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SUGGESTIONS FOR A DEEP SEISMIC INVESTIGATION NORTH OF THE VARISCAN MOBILE BELT IN THE SE NETHERLANDS

by

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(10 figures)

ABSTRACT.- A deep seismic survey across South Limburg (SE Netherlands) should complete the Eupen-Teuven (NE Belgium) BELCORP seismic exploration. The BELCORP line stops just before reaching the area where the concealed eastern end may be found of a major geological structure in NW Europe : the Wales-London-Brabant Massif. Moreover, this area is distinguished in several ways from other regions around the Brabant Massif in Belgium.

The Bilzen magnetic high to the north-west may represent either the Pre-Silurian basement of the Brabant Massif, or a basic intrusion of possibly Variscan age. To the south-east several SW-NE striking faults occur in an area marked by a prominent gravity low. The gravity low is distinguished by high rates of subsidence during the (Late) Devonian and Dinantian followed by important Late Variscan uplift (Visé-Puth and Waubach structures).

Partial coking of low rank organic material in Dinantian sediments followed by the establishment of a narrow high rank coalification belt prove the importance of a regional thermal event during the Late Paleozoic. Hydrothermal precipitation of sulfide ores during the Mesozoic and actual anomalous rock temperatures and the presence of «warm» water wells indicate a high thermal conductivity throughout the geological history.

Remarkable is also the Late Cretaceous/Cenozoic reactivation of faults with a Variscan (SW-NE) strike in this area.

Recognition of these phenomena has produced a number of open-ended questions which may be partly solved by the northward extension of the Eupen-Teuven BELCORP profile.

RESUME.- Une étude sismique réalisée au travers du Limbourg méridional (SE des Pays-Bas) devrait compléter l'exploration sismique entreprise le long de la ligne Eupen-Teuven (NE de la Belgique) du projet BELCORP. Cette ligne s'arrête à proximité de la terminaison Est, sous couverture, de la structure géologique majeure que constitue le Massif du Pays de Galles-Londres-Brabant. C'est une région qui se distingue, en outre, sous divers aspects, de celles qui voisinent, en Belgique, ce massif.

Le pic magnétique de Bilzen, au nord-ouest, pourrait représenter soit le soubassement pré-silurien du Massif du Brabant, soit une intrusion d'âge varisque. Au sud-est, plusieurs failles d'orientation SW-NE caractérisent un domaine marqué par un déficit de gravité. Ce dernier s'explique par la valeur élevée du taux de subsidence défini pour le Dévonien (tardif) et le Dinantien et par l'importance de la surrection qui s'est manifestée lors de la phase terminale varisque (structures de Visé-Puth et de Waubach).

La cokéfaction partielle de la matière organique en faible teneur dans les sédiments dinantiens, suivie par le développement d'une mince zone de carbonification très élevée témoigne de l'importance d'un événement thermique au cours de la fin du Paléozoïque. La précipitation hydrothermale de sulfures au Mésozoïque, les valeurs actuelles des températures anomales des roches et la présence d'eaux minérales «chaudes», indiquent que la conductivité thermique est restée élevée, dans la région, tout au cours de son histoire géologique.

Il faut également souligner que, dans cette même région, les failles définies par la direction varisque SW-NE, ont été réactivées à la limite Crétacé terminal/Cénozoïque.

La prise en compte de ces diverses observations est à la base d'un certain nombre de questions qui pourraient trouver un début d'explication si l'on pouvait poursuivre vers le nord le profil sismique BELCORP d'Eupen-Teuven.

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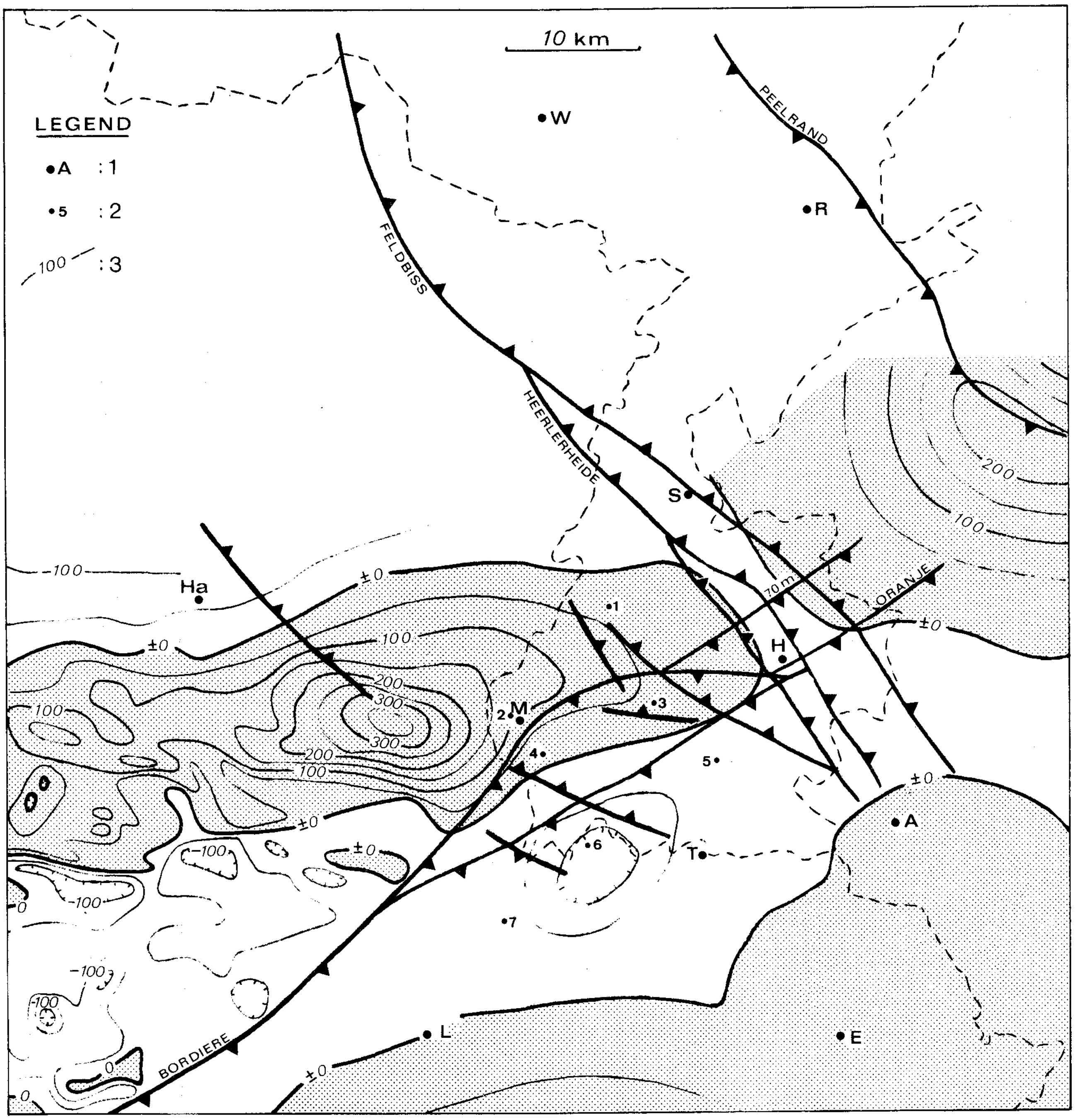

Figure 1.- Geomagnetic anomalies ΔT in the environs of South Limburg (after Bless *et al.*, 1980).
Punctuate shading indicates positive regions (too large values of vertical component), white are negative regions. Magnetic high west of Maastricht is Bilzen anomaly. The southeastern border of this anomaly roughly matches the norther border of a broad residual gravity low (cf. fig. 2). To the east the Bilzen anomaly is bounded by the Bordière-Oranje-70 m faults and by the Rur Valley Graben border Faults (Benzenrade and Heerlerheide faults).

1: cities (A = Aachen, E = Eupen, H = Heerlen, Ha = Hasselt, L = Liège, M = Maastricht, R = Roermond, S = Sittard, T = Teuven, W = Weert). **2**: relevant boreholes which penetrated the Dinantian (1 = Beek-Geverik, 2 = Kastanjelaan-2, 3 = Thermae 2000/2002, 4 = Heugem, 5 = Gulpen-106, 6 = 's-Gravenvoeren, 7 = Hermalle-sous-Argenteau). **3**: ΔT isanomalies in nanotesla.

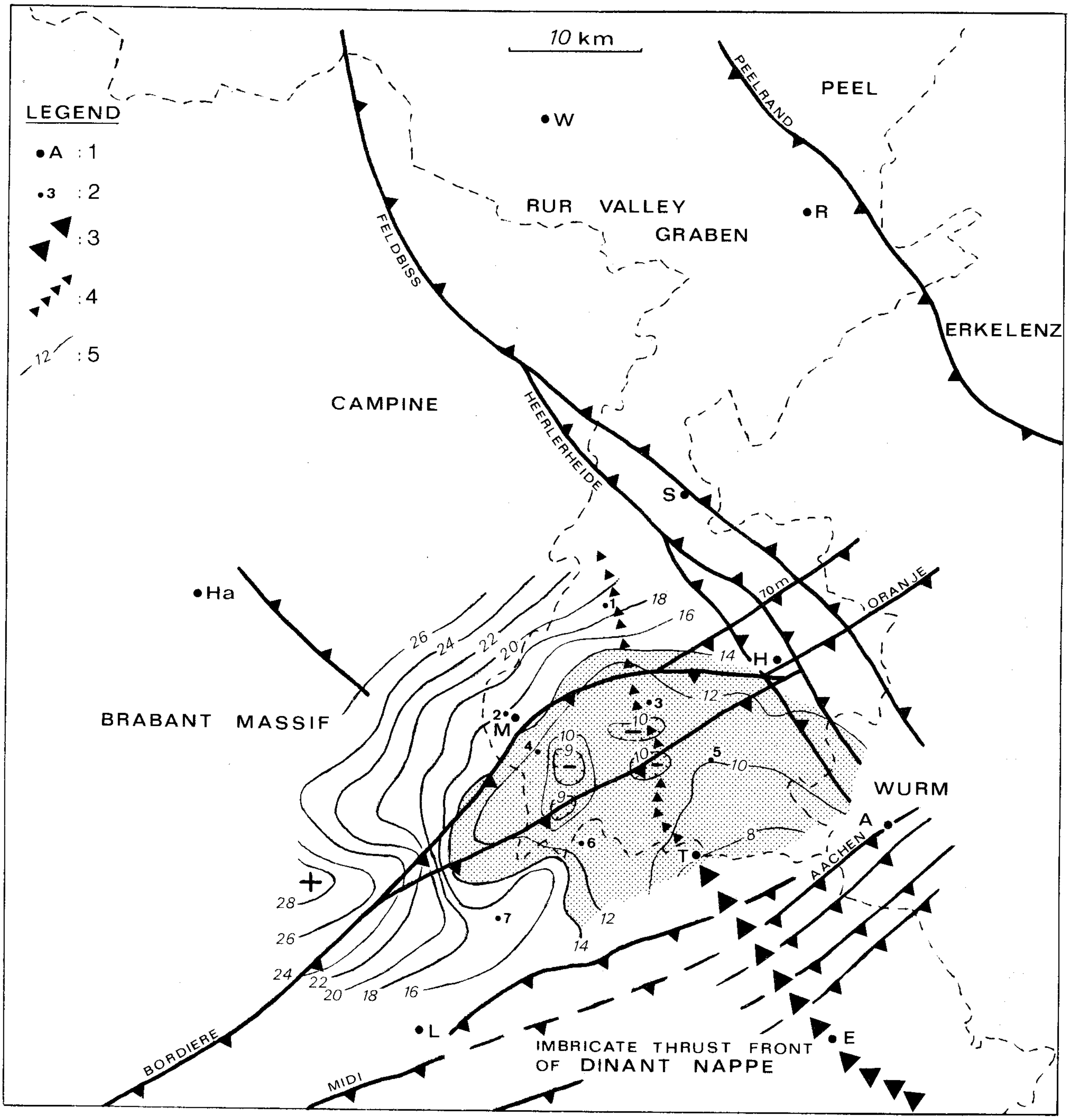

Figure 2.- Residual gravity map of South Limburg and surroundings (after Bless *et al.*, 1980) with position of BELCORP seismic line between Eupen and Teuven, and with proposed line for seismic survey in South Limburg across Bordière-Oranje-70 m faults and gravity lows. The punctuate shading covers a broad residual gravity low that is bounded by the positive magnetic Bilzen anomaly in northern direction (cf. fig. 1).

1: cities (A = Aachen, E = Eupen, H = Heerlen, Ha = Hasselt, L = Liège, M = Maastricht, R = Roermond, S = Sittard, T = Teuven W = Weert). **2**: Relevant boreholes which penetrated the Dinantian (1 = Beek-Geverik, 2 » Kastanjelaan-2, 3 = Thermae 2000/2002, 4 = Heugem, 5 = Gulpen-106, 6 = 's-Gravenvoeren, 7 = Hermalle-sous-Argenteau). **3**: 1987 BELCORP deep seismic survey. **4**: proposed seismic line in South Limburg. **5**: Residual gravity in mgal (after Bless *et al.*, 1980).

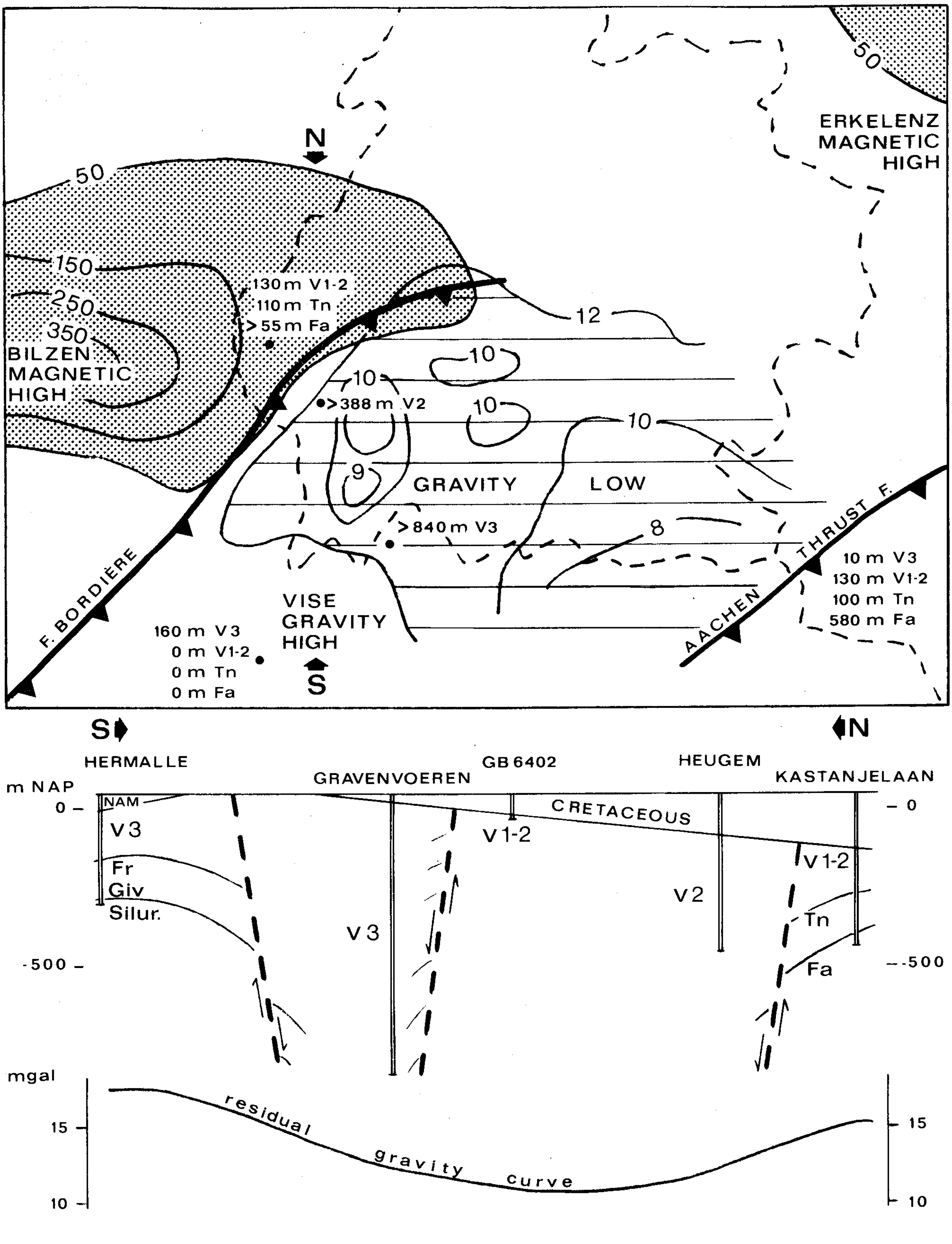

Figure 3.- Map of South Limburg and environs showing extension of (residual) gravity low between Bilzen magnetic high and Visé gravity high; with thickness of Famennian to Upper Visean strata in some relevant boreholes (from south to north : Hermalle-sous-Argenteau, 's-Gravenvoeren, Heugem, Kastanjelaan). For comparison the thickness of the same strata in the (allochthonous) Aachen region is presented. The synthetic N-S section reveals that the gravity low matches the area of maximum subsidence and subsequent uplift/erosion (extreme thick V2; V3 and younger eroded).

INTRODUCTION

During the past decade there has been a rapidly growing interest in deep drilling and deep seismic investigations across Europe. Realization of the many national programmes such as BELCORP (Belgium), BIRPS (Great Britain), DEKORP and KTB (Federal Republic of Germany) and ECORS (France) will substantially increase our knowledge of major structures in the crust and in the upper mantle. One of the major geological features in NW Europe is the Variscan thrust belt with its poorly understood root zone to the south and the Wales-London-Brabant Massif to the north. In order to achieve a better insight of these structures a deep reflection seismic survey has been carried out across the Rheinisches Schiefergebirge as part of the German DEKORP programme and this profile has been extended through Eupen to Teuven in eastern Belgium as part of the BELCORP programme.

Unfortunately, this DEKORP-BELCORP profile stops just before reaching the presumed eastern extension of the Brabant Massif below South Limburg in the SE Netherlands. This concealed eastern end is distinguished in several ways from other regions around the Brabant Massif in Belgium :

- SW-NE striking faults (Antiklinaal-Oranje and 70 m) which presumably connect with the Faille Bordière (the southern border fault of the Brabant Massif in Belgium),
- the Bilzen magnetic high to the north-west, bordered by a prominent gravity low in southeastern direction,
- high rates of subsidence during the (Late) Devonian and Dinantian followed by an enormous uplift during the Late Variscan movements,
- anomalously high rank of coalification of Upper Devonian to Lower Westphalian B strata,
- hydrothermal activity during Mesozoic, anomalous rock temperature and «warm» water wells today, and
- reactivation of SW-NE striking faults during Late Cretaceous and/or Cenozoic.

GEOPHYSICAL DATA

The eastern end of the Brabant Massif is poorly known. According to Legrand (1968) the eastern end would be bounded to the south-east by the Faille Bordière, the southern border fault that can be traced far to the west into Flanders. A NW-SE striking fault would form the northeastern boundary.

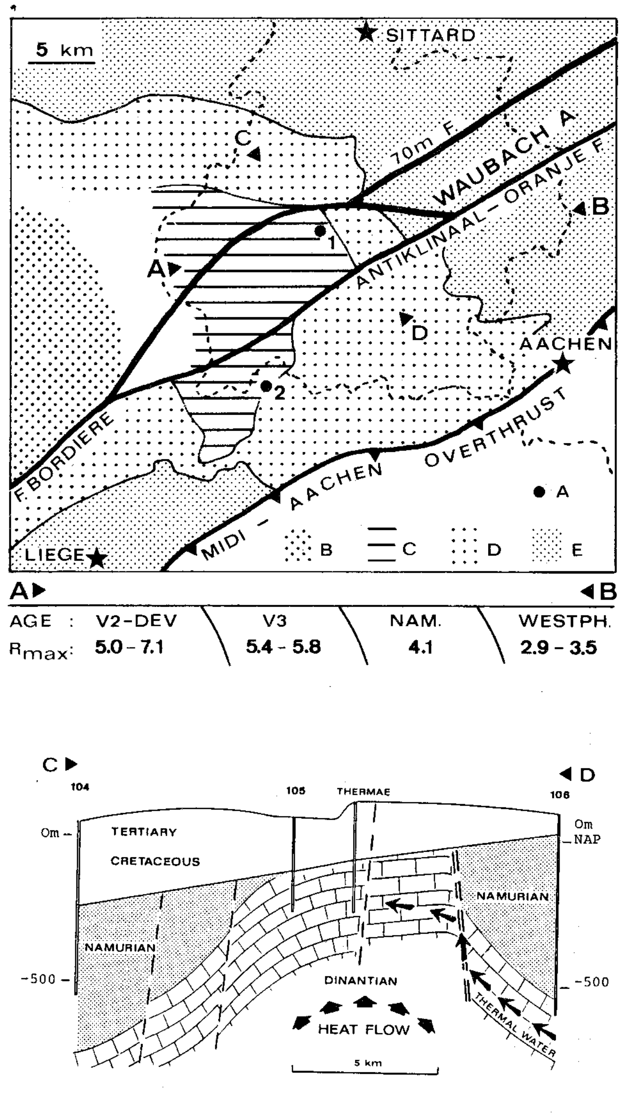

Figure 4

Pre-Permian subcrop in South-Limburg and environs, showing presumed connection between Faille Bordière (southern border of Brabant Massif) and Antiklinaal/Oranje and 70 m faults in former coal-mining area of South Limburg (after Wolf & Bless, 1987). Area between 70 m Fault and Antiklinaal/ Oranje Faults forms a structural high in the Pre-Permian subsurface as exemplified in cross-section through Thermae boreholes (C-D). This area of maximum uplift during Late Variscan seems to have been an area of maximum subsidence during (Devono-)Dinantian.

Simplified cross-section A-B shows maximum reflectance of organic substance in Devonian to Westphalian-A strata on both sides of inferred fault lines. The anomalously high coalification rank of these deposits suggests a post-Westphalian-A heat flow. On the other hand the coalification rank must have been established before erosion of the Upper Carboniferous strata took place in this region. This points to a Late Variscan age for this heat flow. Since reworked spores derived from Lower Westphalian and older rocks apparently abound in Westphalian C sediments of the Belgian Campine and South Limburg (Bless & Streel, 1976), it seems likely that incipient uplift and heat flow occurred already at the end of the Early Westphalian (end Westphalian B?).

Legend : A = recent boreholes in Dinantian (1: Thermae 2000-2002, 2: 's-Gravenvoeren); B = Cambro-Silurian of Brabant Massif, C = Devono-Dinantian of Visé-Puth Uplift, D = Namurian, E = Westphalian.

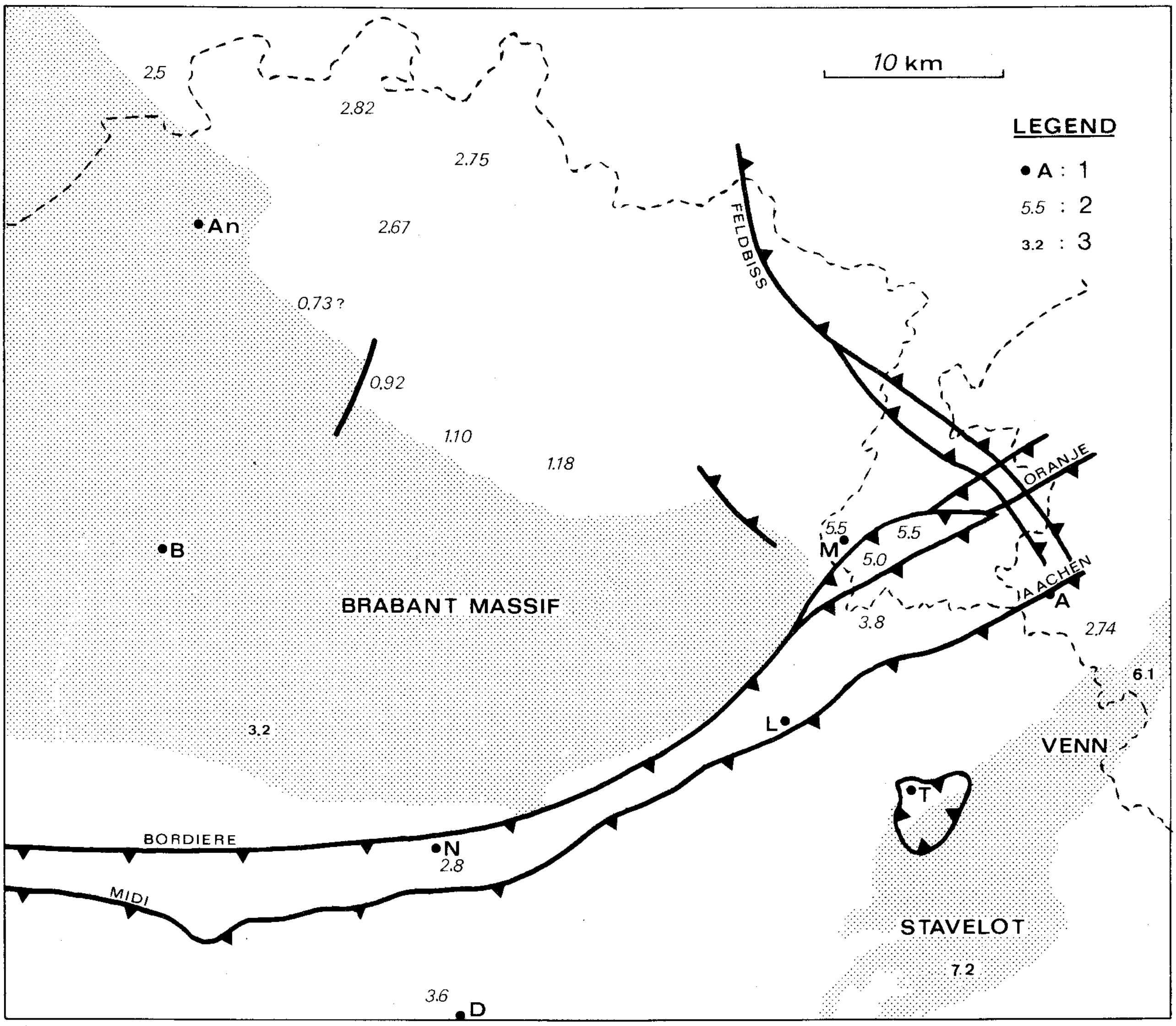

Figure 5.- Coalification data in % Rmax for Dinantian (italics) and Cambrian (bold) around Brabant Massif. After M. & R. Teichmüller (1979), Muchez *et al.* (1987), Bless *et al.* (1976, 1981), Wolf & Bless (1987).
1: cities (A = Aachen, An = Antwerp, B = Brussels, D = Dinant, L = Liège, M = Maastricht, N = Namur, T = Theux); **2**: coalification of (top) Dinantian in % Rmax; **3**: coalification of Cambrian in % Rmax.
Note that highest reflectance values for Dinantian occur east of Brabant Massif around Bordière-Oranje-70 m faults, and that these are much higher than that for the Cambrian in the Bousval borehole (3.2) in the Brabant Massif.

In 1979 however, a magnetic/gravimetric study by the geological surveys of Belgium, the Netherlands and the Federal Republic of Germany (Bless *et al.*, 1980) revealed that the positive magnetic Bilzen anomaly (fig. 1) at the presumed eastern end of the Brabant Massif gradually plunges eastward below South Limburg until the Rur Valley Graben. And furthermore, it was shown that this eastern extension of the Bilzen anomaly is bounded by a prominent gravity low in south-eastern direction (fig. 2).

Accepting the model that the Bilzen anomaly reflects the top of the Pre-Silurian (say Cambro-Ordovician) magnetic basement, we may assume that the Brabant Massif gradually plunges below the Devonian-Carboniferous overburden in eastern direction. Calculations by Bosum (*in* Bless *et al.*, 1980) suggest that the top of this magnetic basement occurs at some 1.5 km below the surface at Bilzen (some 8 km west of Maastricht), and at some 3 km depth immediately north-east of Maastricht.

An alternative interpretation is that the Bilzen magnetic high is caused by an igneous intrusive body as has been suggested for similar positive magnetic anomalies (Erkelenz : Bartenstein & Teichmüller, 1974; East Groningen : Kettel, 1983).

The NW-SE striking border faults of the Rur Valley Graben (notably the Benzenrade and Heerlerheide faults) limit this structure to the north-east. The southeastern border is here formed by the SW-NE trending 70 m Fault and Antiklinaal-Oranje Fault. These presumably pass into the Faille Bordière further to the south-west through two faults. The northern one is the boundary between the Bilzen anomaly and the gravity low. The southern one crosses the gravity minima.

The existence of faults at these positions has been postulated also after the study of the Heugem and Kastanjelaan boreholes at Maastricht (Bless *et al.*, 1981).

The gravity low in South Limburg to the south-east of the Bilzen anomaly covers a fault-bounded area with extremely high rates of subsidence during the (Late) Devonian and Dinantian. In southwestern direction this gravity low is bounded by the Visé gravity high. There the Devonian/Dinantian sequences are very incomplete and thin (e.g. in Hermalle-sous-Argenteau borehole : sedimentation gaps during Lower Devonian, Famennian and Lower Dinantian; Givetian-Frasnian about 120 m, Dinantian about 160 m), at least compared with those to the east and north (more than 840 m Upper Visean in 's-Gravenvoeren borehole; more than 380 m Middle Visean in Heugem borehole; about 100 m Tournaisian and more than 50 m Famennian in Kastanjelaan borehole; fig. 3). It should be noted that an increased thickness of Late Dinantian strata also occurs to the north-east of the Bilzen anomaly, where more than 800 m Visean strata were explored by the Beek-Geverik borehole. It is thus possible that the area of rapid subsidence extended in northern direction beyond the present gravity low.

The observed thicknesses for the Middle-Upper Visean in South Limburg are exceptional for the surrounding of the Brabant Massif. An exception forms the St.-Ghislain/Epinoy area (SW Belgium, N France) where the Dinantian is more than 2000 m thick (including some 760 m anhydrite in St.-Ghislain).

Late Variscan uplift and subsequent erosion during the Permo-Triassic can be deduced from the Pre-Permian subcrop map for South Limburg (fig. 4). The area of maximum uplift and erosion occurs in the south-west where Dinantian strata directly underlie the Cretaceous. To the north, east and south these are covered by Namurian and Westphalian deposits. Noteworthy is that most of the area of maximum uplift/erosion is situated to the south-east of the Bilzen magnetic high, that is considered as the eastern extension of the Brabant Massif. This means that the gravity low in South Limburg (and notably its northern flank) represents the area of maximum Devonian/ Dinantian downwarp and maximum Late Variscan upwarp (fig. 10).

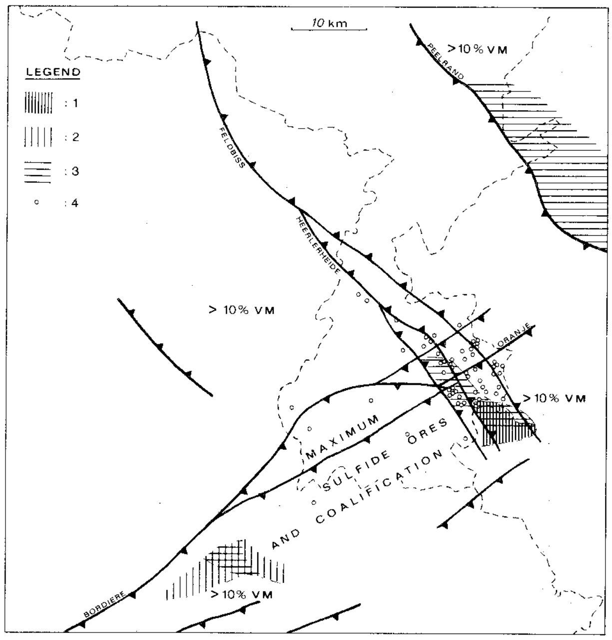

Figure 6

Coalification of Westphalian A coal seams and occurrence of sulfide ores in South Limburg and environs.

1: less than 10 % volatile matter (VM) in coal seam Grosslangenberg (upper part of Upper Westphalian A) after Babinecz (1962); 2: less than 10 % VM in coal seam Finefrau (lower part of Lower Westphalian A) after Patijn (1963); 3: less than 10 % VM in coal seams Steinknipp/Sonnenschein/Merl (near boundary Lower-Upper Westphalian A) after Dubrul (1931), M. & R. Teichmüller (1958, 1971) and Patijn (1963); 4: occurrence of sulfide ores in Silesian (after Kimpe *et al.* 1978) and Dinantian (after Bless *et al.*, 1981, Friedrich *et al.* 1987), sulfide ores in Aachen-Stolberg area and Moresnet-Plombière area not indicated.

Maximum coalification (less than 10 % VM) in Westphalian A coal seams occurs in Peel-Erkelenz area (north of Peelrand Fault and positive magnetic anomaly, cf. fig. 1), and in area east of Brabant Massif (south of Bordière-70 m Fault and positive magnetic Bilzen anomaly, cf. fig. 1). Comparison with maps by Dubrul (1931) and M. & R. Teichmüller (1958) learns that coalification of notably the Steinknipp/Sonnenschein/Merl seams rapidly decreases to the north (Campine), east (Wurm) and south-west (Mons-Charleroi-Huy), and also southwards in the direction of the Midi-Aachen Overthrust. These data suggest anomalous (post-Westphalian-A) heat flows along southern flank of magnetic Bilzen high in Liège-Aachen area and along northern flank of magnetic Erkelenz high. These heat flows cannot be related to the Midi-Aachen Overthrust.

More than 80 % of the sulfide ores known thus far in the Silesian rocks of the former coal-mining area of South Limburg and in the Devono-Dinantian strata to the west (Thermae boreholes at Valkenburg, Kastanjelaan and Heugem boreholes at Maastricht, La Folie Quarry east of Visé) occur to the south of the Bordière-70 m Fault. Sulfide ores in the former mining area are concentrated along the NW-SE striking border faults of the Rur Valley Graben, but south of the 70 m Fault (Kimpe *et al.*, 1978). This indicates that metal-rich solutions mainly ascended somewhere south of the Bordière-70 m Fault towards the crests of the structural high formed by the Visé-Puth Uplift and Waubach Anticline (cf. fig. 4).

COALIFICATION

Numerous authors have investigated the coalification of organic matter in Carboniferous rocks around the Brabant Massif. Comprehensive studies were published by Dubrul (1931 : Westphalian A between Mons, Aachen and Campine), M. & R. Teichmüller (1979 : Paleozoic of Eifel and Brabant Massif) and Muchez *et al.,* (1987: Dinantian of Campine).
The coalification data for the Dinantian (fig. 4) and Westphalian A (fig. 5) around the Brabant Massif reveal a similar pattern : a moderate rank for the area to the south, a low rank for the area to the north, and an extremely high rank for the area to the east (South Limburg and environs).

The coalification rank of the Dinantian north and south of the Brabant Massif (fig. 5) is well below that in the Sub-Variscan Foredeep of NW Germany or in the Saar Backdeep of SW Germany (cf. M. & R. Teichmüller 1986, fig. 13). The high coalification rank to the east however matches well those in the Ruhr and Saar areas. This remarkable difference may be explained by a difference in either the pre-orogenic Carboniferous overburden or the regional heat flow density.

Dubrul (1931, fig. 2) mentioned 10 to 22 % VM (volatile matter; about 1.7-2.4% R_r according to table 2 in M. & R. Teichmüller & Bartenstein, 1979) for the Steinknipp/Sonnenschein/Merl coal seams (near the boundary between Lower and Upper Westphalian A) to the south of the Brabant Massif. North of this massif the VM varies between 20 and 31 % (1.1-1.6% R_r). To the east very low values of 4-10 % VM (2.4-4 % R_r) were found between Aachen and Liège. This rank is relatively high even for most of the Westphalian A coal in the Ruhr Basin (except for regional anomalies such as the Bramsche Massif or areas where the Westphalian A has been deeply buried, say below more than 3000 m overburden). This high rank of coalification is limited to a narrow belt to the south-east of the Bordière-70 m faults between Liège and Aachen (fig. 6). The coalification decreases not only to the north of this fault line (northern part of South Limburg mining area, Campine), but also to the east (Wurm Basin), south-east (into the direction of the Midi-Aachen Thrust Fault) and south-west (Huy-Namen-Mons coal fields). This pattern is confirmed by the investigations on the coalification of the Grosslangenberg coal seam (upper part of Upper Westphalian A; Babinecz, 1962; M. & R. Teichmüller, 1979) and Finefrau coal seam (lower part of Lower Westphalian A; Patijn, 1963).

A similar narrow coalification high in the Westphalian A on the southwestern flank of the Peel-Erkelenz area (fig. 6) has been explained as the result of a basic magmatic intrusion (Bartenstein & Teichmüller, 1974). Is the South Limburg coalification high the result of a comparable magmatic intrusion, has it been caused by extreme heat flow density, or does it reflect a very thick overburden ? A partial answer to this question may be found in a comparison between this area and the Münsterland borehole of NW Germany. Increase of coalification with depth could not be studied in the area to the south-east of the Bordière-Oranje-70 m faults because of the limited depth of mining (Westphalian A practically subcropping below Mesozoic/Cenozoic) and boreholes (maximum 500 m in Dinantian at Maastricht). Moreover most of the Carboniferous has been removed by erosion after the Late Variscan uplift. However, the data for the Westphalian, Namurian and Devono-Dinantian (fig. 4) suggest that a coalification/depth graph for the area east of Maastricht might be constructed accepting that the thickness of the Namurian and Westphalian has been comparable with that to the north, east and south.

In figure 7 the coalification data for the Devonian to Westphalian A in the South Limburg coalification high have been plotted on the coalification/depth graph for the Münsterland borehole. At the right side of this graph a best estimate is presented for the thicknesses of the various stratigraphic intervals. The graph suggests a rough resemblance between the increase of coalification with depth in the lower half of the Münsterland borehole (3000 - 5000 m) and that for the interval Devonian to Westphalian A in South Limburg. This might suggest a comparable burial history for both areas. However, a problem is that the presumed thickness of the Westphalian B-C in this region was only some 1600-1800 m. According to the Münsterland model this means that there is a «deficit» of 1200-1400 m overburden that should have been covered by Westphalian D and younger deposits (Stephanian ?, Zechstein ?, Triassic ?). Permo-Triassic sediments will not have played an important part in the coalification if we accept a Late Variscan uplift and if coalification in this area was largely pre-orogenic as emphasized by a.o. Babinecz (1962).

A narrow, rapidly subsiding Late Westphalian/Stephanian trough at the position of the South Limburg coalification high cannot be excluded completely because of the extreme thickness of the Dinantian in this area. However, in that case the burial time may have been insufficient for reaching the observed coalification rank.
A northward projecting lobe of the Variscan Dinant Nappe as the cause for the coalification high is most unlikely since the coalification rank decreases in the direction of the Midi-Aachen

Thrust front.

In this survey a regional heat flow is accepted as the most plausible cause for the anomalous coalification. There are several arguments favouring this model :

- First of all the South Limburg coalification high is located on the southeastern flank of the Bilzen magnetic high, and it matches an area of maximum uplift. This resembles the situation in the Peel-Erkelenz area where the coalification high occurs on the northeastern flank of the Erkelenz magnetic high and marks an area of important uplift (Bartenstein & Teichmüller, 1974). It also remembers the East Groningen coalification high on the southwestern flank of an important positive magnetic anomaly in an area of strong uplift (Kettel, 1983). Both Erkelenz and East Groningen have been interpreted as igneous intrusions.

- Secondly there is the presence of vitroplast and mesophase textures in the Dinantian of the Thermae boreholes at Valkenburg a/d Geul (Wolf & Bless, 1987). These indicate a short-lived extreme heat flow (more than 450°C) that affected these rocks in the past.

- And finally, positive temperature anomalies in the South Limburg coalification high also occur during the Mesozoic (Post-Variscan/Pre-Late-Cretaceous sulfide mineralization, cf. fig. 6; Friedrich *et al.,* 1987) and at present (relatively high rock temperatures at -749 m NAP in former mining area, Sadée, 1975; «warm» water wells; fig. 8). This means a high thermal conductivity possibly enhanced by structural tilting during Late Variscan uplift and reactivated by Mesozoic karstification and by Mesozoic/Cenozoic tectonic activity along (Pre-)Variscan faults.

M. & R. Teichmüller (1979) indicated regional updoming of the Moho as a possible heat source. Maybe, we should modify this hypothesis by the assumption that regional ascendence of an igneous mass from the upper mantle into the upper parts of the crust has been propagated by the intersection of NW-SE and SW-NE striking deep fractures (see below).

AGE AND LOCATION OF THERMAL EVENT

As indicated above there are several arguments for the assumption that the high rank coalification in South Limburg is due to a thermal event. And furthermore that the area is suited for continuous or at least repeated heat flow albeit of decreasing importance each time. Accepting the reasoning of Babinecz (1962) as valid, the coalification high must have been established before the Late Variscan uplift. M. & R. Teichmüller (1979) stated that the anomalous coalification also affected the Lower Westphalian B. Most curiously, these authors noted no relationship between coalification intensity and block faulting with the exception of the Oranje Fault (M. & R. Teichmüller, 1971). This proves that this fault played an important part in the coalification process; and thus that it was active prior to the Late Variscan uplift of this area. This confirms the above observations (cf. fig. 3) that the Bordière-Oranje-70 m faults were already active during the (Late) Devonian and Dinantian.

Of equal importance appears the fact that a short-lived heat flow (minimum 450°C) affected this area as shown by the presence of coke-like textures in metabituminite (mesophases) and vitroplast textures in vitrinite of Dinantian age (Wolf & Bless, 1987). Most likely this partial coking of low rank organic material formed the first phase of a gradually becoming less intense heat flow that caused the high rank coalification. This model implies that initial intense heat flow (say 400-450°C) followed by high rank coalification (effective heating temperature 250 to 300°C for top Dinantian in Thermae boreholes at Valkenburg a/d Geul) is dated as post-Early Westphalian B. On the other hand we may assume that initial heating was well before the end of the Westphalian C. Otherwise the burial depth of the top Dinantian would have been more than 2500 m and the corresponding coalification rank would have prevented the partial coking of the bitumen. These arguments lead to the conclusion that a Late Westphalian B to Early Westphalian C age is the most probable one for the initial heating.

The most likely cause for this heat flow seems an igneous intrusion at the position of the Bilzen magnetic high. A basic magmatic body might explain the positive magnetic anomaly as well as the heat flow. The same mechanism had already been proposed for the (much younger) Bramsche Massif. The ascendence of the igneous mass might have been facilitated by the structural weakness of the location with NW-SE and SW-NE striking fault lineaments (fig. 1). The same holds for the Erkelenz magnetic high if we assume a northeastern extension of the 70 m Fault. Such a model presupposes that the NW-SE trending Rur Valley Graben faults are at least partly located on old lineaments, coeval with the SW-NE striking Variscan or Hercynian ones. And this model also implies that the Bordière-Oranje-70 m faults differ from the overthrusts which characterize the thin-skinned tectonics of the Dinant Nappe. These rather would represent deep fractures which

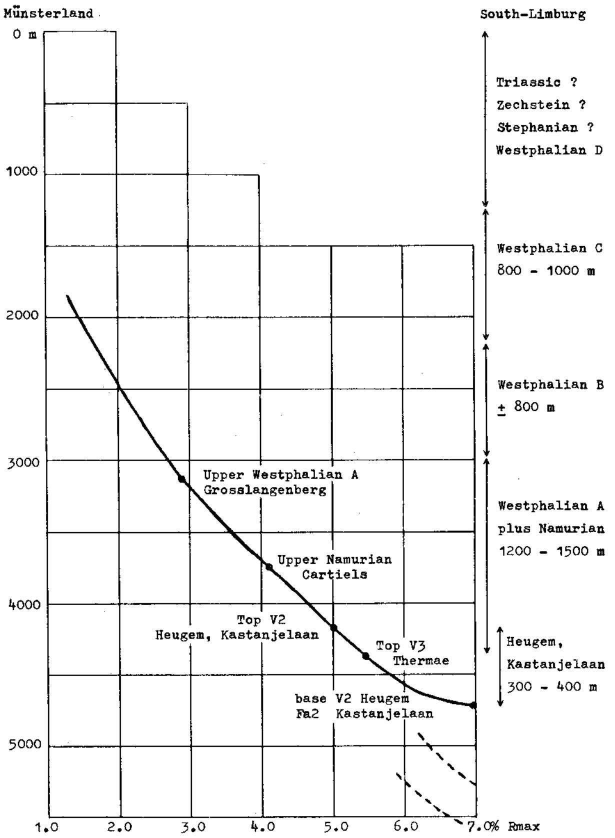

Figure 7

Relationship between (present) burial depth and coalification (in % Rmax) in the Münsterland borehole (NW Germany; after M. Teichmüller, 1982; M. & R. Teichmüller, 1986) compared with coalification rank and thickness of Carboniferous strata in South Limburg. Coalification values and related thicknesses for the Dinantian to Westphalian A strata in South Limburg roughly match those observed for the Upper Namurian in the Münsterland borehole. An open-ended question is the possible thickness and age of the pre-orogenic (= pre-erosion) overburden in South Limburg. According to the available information for South Limburg and environs (Campine, Wurm) the estimated thickness of the overlying Westphalian B-C was some 1600-1800 m. Following the geothermal gradient in the Münsterland borehole there must have been an additional overburden of about 1200-1400 m. It seems unlikely that this was the original thickness of the Westphalian D and Stephanian in this area. This means that either uplift/erosion took place well after the Carboniferous (Permo-Triassic) or that the geothermal gradient in the upper portion of the overburden (Westphalian B and younger) was higher than in the Münsterland borehole. Accepting a Late Variscan (Late Silesian) uplift of the South Limburg Carboniferous the second solution seems the most likely one.

might fit in the subfluence model of Behr (1978) and Weber (1978). Moreover the Bordière-Oranje-70m faults are distinguished from the typical Dinant Nappe overthrusts by their (partial) reactivation during the Late Mesozoic and/or Cenozoic (fig. 9; Legrand, 1968).

M. & R. Teichmüller (1979) suggested a regional updoming of the Moho as as possible heat source. Ascendence of an igneous mass from the upper mantle into the higher parts of the crust may have been propagated by the intersection of NW-SE and SW-NE striking deep fractures.

An alternative possibility is that the Bilzen anomaly might represent the Pre-Silurian magnetic crystalline basement of the Brabant Massif (Bless *et al.,* 1980). But this model doesnot explain the rather consistent coincidence of coalification highs (of different ages!) and positive magnetic anomalies (e.g. East Groningen Massif, Bramsche Massif, Erkelenz High). However, it is not impossible that magma ascended to about the same stratigraphic horizon at Bilzen and Erkelenz. Therefore the here accepted hypothesis of an igneous intrusion doesnot «ipso facto» contradict the model of a possible northeastern extension of the Brabant Massif below South Limburg. On the contrary, the fact that such broad magnetic anomalies are widely extended below the Brabant Massif sensu stricto rather indicates that both ideas may fit in well.

The extremely intense but short-lived initial heating in the South Limburg area was only possible if there was an exceptionally high heat flow. The most indicated heat transport vehicle may have been a salt dome or piercement. The presence of Devono-Dinantian evaporites below South Limburg has been assumed earlier (Bless *et al.,* 1980) and was partially demonstrated by the Heugem borehole at Maastricht (Bless *et al.,* 1981).

SYNTHESIS

The above described geological features are summarized in a synthetic N-S cross section through the Pre-Permian of South Limburg (fig. 10). This section displays a major uplift between the Dinant Nappe in the south and the Rur Valley Graben in the north. The central axis of this uplifted structure is formed by the Bordière-Antiklinaal-Oranje lineament that marks the crest of the Visé-Puth and Waubach uplifts. This lineament was reactivated during the Late Mesozoic and/or Cenozoic.

Further to the north the Bordière-70 m lineament separates the Bilzen magnetic high and a broad gravity low where thermal events resulted in a coalification high before the Late Variscan uplift, in hydrothermal precipitation of sulfide ores prior to the Late Cretaceous inversion, and in anomalous rock temperature and «warm» water wells today.

This peculiar geological setting may be interpreted in different ways. A deep seismic profile across South Limburg might yield a solution for the following problems :

- Nature (presence of evaporites ?) and thickness of (block-faulted or thrust-faulted ?) Devono-Dinantian sedimentary sequence (comparable to that of the Epinoy/St.-Ghislain Trough in SW Belgium and N France ?),

- Position of top Cambro-Silurian rocks (is there a concealed eastern extension of the Brabant Massif below South Limburg ?),
- Nature of magnetic anomaly (Variscan basic intrusion or Pre-Silurian magnetite-bearing sedimentary or crystalline basement ?),
- Geometry of SW-NE structures (shallow overthrusts belonging to imbricate thrust front of Dinant Nappe or deep thrust fault passing into deep seismic reflector below Midi thrust plane ?),
- Actual and Variscan depth of Moho (did a possible Paleozoic updoming of the Moho leave a «scar» in the basement ?).

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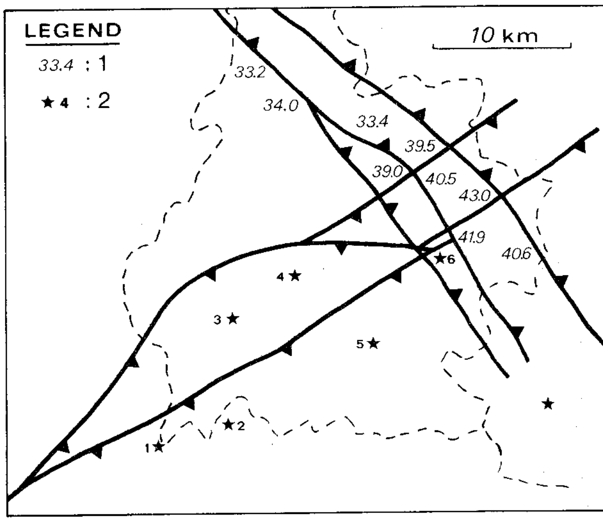

Figure 8
Rock temperatures at -749 m NAP in former coal-mining area of South Limburg (after Sadée, 1975) and occurrence of «warm» water wells. A selection is presented of maximum rock temperatures as calculated from Sadée's isothermal map. These show relatively low values in the north (maximum between 33.2 and 34.0°C, minimum between 31.0 and 32.6°C), but rather high ones around the 70 m Fault and Oranje Fault (maximum between 39.0 and 43.0°C, minimum between 34.2 and 36.1°C). «Warm» water wells apparently occur only south of the Bordière-70 m Fault. The term «warm» is a relative one. Locations 1, 3 and 5 are surface springs with water of 14°C. Locations 2, 4 and 6 yield thermal water with a temperature that normally should be expected at greater depth. The thermal water of Aachen is indicated but not numbered.

1: selected maximum temperature based on isotherms of Sadée (1975). Data calculated for -749 m NAP. 2: «warm» water wells (1 = De Schans, surface temperature of spring 14°C; 2 = 's-Gravenvoeren borehole, 38°C at 865 m bore depth; 3 = «Fontein» at Cadier-en-Keer, surface temperature of spring 14°C; 4 = Thermae 2000/2002 boreholes, 24.5°C at 375 m bore depth; 5 = Wittem castle, surface temperature of spring 14°C; 6 = former Oranje-Nassau-I coal mine, sulfur-rich spring with temperature of more than 50°C some 250 m below surface).

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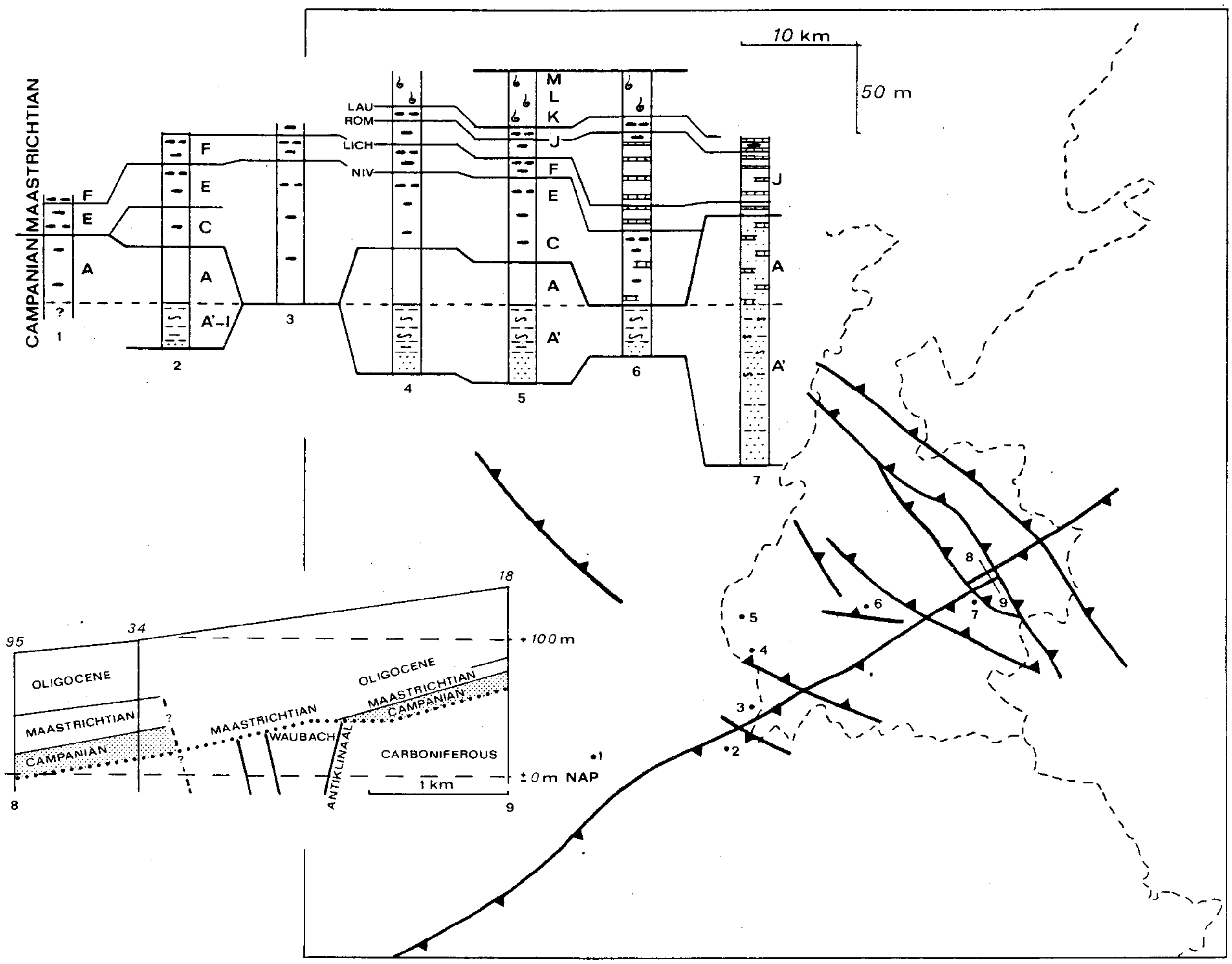

Figure 9.- Influence of Late Cretaceous inversion tectonics on sedimentation. Differential compensating rates of subsidence resulted in comparable total thicknesses for Campanian-Maastrichtian sediments, notably for the interval of foram zones A-J. Increased thickness of Upper Maastrichtian foram zones C-E at Lixhe (section 3) compensates absence of Lower/Upper Campanian deposits. Increased thickness of Upper Maastrichtian foram zone J in Thermae boreholes (section 6) compensates absence of Upper Campanian. Absence of foram zone C in Diets-Heur (section 1) is compensated by an increased thickness of Upper Campanian deposits. Absence of foram zones C-E in Kunrade area (section 7) is compensated by extreme thickness of Campanian and of foram zone J. Note that Campanian deposits near the Rur Valley Graben are sandier than those farther to the WSW. This suggests that the Rur Valley area acted as clastic source during that period. Upper Maastrichtian sediments near the Rur Valley area (foram zones C-J) are marked by frequent hard limestone intercalations, whereas sections to the WSW are characterized by flint layers. The youngest Upper Maastrichtian strata (foram zones K-M) consist predominantly of rather coarse-grained biocalcarenites.

Sections 1: Diets-Heur; 2: Halembaye; 3: Lixhe; 4: ENCI; 5: Kastanjelaan; 6: Thermae; 7: Kunrade.

Differential block movements along Bordière-Oranje faults are shown in section 8-9. This section is based on exploration boreholes 18, 34 and 95, and on numerous upward-directed boreholes made in the former coalmines for recognition of the Carboniferous subcrop (after Kimpe *et al.* 1978). This means that Late Cretaceous/Cenozoic block movements not only occurred along NW-SE directed border faults of the Rur Valley Graben, but also along at least the eastern end of the SW-NE directed Bordière-Oranje faults bordering the Brabant Massif. This matches the observations of Legrand (1968, p. 145) who stated that the Bordière Fault was reactivated during the Mesozoic and Tertiary which resulted in vertical throws in the order of «one to several tens of metres».

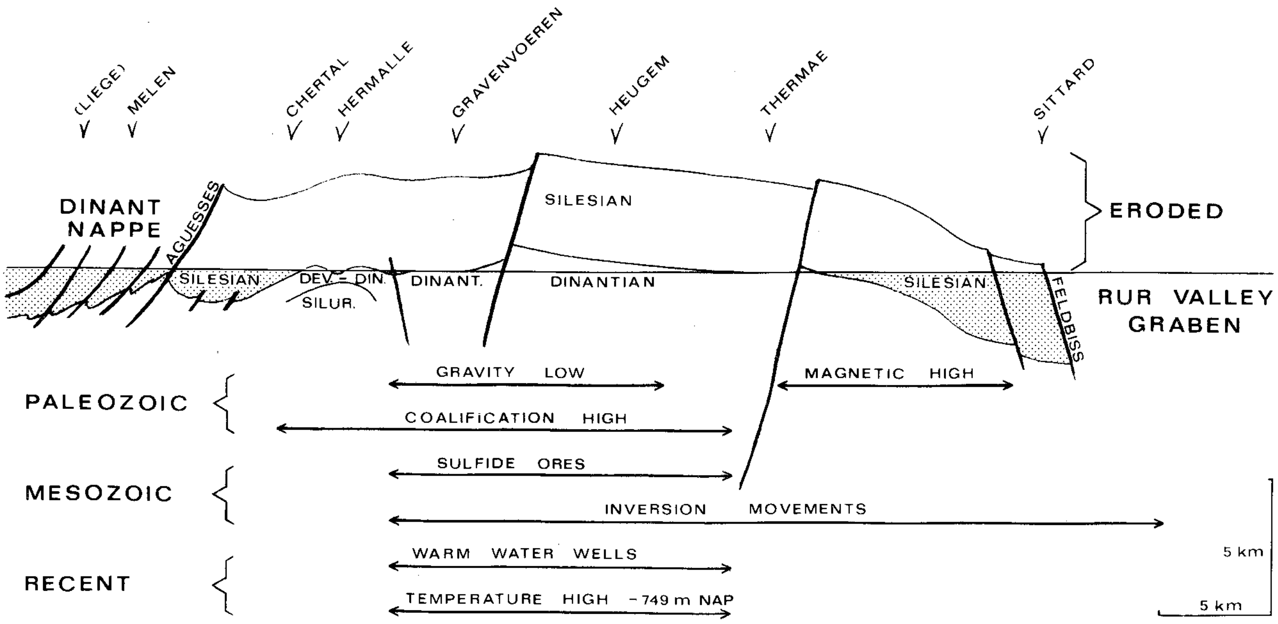

Figure 10.- Summary of anomalies in South Limburg (SE Netherlands).
Note that area of maximum uplift/erosion between Hermalle and Thermae boreholes was area of maximum subsidence during (Late) Devonian and Dinantian. It is there where most anomalies occur. A possible eastern extension of the Brabant Massif should be located at the position of the magnetic high.

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