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Implementation of a seismic velocity model for Flanders

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Introduction

In the past acoustic velocity models were generally linked to the strong demands from the oil and gas industries. This is the main reason why countries like the Netherlands already have a good coverage by regional acoustic velocity models, and others, like Belgium, haven't. Due to the upcoming market for geothermal exploration and seismic subsurface mapping purposes, there is nevertheless a growing market for such models.

Material & methodology

A first step was to make an inventory of all the available acoustic velocity data in Flanders. For this purpose, we gathered sonic log and well shoot data. This inventory showed the regional density of velocity data. Due to the scarcity of the velocity data in the western part of Flanders, velocity models were constrained to the Campine Basin and a part of the Roer Valley Graben.

Due to lithological differences in the subsurface, which will have their effects on the acoustic velocity, the whole subsurface was split up into several intervals. These intervals consist out of several official formations. The factors which influenced the boundaries for these intervals are the tectonics (e.g. hiatus between Oligocene and Neogene), spatial distribution (e.g. local distributions) and lithological differences due to changing acoustic velocity with the type of lithology.

For every well, the interval velocities and z-mid of the previously defined intervals were gathered. A plot of this data on a V_{int}-Z_{mid} graph showed the compaction trend for every unit. On these plots a linear trend could be constructed, which is the compaction trend. This trend shows an increase in acoustic velocity with increasing burial depths. The equation of this linear trend is as follows: $V(z) = k * z + V_0$. With *V(z)* being the actual velocity at depth *z*, *k* being the factor which gives the increase in velocity with depth and V_0 is the base velocity independent of the burial depth. V_z and V_0 can both be used to create velocity models. In order to create the geologically most realistic models, we used the spline interpolation method.

The models based on V(z) will give the actual acoustic velocity for a certain interval at a given location. The models based on V_0 will give the acoustic velocity of an interval independent of the burial depth and therefore independent of the spatial location. Models based on V_0 therefore allow us to check velocity anomalies independent of burial depth.

Results & discussion

We were able to create V_z and V_{int} models for the intervals ranging from the surface up to the base of the Upper Carboniferous (Westphalian) strata. Due to the scarcity and lack of regional coverage of acoustic velocity data, no velocity models could be created for the Lower Carboniferous strata. Another interval that did not give proper models was the one that comprises a gathering of the deposits of Permian to Jurassic age. This is caused by the combination of lack of data and large lithological heterogeneity within this interval.

In order to assess the accuracy of these models they were applied one a certain seismic profile which also contained a well. Therefore the model-derived thicknesses could be compared with the actual ones. The results were very similar for some intervals, but biased in others.

Conclusion

An inventory of all available sonic log data in Flanders was made and proper acoustic velocity models for several defined intervals ranging from the surface up to the base of the Upper Carboniferous (Westphalian) strata were created.

Micropaleontology of the early Cryogenian of Australia and microchemical and microstructural characterization of the acritarchs *Cerebrosphaera spp.*

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Introduction

The Cryogenian is a key period of the history of Life and Earth. This period, extending from 850 Ma to 635 Ma, is characterized by several changes including glaciations at a global scale (known as the "Snow-ball Earth glaciations") (Eyles, 2008) and modifications of the global chemistry of the ocean (Dhal et al., 2011). This is also the moment of a great diversification of the eukaryotes (Knoll et al., 2006) and the time of appearance of the early metazoans (Love et al., 2009). The early Cryogenian can be pinpointed by various techniques, one of these being the use of the acritarchs (acritarchs being organic vesicles of unknown biological affinities (Buick, 2010)) genus *Cerebrosphaera*. This genus comprises organic vesicles possessing a thick wall and prominent, cerebroid-like folds (Butterfield et al., 1994). Two species are part of the genus: *C. buickii* which bears 3 µm wide folds (Butterfield et al., 1994) and *C. ananguae* with 4µm wide folds (Cotter, 1999). Besides these morphological descriptions of the two species, little more is known. To better constrain the paleobiology of these stratigraphically important acritarchs, detailed analyzes of the ultrastructure and chemistry of these different species were conducted in the frame of Y. Cornet's Master thesis.

Material and Methods

The samples and specimens used for this study came from three drill cores of the Officer basin of Australia: the LDDH 1, Lancer 1 and GSWA Empress 1A drill cores. More specifically, they cover the Browne, Hussar and Kanpa formations. To describe the diversity among the populations of the two *Cerebrosphaera* species, the vesicles have been divided into five subgroups. These subgroups are based on the species, the size (<70 µm, >70 µm), the opacity and the color of the vesicles. Samples and specimens were analyzed by several techniques to obtain a large overview of the genus. This includes optical microscopy to assess the biological diversity of the three formations and the diversity of the populations of *Cerebrosphaera*. To achieve those, 72 glass slides prepared from samples of the three drill cores were observed. Environmental scanning electron microscopy was carried out on 10 specimens of both species to study their morphology at the micron-scale. Transmission electron microscopy has been performed on 14 ultra-thin sections of an equal number of specimens coming from the Lancer 1 and Empress 1A drill cores. Some of them were 99 nm thick to counter problems during the making of the sections. This technique was used to observe the ultrastructure of the walls of the vesicles. Finally infrared and Raman micro-spectroscopy were performed on 32 specimens of the Lancer 1 and Empress 1A to obtain a complete chemical and thermal maturity characterization of the organic material of the vesicles.

Results

The micropaleontological observation resulted in the identification of fourteen species of acritarchs. The main part of the total diversity is represented by the genus *Leiosphaeridia* with 5 species. *Cerebrosphaera* (2 species) comes next along with *Pterospermopsimorpha* (one species) and *Synsphaeridium sp.* The remaining diversity is constituted by the other genus like *Satka*, *Simia*, *Arctacellularia* and *Symplassosphaeridium*. Three species of the *Siphonophycus* and *Tortunema* filaments were also found. The global diversity can be described as relatively low, especially if it is compared with other deposits of similar age like the Svanbergfjellet formation, Spitsbergen or the Baffin formation, Canada. The difference came mostly from the absence of acanthomorph acritarchs (acritarchs with processes) in the Australian cryogenian deposits.

The results obtained on the ESEM show the existence of a morphological continuum between the two species of *Cerebrosphaera*. These species are in fact defined based on the two end-members of a single population. This analytical method also allowed the realization of elemental maps and elemental spectra. These analyzes confirmed the carbonaceous nature of the vesicles and they also showed a uniform chemistry for the vesicles.

Transmission electron microscopy also showed interesting results. The ultrastructure has been proved to be complex. The walls of the organic vesicles are made of three different layers. The first layer is an external thin layer, not visible on all of the specimens because it tends to split up from the rest of the walls. The second layer is an intermediate porous layer visible on most of the specimens. The third layer is an internal, electron dense and homogeneous layer found on all of the specimens. No differences have been observed among the subgroups or the species. The detailed observation of the ultrathin sections did not show any morphological feature that could explain on his own the unique highly folded wall morphology of the genus.

Infrared micro-spectroscopy indicates that the vesicles are made of a resilient highly aromatic and lowly aliphatic organic biopolymer, identical for the two species. The Raman performed on the same specimens confirmed these results by indicating a low thermal alteration temperature. This temperature is estimate at a maximum value of 150 °C, by comparison with Raman spectrum of the literature were the temperature is known by other techniques (Lahfid et al., 2010*)* and the calculation of various geothermometers using Raman data. This low temperature excludes the fact that the high aromatic content results from a relative aromatization due to thermal alteration.

Discussion

All of these results allow discussing several issues. The first issue deals with the existence of two species of the genus, *C. buickii* and *C. ananguae*. All the results tend to show that there are no differences among the two species from an ultrastructural and chemical point of view. The morphological studies also indicate a continuum between the two species. The combination of these three types of information leads us to the conclusion that the two species most likely represent the morphological variant within a single population.

The second point concerns the eukaryotic nature of the genus *Cerebrosphaera*. Recognizing if an organic vesicle is or is not a eukaryote is a difficult task. To achieve such work, researchers have defined several remarkable characters that indicate eukaryotic nature. These characters are the presence of an ornamentation of the vesicle's surface, the presence of an excystment structure, the presence of processes, the presence of a complex wall ultrastructure and the presence of a complex wall chemistry (see Javaux et al., 2003 and Knoll et al., 2006 for further details). The size of the vesicle can also be taken into account but only if combined with the other criteria (Javaux et al., 2003). *Cerebrosphaera* show two of the criteria: the complex ultrastructure and chemistry of its organic wall. Moreover, the great size of *Cerebrosphaera* (which is up to 1000 µm), associated with these two criteria, allows classifying *Cerebrosphaera* as a eukaryote.

The last point to discuss is the comparison of *Cerebrosphaera* with other genera described in the literature (see Talyzina & Moczydłowska, 2000 and Peng et al., 2009 for example). Comparisons show that the folds structure and morphology of *Cerebrosphaera* are truly unique among the acritarchs. The ultrastructure is also unique but resembles to the ultrastructures of *Leiosphaeridia tenuissima* from the Mesoproterozoic Roper Group which are also complex and made of various different layers (Javaux et al., 2003, Marshall et al., 2005). Like the ultrastructure, the chemistry is also unique and also resembles the wall chemistry of some species of *Leiosphaeridia* with small differences, notably in the aliphatic content.

Conclusion

Despite all of the analyses, it is still difficult to explain the origin of the unique morphology of *Cerebrosphaera*, either as a true wall ornamentation or as a taphonomic feature linked to the flexibility of the wall, although data obtained in this study would tend to support the latter. These analyses allow classifying this genus as eukaryotic, due to its large size associated with its complex ultrastructure and chemistry. Finally, due to the absence of clear differences between the two species, *Cerebrosphaera ananguae* should be placed as a junior synonym of *Cerebrosphaera buickii*. This study shows that new protists such as *Cerebrosphaera* also diversified besides crown group eukaryotes during the Cryogenian.

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Influence of glass chemistry on properties of glass-metakaolin based inorganic polymer cements

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The cement industry accounts for up to 8% of the anthropogenic emission of CO_2. The production of Ordinary Portland Cement (OPC) has a high energy demand and releases CO_2 during its calcination of limestone. It is therefore important to develop alternatives as for example inorganic polymers. They are formed by the alkaline activation of an aluminosilicate rich source material. Commonly used materials are calcined clays, ground granulated blast furnace slag (GGBFS - a byproduct of the pig-iron industry) and fly-ash (a residue of the combustion of coal). For this work a blend of calcined clay and GGBFS was used, which were provided by Banah U.K. (a British company specialized in inorganic polymer cements). The blend was activated with a K-silicate solution. The GGBFS in the blend was replaced by plasmastone (a vitrified residue of the gasification process). There is a better control on the chemical composition of the plasmastone than of the GGBFS, which results in a better control on the properties of the inorganic polymer cements. Four different plasmastones were used, one with a similar composition as the GGBFS of Banah U.K., and the others with each as main component calcium, magnesium or potassium. The reactivity of the materials can be assessed by the chemical composition, the glass content, the particle size distribution and the specific surface. The last three parameters were aimed equal for each material, in order to be able to determine the influence of the chemical composition. In previous researches, several formulas were proposed, however none of them takes into account the amount of potassium. Therefore, a new formula is proposed, which calculates the ratio of the network-modifying (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) to the network-forming (Si^{4+}, Al^{3+}) cations. The microstructure and chemistry of the inorganic polymers were investigated with optical microscopy, SEM and EPMA. On a short time scale setting time and heat release were analyzed with vicat testing and calorimetry. The mechanical properties were analyzed with three-point bending and compressive tests on a larger time scale. The microstructure and chemistry of the different inorganic polymers were all similar. In the first hours, Vicat testing revealed that the higher the value of the ratio of network-modifying to network-forming cations, the more rapid the inorganic polymers will set and harden. The same can be concluded from the heat release of the materials. The network-modifying cations are responsible for the more rapid dissolution of the raw materials and the availability of Al^{3+} in the solution. After saturation, condensation takes place and the inorganic polymers set. By means of XRD, a similar mineralogical composition was identified. The inorganic polymer mortars obtained a flexural strength of 7-9M Pa after 28 days. A compressive strength of 65-75M Pa was obtained after 33 days. Thus, the chemical composition of the raw materials had a strong influence on the shorter time scale properties of the inorganic polymers, but on the longer time scale the materials obtained the same properties.

Cyclicity of the Upper Cretaceous Apulian platform carbonates (Llogara section, Albania)

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The Llogara section, situated on the Karaburuni Peninsula in the southwest of Albania, consists of a succession of 1425 m of Upper Cretaceous platform carbonates. It is the eastern record of the Apulian carbonate platform and consists of a succession of numerous peritidal to subtidal small-scale sequences. In this study six different intervals were studied, each of them representative for one type of shallowing-upward sequence. A clear cyclicity is present in the stacking of the lithofacies throughout the section. The main objective is to assess if this cyclicity is also expressed in the diagenesis and petrophysical properties of these deposits. In this way, this study aims to contribute to the understanding of the Cretaceous deposits of the peri-Adriatic region.

The identification of benthic foraminifera and other microfossils resulted in the refinement of the biostratigraphical framework. A targeted strontium isotope analysis, mainly carried out on rudist fragments, was finally not successful, likely due to some diagenetic alteration. Clear discrepancies between the Sr-isotope ages and the biostratigraphical framework were identified. The rudist fragments therefore do not reflect the original marine Sr-signature.

Petrographical observations and stable $\delta^{13}C$ and $\delta^{18}O$ analyses document several phases of diagenesis: (1) early contemporaneous dolomitization evidenced by the presence of rhombohedral molds of small dolomite crystals scattered throughout the matrix; (2) early to late meteoric diagenesis evidenced by a clear covariance of $\delta^{13}C$ and $\delta^{18}O$ values; and (3) burial diagenesis evidenced by bedding-parallel stylolites (BPS). No clear relationship between sedimentology and diagenesis could be established. This can be explained by a meteoric overprint that affected the succession as a whole.
Mercury Injection Porosimetry results show that predictability of porosity for the different lithofacies is good. Porosity is mainly dominated by interparticle porosity of the micritic matrix, resulting in low open porosities and a bad connectivity of the pore-network. A general trend of decreasing porosity towards the top of each small-scale sequence is observed which is most likely related to the initial characteristics of the different lithofacies, rather than to diagenesis. The presence of tight, impermeable stromatolitic layers at the top of each small-scale sequence results in a compartmentalization of the reservoir.

The Hockai fault zone: connecting seismo-tectonic and geothermal aspects.

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Introduction

The Hockai Fault Zone (HFZ) is a 1 to 2 km wide tectonic structure (possibly up to 4 km) that extends from the crest of Battice to the South of Malmedy in a NNW – SSE direction. It belongs to the transverse strike-slip fault system in Eastern Belgium. In the Northern part of the area, the HFZ is defined by structural features such as the Graben de la Minerie (Ancion & Evrard, 1957) and the Verviers fault which forms the extension of the Eastern part of the Graben de la Minerie to the South. The Southern part of the HFZ is principally characterized by geomorphic features such as river captures e.g. the Hoëgne (Demoulin, 1986) and the Warche captures (Juvigné, 1985). Although the fault zone was first described during the 20th century, its course and structure are still poorly known. However, instrumental and historical records of earthquakes (e.g. the September 18, 1692 Verviers earthquake (Petermans et al., 2004) or the 1989-1990 seismic swarm of Bevercé (Camelbeeck, 1993)) clearly indicate an increased seismicity along this zone. According to the intensity of faulting (to be studied), the geothermal potential of the HFZ will be significantly enhanced with respect to its surroundings. The aim of this study is to characterize the structure of the HFZ and to evaluate qualitatively the permeability of different sites through this fault zone. The geothermal potential has been evaluated at a regional scale purely on the basis of existing published data.

The structural characterization of the HFZ

Methods used

The structural characterization was performed at local scale on three different sites with two different geophysical methods: the microseismic H/V method and the electrical resistivity tomography method (ERT). The microseismic H/V measurements were performed with a Lennartz 1Hz seismometer (LE-3Dlite MkII) or a Lennartz 5s (LE3D/5s) seismometer connected to a Leas-Cityshark II data acquisition system. The application of the H/V (formerly also called 'Nakamura') method provides information on the relief of the bedrock while the subsurface resistivity measurements allowed us to assess the degree of fracturing and the related permeability of the underlying rocks as well as the presence of water. Measurements were achieved using both a Syscal Junior Switch 48 and a Lippmann 4-Punkt-Light resistivimeter. For one of the studied sites, results were integrated into the geomodeling software GOCAD to create local 3D geomodels.

Results

The investigated sites were chosen for their location near the limits of the HFZ. The first of the studied site, the Crest of Battice, is covered by a layer of Cretaceous sediments slightly dipping to the East. The principal interest of this site is its subsidence morphology that corresponds to the limits of the HFZ. 96 measurements have been carried out by Royen (2014) along a 3.5 km long West to East profile. The lowest fundamental frequencies (between 1.3 and 1.7 Hz) have been recorded in the central part of the profile where the subsidence is the most expressed. This central part is bordered by two areas where fundamental frequencies are higher (up to 2.5 Hz). If an S-wave velocity of 300 m/s is attributed to the Cretaceous layer, the top of the bedrock has a depth varying between about 55 m in the center of the graben structure and 30 m on its borders. As the subsidence structure is marked both through the surface morphology and the bedrock structure, it can be concluded that post-Cretaceous movements created the morphology of the site. Moreover, as the filling of the structure is not yet completed, it means that "recent movements" occurred along the Crest of Battice. The second site that has been studied is the Wesny scarp. This site is located near Verviers on the Eastern border of the HFZ. It is characterized by a 150 m long scarp that has a NNW-SSE orientation crosscutting the Hercynian structures. On this site, 59 microseismic H/V measurements and 7 ERT profiles were performed. From the microseismic measurements, it can be concluded that the Eastern border of the HFZ is located 50 m to the East compared to the limit based on the geomorphic features. The ERT data allowed the characterization of two horizontal resistivity gradients that could be interpreted as faults. Lower resistivity values have been observed on the hanging wall of those faults. The third site to have been investigated is the Belle-Hé scarp. It is located in the Hoëgne valley in the central part of the HFZ. The site is characterized by a scarp with a length of about 500 m that has a NNW-SSE direction; its location makes it interesting for the characterization of the rock fracturing inside the HFZ. 84 H/V measurements and 7 ERT profiles were measured and integrated into the software GOCAD. Two surfaces were defined from the measurements. The first surface has a subhorizontal shape and has been interpreted as being a terrace of the Hoëgne River. The second surface is subvertical separating high resistivity values on the top of the scarp from a low resistivity area. As the limit between the high and low resistivity values is clear and has a direction subparallel to the direction of the scarp and the HFZ, it has been interpreted as being a fault plane.

The evaluation of the geothermal potential

Method used

Using published data, possible reservoir formations have been identified according to their lithological characteristics. Temperature gradients have been evaluated for different logs determined from published regional structural balanced cross-sections (e.g. the balanced cross-sections published by Rogiers et al., 2014). Simulations are based on the analytical solution of the Fourier equation describing the heat flow as a function of the temperature and the thermal conductivity (Norden et al.¸ 2008). As the thermal conductivity depends on the temperature and the pressure, corrections based on Fuchs (2013) and Vosteen & Schellschmidt (2003) have been carried out for the simulations.

Results

From the analysis of published data, it has been concluded that the Hour Formation can been considered as a potential reservoir. This observation is based on the characteristics of the formation which yields thick continuous quartzitic layers. The temperature gradient obtained from the simulation is varying between 25 and 29 °C/km. The variations are due to low conductivity rocks (e.g. from the Revinian Group) lying on the top of a high conductivity layer which act as an insulator and enhance the temperature gradient.

Conclusion

For each of the studied sites, the subsurface structure has been characterized by geophysical methods showing possible faults traces on all the studied sites. The field work done on the Battice Crest and through the Wesny scarp allowed to precise the location of the Eastern border of the HFZ in its Northern part. From ERT measurements, it can be concluded that low resistivity layers interpreted as permeable rocks are always located on the hanging wall of the faults. From the evaluation of the geothermal potential, the insulating role of low conductivity layer has been proved to enhance the temperature gradient. From this observation, the ideal configuration for a geothermal reservoir in the Stavelot Massif should be a reservoir composed of Hour rocks lying under an insulating layer of Revinian rocks.

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