contains silicite.

before local load casting takes place. The massive barite (*B′*) sinks into the underlying unconsolidated, mud-like sediment, bending the black and brown laminae and fraying them, and bending layer *b–b′*. The load casting also applies lateral stress to decimeter-size barite crystal *A*, folding it: a set of fan-like fractures is still visible in the flexure. A slight clockwise movement of crystal *A* explains the position of layer *b–b′–b″–b′″* and of the overlying laminae. Differential compaction may have concurred with load casting in deforming sediment.

This example illustrates the near contemporaneity of several sedimentary processes such as rhythmic layering, discontinuity surfaces, decimeter-size barite crystal floors, gravitational displacement, levelling of irregularities at the sediment/water interface, redeposition of barite crystals, and diagenetic deformation of decimeter-size barite crystals. It clearly shows that the layer rich in millimetric barite crystals (*b–b′–b″–b‴*) is parallel to the bedding. It reveals that millimeter- and decimeter-size barite crystals were deposited by two different processes, i.e., static and dynamic (millimeter-size barite crystals lacking preferred orientation are deposited in layers, fill in depressions and form condensed wedges, whereas decimeter-size barite crystal, roughly at right angles to the sediment/water interface make up crystal floors). Physico-chemical variations give rise to rapid changes in lithology and barite crystal size. Variations in current energy are also suggested by the fact that decimeter-size barite crystal floors, which grew in a low-energy environment, are adjacent to lamellar barite crystals sandwiched between laminae (hence probably deposited in higher-energy currents). The load casting clearly shows that barite existed before consolidation of the sediment.

Conclusions

Table 1 summarizes the main features of the Chaudfontaine ore deposit.

Some fabrics are characteristic of exokinematic behaviour (*sensu* Elliot, 1965) and could not have occurred in any other way (baritic filling sediment, redeposited breccias, redeposited lamellar crystals, levelled irregularities at the sediment/water interface). Other fabrics are caused by endokinematic movements (slumping, intraformational breccias, synsedimentary faults, load casts). Although still other fabrics may also result from non-sedimentary processes (barite crystal-size variations, rhythmic deposits, discontinuity surfaces, growth inhibition), sedimentary deposition has been shown to give a logical explanation for all of them.

Several structures prove that the mineralization appeared before late diagenesis, and some barite crystals were deformed by early diagenetic events such as differential compaction and the movement of hydroplastic sediment. However, compaction did not play a major role in orientating crystals parallel to the bedding, which occurred following the destruction of decimeter-size barite crystal floors and their redeposition.

In fact, the forces of gravity controlled, at least partly, the development of many of the structures. This is true of the baritic sediment filling the decimeter-size barite crystal floors, the levelling of irregularities at the sediment/water interface, slumping with intraformational glide-breccias, redeposited lamellar barite crystals, synsedimentary minifaults, and local pressure.

Other structures may be geopetal without gravity controlling their development, as in the case of barite crystal floors, triplets of centimeter- to decimeter-size barite crystals and upright barite crystals which thicken upwards.

A general feature is the lack of secant fabrics: all the structures observed in the Chaudfontaine ore deposit are conformable.

The sedimentary ore fabrics tell us very little about the paleogeographic conditions. As Conybeare and Crook (1968, p.38) point out: "*slump structures are not indicative of any particular depositional environment (...). Slumping is a common feature in sediments deposited on slopes with gradients as low as 1°*". However, rapid changes in strike and dip occur in environments with varying currents and unstable deposits. In fact, deposition seems to have been controlled both by still water (fine rhythmic layering, decimeter-size barite crystal floors) and higher energy currents (redeposited crystals and breccias).

The upright barite crystals are very similar to selenite gypsum megacrystals from marine evaporites, which also occur through free growth in brine above the sediment/water interface. Nearly all the geopetal structures de-

TABLE 1

Main features and sedimentary structures found in the Chaudfontaine ore deposit

Structures	Abundant	Rare	Syngenetic	Early diagenetic	Late diagenetic	Exokinematic	Endokinematic	Mechanical	Chemical	Geopetal	Gravity control
(1) Decimeter-size barite crystals	*		*						*		
(2) Millimeter-size barite crystals	*			*					*		
(3) Rhythmic layering	*		*	*					*		
(4) Discontinuity surfaces	*		*								
(5) Decimeter-size barite crystal floors	*		*						*	*	
(6) Baritic sediment filling	*		*	*		*		*	*	*	*
(7) Levelling of irregular relief	*		*	*		*		*	*	*	*
(8) Slumping with intraformational breccias		*		*			*	*		*	*
(9) Sedimentary breccias	*		*			*		*			
(10) Redeposited lamellar barite crystals		*	*			*		*			*
(11) Synsedimentary minifaults		*	*				*	*			*
(12) Inhibited growth in barite crystals		*	*	*					*		
(13) Loadcasts		*		*			*	*		*	*
(14) Bent crystals		*			*		*	*			*

scribed here for barite have been mentioned for gypsum from the Messinian evaporites of the Mediterranean (Hardie and Eugster, 1971; Rouchy, 1976, 1982; Lo Cicero and Catalano, 1976; Shearman and Orti Cabo, 1976).

From a more general point of view, we would like to emphasize the association of the Chaudfontaine deposit with a particular paleogeographic and eustatic context: an already partially restricted marine basin (with significant micro-aerophile and reducing environments) encountering a eustatic drop, provoking first the appearance of the cryptalgal facies (top of the micritic bioherms and oncolitic shoals), then the formation of evaporitic lagoons where waters of both continental and marine origin had access and could intermix with each other.

After the formation of the mineralization a eustatic rise seals the deposit under an impermeable layer; the influence of the following burial diagenesis is relatively minor.

It should be noted that most of the structures here described also occur in environments other than lagoonal sedimentation on the sea floor. Most of them have been observed, for example, in internal sediments of paleokarstic ore deposits (Bogacz et al., 1973; Boni and Amstutz, 1982; Orgeval, 1976; Lagny, 1975; Sass-Gustkiewicz, 1975; etc.)

In conclusion, the study of the sedimentary structures found in the Chaudfontaine ore deposit has permitted the deduction of the metallogenic constraints to which it was subjected. All genetic interpretations for this deposit must account for the three main conclusions of this study:

(1) The millimeter-size barite crystals grew from nuclei mechanically deposited from brine and were fed during early diagenesis in unconsolidated sediment;

(2) The decimeter-size barite crystals were fixed at the sediment/water interface and were directly fed from the brine in which they grew (free growth);

(3) Some crystals were broken from crystal floors and carried some distance before being mechanically redeposited.

Acknowledgements

The authors thank H. Förster, M. Lécolle and J.C. Macquar for a very constructive reviewing of this paper and A. Howard for her collaboration in improving the quality of the English version.

References

Amstutz, G.C. and Fontboté, L., 1982. Observations of the genesis of strata-bound Pb–Zn (F–Ba) deposits in carbonate rocks. Preprint Proc. Int. Conf. Mississippi Valley-type Deposits, Rolla, Mo., 10 pp.

Arbey, F., 1980. Les formes de la silice et l'identification des évaporites dans les formations silicifiées. Bull. C.R. Explor. Prod. Elf- Aquitaine, Pau, Vol. 4: 309–365.

Bogacz, K., Dzulinski, S. and Haranczyk, C., 1973. Caves filled with clastic dolomite and galena mineralization in disaggregated dolomites. Ann. Soc. Géol. Pologne, Cracow, XLIII: 59–72.

Boni, M. and Amstutz, G.C., 1982. The Permo-Triassic paleokarst ores of Southwest Sardinia (Iglesiente–Sulcis). An attempt at a Reconstruction of paleokarst conditions. In: G.C. Amstutz, A. El. Goresky, G. Frenzel, C. Kluth, G. Moh, A. Wauschkuhn and R.A. Zimmerman (Editors), Ore Genesis, The State of the Art. Spec. Publ., Soc. Geol. Appl. Miner. Dep., Springer, Berlin, Vol. 2, pp. 73–82.

Boulvain, F., 1989. Observations sur la cimentation des biohermes de "marbre rouge" du Frasnien franco-belge. Ann. Soc. Géol. Belg., 112: 137–149.

Boulvain, F., 1990. Sédimentologie et diagenèse des monticules micritiques frasniens "F2j" de Belgique. Unpubl. thesis Doctorat Sciences, Univ. Libre Bruxelles, 535 pp.

Boulvain, F. and Coen-Aubert, M., 1991. Sédimentologie, diagenèse et stratigraphie des biohermes de marbre rouge de la partie supérieure du Frasnien belge. Bull. Soc. Belge Géol., 100: 3–55.

Boulvain, F., Herbosch, A. and Keppens, E., 1992. Diagenèse des monticules micritiques de la partie supérieure du Frasnien du synclinorium de Dinant (Belgique, France). C.-R. Acad. Sci. Paris, t. 315, sér. II: 551–558.

Brookins, D.G., 1988. Eh–pH Diagrams for Geochemistry. Springer, Berlin, 176 pp.

Cauet, S., Weis, D. and Herbosch, A., 1982. Genetic study of Belgian lead-zinc mineralization in carbonate environments through lead isotopic geochemistry. Bull. BRGM 2, Sect. II(4): 329–341.

Chow, T.J. and Goldberg, E.D., 1960. On the marine geochemistry of barium. Geochim. Cosmochim. Acta, 20: 192–198.

Church, T.M., 1970. Marine barite. Ph.D. thesis, Univ. California, San Diego, Calif.

Church, T.M. and Wogelmuth, K., 1972. Marine barite saturation. Earth Planet. Sci. Lett., 15: 35–44.

Cnudde, C., Dejonghe, L. and Mamet, B., 1986. Paléogéographie des formations givetiennes et frasniennes du synclinorium de Verviers. Prof. Pap. Serv. Géol. Belg., Bruxelles, 225, 45 pp.

Coen-Aubert, M. and Lacroix, D., 1979. Le Frasnien dans la partie orientale du bord Sud du synclinorium de Namur. Ann. Soc. Géol. Belg., 101: 269–279.

Conybeare, C.E.B. and Crook, K.A.W., 1986. Manual of Sedimentary Structures. Dep. Natl. Dev. Bur. Min. Res. Geol. Geoph. (Australia), Canberra, 102, 327 pp.

Davaine, J.J., 1980. Les croûtes silico-fluorées mésozoïques du Bazois. Description et modèle d'évolution. In: Les Paléosurfaces et leur Métallogenèse. Coordination Samama, Mém. BRGM, Orléans, 104: 211–342.

Dejonghe, L., 1979. Discovery of a sedimentary Ba (Fe,Zn,Pb) ore body of Frasnian age at Chaudfontaine, province of Liège, Belgium. Miner. Deposita, Berlin, 14: 15–20.

Dejonghe, L., 1985. Contribution à l'étude métallogénique du synclinorium de Verviers (Belgique). Thesis Doctorat dès Sciences Naturelles, Mém. Sci. Terre, Univ. Curie, Paris, 85-23, 389 pp.

Dejonghe, L., 1986. Liaison de la minéralisation Ba (Zn,Pb) d'âge frasnien de Chaudfontaine (Province de Liège, Belgique) aux évaporites sulfatées. Bull. Soc. Belge Géol., Bruxelles, 95: 203–212.

Dejonghe, L., 1990. The sedimentary structures of barite: examples from the Chaudfontaine ore deposit, Belgium. Sedimentology, 37: 303–323.

Dejonghe, L. and Mamet, B., 1989. Paleogeography of two reef bearing Devonian formations, Verviers synclinorium, Belgium. Can. Soc. Pet. Geol., 14: 599–606.

Dejonghe, L., Wautier, J. and Martin, H., 1978. Occurrence de bravoïte dans la paragenèse Ba, Fe,S (Zn,Pb), du gîte de Chaudfontaine (Province de Liège). Bull. Soc. Belge Géol., Bruxelles, 87: 73–85.

Dejonghe, L., Guilhaumou, N. and Touray, J.C., 1982a. Les inclusions fluides de la barite du gisement sédimentaire de Chaudfontaine (Province de Liège, Belgique). Bull. Soc. Belge Géol., Bruxelles, 91: 79–89.

Dejonghe, L., Rye, R.O. and Cauet, S., 1982b. Sulfur isotopes of barite and lead isotopes of galena from the stratiform deposit in Frasnian carbonate and shale host-rocks of Chaudfontaine (Province of Liège, Belgium). Ann. Soc. Géol. Belg., Liège, 105: 95–103.

Dejonghe, L., Wautier, J. and Laduron, D., 1985. Réflectance et composition chimique des bravoïtes du gîte sédimentaire de Chaudfontaine et du gîte filonien de La Rochette (Province de Liège, Belgique). Bull. Mineral., Paris, 108: 679–690.

Dejonghe, L., Boulègue, J., Demaiffe, D. and Létolle, R., 1989. Isotopic geochemistry (S,C,O,Sr,Pb) of the Chaudfontaine mineralization (Belgium). Mineral. Deposita, Berlin, 24: 132–140.

Elliot, R.E., 1965. A classification of subaqueous sedimentary structures based on rheological and kinematical parameters. Sedimentology, 5: 193–209.

Frykman, P., 1986. Diagenesis of Silurian bioherms in the Klinteberg Formation, Gotland, Sweden. In: J.H. Schroeder and B.H. Purser (Editors), Reef Diagenesis. Springer, Berlin, pp. 399–423.

Graulich, J.M., Dejonghe, L. and Cnudde, C., 1984. La définition du synclinorium de Verviers. Bull. Soc. Belge Géol., Bruxelles, 93: 79–82.

Graulich, J.M. and Dejonghe, L., 1986. Le bien-fondé de la notion de synclinorium de Verviers. Bull. Soc. Belge Géol., Bruxelles, 95: 35–43.

Hanor, J.S., 1969. Barite saturation in sea water. Geochim. Cosmochim. Acta, 33: 894–898.

Harben, P.W. and Bates, R.L., 1984. Geology of the Nonmetallics. Metal Bull. Inc, New York, N.Y., 393 pp.

Hardie, L.A. and Eugster, H.P., 1971. The depositional environment of marine evaporites: a case for shallow clastic accumulation. Sedimentology, 16: 187–220.

Johnson, J.G., Klapper, G. and Sandberg, C.A., 1985. Devonian eustatic fluctuation in Euramerica. Geol. Soc. Am. Bull., 96: 567–587.

Kendall, A.C., 1977. Fascicular-optic calcite: a replacement of bundled acicular carbonate cements. J. Sediment. Petrol., 47: 1056–1062.

Kendall, A.C. and Tucker, M.E., 1973. Radiaxial fibrous calcite: a replacement after acicular carbonate. Sedimentology, 20: 365–389.

Kerans, C., Hurley, N.F. and Playford, P.E., 1986. Marine diagenesis in Devonian reef complexes of the Canning Basin, Western Australia. In: J.H. Schroeder and B.H. Purser (Editors), Reef Diagenesis. Springer, Berlin, pp. 357–380.

Lagny, P., 1975. Le gisement plombo-zincifère de Salafossa (Alpes Italiennes orientales): remplissage d'un paléokarst triassique par des sédiments sulfurés. Miner. Deposita, 10: 345–361.

Lo Cicero, G. and Catalano, R., 1976. Facies and petrography of some Messinian evaporites of the Ciminna Basin (Sicily). Mem. Soc. Geol. It., 16: 63–81

Macquar, J.C., 1978. Les concentrations barytiques stratiformes de l'Hettangien supérieur des Causses. Une minéralisation en milieu margino-litoral dans un environnement évaporitique. Sci. de la Terre, Nancy, XXII: 113–126.

Meyers, W.J., 1978. Carbonate cements: their regional distribution and interpretation in Mississippian limestones of south western New Mexico. Sedimentology, 25: 371–400.

Miller, J., 1986. Facies relationships and diagenesis in Waulsortian mudmounds from the Lower Carboniferous of Ireland and N. England. In: J.H. Schroeder and B.H. Purser (Editors), Reef Diagenesis. Springer, Berlin, pp. 311–335.

Orgeval, J.J., 1976. Les remplissages karstiques minéralisés: exemple de la mine des Malines (Gard, France). Mém. H. Sér. Soc. Géol. Fr., 7: 77–83.

Rodeghiero, F., 1977. Le mineralizzazioni a Pb,Zn, fluorite, barite nel carnico della zona de Pizzo Della Presolano (Prealpi Bergamasche). Boll. Assoc. Mineria Subalpina Torino, XIV: 453–474.

Rouchy, J.M., 1976. Sur la genèse de deux principaux types de gypses (finement lité et en chevrons) du Miocène terminal de Sicile et d'Espagne méridionale. Rev. Géogr. Phys. Géol. Dyn. Paris, XVIII: 347–364.

Rouchy, J.M., 1982. La genèse des évaporites messiniennes de Méditerranée. Mém. Mus. Nat. Hist. Natl., Paris, C, L, 267 pp.

Sabouraud-Rosset, C., 1976. Inclusions solides et liquides dans le gypse. Trav. Lab. Géol. Ecole Normale Supérieure, Paris, 10, 119 pp.

Sabouraud, C., Macquar, J.Cl. and Rouvier, H., 1980. Les inclusions fluides, témoins et faux-témoins des conditions de dépôt. Quelques exemples pris dans les minéralisations Pb,Zn,Ba,F du sud du Massif Central français. Miner. Deposita, Berlin, 15: 211–230

Sass-Gustkiewicz, M., 1975. Stratified sulfide ores in karst cavities of the Olkusz mine (Cracow–Silesian region, Poland), Ann. Soc. Géol. Pologne, Cracow, XLV: 63–68.

Schulz, O., 1976. Typical and nontypical sedimentary ore fabrics. In: K.H. Wolf (Editor), Handbook of Strata-Bound and Stratiform Ore Deposits. Elsevier, Amsterdam, Vol. 3: 295–338.

Shearman, D.J. and Orti Cabo, F., 1976. Upper Miocene gypsum: San Miguel De Salinas, S.E. Spain. Mem. Soc. Geol. It., 16: 327–339.

Strübel, G., 1967. Zur Kenntnis und genetischen Bedeuntung des Systems BaSO[cf15]4[cf1]-NaCl-H[cf15]2[cf1]0. N. Jahrb. Mineral., Abh., Stuttgart, 3: 223–234.

Teodorovich, G.I., 1958. Classificaton des roches silicato-carbonato-argileuses. Ann. Serv. Inf. Géol. BRGM, Paris, (translation of Razredka i okhrana nedr), 33: 6–11.

Wogelmuth, K. and Broecker, W.S., 1970. Barium in sea water. Earth Planet. Sci. Lett., 8: 372–378.