Ber. Inst. Erdwiss. K.-F.-Univ. Graz	ISSN 1608-8166	Band 16	Graz 2011
IGCP 596 Opening Meeting	Graz, 19-24th September 2011		

Drowning of a carbonate platform at the Givetian/Frasnian boundary (Sourd d'Ave section, Belgium): a comparison of different proxies (magnetic susceptibility, microfacies and gamma-ray spectrometry)

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The Sourd d'Ave section at Ave-et-Auffe exposes the upper part of the Moulin Boreux Mbr (8 m of built-up limestones with massive and branched stromatoporoids) and the Fort Hulobiet Mbr (28 m of calcareous shales and argillaceous limestones), both belonging to the Fromelennes Fm (Givet Group). The section exposes also the Pont d'Avignon Mbr (45 cm-thick nodular argillaceous limestone), the Sourd d'Ave Mbr (9.3 m-thick of carbonate nodules and shales with rare thin argillaceous limestone beds). The position of the Givetian / Frasnian boundary in shallow environments is still in debate, and is fixed arbitrary at the Givet Group / Frasnes Group boundary where the first *Ancyrodella rotundiloba* have been identified by BULTYNCK (1974), after a 15 m-thick episode without any conodonts.

Systematic sampling has been carried out in order to establish the evolution of the environments and to detail the Givetian/Frasnian transition. This led to the fabrication of 219 thin sections which alllowed recognition of 13 microfacies types paralleling the standard sequence of MAMET & PRÉAT (1989) from open marine shallow subtidal to restricted supratidal near emersion. The Boreux and Fort Hulobiet members display restricted facies (*Amphipora,* spongiostromid and algal bafflestones and bindstones, loferites with desiccation lumps) with poorly fossiliferous beds interbedded with higher energy peloidal and sometimes oolitic grainstone facies. Laminite horizons, sometimes with small-sized LLH-stromatolites are uncommon; they are associated with dolomicrites showing pseudomorphs of evaporite minerals. These evaporitic facies become common in the upper part of the Hulobiet Mbr. suggesting the paleoclimate may be becoming more arid at the Givetian/Fransian transition. The boundary between the Givetian and the Frasnian which is very distinctive on the field, is therefore characterized by a transition from restricted evaporative lagoonal facies to open marine interbedded marly shales and nodular limestones. Meter-scale cyclicity is very pervasive throughout the Givetian part of the section. Cyclicity was determined by assessing the vertical stacking of facies, the base of a cycle being identified by the initial backpstepping of less restricted facies-type over a restricted facies-type. Cycles have open or semi-restricted subtidal bases with stromatopores, crinoids, corals and restricted supratidal tops with common 'algal chips'. They record a decrease in circulation, a decrease in diversity of organisms, which are endemic (cyanobacteria, stromatolites, ostracods, gastropods, umbellids), and increase in salinity upwards through the cycles. Horizons rich in ostracod are commonly seen representing the impingement of storms in the low energy restricted lagoons. Oncoids are locally abundant in specific horizons. The upper part of the Fort Hulobiet Mbr. consists of interbedded biostromes (semi-restricted stromatoporoid boundstones) followed by *Amphipora* floatstones, then fossil-poor units and restricted supratidal laminites with well-developed fenestral fabrics. The Frasnian Pont d'Avignon Fm. shows a rich faunal assemblage (bryozoans brachiopods, molluscs, nautiloids, tentaculitids) suggesting an abrupt deepening of the Frasnian from the marginal Givetian carbonate platform to a deep basinal environment below or near the storm wave base.

A total of 339 samples were collected for the study of low-field magnetic susceptibility (X_{LF}) in the Sourd d'Ave section. The MS values were measured with a Kappabridge MFK1-A with a CS-3 furnace and CS-L cryogenic apparatus. The MS values range between 6.0 x 10^{-10} m^3/kg and 4.52 x 10^{-7} m^3/kg. The highest X_{LF} values are present in the Fort Hulobiet Mbr and observed at the top of magnetic susceptibility evolutions. A clear decreasing trend of the X_{LF} is discernable at the end of the Fort Hulobiet Mbr and the X_{LF} values remain weaker in the sediments at the base of the Frasnian. Nevertheless, the X_{LF} are quite high and remain around 1 x 10^{-7} m^3/kg throughout the Frasnian. To better constrain and understand the origin of the signal, magnetic mineralogical analyses have been launched through hysteresis measurements and thermomagnetic curves revealing the presence of ferromagnetic *s.l.* and paramagnetic minerals controlling the X_{LF} signal.

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Gamma-ray spectrometry (GRS) measurements (n =188) were measured on the field with a Gamma Surveyor handheld spectrometric probe with a 6.3 in³ BGO detector. Counts per seconds in selected energy windows were directly converted to concentrations of K (%), U (ppm) and Th (ppm). One measurement with a 120-s count time was performed at each logging point, placed on the outcropping rock section and at full contact with the rock. The section was logged at a 0.25-m interval both in the Fromelennes and Nismes formations. K and Th concentrations fluctuate cyclically during the Givetian but remain generally below 1% and 5 ppm respectively. The concentrations start to increase for both elements before the Givetian-Frasnian boundary and continue into the Nismes Fm at the base of the Frasnian. The K values increase up to 5-6% at the top of the section. The Th concentrations follow a similar trend revealing an increase up to 18.6 ppm. GRS data show a strong correlation between K and Th values (R^2=0.97) which indicate a strong positive correlation between these elements. Th and K concentrations usually relate to the presence of aluminosilicates (illite and other clay minerals, potassium feldspars, micas) in carbonates while a good correlation between K and Th is considered to reflect a fine-grained siliciclastic admixture in carbonate rocks (KOPTIKOVÁ *et al*. 2010). U/Th ratios remain generally below 0.8 with few peaks up to 1.0 during the Givetian. The U/Th ratios decrease at the base of the Frasnian in the Nismes Fm. down to an average value around 0.25. The U/Th ratio is generally interpreted as an index to derive information on the paleo-oxygen level of the depositional environments. This ratio is considered as an indicator of the terrigenous-to-marine influence due to the terrigenous affinity of Th and the affinity of U, mostly in the form of soluble U6+, to adsorb to organic matter and/or co-precipitate in calcium phosphates in marine anoxic/dysoxic environments (LÜNING *et al*. 2004). The U/Th ratios indicate relatively well-oxygenated paleo-conditions in the marine waters throughout the section and even more in the Nismes Fm.

A detailed comparison of microfacies and magnetic susceptibility around the Givetian/Frasnian boundary allows the recognition of 14 sedimentary cycles, the first twelve are regressive at the 5th order and characterise the classical carbonate Givetian platform (Fromelennes Fm). The two last cycles are transgressive and related to the development of a siliciclastic ramp setting at the base of the Frasnian. Cycle thickness range from 0.5 to over 3 m, with an average thickness of 1.6 m in the Upper Givetian and is plurimetric (between 5 and 7 m) in the base of the Frasnian. Confrontation of microfacies and magnetic susceptibilty values leads to these three main conlusions:

(i) the semi-restricted subtidal bases of the Givetian cycles consist of high energy peri-reefal floatstones-rudstones (stromatoporoids and corals). They systematically display low X_{LF} values,

(ii) the restricted inter-supratidal tops of the Givetian cycles record very quiet lagoonal environments with cyanobacterial and algal peloidal wackestones. They display high X_{LF} values,

(iii) the ‘deeper’ open marine facies of the Frasnian consist of bioclastic packstones with common tempestites. The X_{LF} values are in the same range as (i).

We may conclude that the key parameters to interpret the X_{LF} values are the energy index and the water circulation. The lagoonal environments trapped the minerals carrying the magnetic signal and coming from the proximal emerged areas, while these minerals were dispersed in the higher energy environments (peri-reefal) or in the ‘deeper’ open marine settings where water circulation was efficient and storms common. These latter facies being partly argillaceous and silty, this mineralogical paramagnetic fraction contribute to the magnetic signal observed in the Nismes Fm as also revealed by increasing K and Th concentrations.

The Givetian/Frasnian boundary is thus characterised by a major transgression recording the drowning of the Givetian carbonate platform and the establishment of a siliciclastic ramp morphology during the Frasnian.

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Zeitschrift/Journal: Berichte des Institutes für Geologie und Paläontologie der Karl-Franzens-Universität Graz

Jahr/Year: 2011

Band/Volume: 16

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