AN INTERPRETATION MODEL OF SEMI-CIRCULAR BOUGUER ANOMALIES FOUND OVER THE PERIPHERAL BELT OF THE ORDENES COMPLEX (NW SPAIN)[1]

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ABSTRACT

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A gravity survey of the peripheral belt of the Ordenes complex in Galicia (NW Spain) has been combined with a little used, although known, interpretation method. From the results of the survey and geological evidence, support was found for the hypothesis that the peripheral belt could be subdivided into separate units of shallow buried, but deep-reaching bodies of high-grade ultramafic material, which appear to have their origin in diapiric movements of upper-mantle material into a crystalline lower crust of continental type.

The depth of the western body, projected underneath the high-grade metamorphic complex of Santiago de Compostela, is computed at a depth of 780 metres, while the bodies of the complexes of Sobrado-Teijeiro and Mellid are computed at a depth of 550 metres and 150 metres, respectively. The semi-circular outline of all three Bouguer anomalies suggested diapiric structures comparative to salt-domes, which have been interpreted using a three-dimensional method.

INTRODUCTION

The peripheral belt of the Ordenes complex, located mainly in the province of La Coruña (NW Spain) was, until recently, regarded as a tectonic unit consisting of a series of high-grade metamorphic rocks bounded by several major faults. These faults, which give the complex a sub-circular outline, are assumed to be deep-reaching (HUBREGTSE, 1973).

High-grade mafic and ultramafic rocks occur in the tectonic unit along the inner side of the boundary. Fault-bounded complexes elsewhere in Galicia contain similar rocks (Fig. 1; see also ARPS ET AL., 1977).

VAN ZUUREN (1969) and HUBREGTSE (1973) suggested a subdivision of the peripheral belt into separate units, i.e. the complex of Santiago de Compostela, the Mellid complex and the complex of Sobrado-Teijeiro.

This paper deals with three diverging geological hypotheses concerning the origin of the peripheral belt:

1) the complexes, consisting mainly of mafic material, are considered to be parts of the crystalline basement, upthrusted along peripheral thrustfaults and blastomylonitic zones (DEN TEX, 1966);

(2) the complexes have their origin in diapiric movements of upper-mantle material (MAASKANT, 1970; KEASBERRY ET AL., 1976; VAN CALSTEREN, 1977-a,b); and

(3) the Ordenes complex and other high-grade complexes are regarded as erosion remnants (klippen) of a large Variscan nappe structure (RIES & SHACKLETON, 1971).

Between the first two hypotheses a justifiable choice cannot easily be made on geophysical evidence. Structural, petrological and geochemical information (MAASKANT, 1970; VAN CALSTEREN, 1977-a,b; VAN ZUUREN, 1969) has resulted in a preference for the second hypothesis. The purpose of this gravity survey was to test the validity of these hypotheses.

The unit of the mafic and ultramafic rocks found in the peripheral belt has a higher density than the surrounding metasedimentary and granitic rocks in- and outside the complexes. Standard two-dimensional interpretation, e.g. by comparing the observed profiles with standard curves or by the method of HUBBERT (1948) was not done, mainly because a two-dimensional interpretation can never fully cover the obviously three-dimensional outlines of the anomalies. An al-

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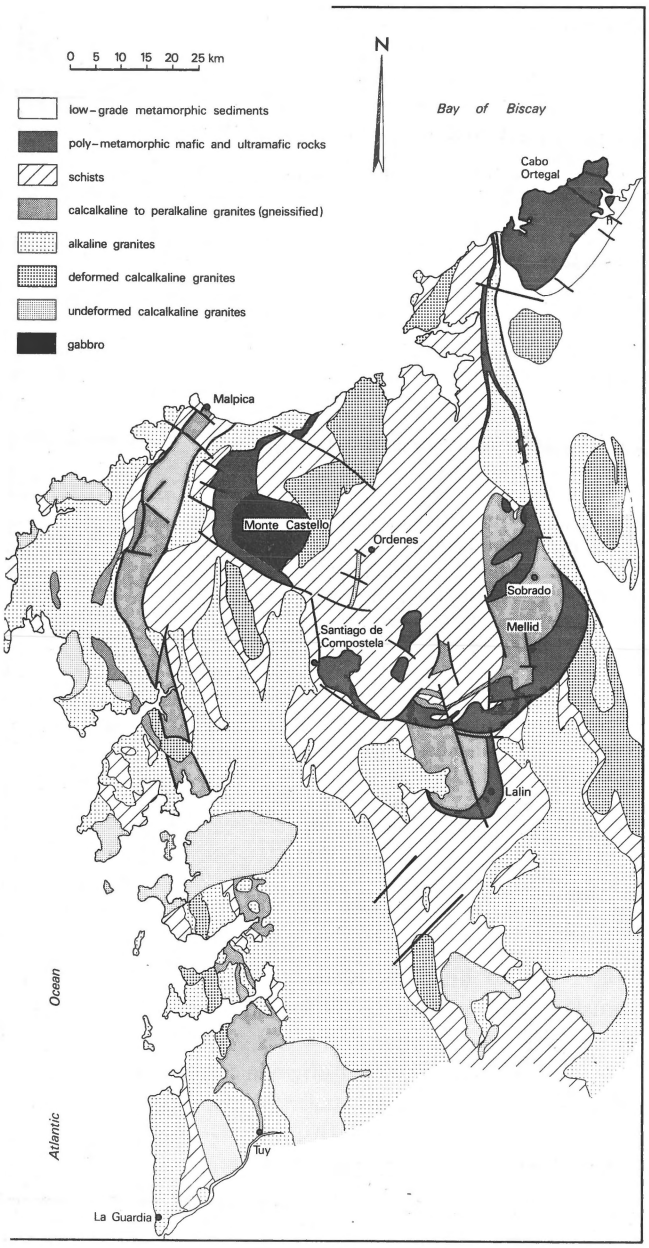

Fig. 1
Index map of the northwestern part of the Variscan orogen of the Iberian peninsula (from Van Calsteren, 1977-b).

ternative was found in using three-dimensional models as defined by NETTLETON (1942) and ROMBERG (1958).

Topography

The area investigated covers a large part of the province of La Coruña and smaller parts of the adjacent provinces of Lugo and Pontevedra. Most of the area has a subdued topography, where high elevations seldom occur. In the south-east region of the area elevations up to 600 m above sea-level occur.

GEOLOGY

The Ordenes complex, and particularly the phenomena along the major peripheral faults, has been subject to study for the last two decennia. The Petrology Department of the State University of Leiden has contributed much to the survey of this area.

The Ordenes 'basin' is a polyorogenic pre-Variscan complex in the axial zone of the Variscan orogen in NW Spain. Schists and gneisses of probable Precambrian age, originally deposited as semi-pelites and greywackes, are found in the centre of the 'basin'. During or shortly after this deposition mafic lavas, tuffs and sills were emplaced. This event was followed in Early Palaeozoic times by an orogeny, during which the complex was subjected to a number of tectonic and metamorphic phases, which resulted in granoblastic and blastomylonitic fabrics and in high-pressure granulite- and amphibolite-facies paragenesis in the peripheral part of the Ordenes complex. In the Ordenes 'basin' proper it resulted in parageneses varying from approximately non-metamorphic to almandine-amphibolite facies.

Pre-Variscan augen- and orthogneisses, accompanied by metagabbros and peridotites are partially intrusive into the meta-mafic and metasedimentary rocks along the eastern perimeter of the 'basin' around Mellid and Sobrado-Teijeiro. This sequence is followed towards the eastern boundary by dismembered meta-ophiolites of probable Early Palaeozoic age (HUBREGTSE, 1973; KUIJPER, in prep.). The intrusion of younger Variscan granites occurred east of Mellid and Sobrado.

The overall influence of the Variscan orogeny in the eastern part of the 'basin' is low to moderate, while along the western periphery the metamafic and metasedimentary rocks are of much higher metamorphic grade. In some places the rocks even are migmatized. The composition of the meta-sediments is here more semi-pelitic, while the structural pattern of this part also appears to be simpler than elsewhere. The major fault dips at a steeper angle than elsewhere in the complex. In this area there is a noticeable decrease in mafic rocks although not only high- to intermediate-grade metamorphic rocks, but also low-grade rocks occur.
The meta-mafic rocks, consisting mainly of garnet-bearing amphibolites of possible granulite-facies derivation, were retrograded during Variscan times. Metatexitic gneisses occur inside as well as outside the Ordenes 'basin', as do the intrusive metagabbros and metadiorites (VAN ZUUREN, 1969).

FIELD PROCEDURE AND DATA CORRECTION

The existing topographic maps (1:25,000 Cartographía Militar de España, 1950; and 1:50,000 Instituto Cartográphico y Catastral, 1a edición, 1942) were too outdated to give all the adequate information on location and elevation. The elevation was locally checked by two altimeters (Paulin system)

with an accuracy of ± 6 metres, equivalent to approximately 1.2 mGal (milligals).

At 662 stations in the area the gravity was measured, using a Worden gravimeter. The readings were corrected with an elevation-, a latitude-, a terrain-, and an instrument-drift correction. An isostatic correction, compensating for the mass-deficiency of a continental plate upon an oceanic plate, was not necessary because the distance to the continental edge is too great. This correction is negligible in comparison to the values of the other corrections (VAN OVERMEEREN, 1975).

193 surface samples, more or less equally dispersed over the area, were taken in order to determine the average density of the two units. 127 samples belonged to the 'light' unit (i.e. granites, schists etc.) and 66 samples belonged to the 'heavy' unit (i.e. the mafic and ultramafic rocks of the peripheral belt). The density of the 'heavy' unit is 2.89 ± 0.14 g/cm³ and of the 'light' unit 2.58 ± 0.31 g/cm³ (Fig. 2). These surface densities are used in the free-air and Bouguer corrections.

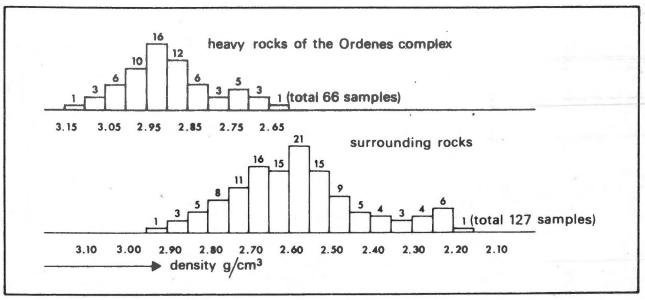

Fig. 2
Histogram of the measured densities of the heavy and lighter unit of the rocks of the Ordenes complex (from Keasberry et al., 1976).

THE BOUGUER GRAVITY MAP

All measurements were calculated with reference to the assumed value (= 0) of the main gravity station at Arzua (Fig. 3). The absolute gravity at Arzua is 980,510.69 mGal and is derived from the absolute gravity at La Coruña: 980,500.40 mGal. The gravity station at the Club Nautico in La Coruña is a regional station and part of the international gravity stations network.

The Bouguer map of the Ordenes complex shows a large asymmetrical maximum in the western part of the 'basin', near Santiago de Compostela, and two minor symmetrical anomalies in the eastern part near Sobrado and Mellid. This outline supports the geological assumption that the peripheral belt of the Ordenes complex can be subdivided.

The anomaly northeast of Santiago is elongated in a northeast direction. A steep slope characterises the southwestern edge near Santiago, the maximum value being + 27 mGal compared to Arzua. Towards the northeast the anomaly declines. The anomalies near Sobrado and Mellid are subcircular and have a maximum value of + 10 and + 15 mGal against Arzua, respectively. Near Mellid the anomaly declines in a southeastern direction, eventually to values of – 35 mGal compared to Arzua. This trend is regarded as the anomaly proper superimposed on a regional effect.

The map suggests that fairly deep-rooted structures, although shallow buried, are to be expected. Similar features have already been observed at Cabo Ortegal, north of the Ordenes complex (VAN OVERMEEREN, 1975). The outlines of the anomalies are an indication of circular and sub-circular bodies, hence the use of a three-dimensional interpretation method.

INTERPRETATION

A preliminary attempt to compute the three Bouguer anomalies of the investigated area was made using a sphere model. This model has been applied in the interpretation of gravity effects over salt domes (NETTLETON, 1942).
The gravity formula of a sphere is given by

$$g = {}^{4}/_{3}\,\pi\, R^3\sigma\gamma z/(z^2+x^2)^{-3/2}$$

in which R is the radius of the sphere in kilometres, σ the density-contrast in g/cm³, γ the gravity constant (6.67 x 10^{-8} c.g.s.), x the depth of the centre of the sphere in kilometres and z the lateral distance in kilometres.

The anomalies of Sobrado and Mellid, being fairly symmetrical, did not present serious problems in fitting the observed picture. A single sphere with a radius of 4.4 km, a depth of the centre of the sphere of 4.95 km and a density-contrast of 0.40 g/cm³ shows virtually the same outline as the observed anomaly picture at Sobrado. A sphere of the same dimension and mass, but at a depth of 4.55 km fits the anomaly observed at Mellid (Fig. 4).

The asymmetrical anomaly near Santiago de Compostela, however, had to be accounted for by several spheres, arranged in such way that the overlap of the spheres, in terms of mass, compensates for the deficiency between the spheres (egg-box effect!). Several configurations were tried and it was found that a double series of six spheres with a radius of 3.72 km and a density-contrast of 0.40 g/cm³, spaced at 6 km at depths of centres of 4.5, 5.0, 5.5, 6.0, 6.5 and 7.0 km, respectively. A plane through these centres has an inclination of 4°47' and is sloping towards the northeast.

ROMBERG (1958) demonstrated the similarity of the resulting computed anomalies of the sphere and the vertical cylinder, for the latter the gravity formula is

$$g = \pi R^2\sigma\gamma/(z^2+ x^2)^{-1/2}$$

Figure 5 *'shows the gravity anomaly of a concentrated structure compared with the anomaly of a structure which is horizontally concentrated, but distributed vertically. This*

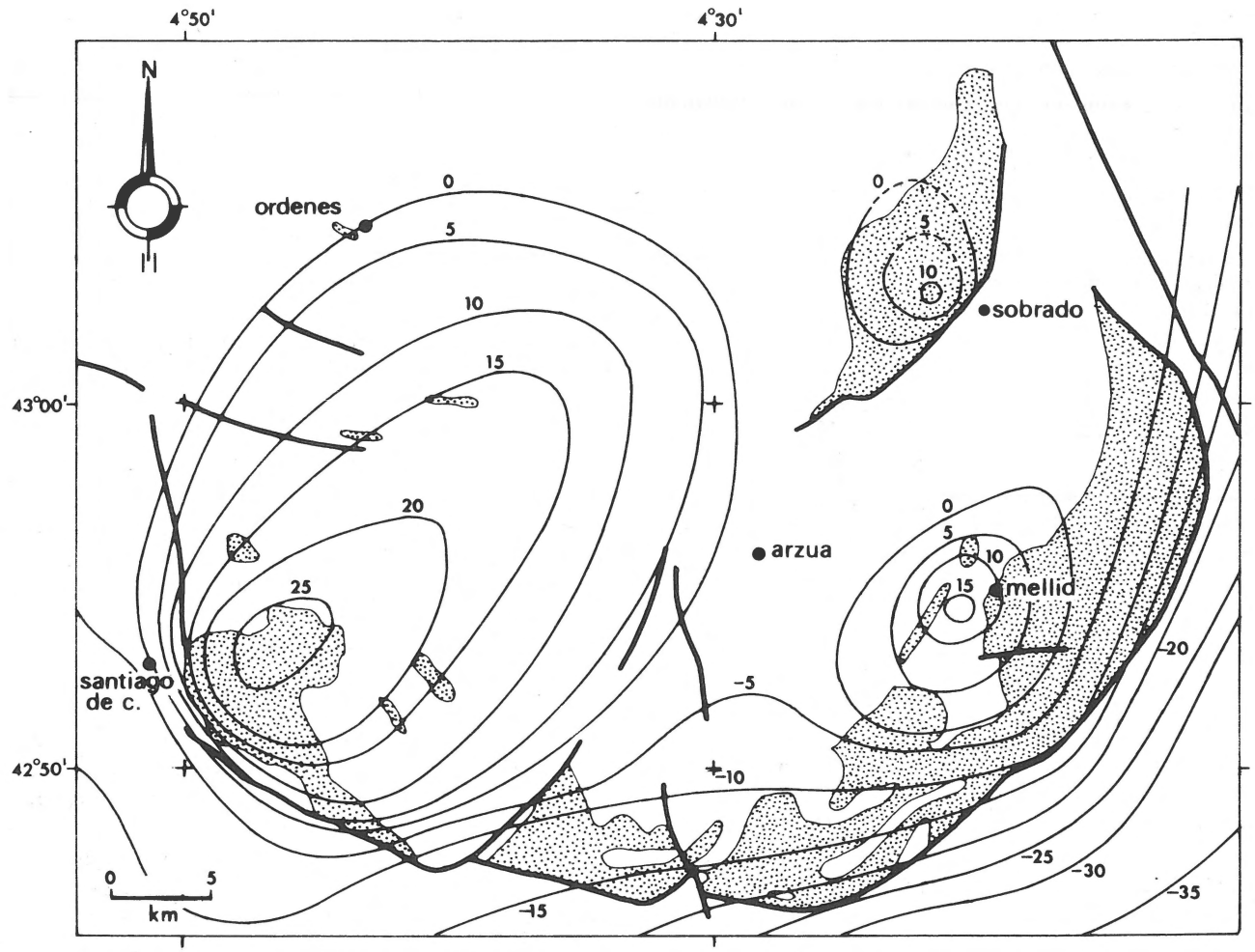

Fig. 3
Simplified geological map and Bouguer anomalies of the Ordenes complex, isogals are drawn at a 5 mGal interval. Stippled areas represent the outcropping rocks of the heavy unit (from Keasberry et al., 1976).

case is perhaps representative of a sharp fold in a thick shale section where the density difference is caused by displacement of material made dense by differential compaction. If the two anomalies are normalized to take care of the broad 'foot' of the second anomaly (which would be diagnostic if it were visible, but is not), then the two anomalies resemble each other closely enough not to be distinguishable in an ordinary gravity picture' (ROMBERG, 1958, p. 696).

From this remark it is clear that the density-contrast of a massive vertical cylinder should be less than in the case of a concentrated form (i.e. the sphere). It was computed that when vertical cylinders were used in the interpretation a density-contrast of 0.31 g/cm^3 gave the same resulting anomaly.

DISCUSSION

A sphere model does not directly suggest adaptation to geological features, although this model has been used in the interpretation of Bouguer anomalies of salt domes (NETTLETON, 1942). WHITEHEAD & LUTHER (1975), however, demonstrated that such a spherical structure can indeed exist. Their laboratory experiments have shown how at a certain level in the mantle, at a few hundred kilometres depth, 'blobs' will rise from a relatively thin layer of lower density than the surrounding mantle material (the Raleigh-Taylor instability). Such an intruding diapir will be arrested when the density-contrast no longer exists. If the upwelling material has greater viscosity than the surrounding (crustal) material, the

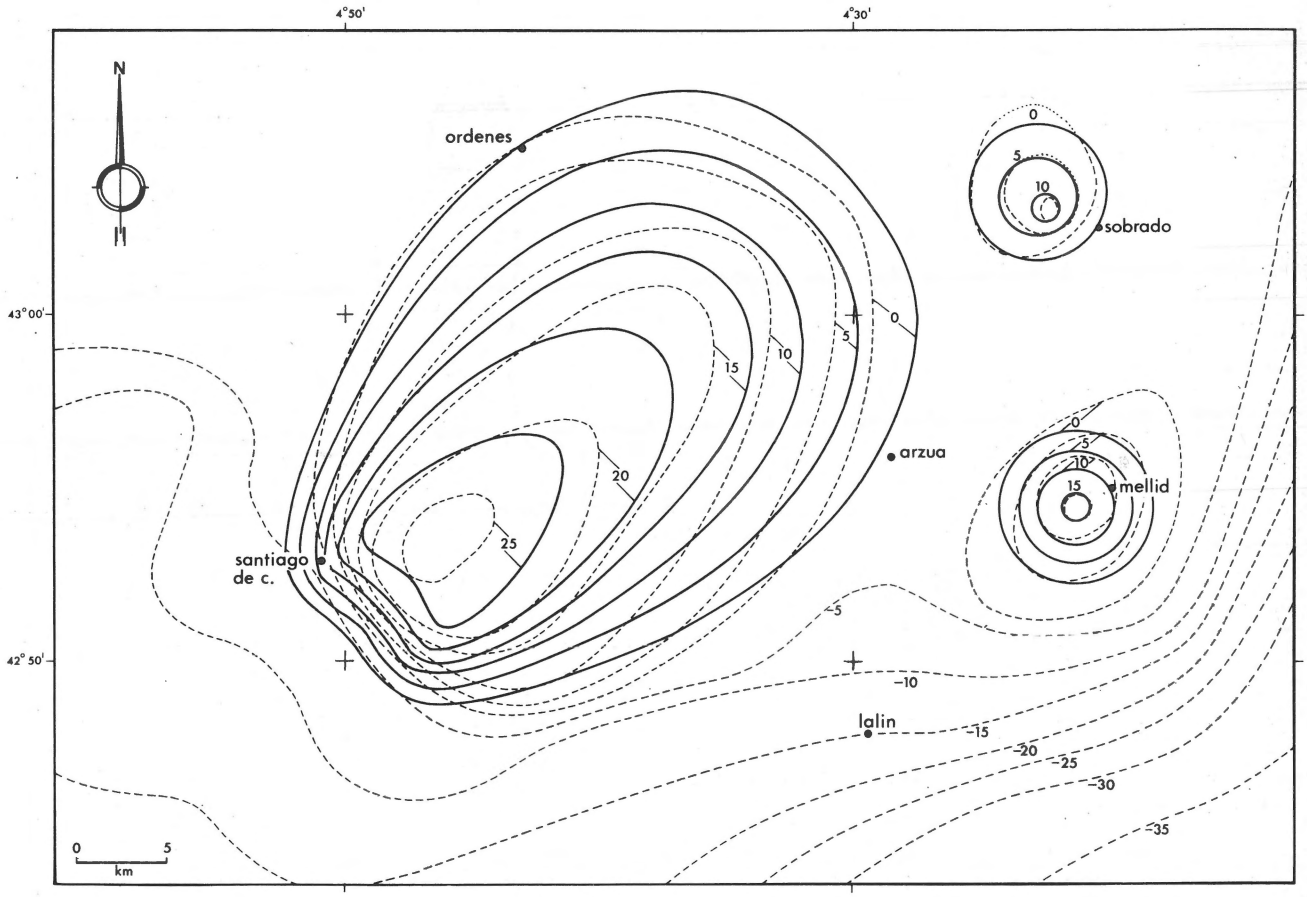

Fig. 4
Comparison between the observed (dashed lines) and computed (solid lines) Bouguer anomaly maps (from Keasberry et al., 1976).

structure of such a diapir will be a long vertical column, occasionally with a decreasing diameter (Fig. 6a). If the upwelling material has lower viscosity, the structure develops a rim syncline and a pronounced overhang and eventually ascends as a spherical pocket (Fig. 6b).

Although the gradient in the southeastern part of the area, near Mellid, is rather high, it is still considered a regional effect. DOBRIN (1960) points out that *'regional contours are interpolated more or less arbitrarily'* and that this *'process is very subjective and empirical'*. Moreover, regional gradients of 10mGals per mile have been observed at the Amarillo-Wichita uplift in the United States (DOBRIN, 1960).

CONCLUSIONS

The three-dimensional interpretation method using gravity formulae for simple structures, although they may seem rather trivial, has confirmed their application in the interpretation of Bouguer anomalies found over the peripheral belt of the Ordenes complex. The three sub-circular anomalies are explained with a diapir model, of which WHITEHEAD & LUTHER (1975) experimentally found an elongated and a spherical form, to which both the cylinder and the sphere model used in the interpretation can be applied.

The diapir is thought to have generated underneath a normal continental crust (VAN CALSTEREN, 1977-b). When the mantle diapir intrudes into the crust, it may have separated gabbroic or noritic melts, which, in turn, may have generated granitic or magmas by partial melting and diapirism, leaving a relatively basic granulite-facies residue (MAASKANT, 1970; VAN CALSTEREN, 1977-a). As a result of cooling of the mantle diapir, a density-contrast with the crust material of 0.3 - 0.7 g/cm^3 develops, sufficient to produce the measured Bouguer anomalies. Although peridotite and gabbro in the complex of Santiago de Compostela are rare (VAN ZUUREN, 1969), their presence seems to support the diapir hypothesis.

Investigations by the research-group 'Galicia' seem to support the speculation that the proposed mantle plume is responsible for several other Variscan tectono-thermal events.

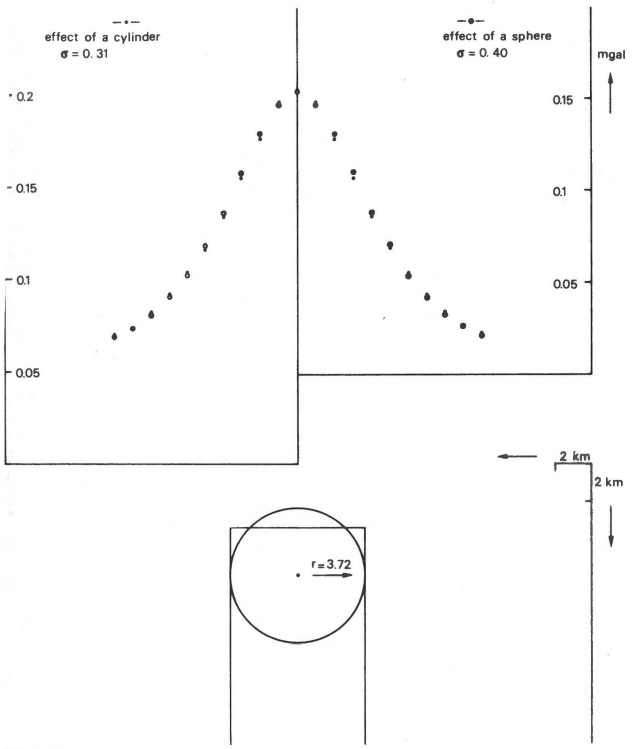

Fig. 5
Correspondence between the effects of a sphere and vertical cylinder (after Romberg, 1958).

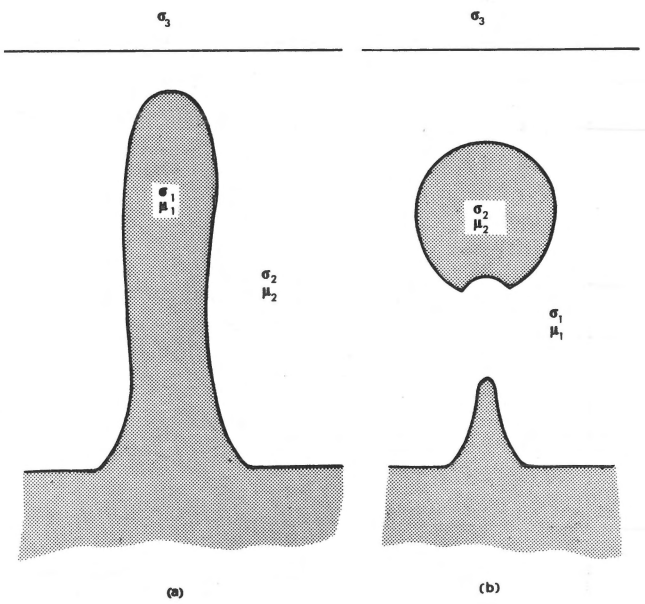

Fig. 6
Diapir models (after Whitehead & Luther, 1975).
a: density $\sigma_1<\sigma_2$ and viscosity $\mu_1>\mu_2$.
b: $\sigma_1<\sigma_2$ and $\mu_1>\mu_2$.
density $\sigma_3\neq\sigma_2\neq\sigma_1$.

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