Anthropologica et Præhistorica, 125/2014 (2016) : 23-43

Geological record and depositional setting of Palaeozoic oolitic ironstones in Western Europa

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Résumé

Cet article décrit les différentes occurrences géologiques d'hématites oolithiques connues dans la partie nord-ouest de l'Europe. Les contextes géologiques, lithostratigraphiques, structuraux et paléoenvironnementaux de certaines couches de minerais de fer oolithique sont explicités pour les gisements belges (Lochkovien, Givetien, Frasnien et Famennien, Aalénien-Bajocien), normands (Ordovicien), grand-ducaux (Aalénien-Bajocien) et provenant de l'Eifel (Emsien-Eifelien). Des données chimiques générales ainsi que leur attribution à un des trois types d'hématites oolithiques complètent le tableau général. Ces données de base sont mises en perspective par rapport aux sites d'habitat du Néolithique ancien des régions concernées.

Mots-clés : *Minerai de fer oolithique, Famennien, Ordovicien, Dévonien moyen, occurrences géologiques, Europe occidentale, Belgique, Eifel, Normandie.*

Keywords: Oolitic ironstones, Famennian, Ordovician, Middle Devonian, geological record, Western Europe, Belgium, Eifel, Normandy.

1. INTRODUCTION

Approximately 175 different oolitic ironstone (OIS) occurrences are known worldwide (Fig. 1). Table 1 presents the age range of OIS in selected Western European countries. They accumulated on shallow shelves after waning of the normal sedimentation that built shoaling-upward detrital sequences (Van Houten & Arthur, 1989). The genesis of oolitic ironstones is poorly understood and is still a matter of controversy and discussion (see Young, 1989). From a sedimentological point of view, OIS formed at low sedimentation rates or even hiatuses in normal sedimentation, often producing lag deposits. From a sequence-stratigraphical point of view, OIS often correspond to transgressive system tracts (TST) and condensed sequences (CS). They are frequently capped by hardgrounds, underlying major flooding surfaces (MFS) (Fig. 2). Therefore, OIS represent excellent stratigraphical marker beds that can be traced over several tens of kilometers throughout sedimentary basins (see a.o. Dreesen, 1989a). Their worldwide abundance is mainly concentrated during two Phanerozoic episodes: the Ordovician through the Devonian and the Jurassic through the Paleogene. Ironstones developed repeatedly in about 15 major successions preserved in only about 10 sedimentary basins throughout the globe. They are uncommon in Cambrian, Permian, Triassic and Cenozoic times. Long episodes comprise composite successions of ironstones interrupted by non-productive intervals of a few tens of million years long. For the unstable post-Caledonian Ardennes shelf in Southern Belgium, 7-8 episodes have been inventoried from the Lower Devonian through the Latest Devonian by Van Houten & Arthur, 1989. Remarkably, Phanerozoic OIS and black shales often developed simultaneously during the above Ordovician-Devonian and Jurassic-Palaeogene 150-170 Ma plate-tectonically controlled intervals. Their recurring stratigraphic association suggests that they were a specific response to mutually favorable conditions, such as: continental breakup and dispersal or subdued orogeny, weak oceanic circulation and widespread oceanic anoxia, moderate detrital influx building shoaling-upward regressive sequences followed by rapid transgression associated with hiatus and unconformities, and accumulation in inland seas or on continental margins where the width of shallow shelves was rapidly modified by transgressions and regressions.

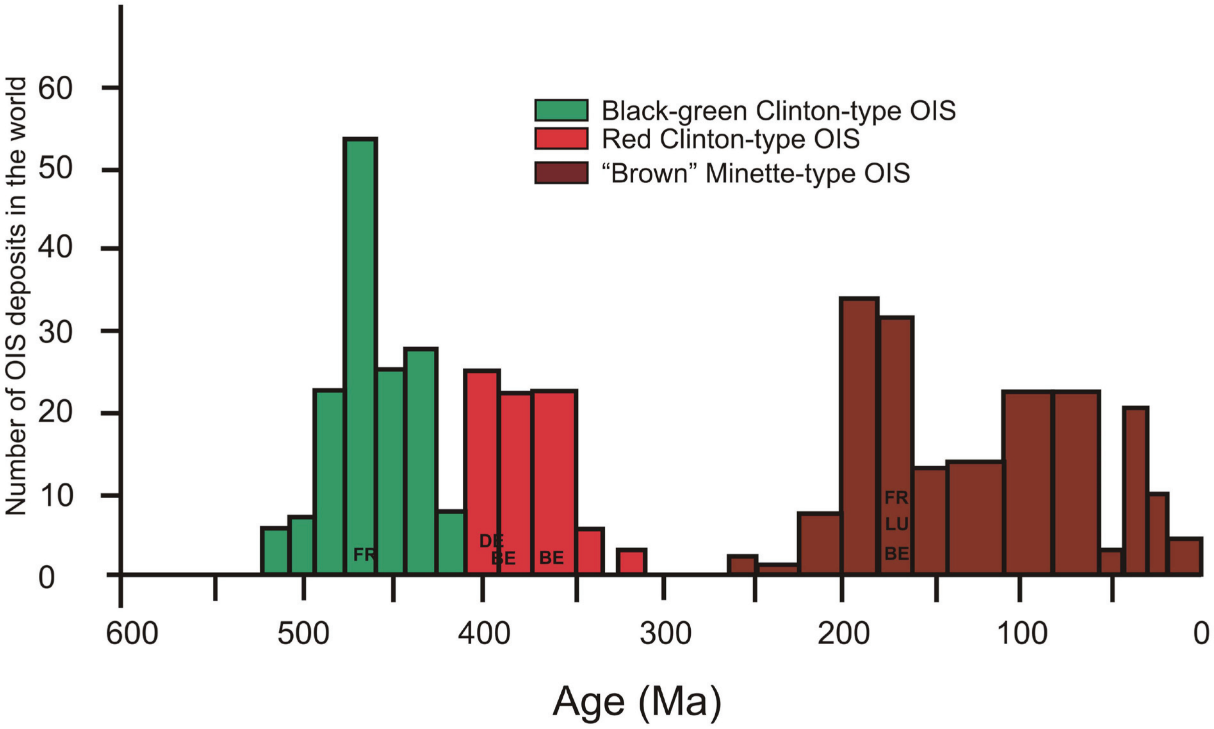

Fig. 1 – Secular distribution of Phanerozoic oolitic marine ironstones. FR= France, DE= Germany, BE= Belgium, LU= Grand-Duchy of Luxemburg. Modified after Bekker *et al.*, 2010, from Petranek and Van Houten (1997).

Fig. 1 *– Distribution temporelle des hématites oolithiques marines. FR = France, DE = Allemagne, BE = Belgique, LU = Grand-Duché de Luxembourg. Modifié d'après Bekker et al., 2010 de Petranek and Van Houten (1997).*

	Czech Rep.	*Austria*	*Germany*	*NL*	*Belgium*	*GDLux*	*N.France*	*UK*
Tertiary	–	–	Eocene	–		–	–	–
Cretaceous	–	–	Middle Cretaceous	–	–	–	Middle Cretaceous	Lower Cretaceous: Valanginian to Hauterivian
Middle Jurassic	–	–	Aalenian to Oxfordian	–	(Aalenian)	Aalenian	Bajocian	
Lower Jurassic	–	–	Sinemurian to Pliensbachian	–	Up.Toarcien	Up.Toarcien	–	Pliensbachian to Toarcian
Devonian - Lower - Middle - Upper	–	–	Eifelian Emsian	–	Frasnian/Famennian Eifelian/Givetian (Lochkovian)	–	–	–
Silurian	–	LLandov Ludlow	–	–	–	–	–	–
Ordovician	Caradocian Llanvirnian –		Caradocian – Arenigian	–	–	–	– Llanvirnian Arenigian	Caradocian Llanvirnian Arenigian

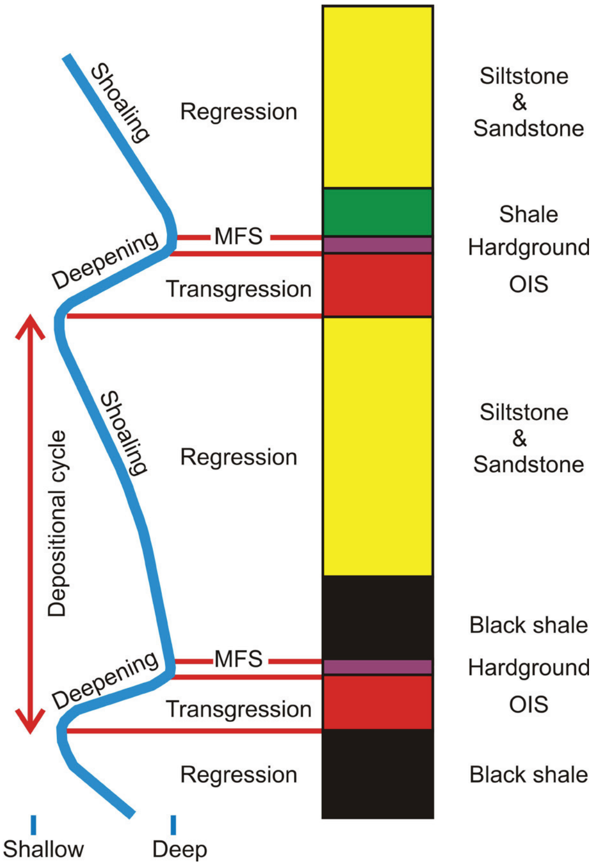

Fig. 2 – Generalised sequence-stratigraphical model for the Phanerozoic OIS (Bekker *et al.*, 2010). MFS: Maximum Flooding Surface.

Fig. 2 *– Modèle général de stratigraphie séquentielle pour les OIS phanérozoiques OIS (Bekker et al., 2010). MFS : surface d'inondation maximale.*

Since 2010 a team of archaeologists and geologists have been studying OIS found on Linear Bank Keramik (LBK) and Mesolithic sites both of the Hesbaye area and the Dendre river area in Belgium and of Normandy in France. As a consequence only the geological occurrences of OIS from the westernmost part of Germany (Eifel), Belgium and North France (Normandy) are here described in detail, so that they can be linked to other papers included in this volume, that were written by members of the same research team. Occurrences are presented country by country, and from the east to the west. An overview of the classification schemes and current terminology of Phanerozoic sedimentary iron deposits, more especially that of ironstones, is given by Dreesen *et al.* (2016: this vollume). In the latter study a comparative petrographical analysis has been applied to the geological samples of OIS susceptible of having being used as raw materials for prehistoric red ochres.

2. OIS FROM THE EIFEL AREA (W-GERMANY)

The Rhenohercynian Zone is the deepest part of the Variscan geosyncline and it is present both in western Germany (Eifel) and in Belgium (Ardennes Allochthon and Brabant Parautochton *sensu* Belanger *et al.*, 2012). It is filled with Devonian and Carboniferous sediments, up to 10,000 m thick. Intensive folding and faulting and locally foliation, took place during the middle part of the late Carboniferous. This zone is known for its important metallogenic belt and its richness in minerals, especially those of the Pb-Zn-Fe-Ag group, but also for its Ba and Cu mineralisations. The iron ore mining started since the La Tène time, more especially in the Lahn-Dill area (east of the Rhine river) that is rich in Devonian silica-rich exhalative ironstone deposits. An iron smelting furnace of Hallstatt age was discovered NW of Hillesheim (Haffner, 1971), whereas Roman slags of iron smelting were found south of Ahrweiler (Kleemann, 1965). Sixty-five iron ore mines were once active in Western Germany but they are all closed since more than twenty years. Information on iron extraction before 1800 and during the Middle Ages is rather scarce. The in-

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Tab. 1 – (opposite page) Age range of OIS in selected Western European countries. In green: Black/green iron ore (Clinton-type OIS); in red: red iron ore (Clinton-type OIS); in orange: Brown iron ore (Minette-type OIS). Definitions of Clinton-type and Minette-type OIS can be found in Dreesen, Savary & Goemaere, 2016.

Tab. 1 – (page précédente) Distribution des OIS dans les pays d'Europe occidentale en fonction de leur âge. En vert : minerai de fer noir/vert (Clinton-type OIS); en rouge : minerai de fer rouge (Clinton-type OIS); en orange : minerai de fer brun (Minette-type OIS). Les définitions des Clinton-type et Minette-type OIS peuvent être trouvés dans l'article de Dreesen, Savary & Goemaere, 2016.

tense and long lasting mining activity in Germany has induced the destruction of most if not all of the older iron extraction sites (Walther, 1986). Presently, natural outcrops are quite rare and they are restricted to deeply incised valleys only. The access to the best iron ore deposits is therefore strictly limited.

The Northern Eifel iron ores are of Lower Devonian through Lower Carboniferous age (Fig. 3-4). They include Lower Devonian ferruginous sandstones and mudstones, Middle to Upper Devonian pseudo-oolitic ironstones (OIS) and Middle to Upper Devonian sulfide-ore gossans (Tertiary alteration deposits; Table 1). The Carboniferous iron ores consist of Lower Carboniferous iron-manganese paleo-karst deposits and Upper Carboniferous manganese-rich fossil bog iron deposits (Rath, 2003; Kronz & Eggers, 2001).

On the left side of the Rhine, the Eifel area is mainly built up of Lower Devonian sedimentary

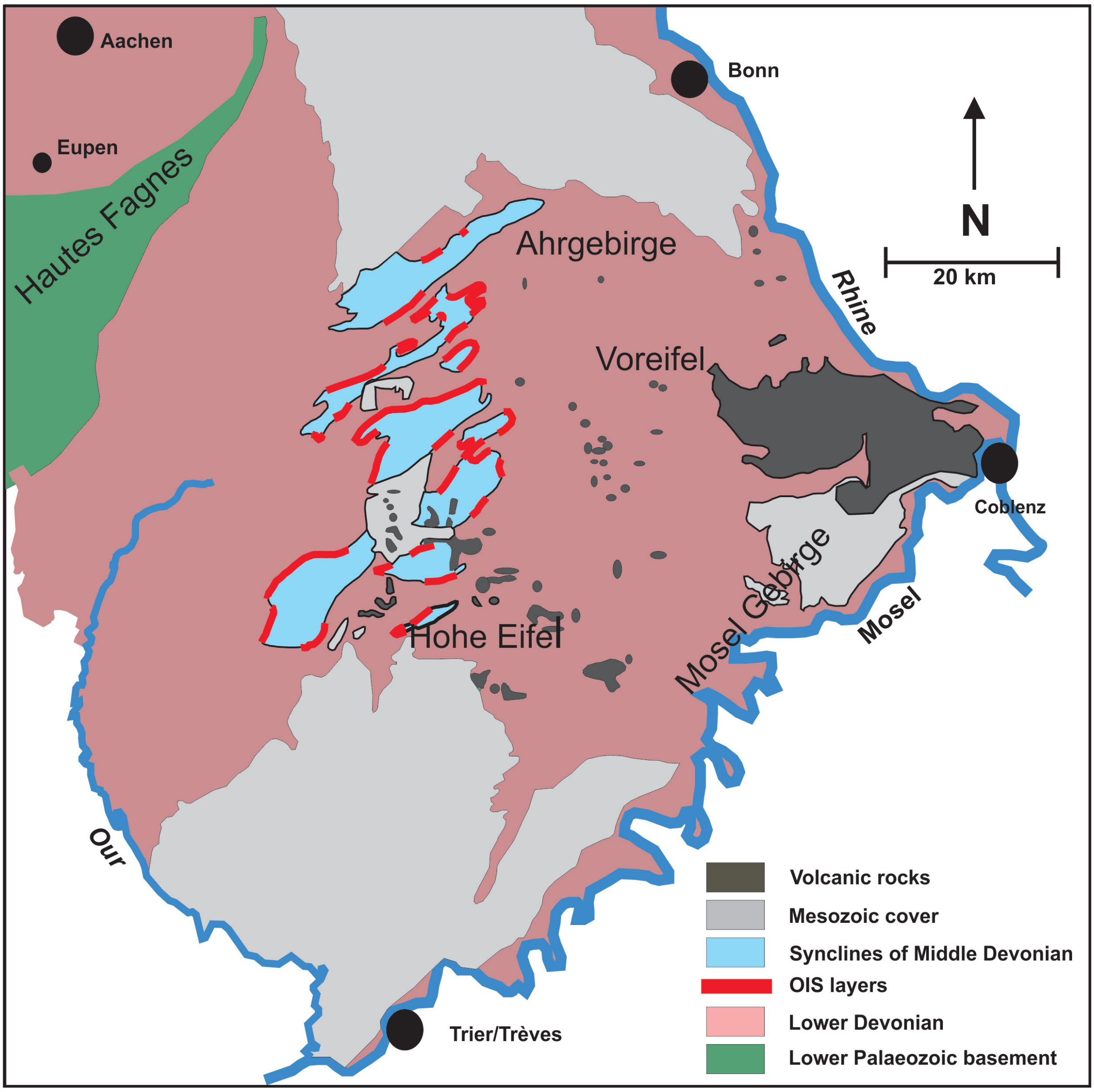


Fig. 3 – Geological map of the Eifel area (modified after Wemmer, 1909; Kasig, 2000; Rath, 2003).
Fig. 3 *– Carte géologique de l'Eifel (modifiée d'après Wemmer, 1909; Kasig, 2000; Rath, 2003).*

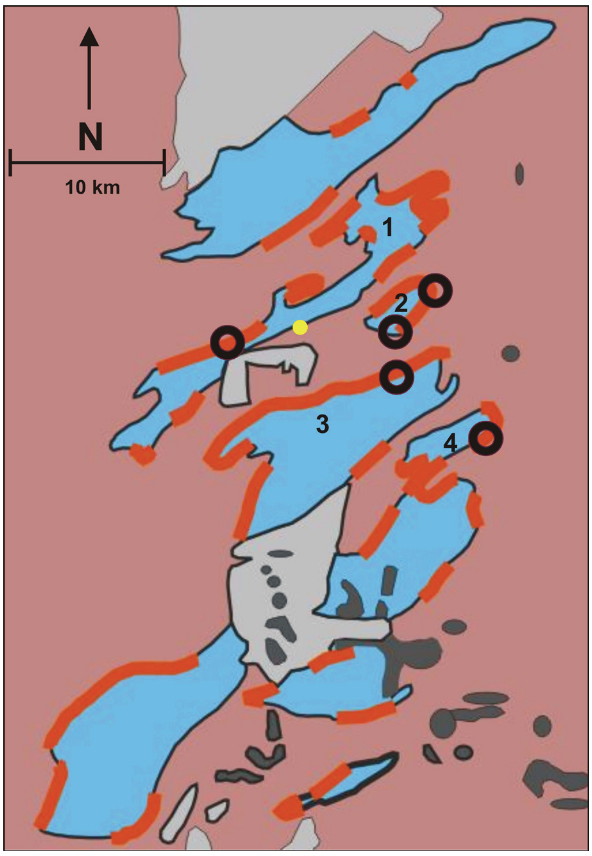


Fig. 4 – Detail of the previous geological map of the Eifel area, showing the location of the sampling points (open black circles). 1: Söttenicher syncline; 2: Rohrer syncline; 3: Dollendorfer syncline; 4: Ahrdorfer syncline. B: Blankenheim; D: Dollendorf; F: Freilingen R : Rohr; S: Stadt Kyll.

Fig. 4 *– Détail de la carte géologique précédente représentant l'Eifel, montrant la localisation des points échantillonnés (cercles vides à bordure noire). 1 : synclinal de Söttenicher; 2 : synclinal de Rohrer; 3 : synclinal de Dollendorfer; 4 : synclinal de Ahrdorfer. B : Blankenheim; D : Dollendorf; F : Freilingen R : Rohr; S : Stadt Kyll.*

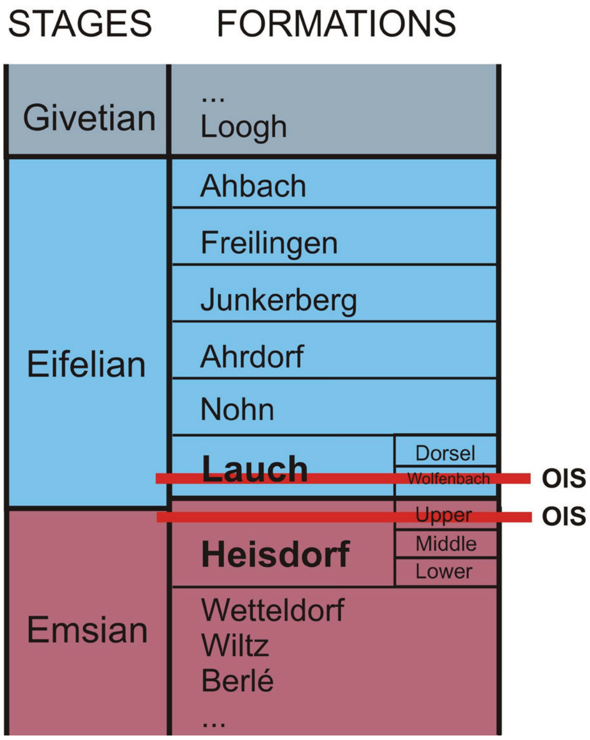


Fig. 5 – Lithostratigraphic column of the studied formations from the western Eifel area (after Struve, 1961).

Fig. 5 – *Colonne lithostratigraphique des formations étudiées de la zone de l'Eifel occidental (d'après Struve, 1961).*

deposits including Middle Devonian carbonate strata in the core of NNE-SSW-oriented synclines (the so-called Eifeler Kalkmulden; Fig. 3-4). Four stratigraphically distinct red pseudo-oolitic (Clinton-type) OIS layers are known, respectively within the Heisdorf Formation (topmost Emsian, Lower Devonian), the Lauch Formation (Basal Eifelian, Middle Devonian), the Nohn Formation (Middle Eifelian, Middle Devonian) and the Freilingen Formation (Uppermost Eifelian, Middle Devonian; Fig. 5). Only the first two levels are important ore deposits and have been sampled for further analysis by us (see Table 2 and another paper included in this book). From north to south, OIS levels are exposed on both flanks of the succeeding Söttenicher, Rohrer, Dollendorfer and Ahrdorfer synclines (Fig. 4). The ironstone-bearing strata are mostly two to three meters thick, but they can reach up to 17 m in the Dollendorfer syncline, and even to 50 m in the Prümer syncline (Meyer, 1994). Detailed information on the lithological composition of the Heisdorf OIS is rather scarce in the literature. However, Wemmer (1909) gave a short overview of its general lithostratigraphical characteristics and mapped its most important outcrops in the Eifel area. The Heisdorf oolitic iron ore consists of fine-grained oolitic ironstones and varies in thickness between 0.5 m (sometimes even less) and 5 m with an average iron content of about 30 %. The Heisdorf OIS layer often comprises several sublevels separated by limestone or shaly interbeds. Locally the OIS laterally grade into an oolitic fossiliferous limestone. Its thickness varies according to its location within the individual synclines: 0,5 m at the SE-border of the Sötenicher syncline, 1.30 m (enclosing a 0,3 m thick limestone bed) at the SE-border of the Blankenheimer syncline and 0.75 m at its SW-border, 1.50-2 m in the Rohrer syncline, 2-3 m at the NW-border of the Lommersdorfer Syncline, 1 m in the Hillesheimer syncline, 0.75 m in the Gerolsteiner syncline and 0.30-1 m in the Prümer syncline. Because of its thinness, the Heisdorf OIS nas bever been extracted underground. Mining activity lasted until 1860 in different quarries (Grubenfelder), called "Valentin" near Nettersheim, "Silistria" near Rohr and "Oskar" near Ripsdorf, Lohscheid (Gerolstein).

On average, the iron ore contains 16-18 % Fe, 5-8 % SiO_2 and up to 28 % of CaO and it has mainly been used for flux purposes (Neumann-Redlin *et al.*, 1977a). The iron ores of the Heisdorf Formation in the Dollendorfer syncline have been mined until 1928. Although the iron ores from the Upper Nohn Formation (so-called Hundsdell-iron) and from the Freilingen Formation have a higher iron content, their thicknesses are not important enough for industrial iron mining (Meyer, 1994).

In the nineties, the Heisdorf and Lauch OIS were geochemically studied in detail by A. Katsch, but the results of this study still remain unpublished. In this study, the lateral variations in thickness and chemical composition (from north to south) of the OIS have been investigated. Moreover, the possibility of geochemically differentiating between the OIS-bearing Lauch and Heisdorf Formations has been demonstrated, corroborating the palaeogeographical evolution scheme of Struve (1961, 1963) for the Eifel limestone synclines (Eifeler Kalkmulden).

In the LBK-settlement of Langweiler (Aldenhoven) located between Aachen and Köln, 118 samples of red ochre (so-called "Rötelproben") have been unearthed. Mineralogical-petrographical and geochemical analysis of the samples pointed to a mix geological origin of the iron ores (Horsch & Keesmann, 1982): only 23 % consists of OIS, possibly derived from relatively nearby Eifel occurrences, besides ferruginous silt- and sandstones, silica-rich hematite ores (related to Lahn-Dill type iron ores) and undifferentiated alteration products.

3. THE NETHERLANDS OIS

The Dutch Linear Pottery Culture (Linearbandkeramik Culture or LBK) sites represent the northwestern most occurrences within the LBK-settlement area. They represent the first farming communities to settle the Netherlands, more precisely within the South Limburg province. Red ochres were found in numerous LBK sites (graveyards, settlements) and contain both

1. **Söttenicher syncline:** SW of Schmidtheim (sample n° 2384 of A. Katsch) – railway cut
2. **Rohrer Mulde**:
    2.1. Reetz, near Blankenheim (60-80 cm sequence of thin-bedded crinoidal limestone containing a more massive 20-30 cm thick limestone bed (grainstone) with ferruginised allochems (oolitic ironstone) assigned to the Laucher Schiechten – followed by marly shales (Obere Lauch) and thin-bedded fossiliferous limestones (with brachiopods & trilobites) (Untere Nohn).
    2.2. Rohr (sample n° 2337 of A. Katsch) - Antonius Busch profile. Heisdorf-Lauch transitional beds: crinoidal limestone (grainstone) with ferruginised allochems and large lithoclasts (brown sandstone), succeeding to green sandstones (= Klerfer Schichten).
3. **Dollendorfer syncline** (nice outcrop, located South of Oberahreck, along road B285 from Blankenheim to Ahrhütte, SW of Freilingen). Estimated total thickness of the Heisdorf oolitic ironstone level: 150 cm divided in different cm- to dm-thick layers. Contains succeeding enrichments with ferruginised allochems. These layers were intensively mined.
4. **Ahrdorfer syncline:** Stahlhof (vicinity of Blankenheim) – Heisdorf level. Thin fossiliferous ironstone level: cloudy or patchy concentrations (of a few cm thick) of hematitic and chamositic allochems = corresponds to the Heisdorf OIS level.
5. **Ahrdorfer-Hillesheimer syncline:** Hammermühle II, Geopfad Hillesheim n° 15: Nice outcrop of fossil ore-type OIS-bearing Heisdorfer Schichten near the Lower-Middle Devonian transition (with ferruginised oncoids and intraclasts).

Tab. 2 – Description of sampled outcrops of the Heisdorf and Lauch OIS.
Tab. 2 *– Description des affleurements échantillonnés des OIS de Heisdorf et de Lauch.*

OIS and compact ironstones (without ooids). The archaeological material from the Dutch South Limburg LBK-sites, has recently been studied by Wijnen (2013). However, there is no geological occurrence of OIS within The Netherlands, so the raw material must have come from elsewhere. The nearest sources of OIS are located more than 40 km from the Dutch LBK sites, more precisely in Belgium or in Germany (Eifel area).

4. THE BELGIAN OIS

The bedrock of Belgium has been mined for different metals, mainly Fe, Pb and Zn, and more accessorily Mn and Au. Iron ores have already been extracted by the Gauls in the Iron Age, before the Roman invasions. The metallic mining industry reached its acme between 1850 and 1870, after which the mining activity steadily declined. The last Clinton-type OIS mine of Couthuin (city of Andenne, north of the Meuse Valley) was closed in 1945. The Minette-type OIS were exploited in the Belgian Lorraine area at Halanzy (city of Aubange) and Musson until 1978 (Dejonghe, 1986). The latter iron ores were used to produce cast iron and steel. Noteworthy is the fact that red waste from the mining of OIS in Andenne, was crushed to produce red powder and that it has been used as a red pigment for industrial applications at the beginning of the 20th century. Besides Palaeozoic OIS ores, Holocene bog iron deposits (in the Campine area), ferruginous sandstones from the Miocene Diest Formation,

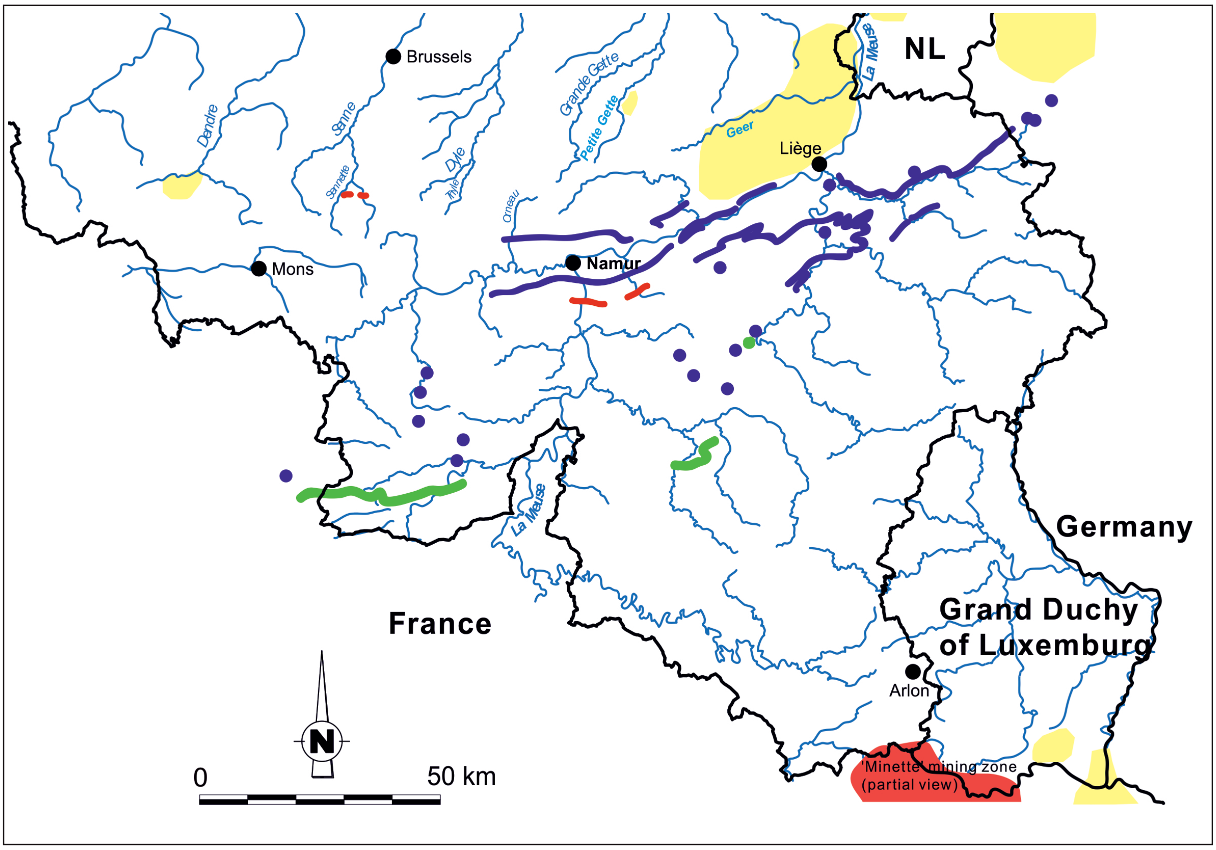


Fig. 6 – Location map of the occurrences of the different OIS layers (after Goemaere *et al.*, 2013) and of the Early Neolithic settlements (yellow areas, after Bosquet). Green lines: the basal Eifelian Clinton-type OIS; red line and dots: Lowermost Frasnian Clinton-type OIS; blue line and dots: Lower Famennian Clinton-type OIS; red area: Jurassic minette.

***Fig. 6** – Carte de localization des occurrences des différentes couches d'OIS (d'après Goemaere et al., 2013) et les habitats du Néolithique ancien (aires colorées en jaune, d'après Bosquet). Lignes vertes : Clinton-type OIS de l'Eifelien ; Lignes et points rouges : Clinton-type OIS du Frasnien basal ; Lignes et points bleus : Clinton-type OIS du Famennien inférieur ; Surfaces rouges : minette-type du Jurassique.*

Lutetian ferruginous sandstones from the Brussels Formation, the "minerai de fer des prés" and the limonitic gossan were mined as well, in order to produce cast steel.

Since the end of the 19th century, several stratigraphically distinct OIS levels have been reported from Lower Devonian (Lochkovian), Middle Devonian (Eifelian), Upper Devonian (Frasnian and Famennian) and Middle Jurassic (Aalenian, Bajocian) strata of Belgium. The Jurassic OIS crop out around the triple point Belgium-France-Grand Duchy of Luxembourg and known as "minette". The geographic distribution of all these iron ores in Belgium and its bordering areas is depicted on figures 6 and 7. The first overviews of the Belgian iron ores are due to Delmer (1912, 1913).

The thin OIS layer enclosed in the Lochkovian shales at the south-eastern limb of the Dinant Synclinorium (Ardennes Allochton) is poorly known (Fig. 6). This level was locally mined as an

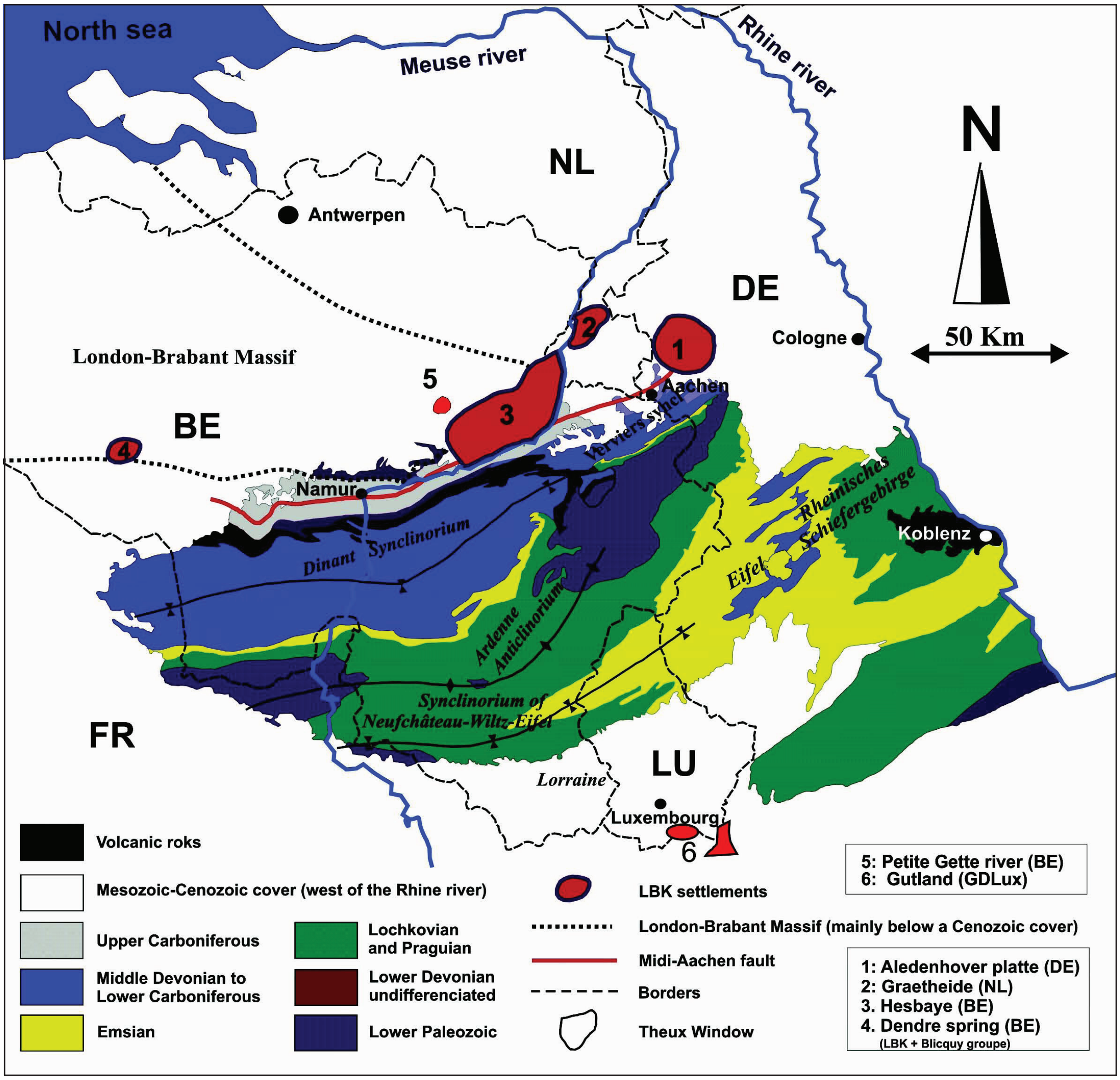


Fig. 7 – Location of the Early Neolithic settlements (in red) plotted on a geological map for Southern Belgium and the Eifel area, west of the Rhine River.

Fig. 7 – *Localisation des habitats du Néolithique ancien (en rouge) superposés à la carte géologique du sud de la Belgique et la partie de l'Eifel située à l'ouest du Rhin.*

iron ore between Couvin – and Chimay (Marion & Barchy, 2001). This ore is rather high grade (43 % Fe), is siliceous (17-21 % SiO_2) and phosphorus (1.03-1.17 % P) (Dejonghe, 1977, Ancion & Van Leyckwijk, 1947). This level is no longer outcropping and representative samples are not present in the Belgian collections.

A Clinton-type OIS level of Eifelian age was mined until 1875 along the 65 km long Wellin-Couvin-Givet-axis, at the southern limb of the Dinant Synclinorium (Fig. 6). This OIS level is not outcropping and representative samples are not available in the Belgian collections. In the area between Sambre-and-Meuse, this OIS level is composed of two individual layers separated by 10 m of interburden. In Momignies, the lower layer consists of 6 thin individual OIS beds enclosed in a ferruginous carbonate matrix. Its total thickness can reach 3 m. Its iron content varies between 34.86 and 42.05 %. It has a relative high. Al and siderite content (Ancion & van Leckwijck, 1947).

An OIS layer associated with shales is interbedded within Givetian limestones at the southern border of the Vesdre massif (Fig. 6). It is only known from one locality, southeast of Verviers (Dejonghe, 1977) and has no economic value.

The Lochkovian, Eifelian and Givetian OIS described above are poorly understood because good outcrops and representative samples are mostly lacking and because no recent investigations were carried out on them. The available data are too old and too imprecise. The iron content is variable and the matrix is often rich in carbonates.

Several stratigraphically distinct, Clinton-type OIS occur in the Upper Devonian of the Ardenne shelf, south and southeast of the Caledonian London-Brabant Massif (Fig. 6, Fig. 8). Where they occur, the thickest levels (mainly those of the basal Famennian, possibly also the one at the base of the Frasnian) have been intensively mined as an iron ore in the middle of the 19th century. However, the first mining activities are much older, probably dating already from Roman times. Medieval forges are located in the vicinity of the outcrops of thin OIS layers when this iron ore was the only available raw material. The individual OIS levels are thin, centimetric to pluridecimet-

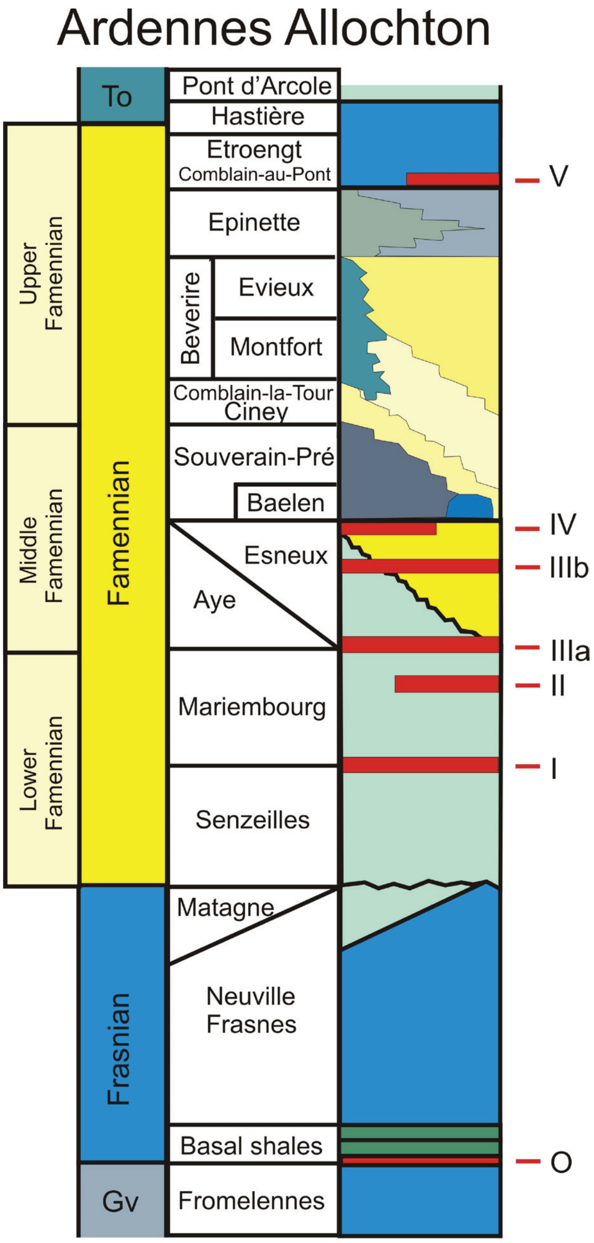
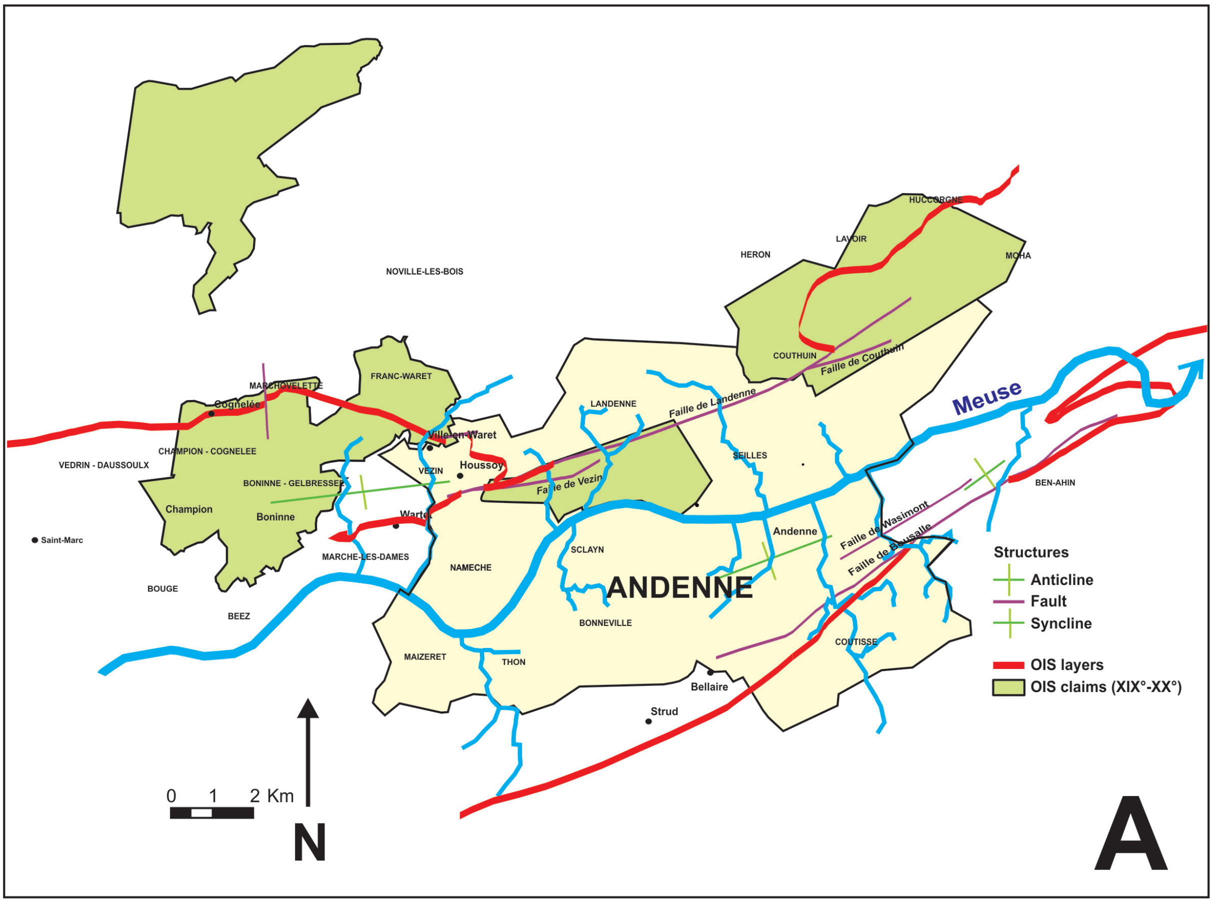


Fig. 8 – Lithostratigraphical setting of the 7 oolitic ironstone levels in the Belgian Uppermost Devonian of the Ardenne Allochthon (Dinant Synclinorium). Red lines with Roman numerals refer to the stratigraphically distinct Famennian OIS levels (modified after Dreesen, 1989a; Thorez et al., 2006).

Fig. 8 *– Cadre lithostratigraphique des 7 niveaux d'hématite oolithique du Dévonien supérieur belge de l'Allochtone ardennais (Synclinorium de Dinant). Les lignes rouges avec des chiffres romains font référence aux différentes couches d'OIS famenniennes stratigraphiquement distinctes (document modifié d'après Dreesen, 1989a ; Thorez et al., 2006).*


NOVILLE-LES-BOIS
HERON
LAVOIR
HUCCORGNE
MOHA
COUTHUIN
Faille de Couthuin
FRANC-WARET
MARCHOVELETTE
Cognelée
CHAMPION - COGNELEE
VEDRIN - DAUSSOULX
BONINNE - GELBRESSEE
Champion
Boninne
Saint-Marc
BOUGE
BEEZ
MARCHE-LES-DAMES
Ville-en-Waret
VEZIN
Houssoy
Warte
Faille de Vezin
LANDENNE
Faille de Landenne
SEILLES
Meuse
BEN-AHIN
NAMECHE
SCLAYN
Andenne
Faille de Wasimont
Faille de Bousalle
ANDENNE
BONNEVILLE
MAIZERET
THON
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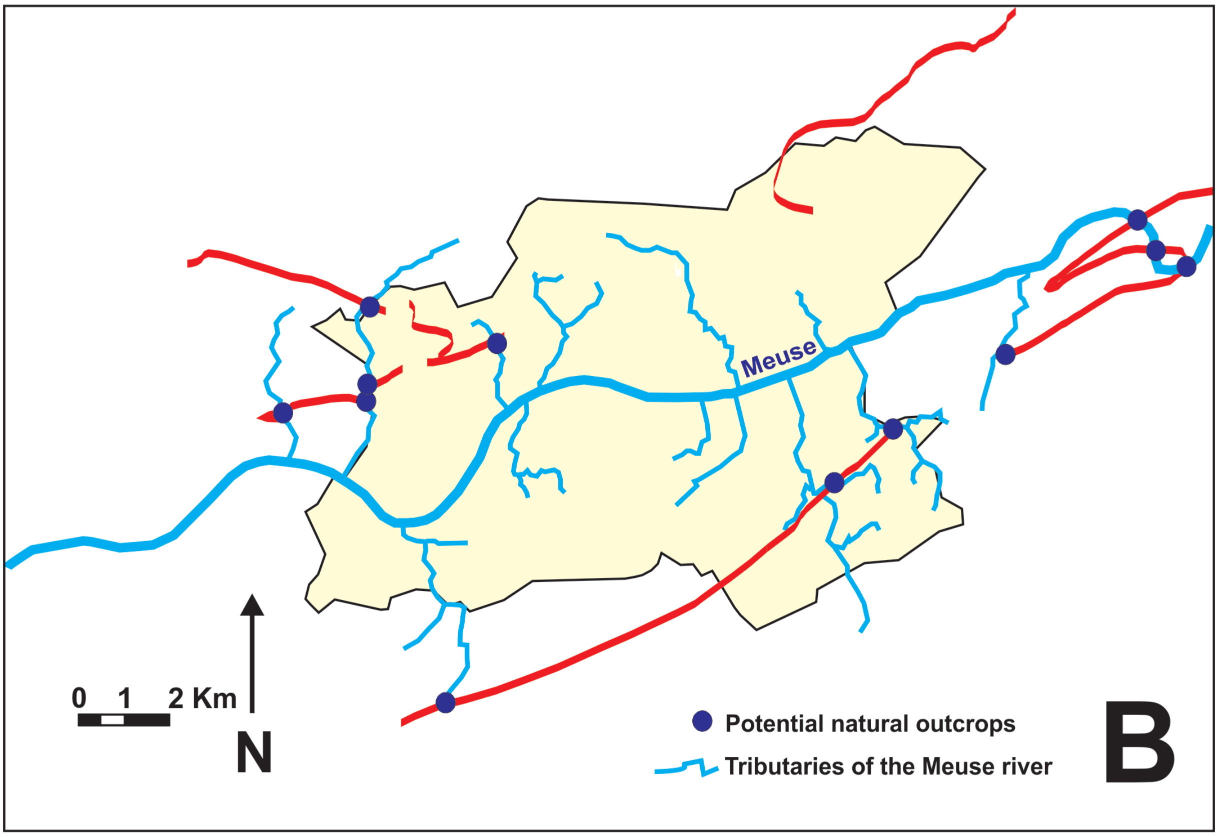
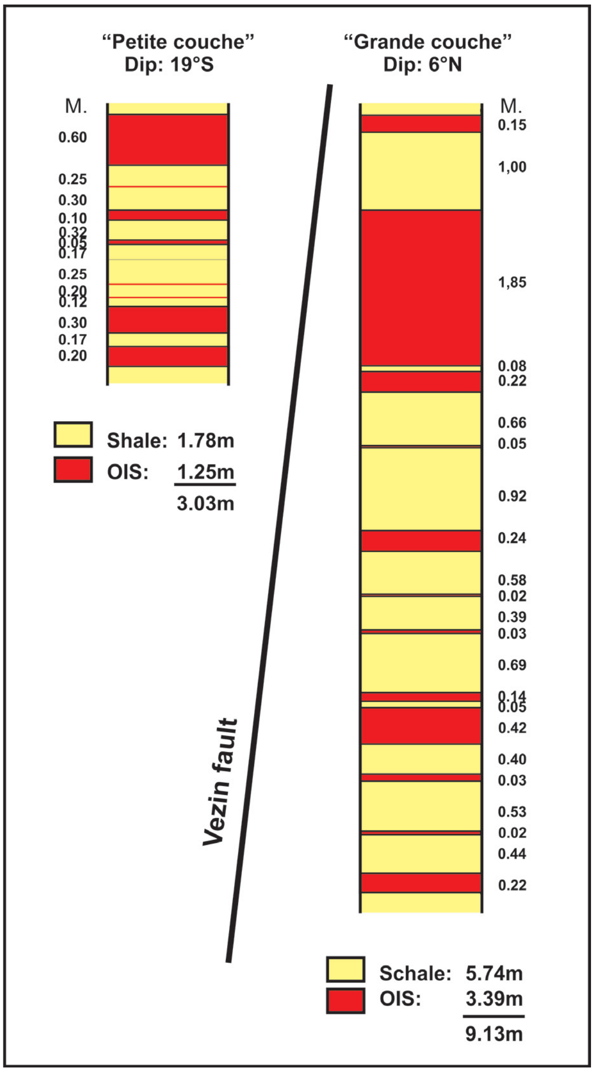

Meuse
0 1 2 Km
N
Potential natural outcrops
Tributaries of the Meuse river
B

ric beds, with a plurikilometric aerial extension. These horizons only crop out in the main valleys or in their deeply incised tributaries.

A very thin layer of Clinton-type OIS is located at the very base of the Frasnian (Fig. 8). It has a rather large geographical extension but only a poor economic value. It occurs on the northern and eastern limbs of the Dinant Synclinorium, on the eastern part of the southern flank of the Namur Synclinorium and in the Verviers Synclinorium (Dejonghe, 1977, 1986). It belongs to the shaly and fossiliferous Presles Formation. It is a pseudo-oolitic ore, composed of both hematitic and chamositic ooids often displaying a fossil ore-type OIS facies. Ferruginous ooids or pseudo-ooids are often scattered within a carbonate matrix (Denayer *et al.*, 2011). This OIS level is composed of several succeeding thin (centimetric to a few decimetre thick) lenticular ferruginised pseudo-ooids-bearing limestones.

The Famennian Clinton-type OIS, considered economically as the second most important iron ores in Belgium after the Minette-OIS, have been previously mined mostly along the northern flank of the Namur Basin (Brabant Parautochton[1]; Denayer *et al.*, 2011 (Fig. 9-10). In the latter tectonic unit, the thickness of the ore beds ranges between 0.25 and 1.50 m, but their geological and geographical distribution is quite large, resulting in a maximum development of the Lower Famennian iron ore level. Different stratigraphically distinct Famennian OIS levels occur also at the southern border of the Namur Basin, at the northern and eastern border of the Dinant Basin and within the Vesdre Basin (Dreesen, 1982).



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[1] The Brabant Parautochton was formerly named Namur Syncline. See Belanger *et al.*, 2012.

Fig. 9 – (opposite page) A) Map of the occurrences of Famennian OIS beds (red lines) in the Brabant Parautochthon, based on the geological map of the city of Andenne.
B) Detail of the previous map showing that the (potential/probable) outcrops are restricted to the Meuse valley and to its tributaries.
Fig. 9 *– (page précédente) A) Carte des occurrences d'OIS famenniennes (lignes rouges) dans le Parautochtone de Brabant, basée sur la carte géologique du territoire de la ville d'Andenne.*
B) Détail de la carte précédente montrant que les affleurements (potentiels/probable) sont limités à la vallée de la Meuse et à ses affluents.

Fig. 10 – Variability of the number and thickness of OIS layers within the Lower Famennian OIS levels (condensed levels I-II?) at the northern flank of the Brabant Parautochton. The "petite couche" (thin bed) and the "grande couche" (thick bed) are separated by the Vezin fault (Denayer *et al.*, 2011).
Fig. 10 *– Variabilité du nombre et de l'épaisseur des couches d'OIS d'âge Famennien inférieur (niveaux condenses I-II?) au bord nord du Parautochtone de Brabant. La « petite couche » (banc mince) et la « grande couche » (couche épaisse) sont séparées par la faille de Vezin (Denayer et al., 2011).*

In the Dinant Synclinorium, supposedly only the basal Frasnian OIS level (level 0 of Dreesen, 1989a) has been mined during historical times, as an iron ore. The distal facies of the other Lower to Middle Famennian OIS levels were probably too thin (uneconomical) and too rich in carbonates for industrial purposes. Moreover, their content in hematitic allochems is much lower than that of the coeval proximal facies in the Brabant Parautochton, where more important and lean accumulations of ferruginous ooids occur. However, the OIS of the northern and eastern borders of the Dinant Synclinorium might well have provided different sources for red ochre manufacturing (e.g. in the Hamoir area).

Both in the Dinant and the Verviers Synclinoria, four conspicuous closely spaced OIS beds (levels I, II, IIIa and IIIb) are described (Fig. 7, Fig. 11). They are located at lithostratigraphical boundaries within the shally Hodimont Formation and the silty-sandy Esneux (Aye) Formation (Dreesen, 1982, 1989a, Laloux *et al.*, 1996, Laenen *et al.*, 2002). Two levels occur in the Lower Famennian Hodimont Formation (I, II) and 2 other levels occur at the base of and within the Middle Famennian Esneux (Aye) Formation (levels IIIa and IIIb l - 0.15 to 0.70 m thick). Moreover, a fifth OIS level (level IV – a few cm to 0.2 m thick) is present near the transition of the Middle Famennian Esneux- Souverain-Pré Formations (Dreesen, 1982). All those levels consist of centimetric to a few decimeters thick bioclastic limestones enriched with ferruginised allochems (ooids, pseudo-ooids, micro-oncoids and bioclasts). For instance, in the Lambermont road section (Verviers Synclinorium), level I is divided in three different beds consisting of lenticular concentrations of ferruginised allochems in a bioclastic carbonate matrix. These OIS contain hematitic flax-seed-type ooids or oncoids, rounded skeletal grains (fossil ore-type) and less important amounts of chamositic and phosphatic, coated grains. OIS beds show a density-stratification with hematitic ooids concentrated near the bottom and chamositic ooids near the top. The amount of chamosite grains also increases from proximal to distal shelf settings. Most OIS beds surmount an erosional unconformity and start with a transgressive lag deposit. They are often topped by ferruginised microstromatolitic hardgrounds developed at the end of a shoaling upward sequence, considered as a flooding surface (Dreesen, 1989a; Laenen *et al.*, 2002). Most of the natural outcrops in the Verviers Synclinorium are restricted to the Vesdre valley and its tributaries, due to the shaly nature of the enveloping sediments of the Hodimont Formation.

A sixth OIS level (level V) finally is located at the base of the Strunian (Uppermost Famennian). It is composed of a 10 cm thick accumulation of ferruginised bioclasts in a bioclastic grainstone. It has only been found in one borehole in the Dinant Basin and does not crop out. The OIS level I of the Hodimont Formation generally consist of different sublevels, i.e. discontinuous or lenticular concentrations of ferruginised allochems within

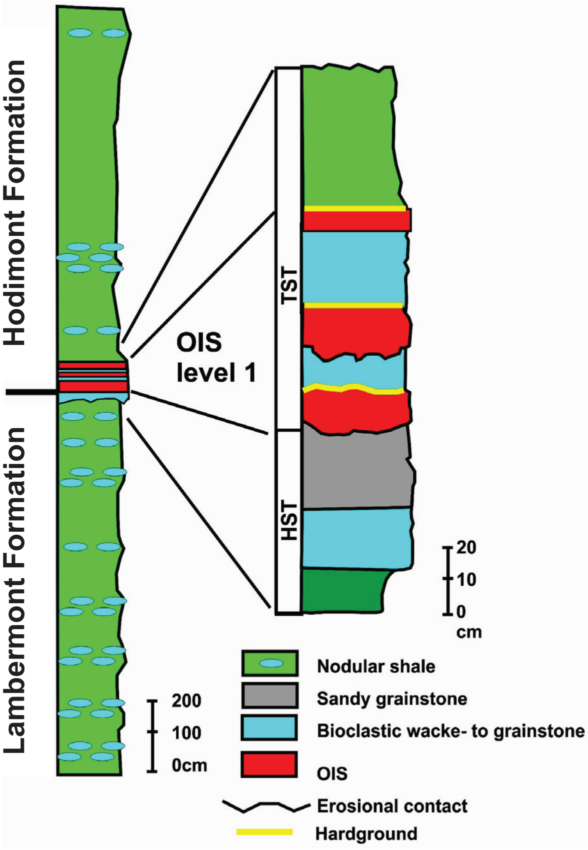


Fig. 11 – Columnar section, lithostratigraphical and sequence-stratigraphical interpretation of the Lambermont road section (Verviers, Verviers Synclinorium) (after Dreesen, 1982; Laenen *et al.*, 2002).

Fig. 11 *– Colonne lithologique, interprétation lithostratigraphique et en stratigraphie séquentielle de la coupe de Lambermont (Verviers, Synclinorium de Verviers) (d'après Dreesen, 1982 ; Laenen et al., 2002).*

bioclastic limestone beds, interstratified within greenish shales.

The exact litho- and biostratigraphical position, the geographical distribution, the macro- and microfacies characteristics of the Famennian OIS throughout the Dinant Basin and the Vesdre Basin, were studied in great detail by Dreesen (1982). Furthermore, a new depositional model has been proposed by the same author (1989a) for the Upper Devonian OIS in Belgium, suggesting a storm-induced origin (tempestites) and a possible volcanic origin for the iron. The variations in concentration of the ferruginised allochems and the quite large aerial distribution of the OIS are both probably related to this storm wave activity. As a consequence, proximal and distal OIS facies have been recognised on the basis of lateral variations in thickness and in mineralogy: the proximal OIS tend to be much thicker and leaner, with dominantly hematitic ooid concentrations, whereas the distal OIS facies are generally thinner, contain more dispersed ferruginised ooids and show a higher chamosite content. The Lower Famennian OIS of the Brabant Parautochton are considered as proximal facies, whereas most of the other Lower-Upper Famennian OIS levels that occur throughout the Dinant and Verviers Synclinoria, are considered as more distal facies. The proximal facies of the OIS generally correspond to stacked pluricentimetric to pluridecimetric beds of mostly hematitic ferruginous ooids within ferruginous shaly, silty to carbonate matrices, separated by often red-stained ferruginous shales or siltstones. The distal facies of the Famennian OIS generally correspond to lenticular pluricentimetric or pluridecimetric ferruginous ooid-bearing, bioclastic wacke- to grainstones (limestone beds) interbedded in shales, nodular shales or micaceous silt- and sandstones. The red staining of these ferruginous ooid-bearing limestones depends on the concentration of the iron pigment. The most distal coeval facies of some particular OIS levels are characterised by a lack of ferruginised allochems and by a conspicuous red staining only (purplish shales or pink carbonate beds). OIS level IIIa has even been correlated with an important red-stained griotte-type cephalopod limestone bed (the Cheiloceras Limestone) in the Upper Famennian of the Aachen area (Dreesen, 1989b). For further details on the microfacies characteristics of the Famennian OIS, the reader is referred to Dreesen *et al.* (2016: this volume). Because of their large areal distribution and their conspicuous synchronism with synsedimentary volcanic-tectonic events, OIS have also been used as event-stratigraphical marker beds throughout the latest Devonian of the Ardenno-Rhenish realm, allowing accurate intrabasinal correlations (Dreesen *et al.*, 1988; Paproth *et al.*, 1986). Moreover, the Famennian OIS levels are frequently used in Belgium as lithostratigraphical marker beds for mapping purposes (Thorez *et al.*, 2006) and for elucidating the geology of complex tectonically affected strata.

5. MINETTE-TYPE OIS IN LORRAINE

The Middle Jurassic minette-type OIS (Formation of Mont-Saint-Martin, dated from the Upper Toarcian to the Lower Bajocian; Boulvain *et al.*, 2001) is considered to be economically important (Fig. 12). The iron mining area, called the "Minette district", extends over three adjacent countries (Grand-Duchy of Luxembourg – GDL, Belgium and France) representing a broad area called Lorraine (Gutland in the GDL) corresponding to the northeastern rim of the Paris Basin. Iron-bearing strata crop out and gently dip towards the southwest. In the minette district of Lorraine, recorded mining traces go back to Gallo-Roman times. The iron-ore deposits were worked by open mines in the GDL and by underground mines in Belgium, GDL and in France.

The northern limb of the Lorraine-Luxembourg iron ore basin, crops out in Belgium, south of Musson and Halanzy, near the top of the Bajocian cuesta. In the Gaume area of Belgium, the ore is less well developed than in the more southern part of the basin. In Halanzy, the thickness of the Aalenian is only 4.8 m, in Musson-Grand Bois, 4.5 m. Two individual ore layers can be observed with respective thicknesses of 2.15 m and 1.35 m, separated by 0.4 m of ferruginous marls. The ore consists of red to reddish brown ferruginous ooids (with a dominant goethite composition and locally glauconite grains), and well-rounded quartz grains in an argillaceous, limonitic or carbonate matrix, locally enclosing fossil shell debris. The interburden contains no or only rare ferruginous ooids (Boulvain, 2014). In the basin, the Minette-bearing formation has a thickness varying between 15 and 65 m.

The conditions for OIS-formation during the Mesozoic corresponded to marine high stands, widespread inland seas or epicontinental seas and a warm humid climate, favouring chemical weathering on the continent. The minette-type OIS mark the top of a regressive, coarsening- and shallowing-upward depositional sequence. The ferruginous ooids themselves were formed during sea-level lowstands or in condensed sections. The Minette is internally composed of coarsening-up sequences representing large-scale subtidal sand bars or shoals, built up during transgressions (Teyssen, 1989).

The ore is composed of goethite-berthierine, it is iron-rich (35-39 % Fe) and phosphorous (0.5-0.6 % P) in Belgium. The iron content varies from layer to layer. The ores are divided into a siliceous group with a CaO/SiO_2 ratio below 4 and a more calcareous group, varying according to the different sub-basins. Generally, the calcareous group overlays the siliceous group. The iron content reaches 35 % in the richest beds, about 12 to 18 % in the interbeds and about 10 % in the poorest beds. The color of the beds changes in function of the mineralogy, the iron content and the weathering state: reddish, brick red, black, green, blackish green, grey, yellow or brownish. The calcareous group has the less economic significance (Neumann-Redlin *et al.*, 1977b).

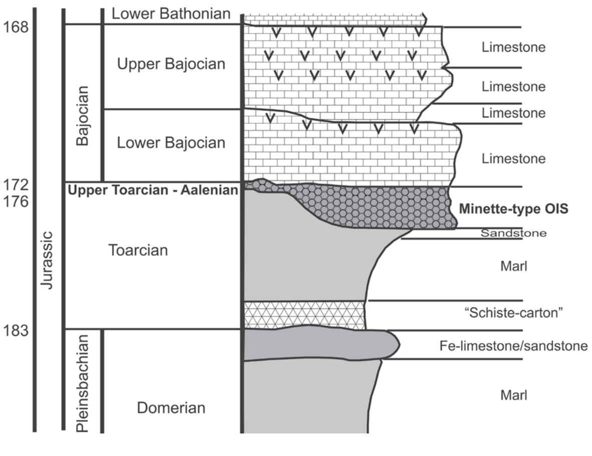


Fig. 12 – Simplified stratigraphical column locating the minette iron ore (after Cartannaz & Dolliou, 2010).
Fig. 12 *– Colonne stratigraphique simplifiée positionnant le minerai de fer appelé « minette » (d'après Cartannaz & Dolliou, 2010).*

6. OIS FROM NORMANDY (FRANCE)

OIS are well known from the Ordovician shelf sequences of SW Europe (the Western European Platform), the Avalonian Terranes of several W-European areas (France, Portugal, Spain, Bohemia, Thuringia...), and North Africa, where they formed at mid to high palaeolatitudes, mostly on the margins of the Gondwana supercontinent. On a global scale, they represent the most important group of deposits of the first of the two major periods of Phanerozoic OIS generation (Ordovician-Devonian and Jurassic-Paleogene) (Young, 1989). The Lower Ordovician oolitic ironstones of the Armorican Massif, were studied in detail by Chauvel (1971), Joseph (1982) and more recently, by Gloaguen *et al.* (2007).

The western part of the Lower Normandy area (Manche, Orne, Calvados) consists of folded Phanerozoic rocks, continuous with those of Great Britain, and that belong to the Armorican massif (Fig. 13-14). Due to their resistance to erosion processes, the gritty bands of the Armorican sandstones form the ridges in the landscape. Folds consist of a succession of anticlines and synclines, oriented WNW-ESE.

The Lower Ordovician OIS layer is 3 to 8 m thick and crops out in the successive synclines of (named from the north to the south) Caen, May-sur-Orne - Saint André-sur-Orne, Soumont-Urville, Falaise - Saint-Rémy-sur-Orne (zone bocaine), Domfront-Mortain-La Ferrière-aux-Etangs, Sées – Ecouves, Pail – Multonne and Coevrons (Fig. 13-14). The synclines of Laval and Menez Belair are poorly mineralised and have never been mined. Only the first three synclines have been sampled, because of their relative proximity to the archaeological sites in the surroundings of Caen.

The OIS layer was intensively mined but all mines are now closed. The layer is divided in two main lithofacies. The lower facies is a grey-green to blackish green (when the rock is fresh) chlorite-siderite rich ore. The upper facies is a red hematite-rich ore. Both the base and top of the OIS layer are silica-rich and have not been mined. This OIS level was studied in detail (by means of petrography and geochemistry – see tables 3 and 4) – by Joseph (1982), but the results of his study were never published. Today, due to inten-

Fe (total)	35.2-40.6%
Fe^{2+} (siderite, Fe-chlorite)	28.4-34.2%
SiO_2	6.5-15%
Al_2O_3	3.2-8.8%
Cao	1.6-2.8%
MgO	0.6-1.9%
Mn	0.15-0.97%
P	0.04-0.14%

Tab. 3 – Mean chemical composition of the OIS from Normandy (data from Schnaebele, 1963 and published by Horon, 1977).

Tab. 3 *– Composition chimique moyenne des OIS de Normandie (données de Schnaebele, 1963 et publiées par Horon, 1977).*

sive extraction activities, outcrops are quite rare and they are mainly restricted to the border facies and/or to the strongly weathering zones, that are enriched in goethite or iron oxy-hydroxides. The mineralogical compositions are variable, not only inside the layer, but also from north to south, a phenomenon linked to the paleographical conditions and the position of the former continent.

The folded Palaeozoic rocks disappear beneath the overlying cover of flat-lying Mesozoic rocks that range from the Trias to the Cretaceous, and represent the western part of the Paris Basin.

The OIS-bearing sequence in Normandy is organised into plurimetric negative sequences (shale-sandstone-iron ore) reflecting progradation phenomena. The oolitic iron ore has been deposited on a subtidal open shelf, exposed to tidal wave activity and located south of the infra-Cambrian continent. Giant parallel-oriented ooid bars were separated by muddy depressions. Field studies demonstrated that the OIS layer can be subdivided in 2 units, locally separated by shaly-sandy interbeds. The aerial distribution of these units points to the perennial role of an ancient Cadomian structure, called the Cap bas-normand of the Domnonée area. Detailed sedimentological, petrographical and geochemical analyses, have been carried out by Joseph (1982) on the extracted iron ores. The author distinguished an "oxide" facies (red or pink unit rich in hematite) and a "chlorite-carbonate" facies (greyish-green or black). The latter unit has not always been exploited over his total thickness, because of the excessive silica content in its uppermost part. The same author showed also the successive steps in the appearance of the following ore minerals: chlorite, hematite and siderite.

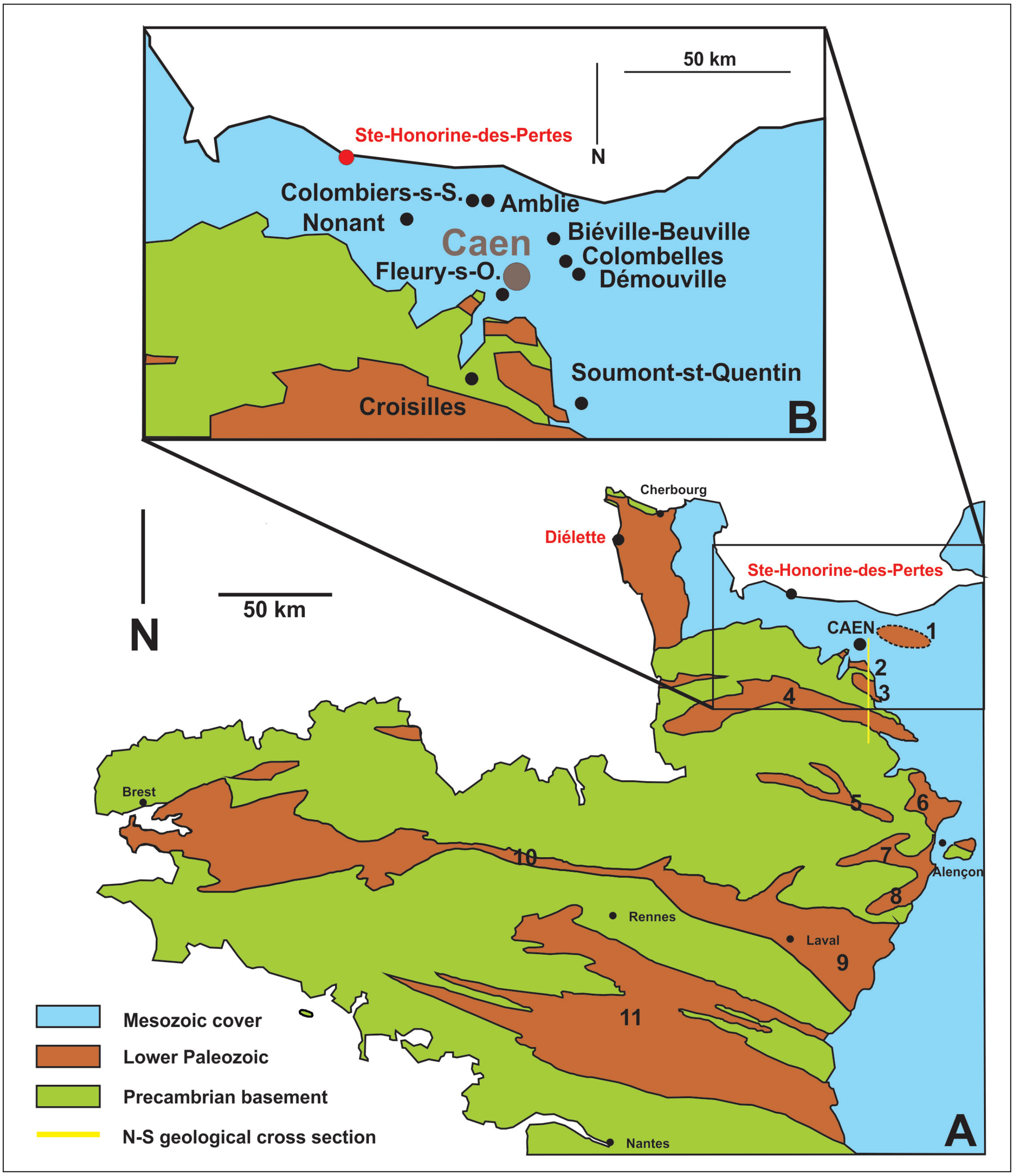
In the Mesozoic cover in Normandy mentioned earlier, a particular minette-type OIS occurs, with good outcrops along the coast. It

Claim	*Nature*	*Fe %*	*SiO_2 %*	*Al_2O_3 %*	*MgO %*	*CaO %*	*S %*	*P %*	*Mn %*	*Perte au Feu %*
May-sur-Orne	Hematite « cru »	45-50	10							
May-sur-Orne	« Taché cru »	35-38	16-20							
May-sur-Orne	Couche totale	41-42	15-16				0.12	0.1-0.4	1	10
Saint-Rémy	Hematite « cru »	53	8	3.32	0.46	3	0.05	0.75	0.24	8.55
Saint-Rémy	Carbonated « cru »	41-42	14	5.5	1.38	2.66	0.09	0.58	0.4	14-15

Tab. 4 – Mean, but incomplete chemical composition of the OIS from two mines of Normandy (after Joseph, 1982).

Tab. 4 *– Composition chimique moyenne et incomplète des OIS provenant de 2 mines normandes (d'après Joseph, 1982).*

is called the "Oolithe ferrugineuse de Bayeux". Most conspicuous is the historical Bajocian stratotype and natural coastal outcrop at Sainte-Honorine-des-Pertes, near Bayeux (Normandy). Here, the formation is extremely condensed (0,5 m) and composed of 4 decimetric beds that contain centimetric rounded ferruginous oncoids, ferruginous microstromatolitic hardgrounds, ferruginised lithoclasts and abundant well-sorted ferruginous ooids of mainly goethite (Préat *et al.*, 2000). The feruginous ooids range in size from 0.3 to 2 mm and may be variably abundant in different beds, but they never give rise to a supporting framework. The intergranular matrix is represented by wackestones to packstones containing bivalve and echinoderm fragments, benthic foraminifera, peloids, and scattered quartz grains (Pavia & Martire, 2009).



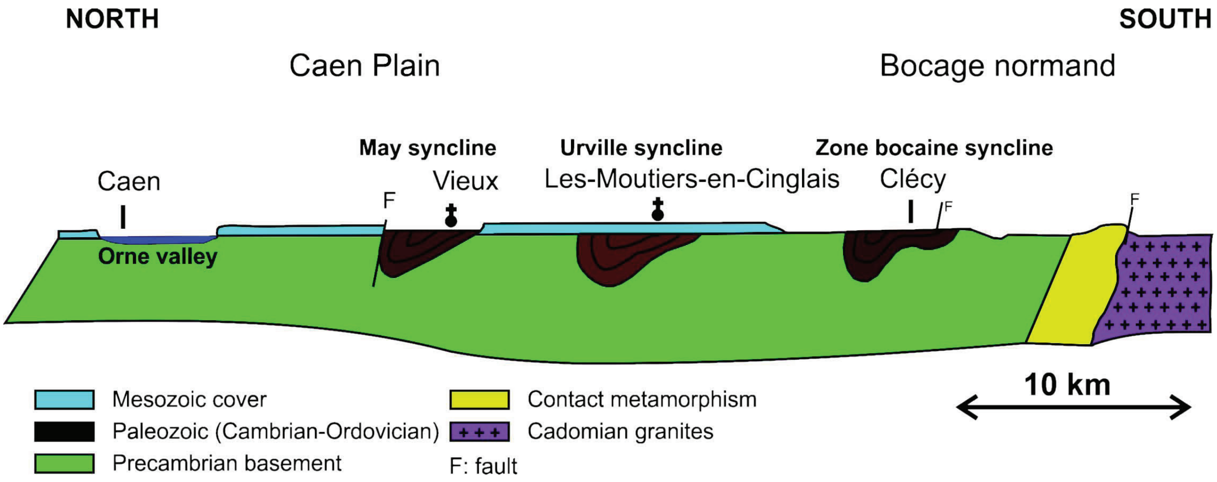


Fig. 14 – Geological cross-section through the Basse-Normandie.
Fig. 14 *– Coupe géologique transversale à travers la Basse-Normandie.*

In the Anjou area, located 60 to 100 km south of the OIS-occurrences in Normandy, a particular OIS ore also occurs within the Lower Member of the Grès Armoricain Formation (Ordovician) in the Châteaubriant anticline. At some places, epigenetic hydrothermal alteration affects this OIS layer, leading to a pervasive and massive sulphidization with the formation of stratoid pyritised lenticular bodies within the OIS layer (Gloaguen *et al.* 2007).

7. SPATIAL RELATIONSHIP WITH THE LINEAR POTTERY CULTURE SETTLEMENTS IN BELGIUM, IN THE NETHERLANDS AND IN NORMANDY.

LBK settlements studied from Basse-Normandy, Hesbaye, the Dendre valley, the Netherlands and the Gutland have been plotted on general large-scale geographical and geological maps (Fig. 6-7, Fig. 13).

Fig. 13 – (opposite page) Geological sketch map showing the location of the oolitic iron ores of the Basse-Normandy area. Note the presence of Lower Paleozoic synclines (brown colour), enclosing Clinton-type OIS levels, and the location of the Early Neolithic sites around Caen (see inset above). A Bajocian minette-type OIS (historical stratotype of the Bajocian stage) is located at Sainte-Honorine-des-Pertes). In Diélette magnetite ores are present. 1: the covered syncline of Caen-Ranville; 2: the May sur Orne-Saint André syncline; 3: Soumont-Urville syncline; 4: the Falaise - Saint-Rémy syncline (zone bocaine); 5: the Domfront-Mortain-La Ferrière-aux-Étangs-Halouze syncline; 6: the Sées – Écouves syncline; 7: the Pail – Multonne syncline; 8: the Coevrons syncline. The synclines of Laval (9), and Menez-Belair (10) contain thin and very iron-poor OIS layers. The large southern structure (11) does not contain any OIS layers (after Bicot, 1930).
Fig. 13 *– (page précédente) Carte géologique schématique montrant la localisation des niveaux de minerais de fer oolithique de la zone de Basse-Normandie. Notez la présence de synclinaux constitués de Paléozoïque inférieur (couleur brune), renfermant des couches de Clinton-type OIS, et la localisation des sites datés du Néolithique ancien autour de Caen (voir partie supérieure du schéma). Un niveau minette-type OIS du Bajocien (stratotype historique de l'étage géologique Bajocian est situé à Sainte-Honorine-des-Pertes). A Diélette, un minerai de magnétite est présent. 1 : le synclinal caché de Caen-Ranville ; 2 : le synclinal de May sur Orne-Saint André ; 3 : le synclinal de Soumont-Urville; 4 : le synclinal de Falaise - Saint-Rémy (zone bocaine) ; 5 : le synclinal de Domfront-Mortain-La Ferrière-aux-Étangs-Halouze ; 6 : le synclinal de Sées – Écouves ; 7 : le synclinal de Pail – Multonne ; 8 : le synclinal de Coevrons. Les synclinaux de Laval (9) et Menez-Belair (10) renferment des couches minces et pauvres en OIS. La grande structure plus au sud (11) ne renferme pas de couches d'OIS (d'après Bicot, 1930).*

These settlement are discussed in detail in several individual papers within the present book.

Similarly, the artefacts characterization and their comparison with the OIS are discussed in their respective articles in this book. Furthermore, they are the subject of a general synthesis and a summary published at the end of this book.

In a very general way, the settlement location is not guided by the immediate proximity of the OIS deposits. The agricultural quality of soils and the presence of fresh water rather seem to represent the most important selection criteria.

OIS found on archeological sites come from regional sources, located several kilometers to dozens of kilometers south of the sites of consumption. OIS are not the only base raw material for red pigment. Red-stained rocks and non-oolitic iron-rich ores that are not present in the immediate surroundings of the villages, were regularily found as well. However, these represent only a small part of the total red material. Their study is still in progress, the first results of which will be presented in a forthcoming paper.

Outcrops are restricted to valleys that cut superficial deposits, such as the loess cover in the Hesbaye area (e.g. Fig. 6). Actually, it is quite exceptional to observe the latter outcrops in the field, because they have been the starting point of initial surficial mining, followed by extraction in underground galleries in various historic times. For geological mapping purposes, the OIS levels are used as lithostratigraphic marker beds as they often correspond to boundaries between geological formations (or members). Furthermore, they have also been used as a high-resolution correlation tool between sections throughout large sedimentological basins (Dreesen, 1989a).

All macro- and microfacies variations of the Devonian and Jurassic OIS described above, are generally related to palaeogeography and, as a consequence, to the actual geographical conditions: these are offering keys to understand and relate archaeological samples to geological and geographical sources. If we consider both the restricted thickness and the folding of the OIS layers, we can imagine the difficulty to find and collect this raw material in the field. However, their conspicuous red colour and their property to stain the enveloping weathered shales, must have been favourable field criteria. The southern flank of the Brabant Parautochton is characterised by reversed strata with a high dip. Otherwise, the northern flank of the Namur Parautochton, is only gently inclined to the south. It is important to consider the influence of the dipping on the width of the outcrop zone. For example, a 0.30 m-thick layer with a dip of 80° has an outcrop width of 0.30 m while the same layer with an inclination of 10°, has an outcrop width of 1.68 m. So, the probability of discovering thin red-coloured OIS layers intercalated within green shales and of the opportunity to collect them in the field, were probably much higher at the northern flank of the Brabant Parautochton.

Short synthesis

This paper deals with the description of the different geological occurrences of oolitic ironstones known in northwestern Europe. The geological, lithostratigraphical, structural and paleoenvironmental settings of some particular oolitic iron ores weare discussed, in particular those of the Belgian Lochkovian, Givetian, Frasnian and Famennian stages, those of the Ordovician in Normandy (France), those of the Aalenian-Bajocian in the Grand Duchy of Luxemburg and those of the Emsian-Eifelian in the Eifel area (Germany). General available chemical data were provided as well as the assignment to one of the three OIS types in order to complete this general overview.

Acknowledgements

We are most indebted to Prof. em. W. Kasig (RWTH-Aachen) for allowing us to use unpublished data from different geological mapping projects carried out under his direction in the Eifel area, and for providing us with the original map of Maximilian Wemmer (1909) showing the geographical extension of the Heisdorf OIS-layer within the Eifeler Kalkmulden area. We thank Frédéric Boulvain (Professeur de géologie et sédimentologie, University of Liège, Belgium) and Xavier Savary (Géologue, Service archéologie DGA Jeunesse, Culture et Territoires, Caen, France) for their constructive review of the manuscript.

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