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ON THE USE OF MAGNETIC TECHNIQUES FOR STRATIGRAPHIC PURPOSES: EXAMPLES FROM THE LOWER PALAEOZOIC ANGLO-BRABANT DEFORMATION BELT (BELGIUM)

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(10 figures, 1 table)

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ABSTRACT. Within the Lower Palaeozoic Anglo-Brabant Deformation Belt, magnetic susceptibility on its own does not allow for a straightforward distinction between different lithostratigraphic units, except for the high-susceptibility levels of the Lower Cambrian Tubize Formation. Moreover, the variation in magnetic susceptibility within individual lithostratigraphic units is often larger than that between different units, but at the same time, this internal variation in susceptibility may show no clear relationship to features obvious in outcrop or hand specimens. Hence, the applicability of magnetic susceptibility for stratigraphic purposes in the Anglo-Brabant Deformation Belt is low.

Better results are obtained using the temperature-dependent variation in terms of percentage of magnetic susceptibility within the "room temperature interval". Also the anisotropy of magnetic susceptibility allows for a better distinction between different lithostratigraphic units than does magnetic susceptibility. The best results are obtained by a comparison of thermal demagnetisation curves of magnetic remanence, used for determining ferromagnetic mineralogy. This method even allows distinguishing lithostratigraphic units in which ferromagnetic carriers do not contribute to overall magnetic susceptibility and its anisotropy.

Ideally, each magnetic technique should be used for stratigraphic purposes only in combination with other magnetic techniques. Moreover, knowledge about the magnetic carriers (s.l.) facilitates this use of magnetic techniques and strongly improves the accuracy of the interpretations.

KEYWORDS: AMS, composite fabric, ferromagnetic mineralogy, magnetic fabric, magnetic susceptibility.

1. Introduction

During the last decades, magnetic susceptibility has become a standard tool in geology, especially for the analysis of Cenozoic deposits. Magnetic susceptibility has been used mainly for stratigraphic purposes but is also used as a proxy for changes in erosion, which in turn are often linked to climatological changes (e.g. Thompson et al., 1975; Hounslow, 1990; Bloemendal et al., 1995; Ellwood et al., 2000 and references therein). The latter relationship essentially relies on the idea that increased landmass erosion will lead to a higher input of ferromagnetic carriers, thus resulting in higher magnetic susceptibilities within the fluvial and marine sediments. In theory, the resulting changes in magnetic susceptibility across a sedimentary sequence can as such be used for stratigraphic correlation purposes, even up to the level of individual horizons. At present, the use of magnetic susceptibility for stratigraphic correlation purposes has been extended beyond the Cenozoic, even down to the Palaeozoic (e.g. Ellwood et al., 2000 and references therein; Boulvain et al., this volume).

However, different individual carriers may have comparable magnetic susceptibilities (e.g. chlorite and muscovite, pyrrhotite and magnetite; Borradaile, 1987; Piper, 1987; Butler, 1992; Tarling & Hrouda, 1993; Hunt et al., 1995; Martin-Hernandez & Hirt, 2003). Moreover, magnetic susceptibility is the result of all magnetic carriers (s.l.; i.e. diamagnetic, paramagnetic and ferromagnetic) present, and variable amounts of two or more different carriers may result in an overall identical bulk susceptibility (Rochette et al., 1992, Tarling & Hrouda, 1993). In addition, the presence of minor traces of different higher-susceptibility carriers may have an insignificant effect on overall bulk magnetic susceptibility and may go unnoticed from susceptibility measurements. Hence, the use of magnetic susceptibility for stratigraphic purposes is by no means straightforward.

In this work, we analyse the use of magnetic susceptibility and alternative magnetic techniques for stratigraphic purposes, using fine-grained samples of the Lower Palaeozoic Anglo-Brabant Deformation Belt (Belgium). In the Anglo-Brabant Deformation Belt marker beds are generally absent, most deposits are thin-bedded and the degree of exposure is low, resulting in a scarcity of thick, continuous stratigraphic sections. Because of this, instead of analysing the detailed magnetic variation throughout a continuous stratigraphic section, we try to characterise different lithostratigraphic units by means of magnetic techniques. Advantages and disadvantages of the different techniques employed are illustrated by several Lower Palaeozoic examples.

The reason for employing these many magnetic techniques lies in the fact that the majority of the lithostratigraphic units of this deformation belt consists of fine-grained cleaved sedimentary deposits which are often quite difficult to distinguish visually (Verniers et al., 2001). At present there are only a handful of people that are able to distinguish more than half of the different formations.

2. Sampling and sample preparation

During the past years, we applied many different magnetic techniques on samples from the Brabant Massif, southeastern Anglo-Brabant Deformation Belt (see Debacker et al., 2004a, 2005a, 2009). Samples were collected in the main outcrop areas, dispersed across the southern part of the massif (Senne-Sennette outcrop area, Dyle-Thyle outcrop area, Gette outcrop area). Investigated stratigraphic units range from the Lower Cambrian to the upper Silurian (see Fig. 1 for sampled lithologies). The sampled lithologies usually consist of mudstone, mainly composed of white mica, chlorite and quartz, with minor amounts of dispersed opaque material (e.g. Geerkens & Laduron, 1996; Debacker, 2001). For a detailed lithological description we refer to Verniers et al. (2001).

As suggested by illite crystallinity studies, the sampled lithologies underwent an anchizonal to shallow epizonal metamorphism (Geerkens & Laduron, 1996; Van Grootel et al., 1997). Cleavage is moderately to well-developed, corresponding to the embryonic cleavage stage to cleavage stage of Ramsay & Huber (1983). Judging from March strains based on phyllosilicate X-ray pole figure goniometry, the amount of shortening of the pelites by cleavage development is relatively constant over large areas, and is in the order of ~50%. Higher amounts of shortening (52 to 66%) are only obtained from within local high-strain zones (e.g. Piessens et al., 2000; Debacker, 2001; Debacker & Sintubin, 2008).

Samples consist of oriented hand samples that were sawn into cubes, on average 7 per sample, with size 2 x 2 x 2 cm. The reason for using hand specimens instead of drilled cylinders is the presence of the cleavage, along which the rocks tend to break during drilling. Broken specimens were glued together using non-magnetic glue. There are no significant differences in results between intact samples and samples that were glued together again.

3. Methods employed and discussion of their use for stratigraphic purposes

3.1. Bulk magnetic susceptibility

3.1.1. Previous work

De Vos et al. (1992) already investigated the bulk magnetic susceptibility of specific lithologies of the Anglo-Brabant

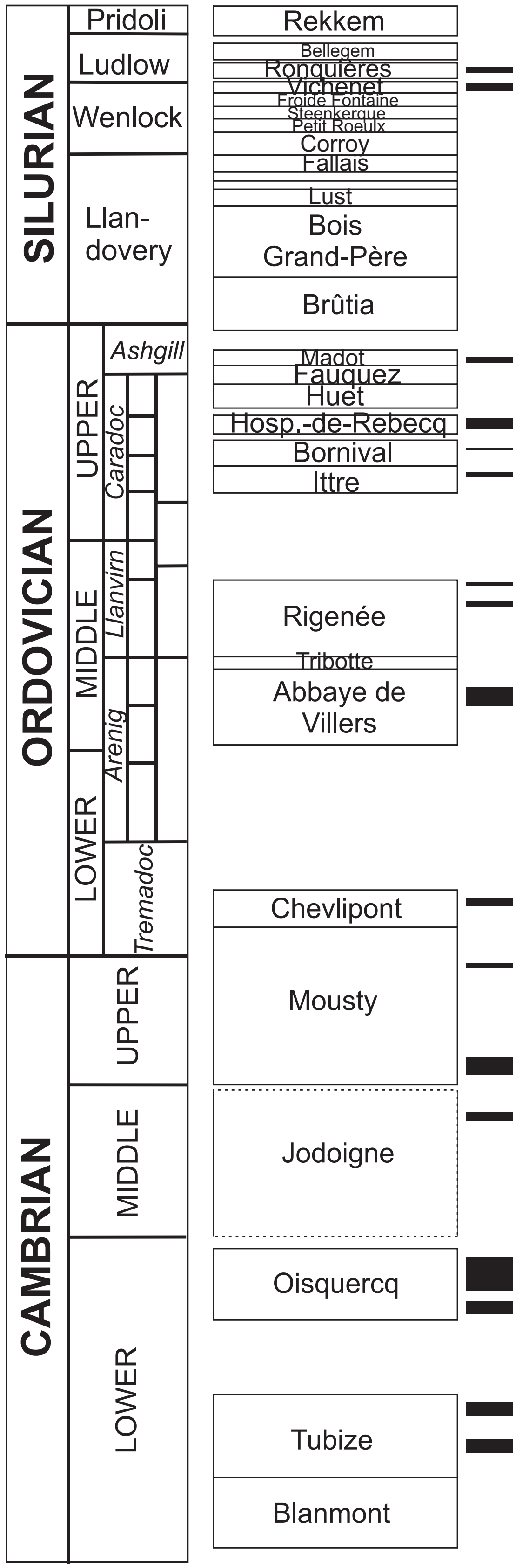

Figure 1: Stratigraphic chart of the Lower Palaeozoic of the Brabant Massif (taken from Verniers et al., 2001, and modified after Herbosch et al., 2008), with the approximate stratigraphic position of levels in which we determined magnetic susceptibility and the anisotropy of magnetic susceptibility (marked in black). For details on the lithology of the different units, the reader is referred to Verniers et al. (2001).

Deformation Belt (see also Piessens et al., 2004). Their results, based on 64 samples, show that for most Cambrian, Ordovician and Silurian samples, and the overlying Devonian, very similar values are obtained, ranging from 200 to 700 10^{-6}SI, with a maximum between 300 and 500 10^{-6}SI. Only parts of the Tubize Formation and the Geraardsbergen diorite have significantly higher susceptibilities, whereas the quartzitic Blanmont Formation and several magmatic rocks have significantly lower susceptibilities. The very high values of parts of the Tubize Formation are attributed to the local presence of magnetite of metamorphic origin (Vander Auwera & André, 1985). The very low values of the Blanmont Formation are probably due to its quartzitic nature, poor in phyllosilicates and virtually without high-susceptibility ferromagnetic minerals. However, as pointed out by Piessens et al. (2004), locally magnetite-bearing shaly intercalations have been reported near Blanmont, implying that like the Tubize Formation also the Blanmont Formation may be very heterogeneous in terms of magnetic susceptibility.

3.1.2. Our work

During the course of magnetic fabric analyses, we investigated bulk magnetic susceptibility of 15 Lower Palaeozoic stratigraphic units, using an AGICO KLY3S kappabridge (Jelinek & Pokorny, 1997) at the Katholieke Universiteit Leuven. In total, 735 cubic specimens were analysed. As can be seen on Fig. 2, many lithostratigraphic units have a similar magnetic susceptibility (compare with De Vos et al., 1992). This holds true, in particular for the Silurian and Ordovician units. Only the Rigenée Formation and the volcanoclastic Madot Formation, both exhibiting quite a large range, often show a shift towards lower values, whereas the Hospice-de-Rebecq Formation and parts of the Rigenée Formation may show a slight shift towards higher values. Within the Cambrian units much more variation is observed. Both the Rogissart and Les-Forges members of the Lower Cambrian Tubize Formation often have very high magnetic susceptibilities. This holds true in particular for the Rogissart Member, in which values between 0.1 and 0.01SI frequently occur. At the same time, however, some parts of this member also exhibit very low magnetic susceptibilities, even lower than that of most Ordovician and Silurian units. The Ripain Member of the overlying Oisquercq Formation shows a slight shift towards higher susceptibility values, whereas for the overlying Asquempont Member, values are closer to those of the Ordovician and Silurian units. The Middle to Upper Cambrian Jodoigne Formation shows a marked shift towards lower values, quite comparable to that of parts of the Rigenée Formation. Also parts of the Upper Cambrian to lowermost Ordovician Mousty Formation show a comparable shift towards lower values.

3.1.3. Interpretation and additional small-scale data

Despite this variation in magnetic susceptibility across the Lower Palaeozoic stratigraphy, stratigraphic correlation or identification on the basis of magnetic susceptibility alone is, with the exception of the high-susceptibility levels of the Tubize Formation, bound to fail in the majority of the cases. This is because a) all lithostratigraphic units show a considerable spread in magnetic susceptibility, which in all cases is more than 100 10^{-6}SI wide and b) even though specific units do have a tendency towards higher or lower values, virtually all lithostratigraphic units contain samples with a magnetic susceptibility somewhere between 250 and 350 10^{-6}SI. In order to be diagnostic, samples with specific susceptibilities outside the 250-350 10^{-6}SI window are necessary. This, however, may take a tremendous amount of sampling and analysis and will often result only in a small narrowing-down of the many different possibilities.

A further inconvenience is the fact that even within specific lithostratigraphic units, magnetic susceptibility may show significant variations without there being a clear one-to-one relationship to features obvious in outcrop, such as changes in grain-size, lithology and sedimentological features. This is exemplified by means of an example of the Tubize Formation and an example of the Ittre Formation.

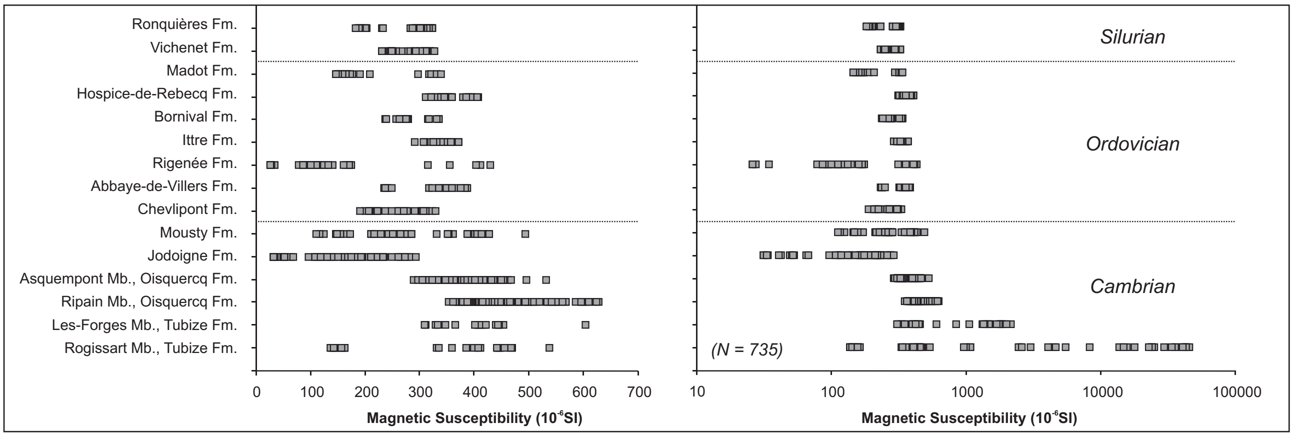

Figure 2: Magnetic susceptibility values of 15 Lower Palaeozoic lithostratigraphic units of the Brabant Massif. The mean magnetic susceptibility is 275 ± 82 10^{-6}SI for the Ordovician to Silurian, 349 ± 126 10^{-6}SI for the Cambrian, with the exclusion of the Tubize Formation, and 318 ± 115 10^{-6}SI for the Cambrian to Silurian, again without the Tubize Formation.

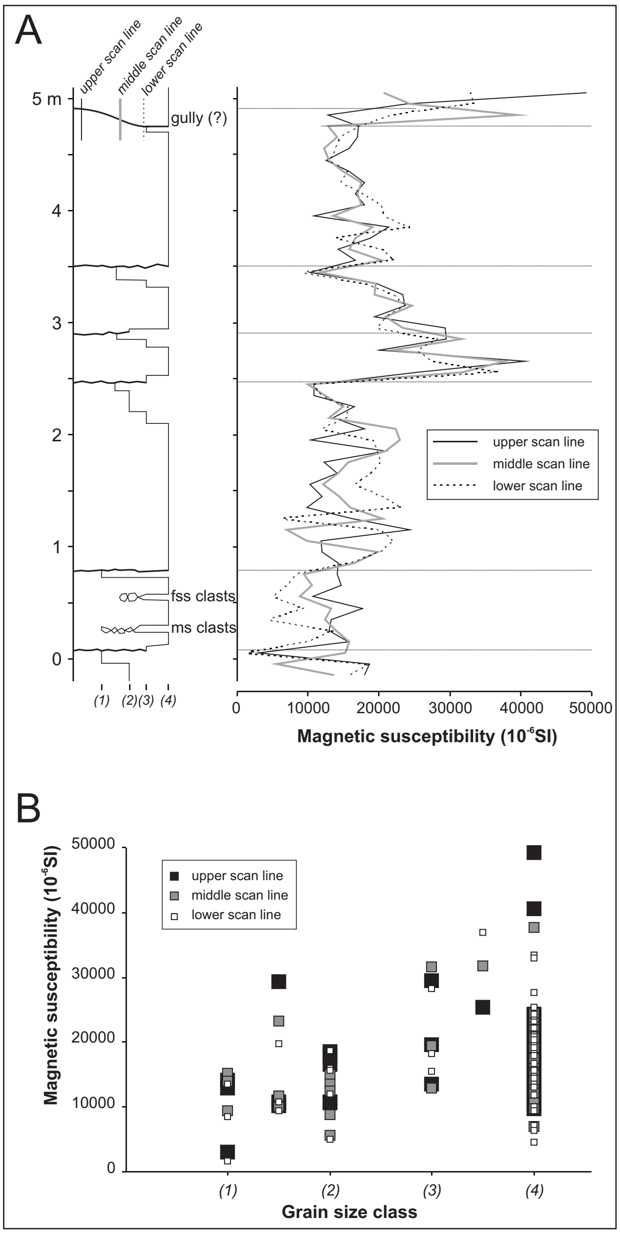

Figure 3: Magnetic susceptibility values measured each 10 cm along three scan lines at 40 cm apart, across a ~5 m thick magnetite-bearing sequence of the Rogissart Member of the Tubize Formation at Rogissart (Haine valley, Senne-Sennette outcrop area). A) Lithological variation compared with variation in magnetic susceptibility. Note the presence of an oblique, curved erosional surface in the top part of the sequence. Fss clasts: fine sandstone clasts; ms clasts: mudstone clasts. (1), (2), (3) and (4) are grain size classes, corresponding to mudstone, fine sandstone, sandstone and very coarse sandstone, respectively. B) Evaluation of changes in susceptibility in function of grain size class. See text.

Fig. 3 shows the variation in bulk susceptibility along three different scan lines across the same ~5 m-thick sequence of turbidite deposits of the Rogissart Member of the Tubize Formation at Rogissart (see also Vander Auwera & André, 1985). Magnetic susceptibility was measured by means of an SM-30 magnetic susceptibility meter manufactured by ZH instruments. Bedding is steeply dipping and the cleavage/bedding intersection and inferred fold hinge line are steeply plunging (Debacker et al., 2004b). The three subhorizontal scan lines, oriented subperpendicular to bedding and to the cleavage/bedding intersection, are separated vertically by ~40 cm, and along each scan line susceptibility measurements were taken every 10 cm. The spatial accuracy of the measurement points is 10 cm or less. Across the sequence, susceptibility changes from ~1500 to ~50000 10^{-6}SI.

As shown in Fig. 3A, most beds do become apparent from the magnetic susceptibility, with the more pelitic parts usually yielding lower values than the coarse-grained parts. Although this might be explained by a sedimentologically-controlled concentration of ferromagnetic carriers within the coarse-grained beds, further analysis shows that there is no one-to-one link between average grain-size and magnetic susceptibility (Fig. 3B). Lower values are usually obtained within the more fine-grained parts, whereas the coarser-grained parts show a much larger spread in susceptibility. This suggests that for comparative purposes special attention should be paid to the fine-grained units. However, comparing the three different scan lines, occasionally quite different results are obtained from within the same horizon, indicative of significant lateral variations in ferromagnetic

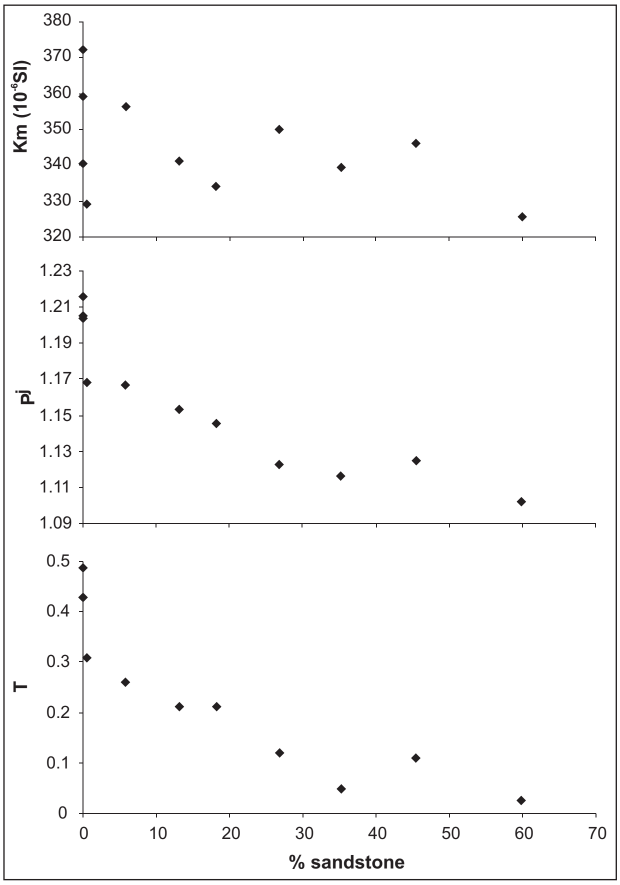

Figure 4: Variation of magnetic susceptibility (Km), corrected degree of anisotropy (Pj) and shape parameter (T) with changing amount of sandstone within distal turbidite deposits of the Upper Ordovician Ittre Formation. Note that whereas a relationship does come forward in the case of Pj and T, there is no clear relationship in the case of Km. See text.

content both within the coarse-grained and fine-grained units.

Fig. 4 shows the variation of magnetic susceptibility (Km), as well as that of the shape parameter T and corrected degree of anisotropy Pj (see lower for significance of T and Pj) in function of percentage of sandstone within distal turbidite deposits of the Upper Ordovician Ittre Formation. The sample analysed consists of a fine-grained sandstone turbidite c(d)-interval of 1.5 cm thick in between pelitic turbidite e-intervals (see also Servais, 1991; Verniers et al., 2001). The sample was sawn obliquely to bedding so as to allow for different amounts of the sandstone bed to be present within each cube. Both the shape parameter T and the corrected degree of anisotropy Pj increase with decreasing amounts of sandstone. However, a clear relationship does not become apparent from the magnetic susceptibility. Hence, in this case, magnetic susceptibility shows significant local variations, without there being an obvious relationship with grain-size. This complicates the use of magnetic susceptibility for stratigraphic purposes.

3.2. Temperature variation of magnetic susceptibility

3.2.1. Importance of temperature registration

Magnetic susceptibility changes with temperature. For paramagnetic materials, magnetic susceptibility changes inversely with temperature, as described by the Curie-Weiss law. This temperature-controlled change in paramagnetic susceptibility can be detected even for temperature changes of only 20°C within the so-called "room-temperature interval" (0-40°C). For most Ordovician and Silurian units for instance, in which magnetic susceptibility is controlled by paramagnetic carriers (phyllosilicates), magnetic susceptibility decreases by ~5-6% for a temperature increase of 20°C in the "room-temperature interval" (Fig. 5; Debacker et al., 2009; Herbosch et al., 2008). This implies that for stratigraphic purposes on the basis of magnetic susceptibility (see above), measurement temperature should always be recorded, especially in the case of low-susceptibility units in which paramagnetic carriers contribute significantly to magnetic susceptibility. Although within a laboratory, ambient temperature is unlikely to change by more than 20°C, even this small change may affect the results by several percents. For susceptibility measurements in outcrop, in which rock temperature can easily change by more than 40°C, we consider temperature registration absolutely necessary.

3.2.2. Application of the temperature-dependent variation

Importantly, the temperature-controlled change in susceptibility on its own may be used for stratigraphic purposes, as suggested by Debacker in Herbosch et al. (2008). Contrary to paramagnetic materials, the magnetic susceptibility of ferromagnetic materials remains virtually constant within the "room-temperature interval" (e.g. Piper, 1987; Butler, 1992; Hunt et al., 1995; Walz, 2002). Hence, an analysis of the temperature-controlled change of magnetic susceptibility may give an idea of the relative importance of paramagnetic and ferromagnetic carriers. This is important information, as the relative contribution of paramagnetic and ferromagnetic carriers will not always be reflected by magnetic susceptibility. Firstly, as magnetic susceptibility is a result of all magnetic carriers present (s.l.; i.e. diamagnetic, paramagnetic and ferromagnetic carriers), comparable susceptibilities can be obtained for units with different amounts of different carriers. Secondly, some ferromagnetic carriers, such as hematite and pyrrhotite, often do not posses very high magnetic susceptibilities (e.g. Piper, 1987; Butler, 1992; Hunt et al., 1995). The presence of minor amounts of such carriers in a mudstone would not lead to significantly higher magnetic susceptibilities as compared to a ferromagnetic-free mudstone, and a clear distinction on the basis of magnetic susceptibility would be impossible.

The method, already outlined in Herbosch et al. (2008), involves measuring magnetic susceptibility on samples cooled or heated to different temperatures between 0 and 40°C. Cooling and heating can be done by means of a standard fridge and a digital laboratory oven,

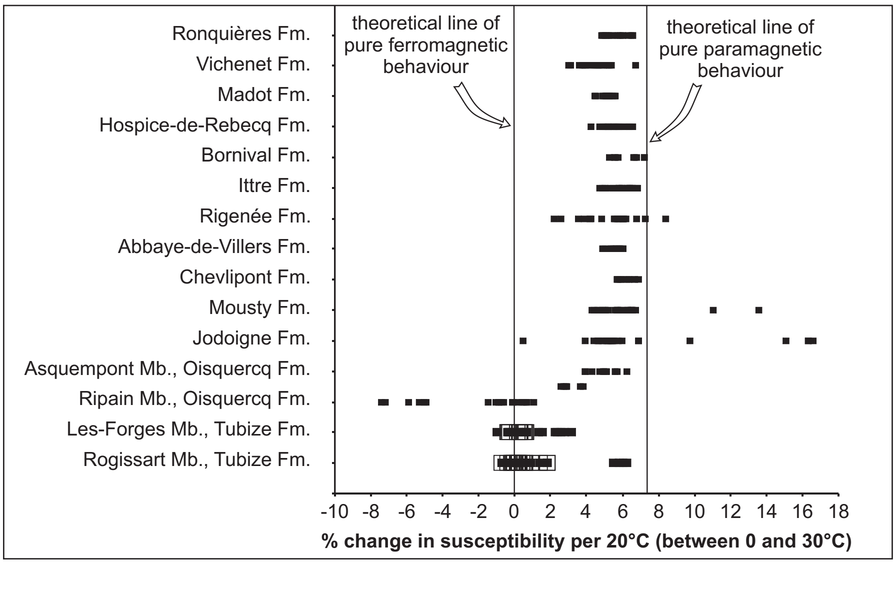

Figure 5: Variation in terms of percentage of magnetic susceptibility per 20°C between 0 and 30°C for 15 lithostratigraphic units. Also shown are theoretical lines of pure ferromagnetic (no change) and pure paramagnetic behaviour (following Curie-Weiss law). For the Tubize Formation, high-susceptibility samples are marked by an open square. See text.

respectively, in which temperatures are checked with the same mercury thermometer. In order to achieve thermal homogeneity, samples should be kept at a given temperature during at least 2 hours before measurement. After verification of the approximately linear nature of the relationship between temperature change and change in measured susceptibility (within this small temperature interval, the relationship approaches linearity), the percentage of change in susceptibility is recalculated for a temperature change of 20°C within the 0-40°C temperature-interval.

Samples were measured using an AGICO KLY3S kappabridge (Jelinek & Pokorny, 1997) at the Katholieke Universiteit Leuven. As can be seen on Fig. 5, most of the Silurian and Ordovician lithostratigraphic units exhibit a relatively constant, temperature-dependent change in magnetic susceptibility, ranging from 4 to 7%. Only the Rigenée Formation shows a much larger spread. The results suggest a predominantly paramagnetic behaviour of the Silurian and Ordovician units, with only a minor ferromagnetic contribution (see theoretical lines). In the Cambrian, however, much more variation is observed. Of the six units investigated, three units show a completely different behaviour from that of the Ordovician and Silurian units (Ripain Member of Oisquercq Formation and Les-Forges Member and high-susceptibility levels of Rogissart Member of Tubize Formation), one unit has a susceptibility change identical to that of the Ordovician and Silurian units (Asquempont Member of Oisquercq Formation), and two units show very large spreads, with several samples having very large susceptibility changes (9 to 17%; Mousty Formation and Jodoigne Formation). Comparison of Fig. 5 and Fig. 2 shows that several of these Cambrian units can successfully be distinguished, something which is impossible on the basis of magnetic susceptibility alone. The Ripain Member can easily be distinguished from the Asquempont Member. Even the gradual transition zone between both these members can be recognised. Moreover, although yet unexplained, the very pronounced negative changes of several samples of the Ripain Member are not observed in any other unit. The Les-Forges Member and the Rogissart Member of the Tubize Formation can easily be distinguished on the basis of the results of the low-susceptibility levels. Distinguishing these units from all other investigated units can be done by means of the magnetic susceptibility of the high-susceptibility levels. Both the Jodoigne Formation and the Mousty Formation can be distinguished from other units by the very large susceptibility changes of several of the samples. It was this similar behaviour that was used by Herbosch et al. (2008) as one of the arguments for modifying the stratigraphic position of the Jodoigne Formation.

3.2.3. Interpretation of the temperature-dependent variation of magnetic susceptibility

As will become clear below, the different amounts of temperature-related change in magnetic susceptibility are related to magnetic (s.l.) mineralogy. Both the Les-Forges Member of the Tubize Formation and the Ripain Member of the Oisquercq Formation appear to contain a significant amount of hematite (see also Debacker et al., 2004a), which is a high-coercivity ferromagnetic (s.l.) mineral, and hence might explain the virtually 0% temperature-dependent susceptibility change. The large spread in temperature-dependent change in susceptibility of samples of the Rogissart Member of the Tubize Formation is directly related to the occurrence of high-susceptibility magnetite-rich zones (~0% temperature-dependent susceptibility change) in between magnetite-poor low-susceptibility zones (~6% change: predominantly paramagnetic behaviour; compare with Vander Auwera & André, 1985). The change in susceptibility of the Asquempont Member of the Oisquercq Formation, being identical to that of the Ordovician and Silurian rocks, suggests a predominantly paramagnetic mineralogy. The cause of the very large temperature-dependent susceptibility change of several samples of both the Jodoigne and the Mousty Formation still remains unknown (possibly diamagnetic behaviour?).

3.3. Anisotropy of magnetic susceptibility (AMS)

3.3.1. Outline of the method

The anisotropy of low-field susceptibility (room temperature) was measured with an AGICO KLY3S kappabridge (Jelinek & Pokorny, 1997) at the Katholieke Universiteit Leuven. The susceptibility tensor is computed using the AGICO software. The eigenvectors of this tensor, K1, K2 and K3, respectively corresponding to the maximum, intermediate and minimum susceptibility, reflect the orientation and shape of the magnetic susceptibility ellipsoid. Three quantitative parameters are used to describe the anisotropy ellipsoid: the corrected degree of anisotropy Pj (Jelinek, 1981), the shape parameter T (Jelinek, 1981) and the mean susceptibility Km (Nagata, 1961; see also Tarling & Hrouda, 1993). In order to investigate the effects of mineralogy on the susceptibility anisotropy, Pj and Km are compared. On a Pj - Km plot, the paramagnetic contribution has an upper limit around Pj ~ 1.2-1.3 and Km ~ 300-500 x 10^{-6}SI (Rochette, 1987; Rochette et al., 1992; Martín-Hernández & Hirt, 2003). The degree of anisotropy Pj is also plotted against the shape parameter T. Whereas Pj reflects the degree of preferred orientation of magnetic minerals (s.l.), T is a measure of the shape of the ellipsoid. If $-1 < T < 0$, the susceptibility ellipsoid is prolate, and if $0 < T < 1$, the susceptibility ellipsoid is oblate (Jelinek, 1981). Whereas Km is only influenced by mineralogy and not by strain, both Pj and T are influenced by mineralogy and by strain. This implies that whereas a Pj - Km plot mainly provides information on the effects of mineralogy, a specific position on a Pj - T plot is the result of both mineralogy and strain (Jelinek, 1981; Borradaile, 1987; Borradaile & Henry, 1997). This implies that for stratigraphic purposes, care should be taken when using a Pj - T plot and one should make sure to compare only samples of similar grain-size that experienced a comparable amount of strain. For this purpose, in cleaved pelites it is useful also to compare both Pj and T with the angle between cleavage and bedding.

Parts of these results were already published in Debacker et al. (2004a, 2009). For an interpretation of the results we refer to these works and to the references therein.

3.3.2. Results plotted on and interpretation of a Km – Pj graph

Figs 6A & 6B show a graph of mean susceptibility (Km) plotted against the corrected degree of anisotropy (Pj). All Silurian samples plot in the lower left quadrant, seemingly suggesting that AMS is carried entirely by paramagnetic carriers. The Ordovician samples show a larger spread as compared to the Silurian samples, with often a slightly higher degree of anisotropy and magnetic susceptibility. Also these values suggest that AMS is mainly controlled by paramagnetic carriers. Some Ordovician units, however, such as the Rigenée Formation and the Madot Formation, have much lower values. For these, a small diamagnetic contribution cannot be excluded. In the Cambrian much more variation is observed. Samples of the Ripain Member of the Oisquercq Formation and the high-susceptibility samples (i.e. > 1000 x 10^{-6}SI) of the Les-Forges Member and the Rogissart Member of the Tubize Formation systematically have high degrees of anisotropy and/or magnetic susceptibility, suggestive of a ferromagnetic contribution to AMS. In the Ripain Member, this ferromagnetic contribution is probably small (Pj > 1.2, but Km ~ 450 x 10^{-6}SI), whereas in the high-susceptibility samples of the Tubize Formation the ferromagnetic contribution may be quite important (1.8 > Pj > 1.2, Km up to 50000 x 10^{-6}SI). The low-susceptibility samples of the Tubize Formation, the samples of the Asquempont Member and those of the Mousty Formation have a lower susceptibility and degree of anisotropy, quite comparable to those of the Ordovician samples. This suggests an AMS controlled by paramagnetic carriers.

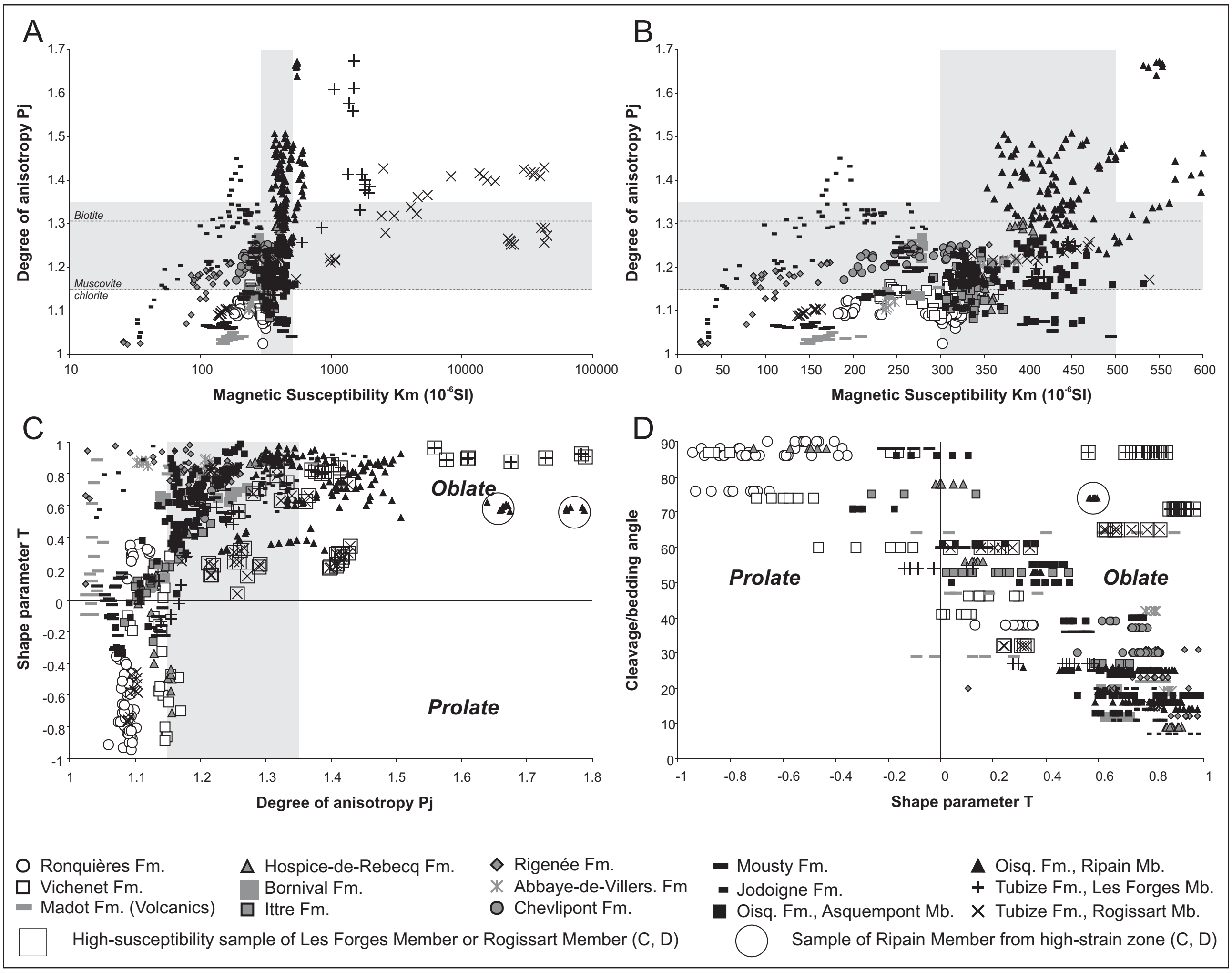

Figure 6: Principal graphs used for the interpretation of the anisotropy of magnetic susceptibility (AMS) with data from 15 lithostratigraphic units of the Brabant Massif. A & B) Graph of mean magnetic susceptibility (Km) versus corrected degree of anisotropy (Pj). The mean upper limits of Pj and Km for paramagnetic rocks and minerals, based on Rochette (1987), Rochette et al. (1992), Hrouda (2002) and Martín-Hernández & Hirt (2003), are added as a grey background. Also added are the degrees of anisotropy of biotite, chlorite and white mica single crystals, taken from Martín-Hernández & Hirt (2003). C) Graph of shape parameter (T) versus corrected degree of anisotropy, a.k.a. Jelinek-plot (Jelinek, 1981). The mean upper limit of Pj for paramagnetic rocks and minerals is added as a grey background. D) Graph of shape-parameter (T) versus cleavage/bedding angle (see also Debacker et al., 2005a, 2009). See text.

Samples of the Jodoigne Formation consistently have low susceptibilities, but show a considerable variation in degree of anisotropy. For those samples with very low susceptibility (~ 50 x 10^{-6}SI) and degree of anisotropy (<1.1), a diamagnetic contribution cannot be excluded, whereas for the samples with a high degree of anisotropy (>1.3), a ferromagnetic contribution is possible (see also Debacker et al., 2004a, 2009).

3.3.3. Results plotted on a Pj – T graph

On a graph of degree of anisotropy (Pj) versus shape parameter (T) the data points describe a rough hyperbola. The Silurian Ronquières Formation and Vichenet Formation dominate the hyperbola's subvertical zone of negative to low T (prolate to neutral ellipses) and low, but fairly constant Pj, with the former formation generally having lower Pj than the latter. Volcanoclastics of the Ordovician Madot Formation plot to the left of the hyperbola, with very low Pj, and an ellipsoid shape ranging from neutral to oblate (T from ~ 0 to ~ 1). The Hospice-de-Rebecq Formation, the Bornival Formation and the Ittre Formation occur within the lower to central areas of the curved part of the hyperbola, with the first formation showing a very large spread in both Pj (~ 1.1 to ~ 1.3) and T (~ -0.7 to ~ 0.8). Samples of the Cambrian Mousty Formation also plot in this area, but the lower ones (around T~0) show a large spread in Pj, extending from values similar to those of the Vichenet Formation, over those of the Ronquières Formation to values similar to those of the Madot Formation. Samples of the Ordovician Rigenée Formation seemingly occupy the curved part of a different, much more angular hyperbola, that is shifted towards lower Pj values with respect to the main hyperbola, and of which the subvertical part joins the Madot Formation towards below. The samples of the Abbaye-de-Villers Formation occupy the upper, low-Pj areas of the hyperbola apparent from the Rigenée Formation and join the upper parts of the main hyperbola around Pj ~ 1.2. The lowermost Ordovician Chevlipont Formation occupies the upper areas of the curved part of the main hyperbola. The Cambrian Jodoigne Formation extends from the curved part of the hyperbola apparent from the Rigenée Formation, over the upper areas of the curved part of the main hyperbola, and follows the subhorizontal part (T of 0.6 - 1) of the main hyperbola up to Pj ~ 1.45. The Asquempont Member of the Oisquercq Formation occupies the entire curved part of the main hyperbola, extending from T ~ -0.2 and Pj ~ 1.1 up to T ~ 0.9 and Pj ~ 1.25, with a maximum around T ~ 0.7 and Pj ~ 1.2. The Ripain Member of the Oisquercq Formation, characterised by a much higher Pj, dominates the upper parts of the main hyperbola, and - with a significant amount of scattering - shows a tendency towards a third hyperbola, situated towards higher Pj and lower T with respect to the main hyperbola. Pj of the main cluster ranges up to ~ 1.5, but some samples, taken from within a high-strain zone, extend up to even ~ 1.8. Samples of the Les-Forges Member of the Tubize Formation follow the high-Pj side of the main hyperbola, with the low-susceptibility samples occupying the hyperbola's curved part, and the high-susceptibility samples occupying the subhorizontal, upper part of the hyperbola, with T-values often higher than those of the Ripain Member for similar Pj values. Also for the Rogissart Member of the Tubize Formation a significant spread is observed. The low-susceptibility samples follow the main hyperbola from the very lower part (position of the Silurian Ronquières Formation), up to the lower areas of the curved part. The high-susceptibility samples are scattered to the right of the curved part of the main hyperbola, quite similar to some samples of the Ripain Member.

3.3.4. Influence of composite magnetic fabrics: graphs of T versus angle between cleavage and bedding

Despite the common use of Pj - T graphs in literature, in particular for deformation fabric analysis, the interpretation of these graphs may be hindered by the strong influence of the angle between cleavage and bedding on the shape parameter T in the presence of composite magnetic fabrics (Debacker et al., 2004a, 2005a, 2009; see also Housen et al., 1993). Composite magnetic fabrics occur when AMS is controlled by two or more differently oriented populations of magnetic carriers (Housen et al., 1993). This is the case for almost all lithostratigraphic units investigated (Debacker et al., 2005a, 2009). Due to the presence of composite magnetic fabrics, of which some populations are oriented along bedding and some along cleavage, more oblate susceptibility ellipsoids (positive T values) are observed for low angles between cleavage and bedding and more prolate ellipsoids (negative T values) for high angles between cleavage and bedding. On a graph of shape parameter T versus cleavage/bedding angle, such as shown in Fig. 6D, this is reflected by a negative, roughly linear(?) relationship. This relationship can be considered to reflect the variation in T with changing cleavage/bedding angles for a constant mineralogical composition. The change in cleavage/bedding angle is related to local finite strain variations across folds. Strong deviations from this trend are either a result of strong local strain variations, or due to mineralogical variations (see Debacker et al., 2009). Indeed, the only investigated samples that do not show this relationship are those of high-strain zones (strain effect), such as observed for a sample of the Ripain Member (see Fig. 6D; Debacker et al., 2009) or those in which only one of the different carrier populations effectively contributes to AMS (mineralogical effect). The latter is the case for the Madot Formation (only low-susceptibility carriers along cleavage) and the high-susceptibility levels of the Tubize Formation (only high susceptibility carriers along cleavage) (see Fig. 6D; Debacker et al., 2005a, 2009).

Contrary to T, Pj remains fairly constant or only shows a very minor change with cleavage/bedding angle, becoming slightly larger as cleavage/bedding angle decreases to very low values (Debacker et al., 2004a).

3.3.5. Overall interpretation of the AMS-data

Because of the presence of composite magnetic fabrics, the large variation in T for samples of the same lithostratigraphic units (subvertical part to central areas of the hyperbola in Fig. 6C) can be attributed to changing angles between cleavage and bedding. As a large part of the Silurian pelites are characterised by convergent cleavage fans in which large cleavage/bedding angles dominate, whereas the Ordovician and in particular the Cambrian pelitic units (e.g. Oisquercq Formation, Jodoigne Formation) have much smaller cleavage/bedding angles, it may be tempting to attribute the different T values on a Pj - T graph for the Silurian, Ordovician and Cambrian to different angles between cleavage and bedding. However, as shown in Fig. 6D, for similar angles between cleavage and bedding, Cambrian units are systematically shifted towards higher T values with respect to Silurian units, with the Ordovician taking up intermediate values (see also Debacker et al., 2005a, 2009). This shows that, contrary to most variations in T observed within individual lithostratigraphic units, the different positions of the Silurian, Ordovician and Cambrian units on a Pj - T graph cannot be attributed only to changing angles between cleavage and bedding (Debacker et al., 2004a, 2009). Instead, the different positions of the different units are essentially due to changes in magnetic mineralogy combined with changes in magnetic carrier (s.l.) orientation, in turn being a result of the long, complex basin history from deposition to inversion (Debacker et al., 2009).

3.4. Determination of ferromagnetic mineralogy

3.4.1. Outline of the method

Ferromagnetic mineralogy was investigated at the university of Cergy-Pontoise (France) by means of a stepwise demagnetization of a "three axis" isothermal remanent magnetization following the procedure of Lowrie (1990). This coercivity/blocking temperature spectrum analysis separates ferromagnetic minerals with different magnetic properties. We applied three successive saturation fields (1.4 T, 0.6 T and 0.12 T) along three perpendicular directions on the samples. These were then demagnetized thermally in steps of 50°C, with finer steps around 325°C, 580°C and 675°C, the Curie temperatures of pyrrhotite, magnetite and hematite respectively. Samples were heated up to 700°C. During this stepwise demagnetization, bulk magnetic susceptibility was monitored with a KLY3S at room temperature in order to detect artificial changes in magnetic properties due to heating.

Even with this method, determining ferromagnetic mineralogy from thermal demagnetisation experiments is not straightforward. Different ferromagnetic minerals may have comparable blocking temperatures, and for a specific mineral group blocking temperature may change in function of chemical composition (see standard handbooks such as Nagata, 1961; Piper, 1987; Butler, 1992). This implies that an interpretation of ferromagnetic mineralogy should not only use the blocking temperatures (Curie temperatures) as such, but should also take into account the amount of coercivity and the actual shape of the demagnetisation curves (straight drop, concave upwards drop,…) (e.g. Lowrie, 1990; Aubourg, pers. comm. 2009). This approach allowed us to recognise the mineral groups magnetite, hematite, pyrrhotite and goethite. As will become clear below, however, for stratigraphic purposes, the exact ferromagnetic mineralogy is not that important, as the pattern shown by thermal demagnetisation curves itself can allow distinguishing the different lithostratigraphical units, irrespective of the fact whether or not the exact ferromagnetic mineralogy is identified.

3.4.2. Results and interpretation

Representative thermal demagnetisation spectra of investigated lithostratigraphic units are shown in Fig. 7. For some of these units, results on the ferromagnetic mineralogy were already published in Debacker et al. (2004a).

The Silurian Ronquières Formation (Fig. 7A) is characterised by low- to moderate-coercivity magnetite. Neglectable amounts of low- to moderate-coercivity pyrrhotite may be present. The Vichenet Formation (Fig. 7B) is characterised by low- to moderate-coercivity pyrrhotite, sometimes accompanied by some high-coercivity pyrrhotite. A neglectable amount of low-coercivity magnetite is present sometimes. The Ordovician Hospice-de-Rebecq Formation (Fig. 7C) mainly contains low- to moderate-coercivity magnetite together with small amounts of moderate-coercivity pyrrhotite. The Rigenée Formation (Fig. 7D) contains low- to moderate coercivity magnetite, together with a very significant amount of moderate-coercivity pyrrhotite. Also minor amounts of an unidentified, low- to moderate coercivity phase with blocking temperature around 150°C are observed. Possibly, this is goethite. The Abbaye-de-Villers Formation (Fig. 7E) mainly contains low- to high-coercivity pyrrhotite, together with a small amount of low-coercivity magnetite. The cause of the drop at 250°C on the X- and Y-curves is unknown. The Chevlipont Formation (Fig. 7F), rather similar to the former formation, is dominated by moderate-coercivity pyrrhotite, and smaller amounts of low- and high-coercivity pyrrhotite. Traces of low-coercivity magnetite may be present. The Cambrian Mousty Formation (Fig. 7G) is quite comparable to the Rigenée Formation in terms of ferromagnetic mineralogy. It contains low- to moderate-coercivity magnetite, together with a small amount of low- to moderate-coercivity pyrrhotite, and some amounts of an unidentified, low- to moderate-coercivity phase with blocking temperature around 150°C (goethite?). Minor traces of high-coercivity hematite may be present as well. The Jodoigne Formation (Fig. 7H) has a comparable ferromagnetic mineralogy, but the relative amounts differ from the previous unit. The Jodoigne Formation mainly contains moderate- to high-coercivity pyrrhotite, together with small amounts of low- to moderate coercivity magnetite, and an unidentified, low- to moderate-coercivity phase with blocking temperature between 150°C and 200°C. Also here, minor traces of high-coercivity hematite may be present. The Asquempont Member of the Oisquercq Formation (Fig. 7I) is dominated by low-coercivity magnetite. Minor amounts of low- to moderate-coercivity pyrrhotite are present as well. A completely different ferromagnetic

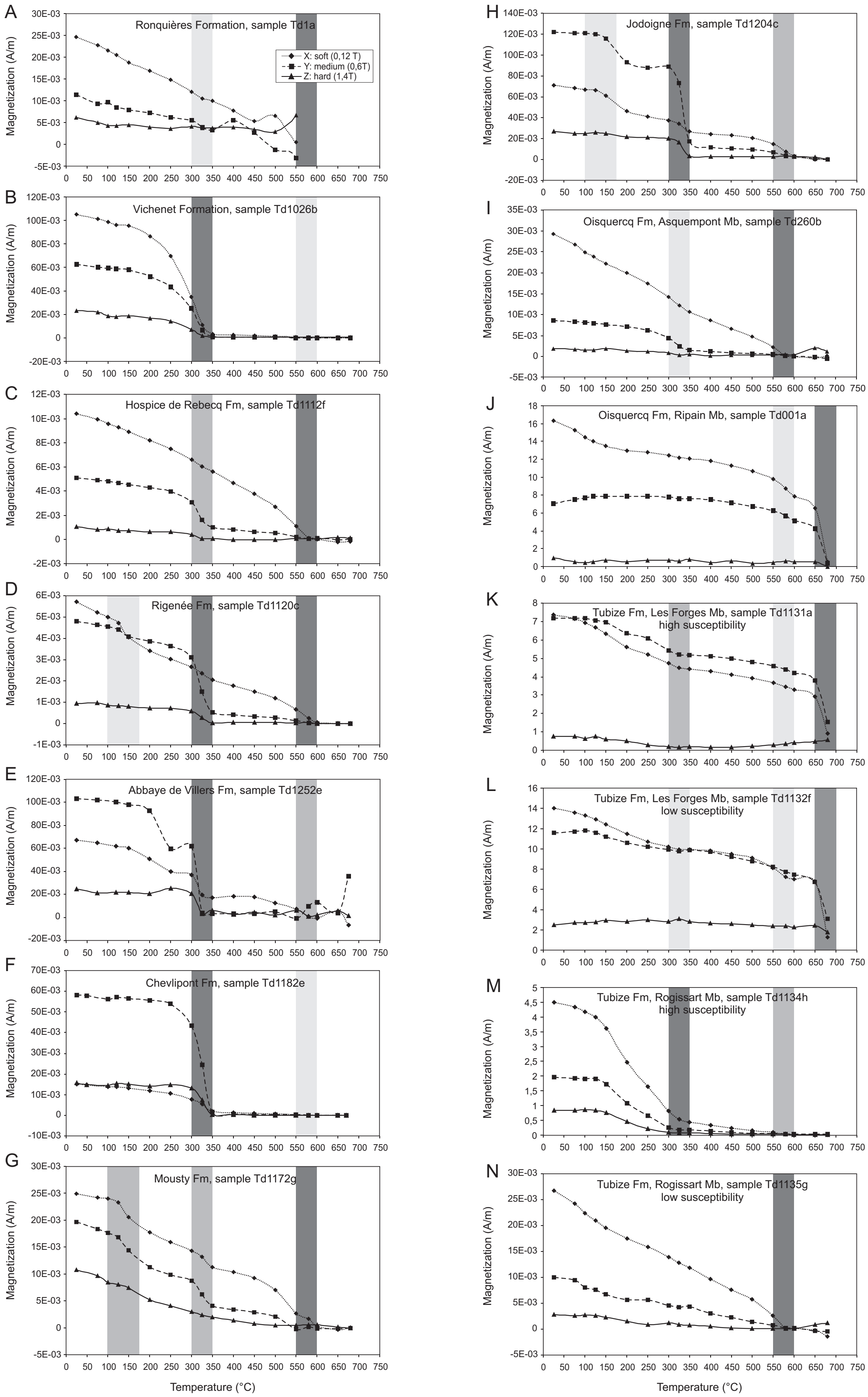

Figure 7: Representative thermal demagnetisation curves of 12 lithostratigraphic units of the Brabant Massif. For the Les-Forges Member and the Rogissart Member of the Tubize Formation both high-susceptibility and low-susceptibility samples are shown. The curves represent the stepwise demagnetization of a "three axis" isothermal remanent magnetization. The three successive saturation fields applied are 1.4 T, 0.6 T and 0.12 T. The three curves respectively reflect hard, medium and soft components, or carriers with high, medium and low coercivities, respectively. Significant drops, corresponding to blocking temperatures of specific carriers, are marked in grey, with the grey values reflecting the relative importance of the drops and hence relative abundance of the different carriers. Dark grey is the most important, pale grey is the least important. See text.

mineralogy is observed in the Ripain Member of the Oisquercq Formation (Fig. 7J). This member, with very high remanence, is dominated by low- to moderate-coercivity hematite and small amounts of low- to moderate-coercivity magnetite. Also traces of high-coercivity hematite occur. Although the presence of hematite is compatible with the purplish colour of this member, the presence of low- to moderate-coercivity hematite may seem strange, as hematite usually has high coercivities. However, low-coercivity hematite has been reported previously also in upper Lochkovian slates from the Ardennes, were it was interpreted by Robion et al. (1997) as coarse-grained hematite (see also Debacker et al., 2004a). The ferromagnetic mineralogy of the underlying Les-Forges Member of the Tubize Formation (Fig. 7K, 7L) is quite similar to that of the Ripain Member of the Oisquercq Formation. Also this member has a purplish sheen. It differs from the latter member, however, by the presence of a low- to moderate-coercivity carrier with blocking temperature between 300 and 350°C. In the low-susceptibility levels (Fig. 7L), the effect of this carrier is much less pronounced, whereas in the high-susceptibility levels (Fig. 7K), the presence of this carrier is also reflected by the high-coercivity curve. Within the underlying Rogissart Member of the Tubize Formation, the low-susceptibility levels (Fig. 7N) are dominated by low- to moderate-coercivity magnetite. By contrast, the high-susceptibility levels (Fig. 7M) are dominated by a low- to high-coercivity carrier with blocking temperature between 300 and 350°C, and only minor amounts of low- to moderate-coercivity magnetite. Hence, in both members of the Tubize Formation, the high-susceptibility levels are characterised by the presence of a significant amount of a low- to high-coercivity phase with blocking temperature between 300 and 350°C. Although this interval coincides with that of the blocking temperature of pyrrhotite, the shape of the curve is very different (compare for instance with Vichenet Formation in Fig. 7B). As determined by A. Hirt by means of a Curie-balance at ETH (Zurich), this carrier is a Ti-poor magnetite. This is compatible with trace element analyses of Vander Auwera & André (1985), showing higher amounts of Ti in the units poor in magnetite as compared to the units rich in magnetite.

3.4.3. Stratigraphic implications

As can be seen on Fig. 7, almost all lithostratigraphic units investigated can be distinguished successfully, even in the case of very low-susceptibility units in which magnetic susceptibility is controlled virtually entirely by paramagnetic carriers. This implies that even traces of ferromagnetic carriers, which do not contribute to overall magnetic susceptibility, do allow distinguishing different lithostratigraphic units.

In addition, the lithostratigraphic units can be identified simply by means of the pattern of the thermal demagnetisation curves, without there really being a need for an exact identification of the ferromagnetic mineralogy.

There are, however, two units that cannot be distinguished on the basis of their thermal demagnetisation patterns. These are the Hospice-de-Rebecq Formation (Fig. 7C) and the Asquempont Member of the Oisquercq Formation (Fig. 7I), both having exactly the same thermal demagnetisation spectra.

4. Case studies: application of the methods outlined above

4.1. Mapping the Cambrian at Braine-le-Château (Sennette outcrop area)

The core of the Anglo-Brabant Deformation Belt is characterised by an aeromagnetic high. This high coincides with the presence of the Tubize Formation at depth (De Vos et al., 1992, 1993). Towards the southern parts, this high becomes more heterogeneous, and consists of roughly NW-SE-trending aeromagnetic highs separated by aeromagnetic lows (Fig. 8a). In the northern part of the Senne-Sennette outcrop area, the lows correspond to the Blanmont Formation (Piessens et al., 2004), whereas in the Dyle-Thyle outcrop area, the lows either correspond to the Mousty Formation (NW-part) or to the Blanmont Formation (E-part) (Debacker et al., 2005b).

In 2008, sewer construction works were performed along the Haine, from Wauthier-Braine to Braine-le-Château. These works traversed an aeromagnetic low, situated directly to the east of the aeromagnetic high of the Rogissart Member at Rogissart (Fig. 8a). Judging from the position to the east of the SW-ward younging, steeply dipping deposits of the Rogissart Member (Fig. 3; Debacker et al., 2004b), the Blanmont Formation was expected (see also Piessens et al., 2004). At the sewer construction site halfway between the Rue du Bailli and the Rue des Comtes de Robiano at Braine-le-Château, directly to the north of the Haine, A. Herbosch encountered a strongly cleaved mudstone, with colours ranging from grey, over bluish-grey to purplish grey or greenish grey. A representative sample of this was analysed by means of magnetic techniques.

Magnetic susceptibility yielded values between 418 and 438 10^{-6}SI (n = 4). Although compatible with a Cambrian unit, these values do not allow any further distinction (compare with Fig. 2). The temperature-related change in magnetic susceptibility yields values of -1.63 and -1.59% per 20°C change between 0 and 40°C. This, combined with the susceptibility data, is only compatible with the Ripain Member of the Oisquercq Formation or the Les-Forges Member of the Tubize Formation (compare with Fig. 5). The degree of anisotropy Pj ranges from 1.25 to 1.27 and the shape parameter T from 0.85 to 0.88. On a Pj – Km graph (see Figs 6A & 6B) these values fall in the zone of overlap of several Cambrian units. Also on a Pj - T graph (Fig. 6C), these values fall in the zone of overlap of several Cambrian units, but are clearly separated from the cluster of the Les-Forges Member. Hence, the magnetic susceptibility techniques, combined with lithological observations, indicate that the sample belongs to the Ripain Member of the Oisquercq Formation. This is confirmed by thermal demagnetisation experiments (see Fig. 8b, and compare with Fig. 7J).

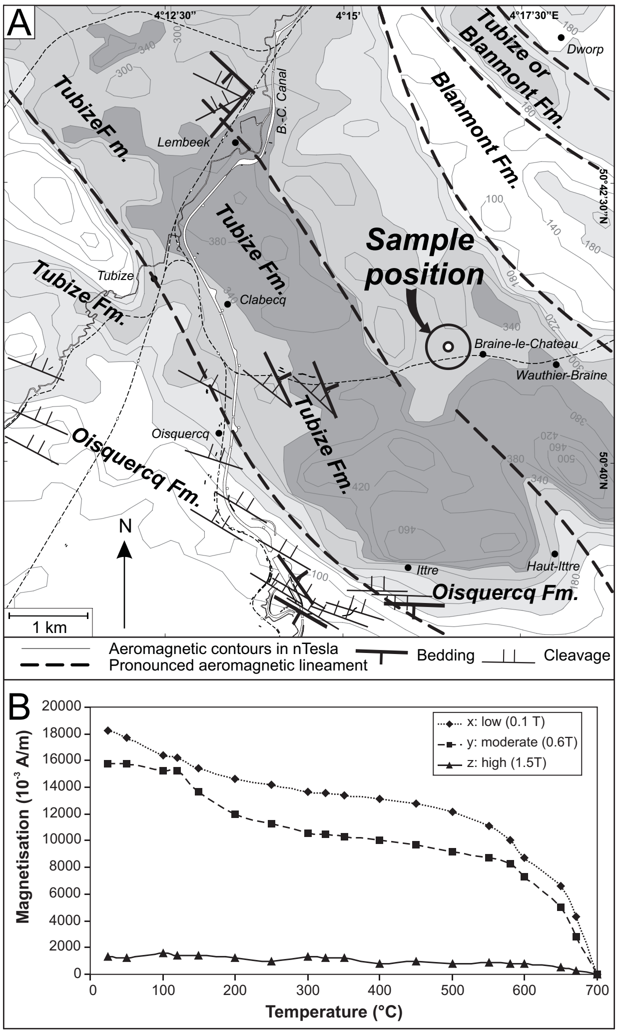

Figure 8: A) Simplified map of the study area, with added aeromagnetic contours (in nT; Belgian Geological Survey, 1994), showing sample position, mean cleavage and bedding orientations and traces of the most pronounced aeromagnetic lineaments (modified after Debacker et al., 2004b). Also indicated are the broad occurrences of the Oisquercq Formation, the Tubize Formation and the Blanmont Formation (adapted after Piessens et al., 2004). B) Thermal demagnetisation curves of sample TD1500b. The pattern clearly corresponds to that of the Ripain Member of the Oisquercq Formation (compare with Fig. 7).

This presence of the Ripain Member in between the Tubize Formation to the west and the Blanmont Formation to the east is entirely unexpected. Considering the SW-ward younging sense observed within the Tubize Formation at Rogissart to the west, this necessitates a fold-related reversal in younging sense or the presence of a fault or shear zone in between the Tubize Formation at Rogissart and the sample position at Braine-le-Château. Previously, folds and/or shear zones have also been put forward by Piessens et al. (2004) in order to explain the apparent re-occurrence of the Tubize Formation in between occurrences of the Blanmont Formation in the vicinity of Dworp (see Fig. 8a).

4.2. Borehole samples of unspecified, supposedly Cambrian units

For the construction of the still unpublished new geological map of the Brabant Massif (Piessens et al., 2005), many cores were re-investigated by the Belgian Geological Survey. This was done mainly on the basis of lithological observations combined with biostratigraphic analyses. For several core samples, supposedly of Cambrian age, no biostratigraphic age could be obtained. In order to better constrain the stratigraphic position of these problematic samples, we investigated their magnetic properties. As can be seen in Table 1, only samples of core 71E238(C) have susceptibility values significantly higher than the background (compare with Figs 2, 6A & 6B). Also these, however, are compatible with at least three units. Hence, for all cores additional techniques had to be applied.

On a Pj - Km graph samples of both cores 71E238(A) and 71E238(B) plot within the main cluster of the Ripain Member of the Oisquercq Formation. On a Pj - T graph, these samples plot around clusters of the Ripain Member and the high-susceptibility levels of both members of the Tubize Formation (compare with Fig. 6). The temperature-related variation in magnetic susceptibility shows extremely low values, suggestive of a strong ferromagnetic contribution (Fig. 9, compare with Fig. 5). This, combined with lithological observations and the low susceptibility values, suggests that the samples belong to the Ripain Member of the Oisquercq Formation. This is confirmed by the thermal demagnetisation curves (Fig. 10 and compare with Fig. 7J).

Judging from the position on a Pj - Km graph, samples of core 71E238(C) may belong to the Ripain Member, the Les-Forges Member or the Rogissart Member. On a Pj - T graph, samples plot amid the fields of the Les-Forges Member, the Rogissart Member, the Asquempont Member and the Mousty Formation (compare with Fig. 6). An

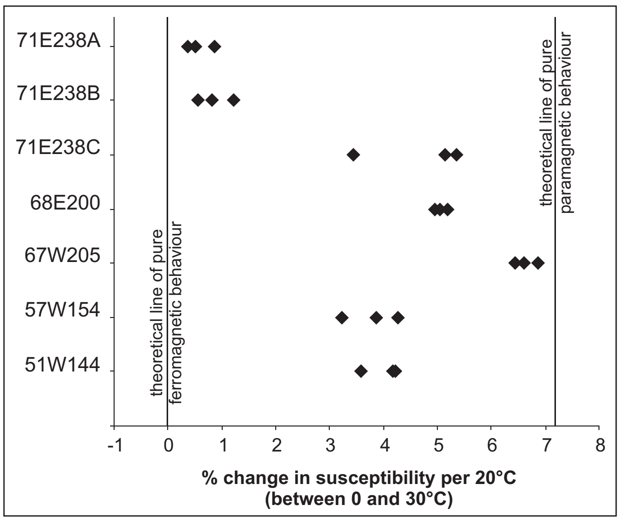

Figure 9: Variation in terms of percentage of magnetic susceptibility per 20°C between 0 and 30°C for samples from specific core levels thought to consist of Cambrian deposits, but with unknown stratigraphic position. See also Table 1 and Fig. 10, and compare with Fig. 5. See text.

Core; depth	Lithology	Sample	AMS parameters		
			Km	T	Pj
71E238(A); 242.5m (note : up/ down unknown)	Very homogeneous mudstone; dark, blue-grey, with locally very vague greenish, patchy banding (bedding). Hard, massive appearance. Cleavage is not pronounced; plumose structures on S1-plane. Lithostratigraphy: probably Ripain Member of Oisquercq Formation, but with less developed cleavage/more massive.	71E238Aa	392.5	0.3604009	1.351085
		71E238Ab	423.9	0.3918691	1.3676072
		71E238Ac	423.9	0.404749	1.3799823
		71E238Ad	420.5	0.4270733	1.3908105
		71E238Ae	379.4	0.3172438	1.3646594
71E238(B); 240.5m (note : up/ down unknown)	Very homogeneous mudstone; dark, blue-grey, with locally very vague greenish, patchy banding (bedding). Hard, massive appearance. Cleavage is not pronounced; plumose structures on S1-plane. Lithostratigraphy: probably Ripain Member of Oisquercq Formation, but with less developed cleavage/more massive.	71E238Ba	454.6	0.6627134	1.4004981
		71E238Bb	431.8	0.576104	1.3619297
		71E238Bc	381.5	0.5602977	1.3593158
		71E238Bd	429	0.5948945	1.3602401
71E238(C); 227.5m (note : up/ down unknown)	Banded (bedding) mudstone-siltstone; mudstone is, very locally, dark blue, but usually strongly purplish coloured (rubefaction), whereas siltstone is rather dark, greenish grey or bluish grey. Cleavage is pronounced; bedding often disrupted along cleavage (shear?). Lithostratigraphy: banded nature and grain size variations atypical for Oisquercq Formation. The original dark blue colour, and the marked bedding are compatible with the Les Forges Member of the Tubize Formation.	71E238Ca	650.8	0.2036984	1.2301774
		71E238Cb	483.1	0.5254437	1.2122251
		71E238Cc	508.6	0.5031827	1.2049122
		71E238Cd	501.9	0.5143138	1.1964292
68E200; 273.5m	Very homogeneous mudstone; green (pronounced! not greenish grey!). Bedding is visible as vague, moderately dipping darker or paler zones. Is hard, not porous, with a massive appearance. A poorly developed cleavage, with fracture-like appearance, is gently dipping. Lithostratigraphy: unknown. Possibly a darker, greener, more compact, les porous variety of the Asquempont Member?	86E200a	494.7	0.098106	1.0650486
		86E200b	585.7	0.1562129	1.0645176
		86E200c	430	0.1019979	1.0763065
		86E200d	507.1	0.1116288	1.0674554
		86E200e	463.4	0.2106438	1.0769275
		86E200f	353.7	0.0681399	1.0698927
67W205; 209-252m (note : up/ down unknown)	Crush breccia; very homogeneous mudstone; greenish grey, with occasional grey, vague banding (bedding), hard but rather porous. Although breccia, main bedding disposition in fragments is still subparallel (give or take 30°), in turn being subparallel to slip planes. Not clear whether breccia is pre- or post-S1. Lithostratigraphy: likely Asquempont Member of Oisquercq Formation. Note that in other samples fragments of (?) Chevlipont Fm are present, rather weathered (i.e. greenish grey mudstone intervals in between white sand-/siltstone).	67W205a	393.3	0.8183778	1.2304665
		67W205b	423.5	0.6711902	1.1874857
		67W205c	419.1	0.7575278	1.2150931
		67W205d	444	0.7766524	1.1922326
		67W205e	397.9	0.6505024	1.2021406
		67W205f	461.7	0.7195017	1.168997
		67W205g	488.4	0.8197036	1.1541929
57W154; 227.44m	Very homogeneous mudstone; pale, slightly purplish blue-grey, with green-grey zones (with patches of chlorite?). Very soft and porous. Bedding is marked by very vague greenish-grey patchy levels. Lithostratigraphy: Oisquercq Formation, uncertain whether strongly altered/weathered Ripain Member or red-coloured (rubefaction) slightly altered/weathered Asquempont Member.	57W154a	235.8	0.1702946	1.1523009
		57W154b	243.2	0.1123083	1.140656
		57W154c	242.9	0.1308032	1.130415
		57W154d	238.3	0.1478159	1.1389736
		57W154e	235.4	0.1602727	1.1444433
		57W154f	231.6	0.1512844	1.1379197
		57W154g	236.6	0.192851	1.133216
		57W154h	230.1	0.198065	1.1560013
51W144; 246.65m	Very homogeneous mudstone; very pale, green-grey, with grey, very vague banding (bedding), very soft and porous. Bedding is marked also by bands of dark spots (dark green to brownish; chlorites?). Lithostratigraphy: Asquempont Member of Oisquercq Formation.	51W144a	370.6	-0.0652871	1.0771027
		51W144b	367.3	0.1425393	1.0806535
		51W144c	366.2	0.1179035	1.0820527
		51W144d	399.8	0.1891812	1.0796204
		51W144e	394.5	0.1275378	1.0777085
		51W144f	369.9	0.0745887	1.0755347

Table 1: Magnetic susceptibility (Km), shape parameter (T) and corrected degree of anisotropy (Pj) of samples from specific core levels thought to consist of Cambrian deposits with an unknown stratigraphic position. Also included is a detailed lithological description of the sampled levels.

analysis of the temperature-related susceptibility variation does not yield exceptional values (Fig. 9). This rules out the Ripain Member (compare with Fig. 5). Combined with lithological observations, we infer a low-susceptibility level of the Les-Forges Member of the Tubize Formation. This is confirmed by the thermal demagnetisation curves (Fig. 10; compare with Fig. 7L). This implies that, along core 71E238, bedding is overturned, with the Ripain Member (71E238(A) & (B)) being situated below the Les-Forges Member (71E238(C)). Moreover, these results indicate that, at a depth of between 227.5 and 240.5 m, core 71E238 contains the transition between the Oisquercq Formation and the Tubize Formation, never observed previously.

Samples of core 68E200 show a large spread in Km and plot along a cluster of the Asquempont Member and the Mousty Formation on a Pj - Km graph and along the low-Pj side of the Asquempont Member and the high-Pj side of the Mousty Formation on a Pj - T graph (compare with Fig. 6). Temperature-related variation in magnetic

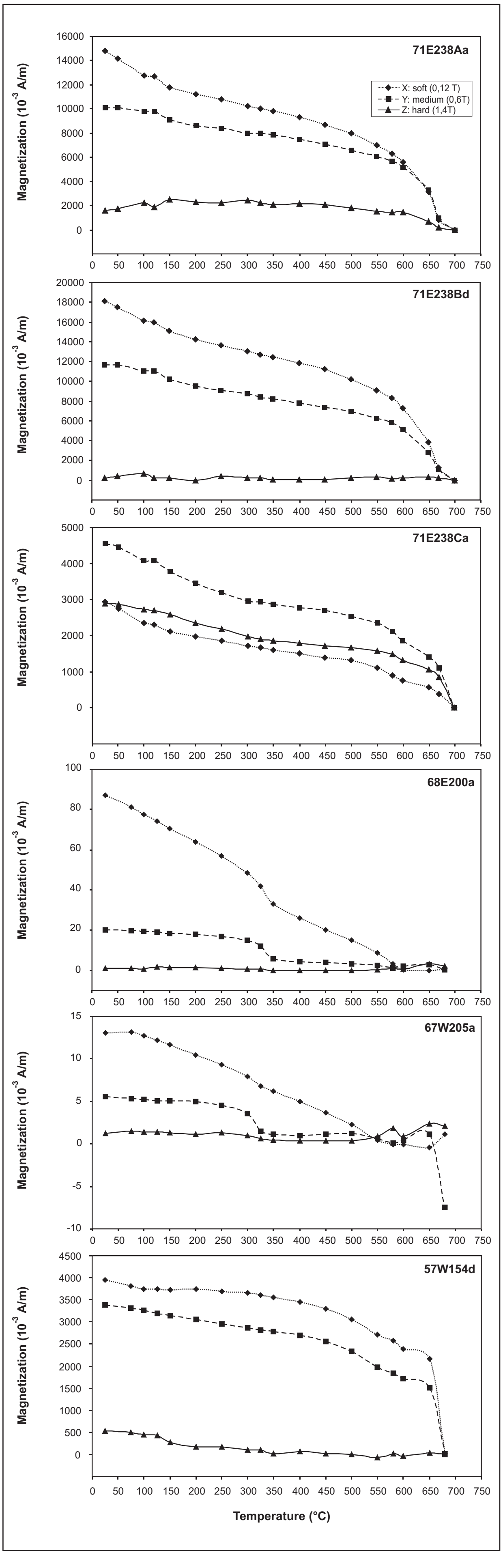

Figure 10: Thermal demagnetisation curves of samples from boreholes 71E238, 68E200, 67W205 and 57W154. 1. The three curves (1.4 T, 0.6 T and 0.12 T) respectively reflect hard, medium and soft components, or carriers with high, medium and low coercivities. See also Table 1 and Fig. 9, and compare with Fig. 7. See text.

susceptibility is compatible with low-susceptibility levels of the Rogissart Member, the Asquempont Member, the Jodoigne Formation and the Mousty Formation (Fig. 9, compare with Fig. 5). Combined with lithological observations, the samples likely belong to the Asquempont Member of the Oisquercq Formation. As can be seen in Fig. 10, this is confirmed by the thermal demagnetisation curves, typical for the Asquempont Member of the Oisquercq Formation (compare with Fig. 7I).

On a Pj - Km graph, samples of core 67W205 plot within a cluster of the Asquempont Member, the Les-Forges Member and the Rogissart Member and on a Pj - T graph within a zone shared by the Asquempont Member, the Les-Forges Member, the Rogissart Member, the Jodoigne Formation and the Mousty Formation (compare with Fig. 6). Temperature-related variation in magnetic susceptibility is high, suggesting a susceptibility virtually entirely controlled by paramagnetic carriers (Fig. 9). This rules out the Ripain Member and the Les-Forges Member (compare with Fig. 5). Although the lithology mostly resembles the Asquempont Member, the samples consist of a crush breccia, in which good lithological observations are not always easy. Because of this, also here ferromagnetic mineralogy was determined. As can be seen in Fig. 10, thermal demagnetisation curves are typical for the Asquempont Member of the Oisquercq Formation (compare with Fig. 7I).

Samples of core 57W154 plot within a cluster of the Mousty Formation on a Pj - Km graph, with lower Km than the Asquempont Member. On a Pj - T graph they cluster at the low-T side of the Asquempont Member and the Les-Forges Member and at the high-Pj side of the Mousty Formation (compare with Fig. 6). Apart from a slight shift towards lower values, the analysis of the temperature-related susceptibility variation does not yield exceptional values (see Fig. 9; compare with Fig. 5). As these results, combined with lithological observations, do not allow a stratigraphic designation, ferromagnetic mineralogy was determined. As can be seen in Fig. 10 (compare with Fig. 7J), the thermal demagnetisation curves are typical for the Ripain Member. Also the lithology complies with the Ripain Member. However, Pj, Km and T values, as well as the temperature-dependent variation in susceptibility are atypical for the Ripain Member. Likely, this is due to a position close to the transition zone between the Asquempont Member and the Ripain Member (See Fig. 5). This also explains the lithology having characteristics of both these members of the Oisquercq Formation.

On a Pj - Km graph, samples of core 51W144 plot within the main cluster, at the low-Pj side of the Asquempont Member and the Les-Forges Member, whereas on a Pj - T graph they cluster at the low-T and low-Pj side of the Rogissart Member, the Les-Forges Member and the Asquempont Member, and within the cluster of the Mousty Formation (compare with Fig. 6). An analysis of the temperature-related susceptibility variation does not yield exceptional values, apart from a slight shift towards lower values (see Fig. 9; compare with Fig. 5). This observation, combined with the very homogeneous, greenish grey mudstone lithology, points to the Asquempont Member of the Oisquercq Formation.

5. Discussion

5.1. Stratigraphic implications

Most lithostratigraphic units can fairly easily be distinguished on the basis of the thermal demagnetisation curves of the isothermal remanent magnetization. This holds true also for units in which magnetic susceptibility is controlled virtually entirely by paramagnetic carriers (e.g. Ronquières Formation; Debacker et al., 2009). In almost all units, a detectable amount of low- to moderate-coercivity magnetite occurs. In only two units, however, the occurrence of magnetite results in high magnetic susceptibilities. These high susceptibilities, only encountered in both members of the Tubize Formation, are due to the presence of a Ti-poor magnetite, characterised by low to high coercivities, reflected on thermal demagnetisation curves by a progressive drop from 125°C onwards towards 300-350°C.

Two units show identical thermal demagnetisation spectra. These are the Asquempont Member of the Oisquercq Formation and the Hospice-de-Rebecq Formation (see Fig. 7, and compare also with 68E200a and 67W205a of Fig. 10). Moreover, on a Pj - Km graph and a Pj - T graph, samples of these units occupy the same position, and also in terms of temperature-controlled variation in magnetic susceptibility both units cannot be distinguished. Furthermore, also lithologically our samples of the Hospice-de-Rebecq Formation, all taken at Rebecq (Senne valley), directly to the south and west of the Quenast plug, cannot be distinguished from the Asquempont Member of the Oisquercq Formation. Also the lithological description of the Hospice-de-Rebecq Formation at Rebecq by Herbosch (2005) can be applied to the Asquempont Member as well (see Verniers et al., 2001). Because of these many similarities, the question may be raised whether the Hospice-de-Rebecq Formation at Rebecq is not in fact the Asquempont Member that resurfaces again. On the geological section of Debacker & Sintubin (2008; their Fig. 11) across the Quenast-Rebecq area, outcrops of the Hospice-de-Rebecq Formation occur within the hinge zone of a large anticline. Tracing the bedding geometry from the north towards the south, the Asquempont Detachment System should reappear within this anticline, together with the Asquempont Member in its footwall, unless very large fault throws are invoked. Similarly, also towards the south many large displacement faults have to be invoked in order to explain the occurrence of the Hospice-de-Rebecq Formation. These considerations should be taken into account in future works on the Ordovician stratigraphy of the Brabant Massif, and urge for further studies on the Hospice-de-Rebecq Formation.

The combination of the magnetic methods employed proves particularly useful for distinguishing the different Cambrian lithostratigraphic units. The fact that comparable results are obtained for the Jodoigne Formation and for the Mousty Formation was used by Herbosch et al. (2008) as one of the arguments for revising the stratigraphic position of the Jodoigne Formation, and shifting it from the lowermost Cambrian (e.g. Verniers et al., 2001) to the Middle to Upper Cambrian, directly below or overlapping with the Mousty Formation. Both in terms of ferromagnetic mineralogy and in terms of lithology, the Jodoigne Formation can clearly be distinguished from the underlying Asquempont Member of the Oisquercq Formation. The Asquempont Member in turn, is, apart from the markedly different colour, lithologically somewhat comparable to the underlying Ripain Member of the Oisquercq Formation. In terms of magnetic properties, however, both members are completely different. The differences are apparent not only from thermal demagnetisation curves, but also from Pj - Km graphs, Pj - T graphs and temperature-related variation in magnetic susceptibility within the "room-temperature interval". By contrast, the Ripain Member is magnetically very difficult to distinguish from the low-susceptibility levels of the underlying Les-Forges Member of the Tubize Formation. Also lithologically, the Ripain Member is difficult to distinguish from the fine-grained parts of the Les-Forges Member. As the Ripain Member is magnetically much more closely related to the Les-Forges Member than to the Asquempont Member it may be considered as a transition unit. Because of this, combined with the fact that the limit between the Asquempont Member and the Ripain Member is well-documented (Hennebert & Eggermont, 2002; Debacker et al., 2004b), and the fact that also the limit between the Ripain Member and the Les-Forges Member is now better constrained (borehole 71E238; see Table 1), we suggest considering both members of the Oisquercq Formation as individual formations. Alternatively, as the Les-Forges Member can clearly be distinguished from the underlying Rogissart Member of the Tubize Formation, both in terms of lithology (Vander Auwera & André, 1985; Verniers et al., 2001) and magnetic properties (Fig. 5, Fig. 7), whereas this member is difficult to distinguish from the overlying Ripain Member of the Oisquercq Formation, it may be considered to group the Ripain Member and the Les-Forges Member into a new formation, separately from (the Asquempont Member of) the Oisquercq Formation above and (the Rogissart Member of) the Tubize Formation below.

5.2. Use of magnetic techniques for stratigraphic purposes: recommendations

Within the Anglo-Brabant Deformation Belt, poor results are obtained when trying to characterise lithostratigraphic units by means of magnetic susceptibility alone. This reflects the overall homogeneity of the investigated lithologies in terms of magnetic susceptibility. This homogeneity may be a primary feature of the deposits and/or may be due to low-grade metamorphism. During metamorphic conditions, the signature of diagnostic original carriers may have been lost, except for some very specific units such as the Tubize Formation, in which the combination of the original lithology combined with the metamorphic conditions was capable of creating new magnetic phases (Vander Auwera & André, 1985), with a magnetic susceptibility standing out from the background. For all other lithologies, metamorphism appears to have resulted rather in a homogenisation of magnetic susceptibility between the different stratigraphic units.

The fact that magnetic susceptibility (Km) may change dramatically across individual graded beds ranging from very fine sand to mud, without there being a clear link to differences in grain size, suggests that magnetic susceptibility will mostly reflect very local mineralogical and lithological changes, rather than differences between entire stratigraphic units. Hence, in general, within the Anglo-Brabant Deformation Belt, magnetic susceptibility cannot be used for characterising formations or members, nor for correlating formations or members, but can only be used for very local correlations in between different (parts of) beds.

The temperature-dependent variation of magnetic susceptibility within the "room-temperature interval" yields slightly better results. This method allows pinpointing lithostratigraphic units rich in ferromagnetic carriers of moderate to high coercivity, both with high (e.g. magnetite in Tubize Formation) and low magnetic susceptibilities (e.g. hematite in Ripain Member). Moreover, also units with very low coercivity carriers become readily apparent from this technique (e.g. Jodoigne Formation). When combined with classical magnetic susceptibility measurements at "constant" ambient temperatures, this method offers much more information of use for stratigraphic purposes than does simple magnetic susceptibility at "constant" ambient temperature.

A comparison of the main parameters of the anisotropy of magnetic susceptibility, by means of a Pj - T graph and a Pj - Km graph, is a more powerful tool for distinguishing different lithostratigraphic units as compared to measuring bulk magnetic susceptibility (Km) or the temperature-dependent variation in Km, provided that the samples underwent a comparable amount of strain and experienced a similar tectonometamorphic history (see also Borradaile & Henry, 1997). In addition, Pj and T also appear to show systematic variations with changes in grain size, and in the presence of composite magnetic fabrics T shows a clear relationship with the angle between cleavage and bedding. Also the presence or absence of the latter relationship can be used for diagnostic purposes. Moreover, in theory, both relationships could be used to recalculate Pj and T for specific grain sizes or specific angles between cleavage and bedding, which could then be used for comparative stratigraphic purposes.

In our case, by far the best way for distinguishing different lithostratigraphic units is by means of thermal demagnetisation of a remanent magnetisation. This method even allows distinguishing between different units in which ferromagnetic carriers do not contribute at all to overall magnetic susceptibility (e.g. Ronquières Formation and Vichenet Formation; Debacker, et al., 2009). When combined with lithological observations, magnetic susceptibility at ambient temperature, temperature-dependent variation of magnetic susceptibility within the "room-temperature interval" and AMS, this method will allow distinguishing the vast majority of the different lithostratigraphic units.

Hence, for the magnetic characterisation of lithostratigraphic units, and for stratigraphic correlation by means of these characteristics, as many magnetic methods as possible should be applied, and all should be combined with detailed lithological observations and with ferromagnetic mineralogy analyses.

6. Conclusions

Within the Anglo-Brabant Deformation Belt, stratigraphic correlation on the basis of magnetic susceptibility alone is virtually impossible. As exemplified, only some parts of the Lower Cambrian Tubize Formation clearly stand out because of their much higher magnetic susceptibility.

Better results are obtained if magnetic susceptibility is measured at different "room temperatures", and these relative changes in magnetic susceptibility with changing "room temperatures" are used for correlation purposes. When combined with lithological observations, the Rogissart Member of the Tubize Formation, the Les-Forges Member of the Tubize Formation, the Ripain Member of the Oisquercq Formation and the Jodoigne Formation/Mousty Formation can successfully be distinguished from other lithostratigraphic units of the Anglo-Brabant Deformation Belt.

By means of an analysis of the relationship between the main anisotropy parameters, such as Pj, T and Km, the anisotropy of magnetic susceptibility (AMS) becomes a much more powerful tool for stratigraphic correlation than simple magnetic susceptibility, provided that the sampled units experienced a comparable degree of strain and a comparable tectonometamorphic history. Such conditions are met within the largest parts of the Anglo-Brabant Deformation Belt.

However, ideally, all the above methods should be used for stratigraphic correlation only in combination with a rigorous analysis of the source of magnetic susceptibility. This can be done by means of a determination of the ferromagnetic mineralogy, the paramagnetic mineralogy and the diamagnetic mineralogy. Moreover, if combined with the paramagnetic anisotropy (determined by low-temperature AMS; Lüneburg et al., 1999; Debacker et al., 2009), and the ferromagnetic anisotropy (determined by the anisotropy of the anhysteretic remanent magnetism; McCabe et al., 1985; Debacker et al., 2004a), knowledge of magnetic (s.l.) mineralogy will lead to a much better understanding of AMS and its stratigraphic variation, and may even result in a better understanding of the basin evolution history.

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