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Structural and mineralogical study of a Cu-Ag-mineralisation in the Kundulungu foreland of the Katanga orogen, Dikulushi, Katanga, Democratic Republic Congo

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The Katanga province is located in the south-east of Congo and consists of two geologically important regions: (a) the Lufilian arc in the south on the border with Zambia, which developed in the Neoproterozoic, during the Pan-African orogeny and (b) its Kundulungu foreland to the North. The Cu-Ag-deposit of Dikulushi is located in the Cu-poor Kundulungu foreland, 300km to the north of the Cu-rich Lufilian arc.

This thesis project examines the rich Cu-Ag appearance in the Dikulushi region. The project is based on three types of investigations. The first concerns a field study during which special attention was given to the relation between deformation and mineralization in space and time. The result of this field study was a detailed structural analysis of the quarry, which is incorporated in a geological map of the pit. During the campaign many rock samples were taken for a detailed mineralogical examination in Leuven. This mineralogical approach forms the second pillar of the thesis project and resulted in a paragenetic sequence for the mineralization. Both studies revealed that the mineralization at Dikulushi is separated in two different mineralizing phases.

A first mineralizing phase appeared in the footwall of a reverse fault. This reverse fault broke through the forelimb of a second-order periclinal detachment anticline. The anticline developed on top of a mobilized mélange, which acted as a source for the mineralising fluids. These fluids were sucked out of the mélange into the footwall due to break-thrust folding. Mineralogical investigations pointed out that the mineralization consists of Fe-Pb-Cu minerals, which precipitated out of a high salinity Ca-Na-Cl-rich brine at a homogenization temperature of 150°C. In the mineralization one can recognize a transition from a reducing to an oxidizing environment. A second mineralising phase occurred in the hinge zone of steeply plunging, third order perclinal antiforms, where they are crosscut by NE-SW trending fractures. This mineralisation consists of massive chalcosite with high Cu- and Ag-concentrations. The mineralisation precipitated out of a moderate-salinity Na-X-Cl-brine at a homogenisation temperature of approximately 75°C.

The third pillar consisted of remote sensing and geophysical data. It revealed a good insight in the geology of Dikulushi and its surroundings. Dikulushi itself is located in the culmination zone of a first-order detachment anticline running from the Kiaka anticline in the south to the Kabangu anticline in the North. These anticlines developed during Neoproterozoic tectonics. The first mineralising phase is situated in the forelimb of a second-order pericline and has developed together with the pericline during this Neoproterozoic folding event. The second mineralising phase developed along NE-SW trending fractures, which belong to a larger fracture system along this direction. This fracture system is parallel to the border faults of the incipient Mweru-Tschangalele rift zone and is believed to lie in the tip zone of one of these bordering faults. Following this hypothesis, the second mineralising phase developed during Phanerozoic tectonics.

The formation of the high-grade Cu-Ag vein-type deposit at Dikulushi is closely related to Phanerozoic rifting in southern Africa. The concentration process is, however, strongly controlled by the pre-existing structural architecture that resulted from the Neoproterozoic Katanga orogeny.

Geologic and mineralogical study of the zeolite deposits of the Cayo Formation at the coast of Ecuador

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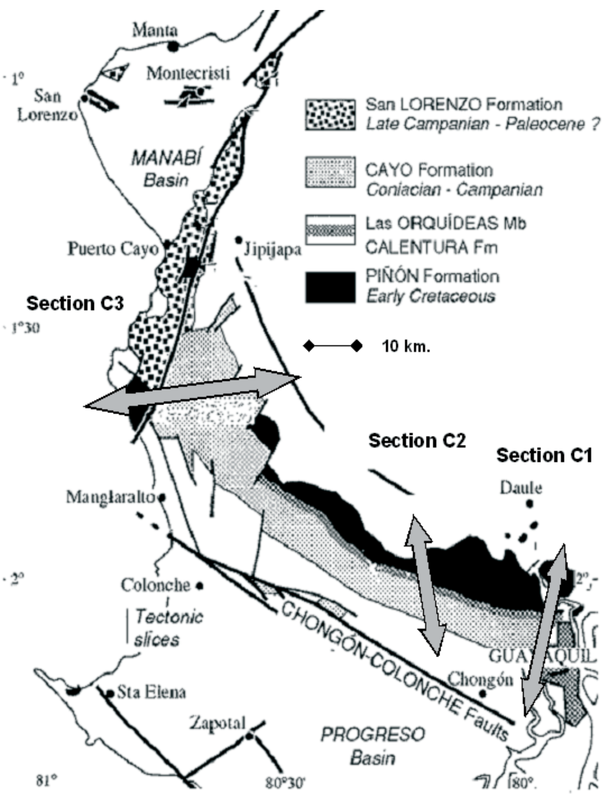
The occurrence of zeolites in coastal Ecuador has been demonstrated at the end of the last decade. The zeolites are found in the Cayo formation, a rock unit of Cretaceous age consisting of volcaniclastic and sedimentary rocks. The Cayo formation was first described in 1942 in the village of Puerto Cayo, which was later on abandoned as the type locality. In 1995 Benítez redefined the Cayo formation at the Via Perimetral near the city of Guayaquil. Morante (2004) investigated the zeolite mineralogy of the Cayo formation at the campus of the ESPOL University near Guayaquil. Zeolites of the clinoptilolite-heulandite (cli-heu) solid solution series occur in rock types locally named "lutitas" and "agglomerados". Several local applications of zeolites have been developed by ESPOL. They can be used as fertilisers in agriculture, as pozzolans in cement industry, for the extraction of heavy metals from wastewaters, etc.

Up to now very little is known about the geology and mineralogy of this deposit. The aim of this licentiate study is to investigate the zeolite mineralogy and geology in the entire area of its occurrence, a region of 1000 km^2. This study is part of a VLIR-UOS project and supports the investigation of the ESPOL University of Guayaquil.

Three cross-sections were sampled through the Piñón (basement basalts, accreted oceanic plateau), Calentura (platform sediments), Cayo and Guayaquil (deep marine radiolarites and cherts) formations (see figure - cross-sections C1, C2, C3). A mineralogical study (XRD, 53 samples) showed that zeolites are absent in the Piñón and Guayaquil formations, are rare in the



Three profiles across the Cayo formation near Guayaquil, Manabi province, Ecuador (modified from Reynaud et al. (1999).

Calentura formation and are widespread in the Cayo formation. Zeolites occur in the three profiles over the entire cross-section of the Cayo formation. Mordenite and cli-heu are the main zeolite minerals, they occur in most of the samples. Analcime and laumontite occur, but are rare. The zeolites are associated with autigenic quartz, montmorillonite and calcite and with detrital feldspar and quartz.

A petrographic study has been performed using optical and scanning electron microscopy. A decrease in grain-size is found from east (agglomerados) to west (lutitas). This is explained by a proximal to distal distance from an unknown volcanic source in the east. Three main rock types can be distinguished:

- Green-blue tuffs: consisting of glass shards (lutitas). This rock type is rare in C1, where it occurs as thin intercalated layers. It dominates the base of C2 and the entire C3. The silica content is up to 75wt.%. An interlocking pattern of mordenite and quartz occurs in the glass shards and matrix. The zeolite content is high (estimation by XRD and microscopy of 60-70 %).
- Coarse to fine-grained brown lapilli-tuffs (agglomerados): consist of basaltic to rhyolitic fragments. This rock type dominates C1 and the top of C2. Silica content is approximately 50 wt.%. Cli-heu occurs as fragment cementation and fills vesicles in silica-rich fragments. The zeolite content is medium (approximately 20%).
- Brown (C1-C2) or green-blue (C3) pelagic rocks (lutitas): consist of crystal fragments and pelagic fauna embedded in a clay rich, silica-cemented matrix. This rock type occurs intercalated with both other rock types. The zeolite content is low, cli-heu (C1-C2) or mordenite (C3) fills micro-organisms and glass fragments.

Notice the strong lithologic-mineralogic relation: mordenite occurs in tuffs and cli-heu in agglomerates, two rocktypes that are easily distinguished in the field.

The zeolites were formed in a marine volcaniclastic environment, soon after deposition. Possibly an open hydrologic system was formed in the tuffs, while a geo-autoclave closed system was formed in ignimbritic deposits (agglomerates). Laumontite developed later in vein systems. More research is needed to reconstruct the genetic history of the zeolites.

It can be concluded that the Cayo formation is a very large and rich zeolite deposit, of great importance for a developing country such as Ecuador. The mineralogical and geologic investigation of this study is very important for an optimal exploitation and local application of the zeolites.

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Seismic stratigraphy of Lago Puyehue (south-central Chile): mass-flow deposits as a potential record of past seismic activity

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Historical records of destructive mega-earthquakes in seismically active areas usually do not extend back in time further than a few hundred years. However, the recurrence rate of such strong seismic events is often much longer. Paleoseismologic studies are therefore needed to reveal any statistically significant earthquake frequency in these regions.

South-Central Chile is located at the slightly oblique convergence of the oceanic Nazca plate and the continental South American plate. This subduction zone segment has ruptured in several destructive mega-earthquakes during historical times (1575, 1737, 1837 and 1960 AD), with as tragic highlight the 1960 Valdivia earthquake (M_w: 9.5), the strongest, instrumentally

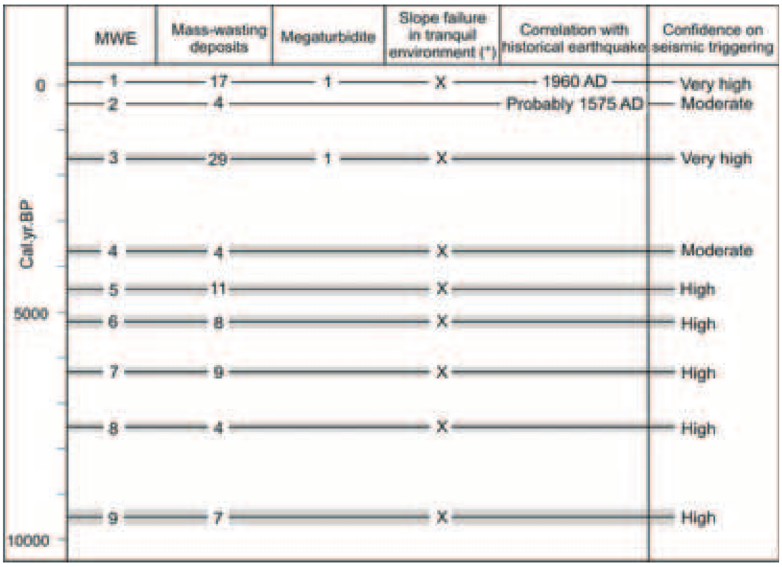

Figure 1. Summary table of the identified mass-wasting events and the confidence level on the interpretation as seismically triggered. Grey shadings inicates error bars.

(*) A "tranquil" depositional environment is located at significant distance from direct clastic supply and at water depths > 30 m.

recorded earthquake ever. Such strong seismic events are capable of triggering soft-sediment in-situ deformations and multiple slope instabilities in lake basins. The moderate to steep-sloped glacigenic lakes in the Lake District of South-Central Chile therefore have a high potential to have registered seismically triggered mass-wasting deposits in their sedimentary infill, establishing themselves as very promising paleoseismological archives.

In order to examine the paleoseismological potential of these lakes, a very-high-resolution seismic reflection investigation was conducted on Lago Puyehue (41°S). In total, 155 km of 3.5 kHz pinger seismic profiles were collected with a resolution of 25-30 cm, making it possible to identify large-scale mass-wasting deposits. A detailed seismic stratigraphy was established, based on seismic reflector terminations and seismic facies analysis.

All mass-wasting deposits in the sedimentary infill were studied in detail. Deposits resulting from slumping and debris-flows or seiche processes were identified on the seismic profiles. Typical phenomena such as fluid expulsion structures and deformation of basin-plain stratification were observed. In several cases, multiple mass-wasting deposits occur on a same seismic-stratigraphic horizon, indicating that they are coeval and caused by a single mass-wasting event (MWE) of basin-wide importance. The geographical distribution of mass-wasting deposits has been mapped for each mass-wasting event. Evaluation of all possible failure processes led us to infer that very strong earthquakes (I > VI-VII) are the most likely trigger mechanism of mass-wasting events in Lago Puyehue. This assumption is supported by the observation that the simultaneous slope failures also affect tranquil depositional environments at water depths of about 80 m. Mass-wasting in this location excludes other triggering mechanisms such as delta oversteepening, wave-action and lake-level fluctuations, and possibly even seismic events of lower magnitude.

An age-depth model, based on 9 AMS radiocarbon datings (Bertrand, 2005) and varve-counting (Boës & Fagel, in press) on an 11 m-long sediment core, has been used to develop a "seismic chronostratigraphy" which can be extrapolated and applied to the whole basin. It allows dating of mass-wasting events by interpolation between dated seismic horizons to the distal parts of the mass-wasting deposits.

The outcome of our study is a time series of nine major mass-wasting events –most likely caused by strong earthquakes (I > VI-VII)– during the Holocene. Determination and dating of older mass-wasting deposits is inaccurate due to a limited seismic penetration and large extrapolations. The seismic recurrence interval varies between 500 and 2000 yrs with an average of ~1000 yrs, which is rather large compared to other subduction zones worldwide that usually have recurrence intervals of 200-600 yrs. These longer periods of stress build-up possibly explains why seismic events with an extremely high magnitude (cfr. AD 1960) can occur in South-Central Chile. Although the recurrence interval of the relatively large historical earthquakes is about 128 yrs, not all of the accumulated plate motion is released in every earthquake (Cisternas et al., 2005). This results in significant magnitude variations of the Valdivia seismogenic zone ruptures and consequently a differential encoding in the Lago Puyehue's sedimentary archive.

Periods without mass-wasting events do not necessarily point to a temporary absence of very strong earthquakes, but can also be caused by a temporary lack of potentially unstable slope sediments due to climate-induced variations in the sediment supply towards the lake. This implies that the paleoseismological significance of these lacustrine sedimentary arhives should be investigated in a broader context, involving an assessment of variations in climate and in volcanic activity in the area.

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Promotor: Marc DE BATIST.

Optimisation of the monitoring network of the PIDPA well field in Merksplas

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The drinking water supply company PIDPA has a piezometric head monitoring network of 81 observation wells around the pumping wells in Merksplas, in the north of Belgium. Groundwater is pumped from a depth of 175 m, in the Diest Sand Formation. To improve efficiency and enable automatisation of the measurements, it is necessary to select those head observation wells which provide maximum information, with minimum measuring effort. The objective of the research is thus the optimisation of the monitoring network for piezometric head. Observation wells are grouped based on the hydrogeological behaviour. Then a regional, transient groundwater model is developed to gain a better understanding of the hydrogeology of the study area and to check the first grouping of the observation wells.

The head observation wells are grouped by two different methods: first on the basis of geography and geology, and secondly by means of "self organizing maps". In the first method the observation wells are classified taking into account the location, the distance to the pumping wells, the screen elevation, the lithology and the possible presence of a surface water in the neighbourhood of the observation well. On the basis of these criterions the observation wells are divided in 4 groups and 12 subgroups. The 4 main groups are formed by the wells in the 4 main geological formations: the Quaternary coversands, the Campine Clay and Sand Formation, the Pliocene Merksplas Sands and the Miocene Diest Sands.

Secondly the method of "self organizing maps" is used for grouping of the head observation wells. "Self organizing maps" is an unsupervised artificial neural network technique designed to classify multidimensional data based on the euclidean distance between samples and to visualize these multidimensional data on a two-dimensional grid in a topology preserving manner. In this study the normalized time series of the head measurements are classified by means of "self organizing maps". The results are visualized through the so-called U-matrix, which shows the classification of wells into groups by visualizing the average euclidean distance between head observations. In the U-matrix the head observation wells are clustered in 6 groups and 11 subgroups. The separation in subgroups is based on the differences in the observed heads in the time series of the observation wells.

By comparison of the classification by these two methods 7 groups are formed, but 12 head observation wells could not be classified in a group.

A groundwater model is developed, using all available data at this stage, for a better understanding of the groundwater system in the investigated area. A stationary approach is developed to serve as a basis for a transient model, spanning a period of ten years. The calibrated transient model is used to check the behaviour of each head observation well. After verification of the ordering, 10 groups of wells are formed, with in a group a similar hydrogeological behaviour. In each group one (or more) representative well(s) can be chosen to be measured. The head observation wells to be measured can by this way be reduced from 51 to 32.

The transient model can also be used to optimise possible locations for new head observation wells in zones where information is lacking.

For further optimisation of the monitoring network, the groundwater quality aspects will be considered, in order to obtain as far as possible representative indicators of the groundwater quality, from sampling and analysis in few wells.

Promotor: DASSARGUES Alain

Study of Cu-U-Se mineralization of Musonoï Mine, Kolwezi, Katanga, Democratic Republic of Congo

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Musonoï Mine lies in the westernmost part of the Katanguian Copperbelt in D.R.Congo, Central Africa. This ore deposit has been formed during Roan time, 950 millions years ago on the side of Congo-Kasaï craton (Kroner, 1977). This Cu-Co mineralization is famous for its *'écaille 2400'* (thrust-sheet 2400) which has provided some of world's finest samples of uranium supergene minerals (Gauthier *et al*., 1989).

During this present mineralogical study, more than thirty minerals have been recognized at Musonoï including four new minerals : a sulphur-bearing berzelianite [$Cu_{2-x}(Se,S)$], billietite [$Ba(UO_2)_6O_4(OH)_6 \bullet 4H_2O$], meta-uranocircite [$Ba(UO_2)_2(PO_4)_2 \bullet 6\text{-}8H_2O$] and volborthite [$Cu_3V_2O_7(OH)_2 \bullet 2H_2O$]. The data collected on five samples also indicate that they probably correspond to new mineral species : an uranyl-selenite exhibiting a formula close to [$(Cu,Mg,Ca)(UO_2)_3(SeO_3)_2(CO_3)_4(H_3O^+)_4 \bullet H_2O$], a Fe-Cu-U hydroxide and three species which are still on work but probably copper-bearing. Those mineral species have been analyzed by powder X-ray-diffraction, electron microprobe data and infrared spectroscopy.

Several results have to be noticed such as the application of Vegard's law to digenite-berzelianite series, which shows that the S-Se replacement in digenite structure has not an ideal solid solution behaviour. The confirmation of $(UO_2)_2(SiO_4)•2H_2O$ chemical formula for natural soddyite and a middle term between meta-torbernite, przhevalskite and chernikovite for $(Cu, H_3O^+, Pb)(UO_2)_2(PO_4)_2•8H_2O$ are also relevant results. New data show that Musonoï's sengierite, $Cu_2(UO_2)_2(VO_4)_2(OH)_2•6\text{-}9H_2O$, has a 50% vacancy of its Cu octahedral site and further structure refinement are necessary to understand this U-V-Cu sheet structure.

The examination of petrographic textures under the ore microscope permitted to establish a crystallization sequence showing three episodes in Musonoï mineralization. A genetic model can also be developed for the Musonoï Mine, in agreement with Okitaudji (2001) metallogenic hypothesis. Firstly, contemporaneously to shale and sandstone deposit, a precipitation of dolomite is visible as well as a primary sulphides mineralization of chalcocite and carrollite. The formation of sulphides seems to be explained by bacterian precipitation in Roan epicontinental sea, forming a succession of dolomite – sandstone – (Cu-Co) sulphides sequence. Uraninite is probably deposited during this first phase.

Kundelungu time has probably seen the expulsion of diagenetic fluids out of Roan sandstone and notably out of basal volcanoclastics levels, allowing an enrichment of Cu-Co- bearing layers in various elements. Moreover, intense tectonic events correlated with Katanguian orogenesis has also brought P-T conditions which have deeply affected the deposit by metasomatic effects, thus forming seleniferous phases such as Se-digenite and Se-covellite, and selenides (berzelianite, trogtalite and PGE-selenides).

During Cenozoic times, meteoric waters affected deeply the ore, forming numerous minerals in alteration of sulphides and selenides. Crystallization sequences of this later phase are much more complex and strongly variable depending of lithology, tectonic and karstologic features.

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Petrogenesis of Fe-Ti ore deposits from the Suwalki anorthosite massif (NE Poland) and crystallochemistry of associated Ti-phlogopites

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The Suwalki massif-type anorthosite (NE Poland) together with the associated (rapakivi-) granites of the Mazury complex constitute a typical AMCG (Anorthosite-Mangerite-Charnockite-(rapakivi) granite) suite dated at ~1.5 Ga (Dörr *et al*., 2002). As the Suwalki anorthosite is buried under a 580-1200m thick Phanerozoic cover, it has been essentially explored by drilling. Several Fe-Ti ore deposits have been recognized and reserves have been estimated at ~1250 Gt of ore. In cross-section, the Suwalki anorthosite displays a domical shape and is surrounded by gabbronorites and diorites. The parental magma has a ferrodioritic composition, close to typical jotunites, and probably results from partial melting of a mafic lower continental crust (Wiszniewska *et al*., 2002).

A series of 70 samples have been collected in the bore holes of 4 ore deposits (Krzemianka, Udryn, Lopuchowo and Jeleniewo). They usually represent cumulates ranging in composition from pure anorthosite to gabbronorites but fine-grained rocks have also been observed. These latter may be representative of liquid compositions. Even if the cumulates are deeply recrystallized due to the diapiric emplacement of the anorthosite, detailed petrography has enable us to propose the following sequence of crystallization: plagioclase, magnetite + ilmenite, orthopyroxene, apatite and clinopyroxene. Because of the large density contrast between oxides and plagioclase, ilmenite and magnetite can be easily segregated to form enriched- to pure-oxides layers.

Major elements of fine-grained samples show continuous trends from ferrodiorite to (rapakivi) granites. This liquid line of descent can be explained by the appearance of the successive liquidus phases. The crystallization of magnetite and ilmenite is responsible for the progressive decrease in FeO_t and TiO_2 and for the increase in SiO_2. P_2O_5 and CaO decrease in residual liquids as a result of the appearance of apatite and clinopyroxene, respectively.

The variation of Al_2O_3 in orthopyroxene (0.8-4.0 wt%) from several ore bodies helps constraining the depth of emplacement of these deposits This range of composition implies a crystallisation pressure varying from 2 to 6 kbar (Longhi *et al*., 1993). The Krzemianka deposit started to crystallise around 6 kbar (~ 20 km). This is deeper compared to the Udryn deposits, which started to crystallise at 4.5 kbar. The final level of emplacement of the Suwalki massif corresponds to the crystallisation depth of the Lopuchowo ore deposit at 2 kbar (~7 km). Polybaric crystallization of the ore deposits is evidenced by the relation between Cr in magnetite, considered as a differentiation index, and the decrease of Al_2O_3 in orthopyroxene. An alternative model would involve two parental magmas with different Cr content.

The crystallochemical study of phlogopites in cumulates evidences the factors responsible for the significant Ti- and Al-enrichment in these minerals. The Ti-incorporation results from two mechanisms: $^{[6]}Ti^{4+} + 2^{[4]}Al^{3+} = (^{[6]}Mg^{2+}, ^{[6]}Fe^{2+}) + 2^{[4]}Si^{4+}$ and $^{[6]}Ti^{4+} + ^{[6]}\square = 2(^{[6]}Mg^{2+}, ^{[6]}Fe^{2+})$. The Al-incorporation may be explained by: $(^{[6]}Mg^{2+}, ^{[6]}Fe^{2+}) + ^{[4]}Si^{4+} = ^{[6]}Al^{3+} + ^{[4]}Al^{3+}$. These different substitution mechanisms are related to the crystallisation temperature of phlogopites. A series of spectroscopic analyses (infra-red and Mössbauer) also revealed the presence of Fe^{3+} and water in the network of these micas and the low abundance of vacancies in octahedral sites.

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Changes in the malacofauna of Lake Malawi since mid-Holocene times

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It is generally accepted that Lake Malawi, the second largest African rift lake (surface: 29,000 km^2), is a prime example of an 'ancient lake', i.e., an extensive lacustrine system that persisted for at least 100,000 years (Gorthner, 1994). The assumption that the modern Malawi fauna is the result of a long-lasting evolutionary process is principally based on the marked diversity and endemism of its modern fish and molluscan communities. During the missions of the Hominid Corridor Research Project under the direction of Prof. Dr. Friedemann Schrenk in the nineties, a well preserved fossil mollusc assemblage of mid-Holocene age (^{14}C: 5,845 ± 85 BP) was discovered at the southern outlet of the lake, allowing a glance at the fauna in the near geological past.

A morphological and conchyometric study was carried out on the named fossil assemblages, comparing the mid-Holocene shells with series of modern specimens. Differences in community structure were also analysed and the results were correlated with available data on fluctuations of abiotic factors in the Malawi Basin during the Holocene. The purpose of this study was to assess the evolutionary changes in morphology and community structure that took place in this endemic 'ancient lake' fauna over a period of *c*. 6,000 years.

The modern malacofauna of Lake Malawi consists of a mixture of lake endemics and non-endemics. This in contrast to that of 'ancient lake' Tanganyika, which is exclusively endemic. At present five gastropod genera occur in Lake Malawi, namely *Bellamya* represented by a clade of 3 endemic species and 1 non-endemic species, *Lanistes* (3 endemics/2 non-endemic), *Gabbiella* (1 endemic), *Melanoides* (7 or 8 endemics /1 non-endemic) and *Bulinus* (2 endemics/2 non-endemics) (Mandahl-Barth, 1972; Brown 1994). The mid-Holocene community consists of the same five gastropod genera with the following endemic/non-endemic ratio: *Bellamya* (0/1), *Lanistes* (3/2), *Gabbiella* (1/0), *Melanoides* (5/0) and *Bulinus* (2/1). This shows that all gastropod genera, except *Gabbiella*, underwent marked changes since the mid-Holocene and the comparative morphological study shows that most modern clades of endemics did originate from non-endemic lineages during the last 5,000 to 10,000 years. As to the bivalves, at least one of the three genera with an endemic representative in L. Malawi shows marked morphological changes since the mid-Holocene. The young age of the endemic lineages is corroborated by recent genetic research on the parthenogenetic *Melanoides* clade, which appears to consist of different, genetically virtually identical, stable morphs (Genner *et al*., unpublished).

Since the mid-Holocene a distinct trend of decrease in shell size and shell thickness in all genera and a shift in dominance in favour of the most opportunistic non-endemic lineage (i.e. *M. tuberculata*) in the genus *Melanoides* suggest suboptimal ecological conditions in the modern lake compared to 6,000 years ago.

The general conclusion of the study is that most species of the endemic malacofauna of Lake Malawi, supposedly one of the most important 'ancient lakes' in the world, are only 5,000 to 10,000 years old. The persistence of a lake over a period of several hundred thousands of years does hence not imply the persistence of its fauna and therefore major parts of the lacustrine ecosystem. From the present study it would appear that the unstable climate conditions in subequatorial Africa since the Pleistocene caused oscillatory patterns in lake levels and physico-chemical characteristics of the lacustrine ecosystem. These oscillations were of such magnitude that they caused a cyclic pattern of brief extinctions and radiation events in slow moving epi- and endofaunal biota, e.g. the mollusca, that are more vulnerable to such changes than more mobile groups such as fishes and crabs.

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Biostratigraphical analysis with dinoflagellate cysts and geological mapping of the Couches Rouges at Mégevette (Préalpes médianes, Chablais).

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Tardi- and pleniglacial deposits occur at Bouttecul in the Haute-Savoie (France). These deposits lie below 10 m of Holocene peat and contain reworked Maastrichtian marine palynomorphs. The presence of these palynomorphs is explained by glacial transportation during pleniglacial times (Streel, pers. comm.). They were eroded from their source rocks and were transported by glaciers high enough to reach Bouttecul (1275 m high) and which flowed along the valleys of the Risse, the Arve and the Giffre rivers. According to the geological map (Plancherel, 1998), Late Turonian to Santonian, Late Maastrichtian and Late Paleocene to Early Eocene rocks belonging to the "Couches rouges", are exposed at Les Jottis (max. 1548 m high), east of Mégevette, a village in the valley of the Risse. They are covered or intercalated by a flysch unit. It is possible that one of all these rocks are the source of the reworked Maastrichtian palynomorphs.

The first objective of this study was to evaluate the presence of Maastrichtian dinoflagellate cysts at Les Jottis. A detailed mapping of the Maastrichtian deposits in the area was carried out, as the geological map (Plancherel, *ibid.*) makes no distinction between the three aforementioned units. A fourth and underlying formation, the mid Cretaceous Intyamon Formation, also needed detailed mapping. The second objective of the study concerned the flysch deposits south of Les Jottis. According to the geological map (Plancherel, *ibid.*) the flysch is of Eocene age. However, preliminary palynological analysis rather indicated a Maastrichtian age for the deposits (De Coninck, pers.comm.). This contradiction together with the unclear relation between the Flysch and the rocks of the Couches rouges formed an additional problem to solve in this study.

At first, a reconnaissance geological mapping of the Couches rouges and the Flysch units has been undertaken in order to distinguish between the different subunits of the Couches rouges, and to determine the main geological structure of the study area. Secondly a biostratigraphical study of dinoflagellate cysts was used for a relative dating of the deposits. We divided the deposits of the Couches rouges into six different units, from which thirty samples were palynologically prepared and analysed. Only fourteen samples yielded enough dinoflagellate cysts to draw biostratigrafical conclusions. We identified 105 palynomorph species including 94 species of dinoflagellates. Most of the samples showed a (very) poor conservation of the organic material.

The lowest unit is the Intyamon Unit (In), which corresponds lithologically with the Intyamon Formation. Based on the contents of dinoflagellate cysts we propose a Santonian to Early Campanian age, which is somewhat younger than the age given by the geological map. The second unit is the Mixed Red Unit (Rg). A third unit is the Lower Red Unit (R2) continuously followed by the White Unit (W) for which we propose a Maastrichtian age based on the dinoflagellate cysts. The Upper Red Unit (R1) follows the White Unit conformably and must be younger than the latter. The last unit of the Couches rouges is the Red flysch Unit (Rf). The four red units could not be dated because of the lack of diagnostic dinoflagellate cysts. We were not able to determine the relation between the Rg unit and the R1 and R2 units. Because of lithological and structural features we suggest that the Rf and the R1 units possibly are partially lateral equivalents of each other. The Flysch Unit (F), for which we propose an early Cenozoic age, probably follows the Rf unit conformably. Both units are repeated by overturned folds, which are faulted at two places.

The study area is structurally complex with different phases of deformation, together or after the nappe stacking phase. However during our reconnaissance mapping we could recognise the main geological structures of the study area.

We can conclude that Early Maastrichtian deposits occur at Les Jottis. It is therefore possible that the rocks of the Couches rouges at Les Jottis are the source rocks for the Maastrichtian dinoflagellate cysts in the Pleistocene deposits at Bouttecul. The Flysch Unit (F) contains mostly reworked Early Maastrichtian dinoflagellate cysts with only a little percentage of dinoflagellate cysts of Cenozoic age. They could also be part of the source rocks.

Future research should focus on a more detailed structural analysis to determine a more detailed lithostratigraphy. Also, a relative dating using other microfossils, e.g. foraminifers, of the palynomorph poor red units R1, R2, Rf and Rg could give more detailed dating of those units.

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New insights on the structural architecture and deformation history at the southern unconformity of the Lower Palaeozoic Rocroi Inlier, Naux, France.

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A new deformation model is proposed, contributing to the ongoing discussion on the existence of an Early Palaeozoic deformation event affecting the Lower Palaeozoic Ardenne basement inliers (France, Belgium, Germany), exposed in the culmination zone of the High Ardenne slate belt. The main argument for an Early Palaeozoic deformation event in these basement inliers is the abundance of structures, like folds, that are not present above the unconformity, which is moreover of an angular nature. Although these structures are clearly co-genetic with the cleavage development, only one pervasive cleavage can be recognized at the unconformity, affecting both the basement and the Pridoli cover. These contradicting observations gave rise to the ongoing discussion about the importance of an Early Palaeozoic tectonometamorphic event, called the Ardennian orogeny.

In an effort to provide a conclusive answer to this question, we revisited a well-exposed outcrop area – the Gire valley, Naux, France – at the southern unconformity of the Rocroi Inlier, focusing on identifying the deformation history at the basement-cover interface.

Several outcrops studied near the unconformity are dominated by a shear zone affecting both the basement and cover sequences. In the Cambrian rocks, the structures developed in the footwall of this shear zone are characterized by N-verging, recumbent, non-cylindrical folds. The Variscan shear on these folds is further expressed by a differential deformation in both limbs of the folds. This different deformation pattern is reflected by the development of drag folds in the upper normal limb, while the inverse limb is affected by boudinage. Fluid inclusions, studied in the interboudin veins, provide the same pressure-temperature conditions (~350°C and 250 MPa) as Variscan veins, studied at the unconformity. The syntectonic origin of the fluid inclusions remains however unclear. The formation of the folds was co-genetic with the cleavage development, as shown by the cleavage-bedding relationships. The resulting cleavage refraction pattern, however, differs in both limbs of the non-cylindrical folds. This can be explained by a rotation of an initial cleavage refraction pattern during folding. While in the upper normal limb, the bedding-cleavage intersection in the competent layers is plunging eastwards to south-eastwards, the lower, structurally inverse limb is characterised by a NS trending bedding-cleavage intersection. The bedding-cleavage intersection in the slates is, on the other hand, parallel to the curved hinge line, generally having an intermediate orientation. These observations are corroborated by AMS data, of which the orientation of the maximum susceptibility axis is oriented parallel to the bedding-cleavage intersection. At the unconformity only one cleavage can be observed, representing a shortening of ~50% in both cover and basement. This shortening is, however, only present in the incompetent layers and is clearly less intense in the competent layers as expressed by the cleavage refraction pattern which can be observed above the unconformity.

The generation of this cleavage refraction pattern above the unconformity, representing a top-to-the-north shear parallel to the unconformity, will have serious implications on the deformation style of the strata below the angular unconformity and is therefore, in a kinematic point of view, an important contribution to the understanding of the deformation history of the Lower-Palaeozoic basement inliers. During the onset of the Variscan deformation, an initial layer-parallel shortening formed a vertical incipient cleavage plane in both basement and cover. As a result of the inherent rheologic heterogeneity of the tilted basement further shortening had a completely different effect on cover and basement. While in the cover this shortening mainly occurred in the pelitic horizons, shortening of the pelitic horizons in the basement forced the competent layers, which are misoriented to the imposed shortening, to buckle. In the sandstones this buckling caused the passive rotation of the incipient 'frozen' cleavage, while cleavage further developed in the pelites, giving rise to a slaty cleavage that is identical to that developed in the pelitic horizons in the cover sequence.

This kinematic model of Variscan progressive non-coaxial deformation is able to explain all the structures observed, without the need of a poly-phase deformation history. Only a tilted basement is postulated. This study also demonstrates that it is crucial to include the deformation of the unconformity in any attempt to determine an Early Palaeozoic tectonometamorphic event.

Promoters: Manuel SINTUBIN & Philippe MUCHEZ

Geophysics contribution in the search of old mine shafts

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Introduction

Since the XIIth century, extensive mining activities were conducted in the Walloon Region. This mining history of the area left more than 12 000 shafts and exits. Because of the age of many of these mine works, the exact location of these mine shafts is now forgotten. Even if an effective analysis of the mine plans and records may suggest the location of the old works, large areas have still to be searched to secure the shafts. Nowadays, the search consists in digging. The use of subsurface geophysics could therefore reduce the extent of the surfaces to be excavated. Previous works were undertaken abroad to evaluate the potential of geophysical methods to locate old mining works and also on similar problems linked to archaeological sites (i.e. Goodman *et al.*, 2004; Rizzo *et al.*, 2004; Sambuelli *et al*, 1998; Shoemaker *et al*, 1999).

Geophysical field experiments

In order to evaluate the potential of geophysics to locate the old works in Walloon Region, seven shafts distributed in four distinct search areas were selected. This selection was based on a synthesis of the most common contexts for the old Walloon mine shafts and on the favourable conditions of the sites to the application of geophysical methods. Sites were seen as favourable to geophysics where open space exists around the shafts, the shafts diameter is large enough (2-4 m) to reduce the influence of smaller bodies, the nature of the infill differs significantly from the surrounding soil, the soil cover over the shaft is thin and the shafts localization is precise enough to limit the search area.

The methods to be tested within this work were selected according to three criteria. The relation between the shaft properties and the method used, the complexity of the treatments and corrections to apply, the possibility of implementation (cost, equipment availability). The methods selected were magnetics, spontaneous potentials, ground penetrating radar (GPR) and electrical resistivity. On metal mines, we carried out magnetic, electric and GPR prospecting while on the sites of coal mines, we applied spontaneous potential method and GPR method.

Site description

Only one of the chosen shafts will be described in this paper in order to allow going deeper in the results and the interpretations. This site called the "Marquis de Croix" is an old iron mine situated at Franc-Waret, near Namur (Delforge, 2002). This shaft has a squared section of three by three meters and has been excavated in sandstone. At the end of the mining works, the shaft has been closed by a wooden floor. An infill composed by mining works wastes (richer in ore than the surrounding ground material) was used to cover the wooden floor. This infill should have physical properties (especially magnetic susceptibility) contrasting with the surrounding soil.

Modelling

In order to improve the interpretation of our measurements, magnetic and electric responses were modelled numerically. The modelling results were then compared with our measurements.

The first step was to build a model based on some assumed parameters (dimensions of the shaft, depth to the top of the shaft, range of magnetic susceptibilities and resistivities of soils and infill), known from the records or evidences or from similar mining works. The second step was to compute the response associated with the model to show what should be expected on the site.

Magnetic model: A model of the shaft on the "Marquis de Croix" site was constructed with the assumed dimensions of the shaft, the presence of an infill and a void below it. Several values of the infill magnetic susceptibility were tested. Thanks to these models, the shape and size of the expected anomaly can be predicted.

Electric model: The electrical resistivity modelling of the same site was realised. The apparent resistivities as if measured from electrodes placed on the ground were modelled and noise was added to better match the measurement conditions. These results were then inverted to construct an image of the subsurface effective resistivities. This image will be compared to inverted field data.

Measurements and results on the "Marquis de Croix" site

The measurements points are disposed on a regular grid of one by one meter. According to the records, the shaft should be situated within ten meters around the center of the search area.

A map of the magnetic field intensity on the search area was realised. To reveal the anomalies we applied diurnal correction to the data to compensate the daily variation of the magnetic field. A zeroing of the modal value and a median filter to smooth the variations were also applied. Through the anomaly, we took the intensity of the magnetic field along a profile. We compared the experimental curve (dotted line) with the theoretical one (Fig. 1). We obtained a juxtaposition of the two curves if dimensions of the infill slightly decrease (only fifty centimetres from each side). So the observation in the field is consistent with the model and the anomaly detected is probably due to the shaft.

To confront the results of the magnetic method, a resistivity tomography was carried out. This N-S profile

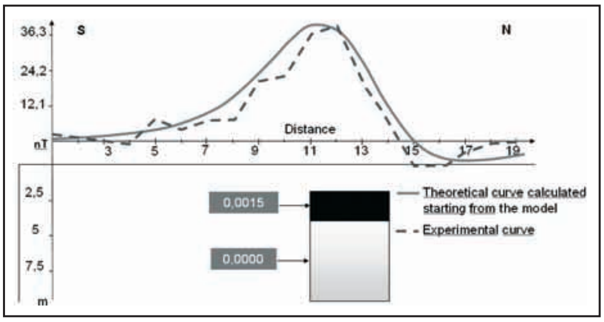

Figure 1: Variation of the magnetic field intensity – experimental results and modelled response

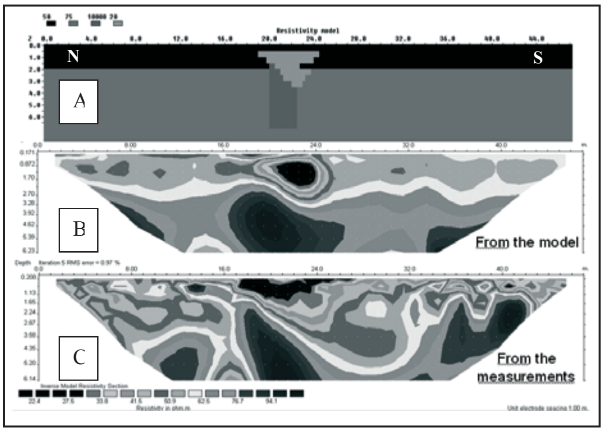

Figure 2 : Section A - modified shaft model. Section B – effective resistivities in the subsurface from inverted apparent resistivities computed on the model of section A. Section C – effective resistivities in subsurface from inverted measurements

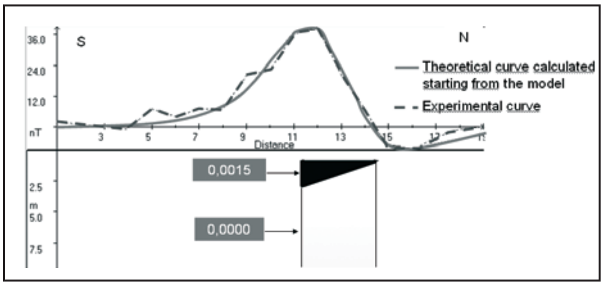

Figure 3: Variation of the magnetic field intensity over the updated model

count 48 electrodes located every meter. It is centred on the coordinates of the shaft pointed out by the magnetic anomaly.

The resistivity tomography realised along profile is given in section C on Fig. 2. This result is rather different than the effective resistivities computed from the previous model. Therefore, we adapted our model to the observations as well as possible. The new model result (section B on Fig. 2) is quite similar to the one obtained from the measurements. To achieve this, the infill had to be inclined and placed closer to the ground surface. This configuration is plausible because it matches observations made on a neighbouring collapsed shaft where traces of a slipping of the floor were seen in the sandstone.

As the geometry of the shaft has changed, the magnetic model had to be updated. To see the effect of these changes, the infill was brought closer to the surface, the shaft was shifted to the North and a triangular infill was used instead of a rectangular one. As shown on Fig. 3, there is also a better match between the updated model response and the field data.

Finally, the search area was covered with G.P.R. parallel profiles every thirty centimetres. A radar section along one of these profiles showed an anomaly which is a resonance phenomenon that could reveal the presence of a gap. The size of this anomaly is equivalent to that of the searched shaft. The comparison between this result and electric and magnetic results shows that anomalies locations are very close together and thus seem to accurately delineate the shaft.

Conclusion

For 4 shafts out of 7, the results obtained were more than satisfactory as they highlighted anomalies associated with objects whose dimensions and physical properties are in agreement with the models. Given this adequacy between theory and experiment, it is thus probable that the identified anomalies represent the searched shafts. Moreover, thanks to a combination of methods, a fifth shaft also seems to be detected.

The results obtained during this work thus showed that the geophysical methods tested contribute to improve the localization of old mine shafts. Indeed, the initial search surface of 7000 m^2 (total of 4 sites) was reduced to less than 1000 m^2. Moreover this calculation does not take into account the fact that even if the results of a method are not conclusive, they often make it possible to guide digging works by indicating “suspect” zones to begin with. Finally, on the basis of this limited experiment in the Walloon Region, it seems that the quality of results differs according to type of concession (metal concession or colliery). The detection of shafts in metal ore concessions was less difficult than in coal concessions.

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