

The character of the Erkelenz intrusive as derived from geophysical data

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Received 25 January 1989; accepted in revised form 23 May 1989

Key words: Erkelenz, Roer valley graben, intrusive, geothermal potential, gravity stripping

Abstract

In the framework of the first National Research Program for Geothermal Energy in The Netherlands, geophysical measurements were performed in an area in the Dutch province of Limburg and the adjacent part of Germany, covering the Erkelenz intrusive.

Surface magnetic data confirm the magnetic anomaly known from the German magnetic maps. That anomaly had been interpreted by Bosum (1965) to be caused by a huge intrusive of basic composition (the Erkelenz intrusive). The gravity data, those at the surface as well as those measured in the Sophia Jacoba colliery, do not show a big anomaly. This agrees better with an intrusive of acid than one of basic composition and it means that relatively high temperatures can still be expected due to radio-active heat production. The existence of high temperatures in the past could be proven by analysis of rock samples from the colliery. For recent high temperatures there are a few indications.

Introduction

One of the objectives of the Dutch Research Program for Geothermal Energy was to investigate the possibility that unusually high temperatures occur anywhere in the subsurface of The Netherlands. Since in the Province of Limburg there is an unexplained discrepancy between the gravity map (Van Weelden, 1957) and the magnetic map (Veldkamp, 1951), i.e. the contours of the gravity map parallel the major NW-SE fault direction while the magnetic contours do not, the existence of deep structures that could be associated with high temperatures was not unlikely. It is true that for The Netherlands the maps of subsurface temperatures (Commission of the European Community, 1980) do not show any significant anomaly at depths below 2000 m, but it must be realised that for the southern part of the country only a few deep wells were available to prepare these maps.

It was therefore decided to start a detailed gravimetric and magnetometric survey in this area. Measurements in Germany were also performed, since in the adjacent German area near Erkelenz, a magnetic anomaly was known to exist (Reich, 1926). That anomaly had been interpreted by Bosum (1965) as being caused by a huge basic intrusive. His interpretation was supported by Teichmueller & Teichmueller (1971). They explained the high rank of coalification in the area by the elevated temperatures caused by the intrusive. Later also Wrede (1985) adopted this hypothesis.

In addition to the gravimetric and magnetometric survey other geophysical measurements were performed and the complete research program consisted of:

1. magnetometric measurements in Central-Limburg and surrounding area;
2. gravimetric measurements in Central-Limburg and surrounding area;



Fig. 1. Location of survey area.

3. subsurface gravity measurements in the Sophia Jacoba colliery;
4. determination of densities and susceptibilities of cores from boreholes and of samples collected in the Sophia Jacoba colliery;
5. determination of paleo-temperatures.

The total area investigated is indicated in Fig. 1 by broken lines.

Geological setting and densities

The geology of the deeper subsurface in the Roer valley graben (Roerdal slenk) is poorly known. The well Straeten, in the eastern part of the area, was described by Fabian (1958), and the well Nederweert, to the north-west of the area, was published in the Stratigraphic Nomenclator of The Netherlands (NAM & RGD, 1980). In Straeten the Cretaceous directly overlies the Carboniferous at a depth of 1291 m. In Nederweert a 980 m thick series of rocks, mainly belonging to the Bunter Group, is encountered between Cretaceous and Carboniferous (for location see Fig. 2).

The geology of South-Limburg and of the Peel

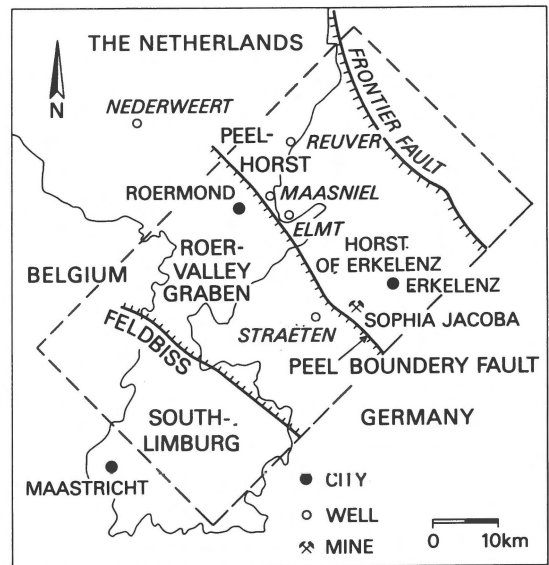


Fig. 2. Survey area (within broken lines), with major faults and location of wells.

horst and the horst of Erkelenz on the contrary is very well known, as a result of the exploration for and the exploitation of coal. The general picture is a system of NW-SE striking normal faults. The major faults are the Feldbiss and the Peel boundary fault (Peelrand breuk) and they constitute the SW and NE limits of the Roer valley graben, which by some authors is called Central Graben (see Fig. 2). A third important fault is the Frontier fault (Grensbreuk).

Many publications on this subject are available (Thiadens, 1963; Patijn, 1963; Patijn & Kimpe, 1961; Peelcommissie, 1963; Herbst, 1971; Teichmueller & Teichmueller, 1971; Kimpe, 1973; Heijbroek, 1974; Wrede, 1985).

For the interpretation of the gravity data the densities of the different geological formations are required. They were obtained as follows:

a. Literature.

Measurements of densities in this area, mainly of Carboniferous rocks, are reported by a few authors (Van Gemert, 1939; De Sitter et al., 1949; Karrenberg & Meinicke, 1962; Duerbaum & Wolff, 1958; Bless et al., 1980).

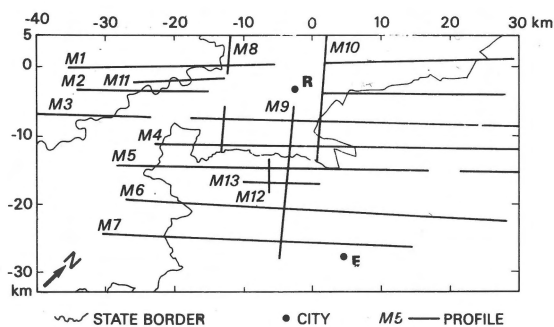


Fig. 3. Location of the magnetic measurements along profiles M1–M13. N.B.: this and the following maps have been rotated. R = Roermond; E = Erkelenz.

b. Unpublished data.

Density data of the Carboniferous in South-Limburg were put at my disposal by Dr. J. Stuffken of DSM. The average density of 105 samples was 2674 kg m^{-3} .

c. Measurements on cores.

The densities of 80 cores from the wells Nederweert, Veldhoven, Meyel, Gulpen, Woensdrecht, Swalmen and Meynweg (all located in the vicinity of the research area) were measured. Corrections were applied for the fact that the cores are dry.

d. Sonic logs.

In the area no density logs had ever been run in wells. For only two wells (Straeten and Nederweert) sonic logs are available. Using the empirical relation $\rho = C \cdot v^{0.25}$ (Gardner et al. 1974) the acoustic wave velocity v can be converted into the density ρ . For the constant C Gardner found the numerical average value 310 (v in ms^{-1} and ρ in kg m^{-3}). For the well Nederweert we could compare densities measured on cores with the sonic log. As best values for C we found: limestones and compact sandstones 300, shales (low densities) 316, shales (high densities) 330, dolomite 311. Having determined the factor C in this way, we could calculate the densities at depths where no cores were available from the sonic log for the well Straeten and the well Nederweert.

e. Samples from the German Sophia Jacoba colliery.

Using 60 fresh samples collected in the mine, the average density of the Carboniferous could be accurately determined. It turned out to be 2681 kg m^{-3} , not taking into account the coal seams. A few samples, from just underneath a coal seam, showed an extremely high density up to 3500 kg m^{-3} . Geochemical analysis showed this to be due to a high content of siderite. We will return to this later.

All the old and new data together led to the following scheme for the densities (in kg m^{-3}).

- Upper Oligocene and younger: 2050
- Lower Oligocene, Eocene and Paleocene: 2200
- Cretaceous: South-Limburg: 2100–2300
Roer valley graben: 2450
Peel horst and Erkelenz: 2300
- Jurassic + Keuper (only in Roer valley graben): 2300
- Muschelkalk + Bunter: in Roer valley graben: 2540
- Bunter + Perm: In South-Limburg and on the Peel horst: 2450
- Carboniferous and older: everywhere: 2670

Magnetometric data and their interpretation

The measurements of the total field were performed with a proton magnetometer, with an accuracy of 1 nT. By continuously recording the earth's magnetic field at a fixed base station, corrections for the diurnal variation and other temporal variations of the field could be applied. Due to the proximity of built-up areas and the presence of high-voltage powerlines and electric railways (DC!), the accuracy of the final results is not better than 5 nT for most locations and even 10 nT at a few locations.

Measurements were made in 1979 at 1300 locations, the majority with a spacing of 400 m along 13 profile lines (see Fig. 3). In the vicinity of the intersection of the profiles M7 and M9 measurements were made between the profiles at an additional 40 stations, on average 1 km apart, to locate the maximum of the anomaly more precisely. Railways, powerlines, cities and industrial causes of

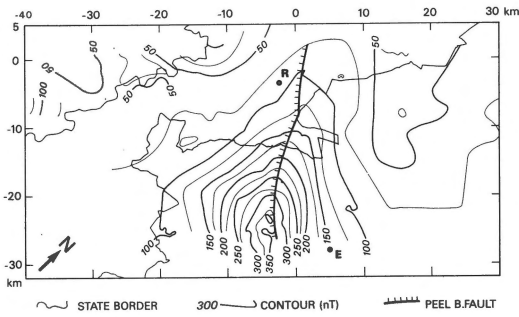


Fig. 4. Contour map of measured magnetic anomaly (total field).

disturbances prevented a more regular pattern of survey lines.

The correction for the normal field was performed using the international reference field WC 80 (World Chart 1980, published by the Defence Mapping Agency Hydrographic Center). The anomalies are shown in the contour map depicted in Fig. 4. A maximum of 350 nT appears, situated close to the Peel boundary fault, 8 km SW of Erkelenz in Germany. Fig. 5 shows the results along the profile line M6.

The anomaly in Germany also appears on the German aeromagnetic map (Bundesanstalt, 1976). On this map an anomaly of 225 nT appears SW of Erkelenz. The differences between our results and this aeromagnetic map (both in magnitude and in location of the anomaly) are due to the fact that the aeromagnetic data were measured at a higher level, and that a different reference field was used. Our data confirm the aeromagnetic map and show how the anomaly continues in the Netherlands. It is this anomaly that causes the discrepancy between the magnetic and the gravity map, as described in the introduction.

As mentioned before, the magnetic anomaly had been studied already by Bosum (1965). His interpretation was based upon measurements of the vertical component of the magnetic field. Bosum comes to the conclusion that the anomaly can best be explained by a big, deep-lying intrusive of large extent, probably consisting of basic rock. The horizontal extent of the intrusive is depicted in Fig. 6. Its upper surface is lying at a depth of about 3000 m

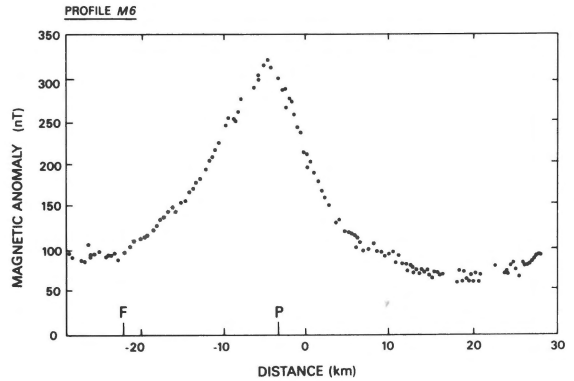


Fig. 5. Magnetic anomaly of profile M6. The positions of the Peel boundary fault and the Feldbiss are indicated by P and F, respectively.

at the centre and at a depth of about 5000 m near the flanks (see also the vertical cross section A-A' in Fig. 13). The bottom extends between 11 and 15 km.

Since our measurements are in agreement with the German magnetic maps, we did not repeat the model calculations. It can be expected that the intrusive as postulated by Bosum also yields a fair description of our additional data. It should be stressed, however, that this rather artificial model is not the only one that can explain the anomaly. There are many other possibilities.

Let us consider the possibility of a much smaller intrusive, consisting of rock with a much higher susceptibility. Bosum needed a susceptibility $k =$

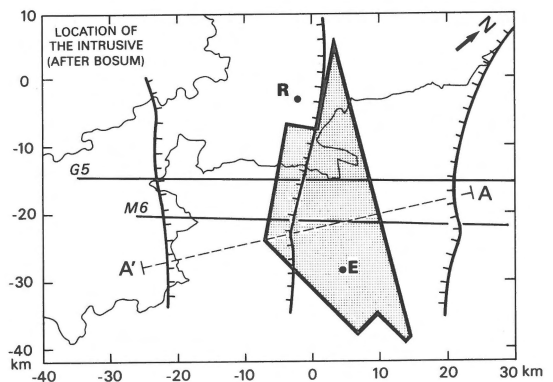


Fig. 6. Location of the assumed intrusive (after Bosum). Cross section A-A' is shown in Fig. 13.

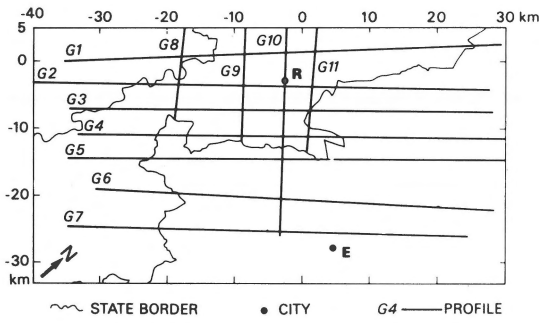


Fig. 7. Location of the gravity measurements along profiles G1–G11.

2.5×10^{-2} (SI-units) for the intrusive to explain the anomaly. According to the relation $k = 0.0361 \times V$, derived by Mooney & Bleifuss (1953), this corresponds with a magnetite content $V = 0.7$ volume percent. Even with a maximum magnetite content of the intrusive rock as high as 7 volume percent, the minimum rock volume required to explain the anomaly, is still one tenth the volume of Bosums intrusive.

Therefore, the anomaly can not be explained by rocks of high susceptibility that are scattered over a large area, at shallow depths down to a few kilometres. It is true that ores have been found in the area, but no occurrence of magnetic minerals is mentioned in the literature (Herbst & Stadler, 1971). We found siderite in the rock samples we collected in the Sophia Jacoba colliery. Measurements in the laboratory revealed that these rocks have, at most, a susceptibility of 0.30×10^{-2} (SI-units). This is nearly 10 times less than the susceptibility that Bosum used for his intrusive. Siderite can therefore not be responsible for the observed anomaly.

Gravity data and their interpretation

The measurements were performed with Worden gravity meters. The total number of stations was 3250, the majority of them lying on the profile lines G1–G11, with a spacing of 300 m (see Fig. 7). The area between the profiles was for the greater part filled with one station per km^2 . Elevations of the

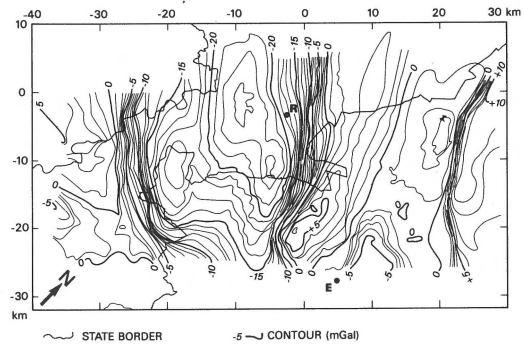


Fig. 8. Bouguer anomaly map of the gravity. Contour interval 1 mGal.

stations were determined from 1:10 000 and occasionally from 1:25 000 topographic maps, giving an accuracy of 0.3 and 0.5 m respectively. For the Free air and Bouguer correction together 0.222 mGal per m was used (density 2050 kg m^{-3}). Topographic corrections were not applied, because the area is nearly flat.

For every station the anomaly was obtained by subtracting from the corrected measurement the Chebycheff approximation of the normal field, adopted in 1967 by IUGG (IAG, 1971). The anomalies thus obtained are depicted as contour map in Fig. 8. This contour map gives a good picture of the overall geological situation: a minimum in the Roer valley graben, flanked by positive values in South-Limburg and on the Peel horst and horst of Erkelenz.

The concentrations of contours indicate the position of the major faults: the Feldbiss in the southwest, the Peel boundary fault northnortheast of the graben and the Frontier fault even more to the northeast. Also on the profiles this structure is clearly visible. See for instance Fig. 9. Assuming that Bosums interpretation of the magnetic anomaly is correct, i.e. that a huge basic intrusive is present, we can also expect a positive gravity anomaly, because basic rocks have a relatively high density ($2900\text{--}3300 \text{ kg m}^{-3}$).

Due to the proximity of the Roer valley graben, the Peel horst, the horst of Erkelenz and their associated faults, one can not immediately conclude from the Bouguer map whether a gravity anomaly (caused by the intrusive) exists at the ex-

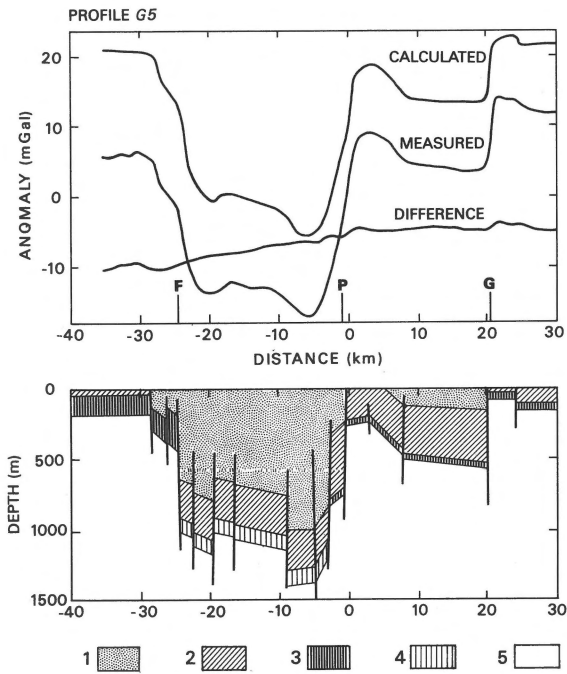


Fig. 9. Lower part: Model of the geological section of profile G5. Carboniferous is indicated by 5, Cretaceous + Jurassic + Triassic in the Roer valley graben by 4, Cretaceous on the horsts by 3, Tertiary (lower Oligocene and older) by 2, Tertiary (upper Oligocene and younger) by 1. All 5 units have different densities, and unit 4 is even subdivided.

Upper part: Gravity anomaly of profile G5. Values calculated for the model and measured values are shown, together with the difference between both. For the sake of clearness the curves have been shifted vertically. The scale on the vertical axis is therefore only relative. F, P and G are the locations of the faults: Feldbiss, Peel boundary fault, and Frontier fault, respectively.

pected position, however. Therefore we proceeded as follows: For each of the profiles G1–G7 we constructed a realistic 2-dimensional model of the subsurface, down to the top Carboniferous. These models are in agreement with all available geological data. Using the right densities for the various geological formations the gravity anomaly belonging to each model was calculated, according to the method of Talwani et al. (1959). The model for profile G5 is shown in Fig. 9, together with the result of the calculations. On this profile the difference between measured and calculated anomaly (which we will call ‘difference anomaly’) changes by about 5 mGal from SW to NE. This must be caused by unknown structures, lying below the top

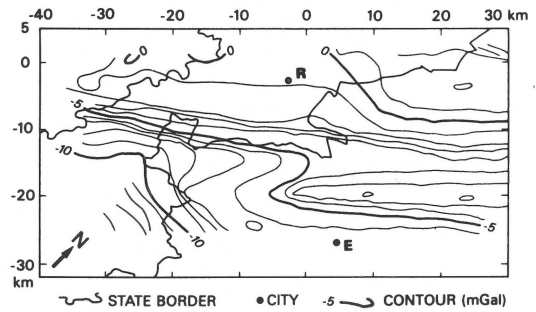


Fig. 10. Contour map of the ‘difference anomaly’. The effect of known geological structures has been removed from the Bouguer map.

Carboniferous and therefore not included in the model, or by a regional trend. The difference anomalies, obtained by this so called gravity stripping on all seven parallel profiles, are plotted as contour map in Fig. 10. It is evident that a considerable regional trend still remains in this map. We chose as the regional the trend shown in Fig. 11, which is very simple in order to avoid including therein the effect of the assumed intrusive. By subtracting this regional field from the difference anomalies of Fig. 10, we obtained the ‘residual anomalies’ shown in Fig. 12. These ‘residual anomalies’ are anomalies from which the effect of known geological structures and the regional trend have been removed. They can therefore indicate unknown geological structures, which were not included in the model.

The most striking feature of the residual anomalies obtained is their smallness: no more than 3.5 mGal, the absolute maximum lying slightly NW of Erkelenz. The question arises whether this anomaly can be caused by an intrusive of the dimensions postulated by Bosum. To answer this question we did a 2-dimensional model calculation for a SW-NE running line over the top of the intrusive (line A’-A of Fig. 6). For the density we took 3030 kg m^{-3} , that is 360 more than the 2670 of the surrounding rock. The result is shown in Fig. 13. The maximum anomaly turns out to be about 65 mGal. Although the map of residual anomalies (Fig. 12) was obtained by 2-dimensional modelling along parallel lines (resulting sometimes in artefacts in the map) and although the intrusive was

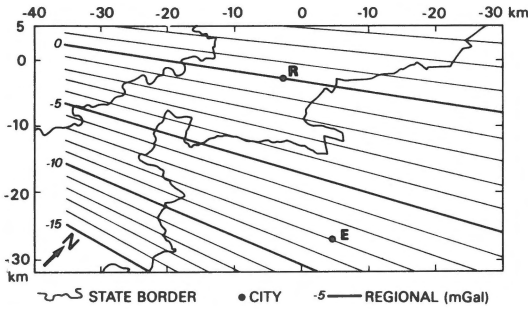


Fig. 11. Assumed regional trend of the gravity field.

approximated in the calculations by a 2-dimensional body (which is a rather crude approximation) it is evident that the maximum residual anomaly of Fig. 12 (3.5 mGal) is not compatible with the calculated 65 mGal resulting from Bosum's model assuming a density contrast of 360 kg m^{-3} .

Three conclusions are possible:

1. The intrusive has the dimensions as postulated by Bosum and it contains sufficient magnetic minerals to cause the observed magnetic anomaly, but it is composed of *acidic* rather than basic rock. This must be so because its density can not be higher than 2700 kg m^{-3} to still be in agreement with the observed gravity anomaly (basic rock would have a density of 3000 kg m^{-3} or higher). The advantage with respect to geothermal applications could be

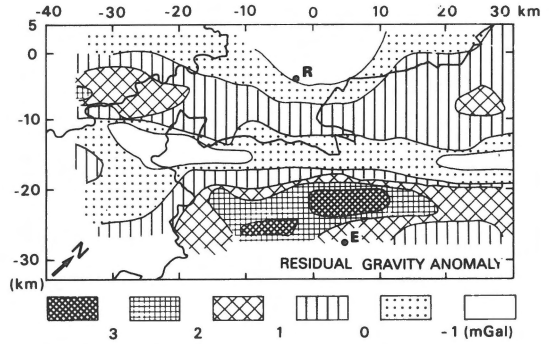


Fig. 12. The residual gravity anomaly. The effect of known geological structures and the regional trend have been removed from the Bouguer map.

that the intrusive is at a higher temperature than its surrounding, due to the radio-active heat production expected in acidic rock. A basic intrusive would have already cooled down completely.

2. The intrusive is of a swarm type, i.e. magma of basic composition containing a great amount of magnetite, and has intruded as small gangs into an area of the same size and volume as Bosum's intrusive (Bartenstein & Teichmueller, 1974). This explains the magnetic anomaly. Due to its small total volume (as mentioned earlier, one tenth of the volume of Bosum's intrusive could be sufficient) the intruded magma doesn't cause an appreciable gravity anomaly, in spite of its high density. However, the high grade of coalification can in that case not easily be explained by the intrusive, because the amount of heat is then also ten times smaller.

3. There is no intrusive at all. This is very unlikely, because there is no evidence of another source of the magnetic anomaly. Moreover, there is no other plausible explanation for the coalification anomaly (Wrede, 1985, p. 30).

In our opinion the first possibility, i.e. a big intrusive of acid composition, is the most likely.

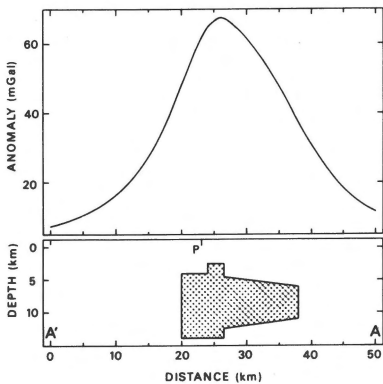


Fig. 13. Lower part: Vertical cross section of Bosum's intrusive along line A'-A (see Fig. 6). P is position of Peel boundary fault. Upper part: Calculated gravity anomaly for this intrusive, assuming a density of 3030 kg m^{-3} for the intrusive and of 2670 kg m^{-3} for the surrounding rock.

Subsurface gravity measurements

As an independent check on the existence of a gravity anomaly, subsurface gravity measurements were performed in the Sophia Jacoba colliery.

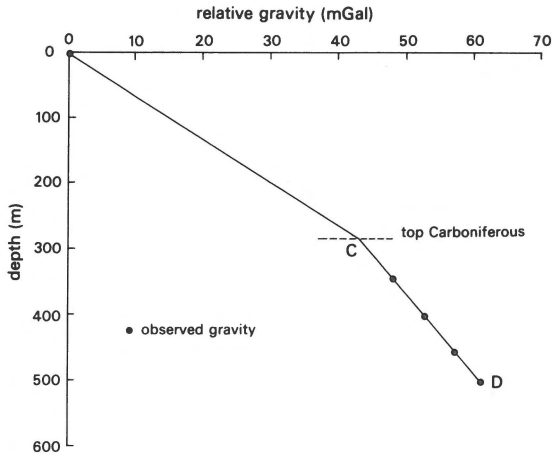


Fig. 14. Relative gravity values at the surface and at four depths below the surface, all at the same horizontal position. From the slope of line CD the *apparent density* of the Carboniferous is calculated.

If the density of the rocks is a well known function of depth only, then the gravity variation as a function of depth can be calculated. Inversely one can, if gravity has been measured as a function of depth, calculate the density of the rocks penetrated, under the assumption that the density does not vary laterally. When, however, at a greater depth underneath the gravity stations there is an intrusive of high density, then the above statement does not hold any more. The *apparent density* determined from the vertical gradient of the gravity will then be different from the true density. This is so, because going deeper one comes closer to the anomalous mass, which results in an extra increase of the measured gravity value.

For 5 horizontal locations gravity measurements were made in the Sophia Jacoba colliery, each time at 4 stations lying nearly on a vertical line. Measurements were also made at the surface. The measurements were corrected for the surface topography, the effect of known geological structures and the effect of coal seams and of the galleries. Fig. 14 gives an example of the results for one location. For every location the apparent density of the Carboniferous rocks is determined from the measured gravity gradient, taking into account a free-air effect of .3086 mGal per m. The average

value found for all five stations is $2678 \pm 20 \text{ kg m}^{-3}$. This is not significantly different from the result obtained by direct density determinations on samples from the same colliery which yielded a value of $2681 \pm 3 \text{ kg m}^{-3}$. A 2-dimensional calculation of the vertical gradient of gravity for Bosum's intrusive with a density of 3030 kg m^{-3} on the other hand results in an expected value of 2580 kg m^{-3} for the apparent density of the Carboniferous.

Again the conclusion is that there is no indication of a big intrusive with a density over 2670 kg m^{-3} .

Subsurface temperatures

The high degree of coalification in the area is an indication for high temperatures in the past. The region of the highest coalification grades corresponds with the location of the shallowest part of Bosum's intrusive. (Teichmueller & Teichmueller, 1971). We did a few investigations concerning the temperatures.

Some of the samples collected in the coal mine Sophia Jacoba (from a depth of 750 m below the surface) contain quartz veins in which fluid inclusions can be observed. By studying in the laboratory the phase transition in these inclusions while heating the samples, it could be established that these samples must once have been at a temperature of 204°C . This temperature is much higher than that which corresponds to the present depth and also with the depth of burial in the past (no more than 2 km). It is therefore an independent indication of the existence of the intrusive.

Also tracks of damage in the crystal lattice of the minerals, caused by fission products of instable isotopes, have been used to study the thermal history of the samples. Above a certain temperature (characteristic for each mineral) the lattice will repair itself, but after cooling below that temperature, all later tracks will survive. It can be determined in this way how long ago the sample cooled to below the characteristic temperature. Two samples from depths of 750 and 500 m indicated a time of cooling below 95°C of 90×10^6 and 105×10^6 years ago respectively. This means that the supposed intrusion must have taken place before that

time, so during the lower Cretaceous or earlier. This is in agreement with the opinion of others who place the intrusion in Permo-Carboniferous time (Teichmueller & Teichmueller, 1971 and Wrede, 1985).

Little information is available about recent temperatures in this area. Kimpe (1963, 1973) and Balke (1973) report slightly elevated temperatures, but these are probably due to groundwater locally ascending along faults. The following Carboniferous geothermal gradients are reported by other investigators:

South		
Limburg	37° C km ⁻¹	(De Braaf & Maas 1952, Sadee 1975)
Well Reuver	37° C km ⁻¹	(Peelcommissie, 1963)
Well Maasniel	45° C km ⁻¹	(Peelcommissie, 1963)
Well Elmpt	45° C km ⁻¹	(Peelcommissie, 1963)
Sophia Jacoba	46° C km ⁻¹	

We see that on the Peel horst (Maasniel and Elmpt) and the Erkelenz horst (Sophia Jacoba) the gradient is higher than to the north (Reuver) and to the south (South Limburg). Provided that the heat conductivity of the Carboniferous is the same at all locations, this means that there still exists an increased heat flow above the intrusive. Because of its usually higher concentration of radio active elements an intrusive of acidic composition is more likely to show this increased heat flow than an intrusive of basic composition.

(Temperature data of the Sophia Jacoba colliery were kindly made available by Markscheider W. Born).

Conclusions

The existence of an intrusive underneath the Peel boundary fault is indicated by:

- a magnetic anomaly extending also into the Netherlands
- high grade of coalification
- high paleo temperatures

The time of intrusion must be Early Cretaceous or before.

Since no gravity anomaly is observed, this supposed intrusive must be of acidic composition and may contain radio active elements resulting in elevated temperatures even at present. The observed high temperature gradients in the Carboniferous are in favour of this possibility.

In connection with this it should be mentioned that seismic investigations executed in this area (reflection as well as refraction surveys) did not give any indications of an intrusive (Querfurth 1974). This also favours the supposed intrusive being *acidic*, because its seismic velocity nor its seismic impedance will in that case be very different from those of the overlying Carboniferous rock. We found 2670 kg m⁻³ for the density of the Carboniferous, while velocities over 5000 ms⁻¹ are reported by Fabian (1958) and Duerbaum & Wolff (1958), numbers that can also be expected for acidic rock. A *basic* intrusive would show different seismic characteristics: a density of about 3000 kg m⁻³ and a velocity of more than 6000 ms⁻¹. Basic rock is therefore more likely to be observed with seismic methods than acidic rock.

Acknowledgement

The research described in this paper has been made possible by financial support from the Dutch Ministry of Economic Affairs and the European Community. A great number of geophysics students participated in the field measurements. Among them A.D. de Jager deserves special mention because he also coordinated the activities of the other students and was responsible for the reduction of the surface gravity and magnetometric data.

I am grateful to Professor Schuiling of the Department of geochemistry and Professor Zijderveld of the Paleomagnetic Laboratory of the Instituut voor Aardwetenschappen in Utrecht for taking care of the geochemical and magnetic investigations on the samples.

The kind cooperation of many persons and authorities was appreciated particularly. I mention: the Dutch Geological Survey (RGD), Dr. Quer-

further of the Geological Survey of Nordrhein Westfalen, the management of the Sophia Jacoba colliery for the permission to work in the mine, and Dr. Bless, former director of the Geological Office in Heerlen.

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