# Geologic mapping of the basement of the Paris basin (France) by gravity- and magnetic-data interpretation

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ABSTRACT

Simultaneous interpretation of gravity and magnetic data, taking into account all available information (geology, borehole, and nonconfidential seismic surveys), has been carried out with the help of potential-field transformation, modeling, and inversion software. Geophysical synthesis led to the delineation of a geologic map of the pre-Triassic basement of the Paris basin and to the delineation of the most important structural features of the Hercynian and Caledonian Ranges in France between outcropping Paleozoic massifs. Recent boreholes, drilled at the end of this synthesis, largely confirm the proposed interpretation. Thanks to simultaneous gravity and magnetic inversion, models of the Magnetic Anomaly of the Paris Basin can be proposed, and the origin of this anomaly can be related to a scheme of the structural evolution of the basin.

## INTRODUCTION

The Paris basin is an intracratonic basin of approximately 180 000 km$^2$ lying between areas of outcropping Paleozoic rocks (Armorican massif, Central massif, Vosges, Ardenno-rhenan massif). The depth of the Permian basement is greater than 3 000 m in the center of the basin (Figure 1).

Knowledge of the basement has been vastly improved from petroleum-exploration studies, particularly seismic prospecting and borehole investigations (Heritier and Villemin, 1971). Interpretation of gravity data (Goguel, 1954; Gerard, 1971) has led to hypotheses on the intrabasement origin of some of the most important anomalies. The study of aeromagnetic maps gives complementary information (Gerard and Weber, 1971).

The present work resulted from an integrated investigation using gravity and magnetic data, and which took into account all other available information, such as geology, borehole logs, and nonconfidential seismic surveys. These interpretations were carried out with the help of transformations, modeling, and inversion software.[1]

The nonconfidential petroleum seismic data and information from the deep boreholes were used to map the depth of the pre-Triassic basement. The interpretation of the gravity and magnetic data enabled us to sketch a geologic map of the basement under the sedimentary cover.

## BASIC DATA

The gravity map of France, surveyed for the most part and published by the Bureau de Recherches Géologiques et Minières (BRGM) includes, for the Paris basin, a measurement density ranging from 1 to 0.2 station per square kilometer. The error of the measured anomaly is about 0.2 mGal, so the mean accuracy of the mapping is generally better than 1 mGal.

The basic aeromagnetic data used for this synthesis were taken from the aeromagnetic map of France published by BRGM at a scale of 1 : 1 000 000 and issued from the survey carried out by the Centre National de la Recherche Scientifique in 1964 (barometric flight altitude, 3 000 m; spacing of lines and traverses, respectively, 10 and 100 km). More detailed surveys for petroleum prospecting are available locally. The most important anomaly of this map is termed the Magnetic Anomaly of the Paris Basin (MAPB), which extends from the English Channel to the northern boundary of the Central massif (Figure 1), about 400 km in length. The intensity of this anomaly reaches 250 nT in its southern part.

## GEOLOGIC MAPPING OF THE BASEMENT

The synthetic interpretation of the gravity and magnetic data in the central part of the Paris basin was preceded by study of the geophysical behavior of the surrounding Hercynian massifs (Weber, 1967, 1968). Some well-logging results were also examined.

Figure 2 summarizes the density properties of the Hercynian basement of the Armorican massif and of the northern

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Central massif. The Brioverian and Armorican Paleozoic sequences show densities varying largely with age and lithology; the Brioverian has the largest density (2.69 g/cm$^3$ on the average), and the Carboniferous the smallest (2.57 g/cm$^3$ on the average).

In the eastern part of the Paris basin, well data indicate strong density contrasts within Paleozoic strata, particularly between the Devonian and the Carboniferous formations. The metamorphic formations range from a low density of 2.55 g/cm$^3$ to a high density of 2.70 g/cm$^3$ where the metamorphic grade decreases. Amphibolite densities range from 2.7 to 3.0 g/cm$^3$. Likewise among the plutonic rocks the most mafic formations have the highest densities (2.90 g/cm$^3$). Granites show a wide variety of density: 2.6 g/cm$^3$ on the average for leucogranites, 2.65 g/cm$^3$ for biotite granites, and up to 2.75 g/cm$^3$ for granodiorites.

With respect to magnetic properties, except for the south Armorican iron-ore bodies, the highest values of magnetic susceptibility (up to 0.025 SI) are found in some granitoids (granodiorite type) on the northern border of the Central massif. Most granites have a very weak magnetic susceptibility, as do the Brioverian and Paleozoic series, in the absence of contact metamorphism. The susceptibility of metamorphic rocks rarely exceeds 0.0025 (SI). The volcano-sedimentary formations can reach values of 0.01 (SI).

Preliminary interpretation of the gravity and magnetic data, carried out on the Hercynian basement and its border (Weber, 1972), confirm the characteristic behavior of Paleozoic units whose limits can be extrapolated beneath the sedimentary cover. Localized control of these interpretations is possible from the data obtained from deep boreholes.

**Structural interpretations using transformed maps**

The goal of these transformations is to put potential-field data into a form that facilitates structural interpretation.

Maps of the vertical gravity gradient (Figure 3a) and of the

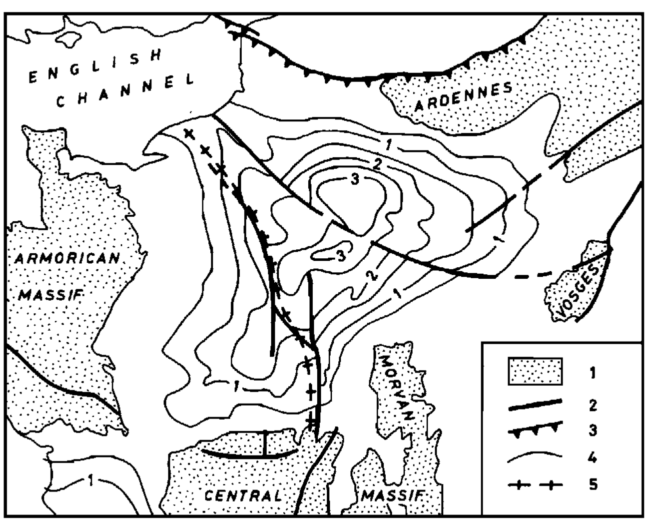



FIG. 1. Geologic setting of Paris basin. Explanation: 1 = outcropping basement; 2 = fault; 3 = overthrust fault; 4 = depth of basement, in thousands of meters; 5 = axis of Magnetic Anomaly of Paris Basin (MAPB).

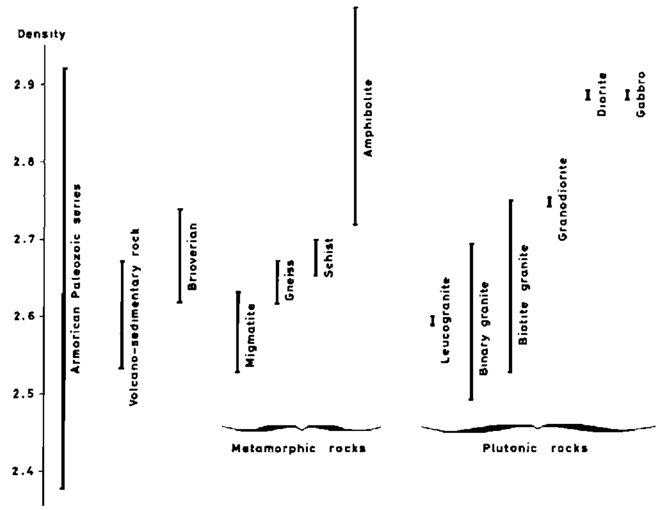



FIG. 2. Density (g/cm$^3$) of outcropping basement.

magnetic field reduced to the pole (Figure 3b) have thus been calculated. Gravity has been, in this way, brought to a degree of derivation comparable to that of the magnetic field. In fact, if the susceptibility of the body considered for interpretation were proportional to the density, and if the Earth's magnetic field were vertical, the vertical gradient of gravity would be proportional to the vertical component of the magnetic field (Goguel, 1972). The preceding transformations were carried out by applying, in the frequency domain, the corresponding operator (Gerard and Griveau, 1972).

Assuming that the gravity effect of the sedimentary sequence is negligible, the downward continuation of gravity data to the top of the Paleozoic basement can be calculated by transforming and filtering in the frequency domain (Debeglia, 1979). In the central part of the Paris basin, the Bouguer anomaly (Figure 4a) has been continued downward to a surface approaching the top of the Paleozoic basement (Figure 4b). The vertical gradient of this continuation (Figure 4c) allows preparation of a map of the schematic distribution of basement densities (Figure 4d; here, on the hypothesis of infinite downward structures). The effect of the resulting model is compatible with the initial field, as profile modeling shows (Figure 5). With the aid of well data, a table can be proposed (Table 1) relating the structures thus defined and the possible lithologies.

The transformations have greatly contributed to geologic mapping of the top of the basement (Figure 6). This map also includes some intrabasement units that have a strong gravity or magnetic effect (in particular, the magnetic and dense formations associated with MAPB).

**Control by recent boreholes**

It is possible that the basement mapping here presented will be superseded when direct knowledge of pre-Triassic terrain is obtained. In fact, the low resolution of potential-field data does not allow us to point out the complexity of the

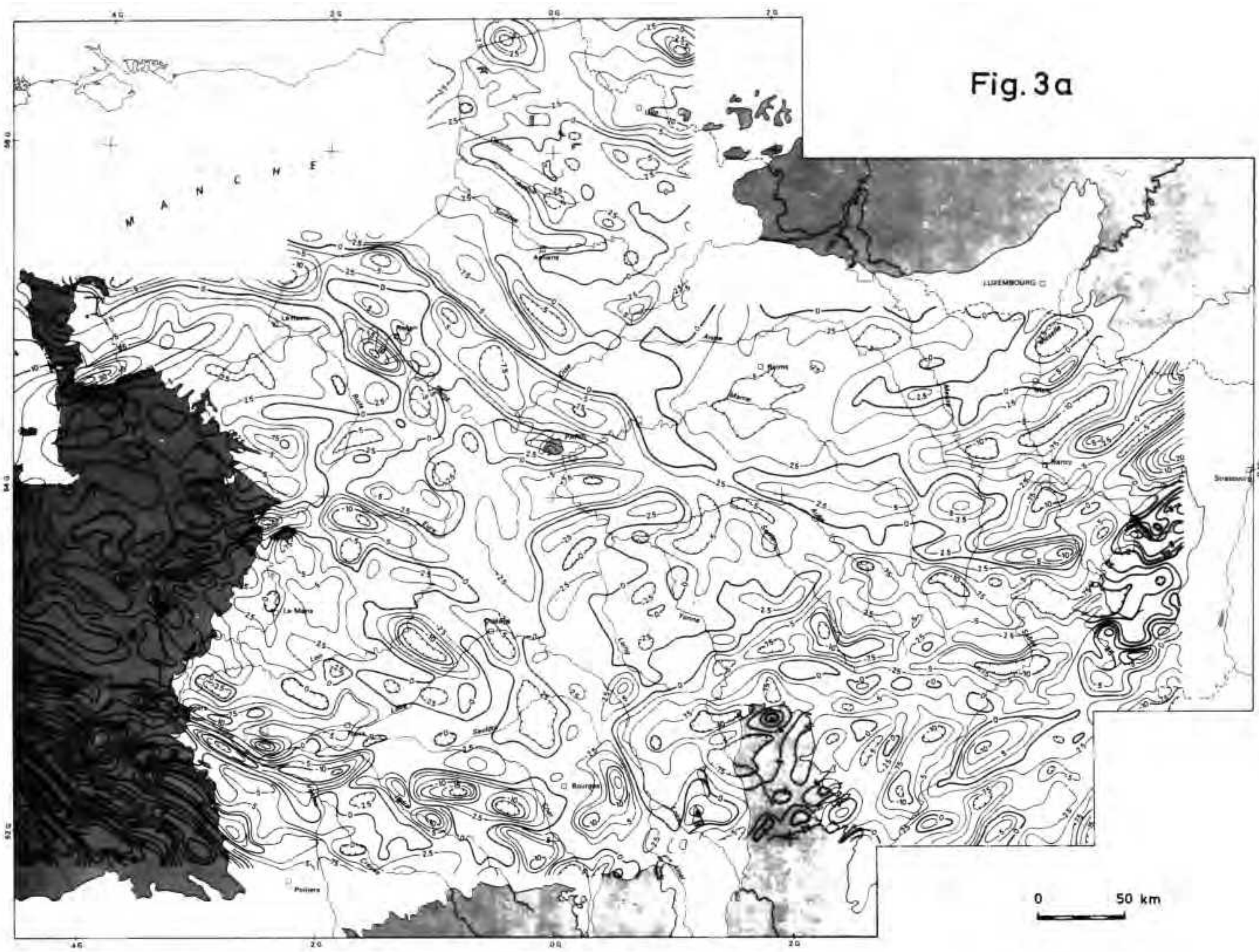



FIG. 3a. Paris basin region. Vertical gradient of gravity field (in 0.1 mGal/km).

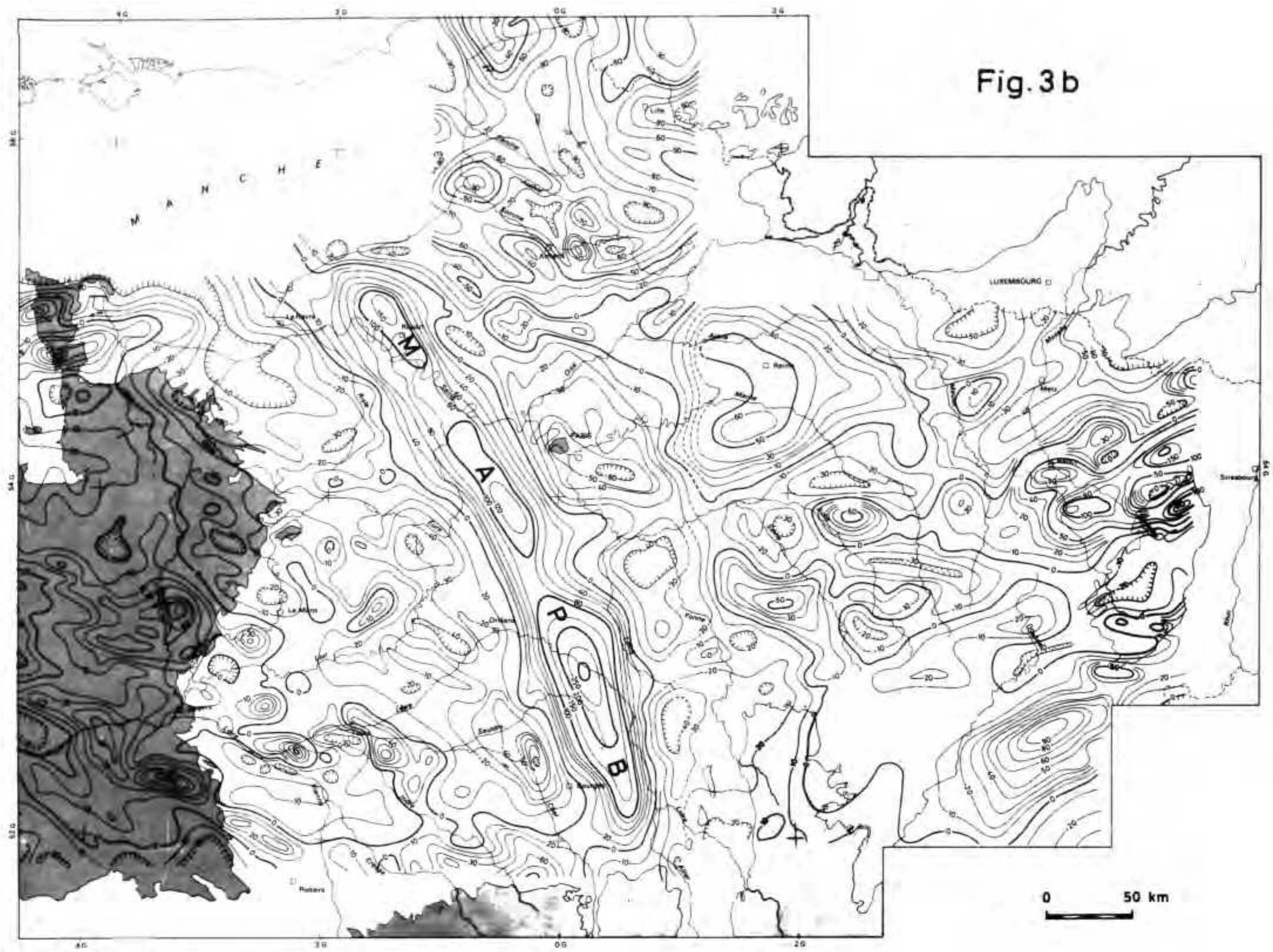



FIG. 3b. Paris basin region. Magnetic field reduced to the pole, elevation 3 000 (in nT).

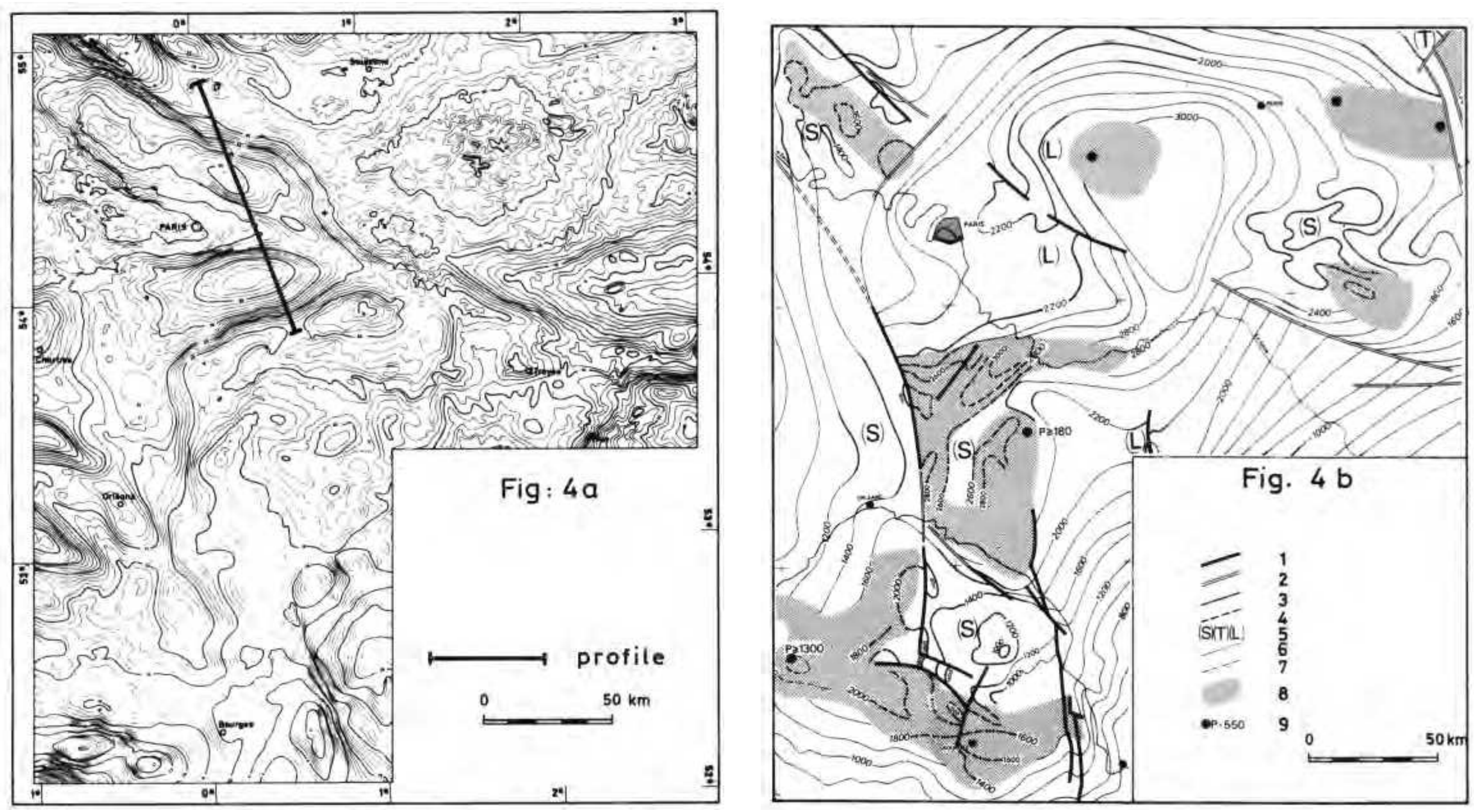
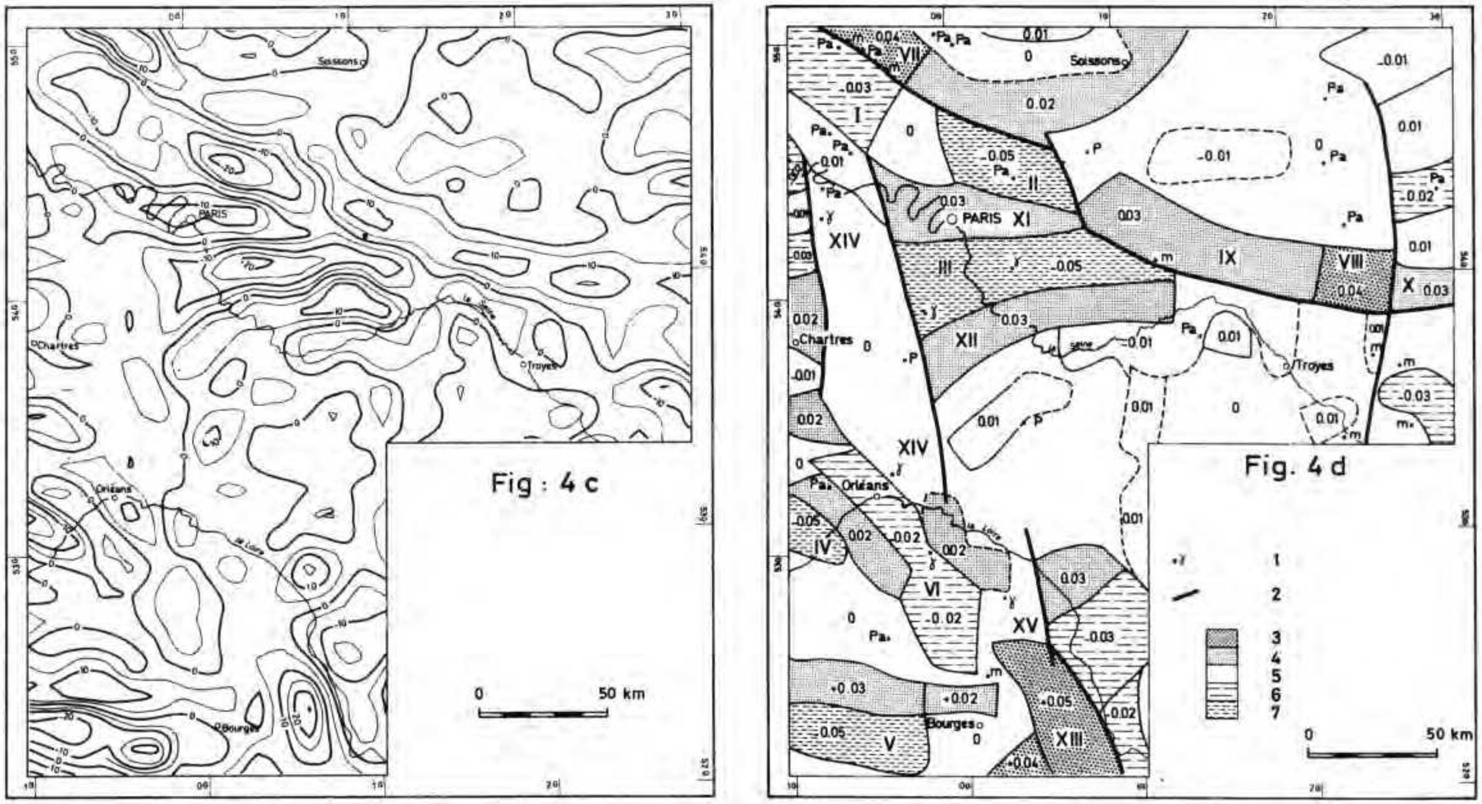



FIG. 4. Examples of the use of downward continuation to the top of basement, Paris basin region.
4a: Bouguer anomaly (in mGal).
4b: Isobath map of the top of basement:
1 = discontinuities according to seismic data.
2 = discontinuities according to gravity and aeromagnetic data.
3 = isobaths according to seismic data on Paleozoic basement.
4 = isobaths according to seismic data on pre-Permian basement.
5 = levels mapped by seismics: basement (S), Trias (T), or Lias (L).
6 = isobaths according to well data on Paleozoic basement.
7 = isobaths according to well data on pre-Permian basement.
8 = Permian basins.
9 = boreholes drilled to the Permian, showing Permian thickness (in meters).




4c: Vertical gravity gradient at the top of basement (in 0.1 mGal/km).
4d: Density sketch map of the top of basement:
1 = principal boreholes showing the nature of basement (γ = granite; m = metamorphic; Pa = Paleozoic; P = Permian).
2 = gravity faults.
3 = gravity structures with highly positive contrasts (mafic rocks).
4 = gravity structures with positive contrasts (metamorphic rocks).
5 = gravity structures with near zero contrasts.
6 = gravity structures with negative contrasts (granites, Permian basins).
7 = gravity structures with highly negative contrasts (leucogranites).

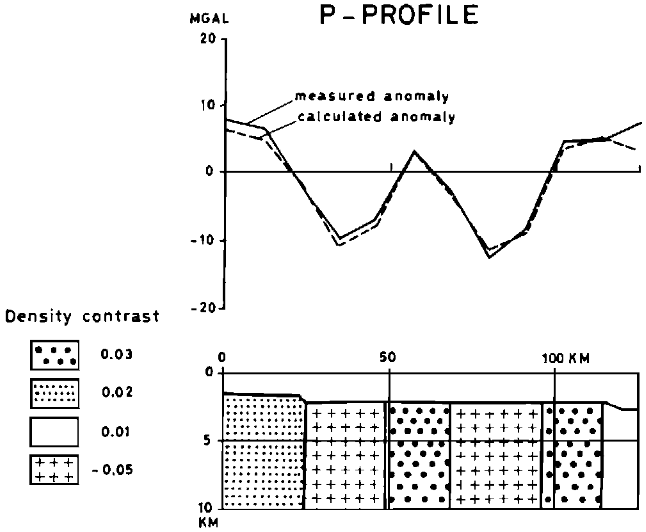



FIG. 5. Gravity modeling of a profile, P′, of density distribution taken from Figure 4d, with depth of basement taken from Figure 4b.

**Table 1. Proposed correlation between structures of Figure 4d and lithologies.**

| Structures | Mean density (for the hypothesis of infinite downward structures) | Proposed lithology |
|---|---|---|
| II, III, IV, V | $-0.05$ g/cm$^3$ | Leucogranite |
| I | $-0.03$ g/cm$^3$ | Permian |
| VI, XIV, XV | 0 to $-0.02$ g/cm$^3$ | Granite and Paleozoic |
| VII, VIII, IX, X, XI, XII | 0.02 to 0.04 g/cm$^3$ | Metamorphic rocks |
| XIII | 0.05 g/cm$^3$ | Mafic rocks |

geological reality. Thus, a single geophysical discontinuity can correspond to a complex grouping of faults or of contacts. Moreover, only the large geologic units that have strong density or magnetic-susceptibility contrasts can be detected in this manner. Finally, a thin cover with a density approaching that of overlying sedimentary rocks (Permian, Paleozoic, schists) cannot be detected.

This is the reason why it is important to verify the interpretations established by geophysical synthesis, using recent well data. Since completion of the geophysical interpretation, nine boreholes have reached the Paleozoic basement. For the most part, they confirm the given interpretation (Table 2).

### Structural results

Two major geophysical features are evident in the geophysical synthesis.

The first, the Bray–Vittel fault (BVF in Figure 6), extends from Pays de Bray to the Vosges, striking N 130 degrees to east–west. North of this discontinuity a metamorphic unit can be considered as the western extension of the crystalline Hercynian zone that crops out in Germany. Northward, a thick Paleozoic sequence (Rhino–Hercynian zone) occurs, into which magnetic and highly dense igneous bodies have intruded. In the north of France this unit overthrusts autochthonous Paleozoic strata.

The second feature is a grouping of nearly north–south faults extending along the MAPB. The MAPB axis marks an obvious discontinuity of structural trends, averaging N 110 degrees W (Armorican direction) and N 70 degrees E (Morvano–Vosgian direction).

The intensity of the magnetic effect observed in the MAPB has led us to assume that extensive mafic units occur in the Paleozoic basement. However, none has been reached by boreholes. Along the MAPB, only granitic formations have been shown by well data and confirmed by local negative gravity anomalies.

### Modeling of the southern part of the MAPB

Simultaneous gravity and magnetic inversion have been carried out on profiles in the southern part of the MAPB

**Table 2. Results of principal petroleum boreholes drilled after geologic mapping of the basement.**

| Borehole | Level reached and depth below sea level (in meters) | | Lithology and depth (below sea level, in meters) predicted by geophysical synthesis | |
|---|---|---|---|---|
| La Houssay en Brie | Metamorphic basement | 2390 | Granite–Paleozoic contact | 2350 |
| Lhuitre 1 | Permo–Triassic | 2322 | | |
| | Permian | 2593 | Permian | 2500 |
| | Lower Autunian / Upper Stephanian | 3304 | | |
| | Metamorphic basement | 3555 | | |
| Crecy en Brie 1 | Metamorphic basement | 2469 | Metamorphic basement | 2300 |
| Heurtebise | Metamorphic basement | 2594 | Paleozoic basement, not far from contact with granite | 2700 |
| Donnemarie 1 | Triassic to Permo–Triassic | 2387 to 3489 | Undifferentiated Paleozoic basement, less than 5 km from Permian basin | 2900 |
| Corfelix | Permian | 3250 | Permian | 3200 |
| Marsangis 1 | Permian | 2765 | Undifferentiated Paleozoic | 2800 |
| Tousson 101 | Permo–Triassic | 2300 | Permian | undefined (2700: pre-Permian basement) |
| Videlles 1 | Undifferentiated basement | 2300 | Undifferentiated Paleozoic | 2100 |

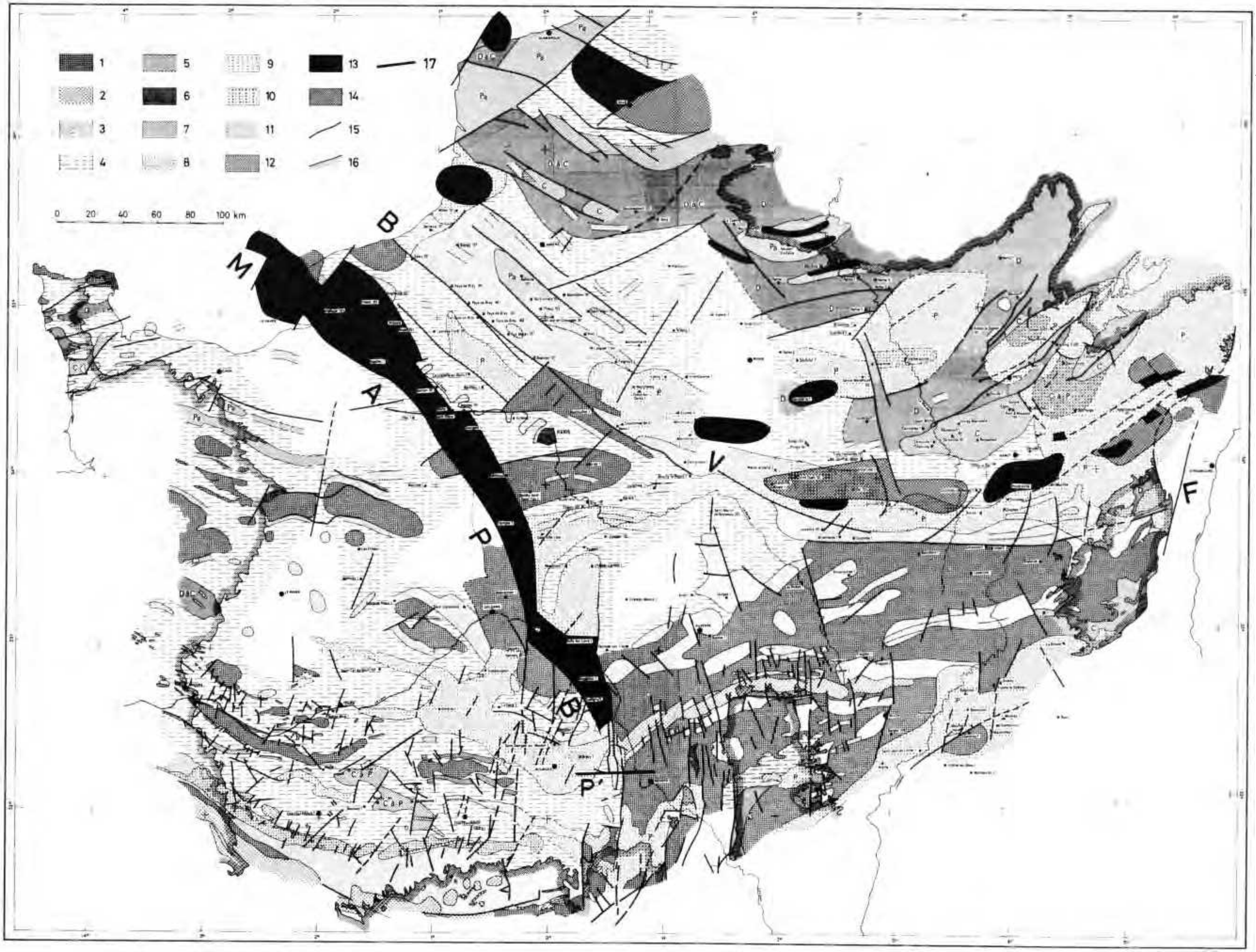



FIG. 6. Geologic map of the Paleozoic basement. BVF: Bray-Vittel fault. MAPB: Magnetic Anomaly of Paris Basin.
Low-density and weakly magnetic formations: 1 = granite (sensu lato); 2 = leucogranites; 3 = metamorphic rocks; 4 = undifferentiated Brioverian or Paleozoic; 5 = lower Paleozoic; 6 = Devonian; 7 = Carboniferous; 8 = Permian.
Dense and magnetic formations: 9 = mafic rocks; 10 = granodiorites; 11 = metamorphic rocks and contact metamorphism; 12 = iron-bearing formations; 13 = deep magnetic masses; 14 = deep heavy masses; 15 = fault; 16 = limit of outcropping basement.
17 = location of profile P' of Figure 7.

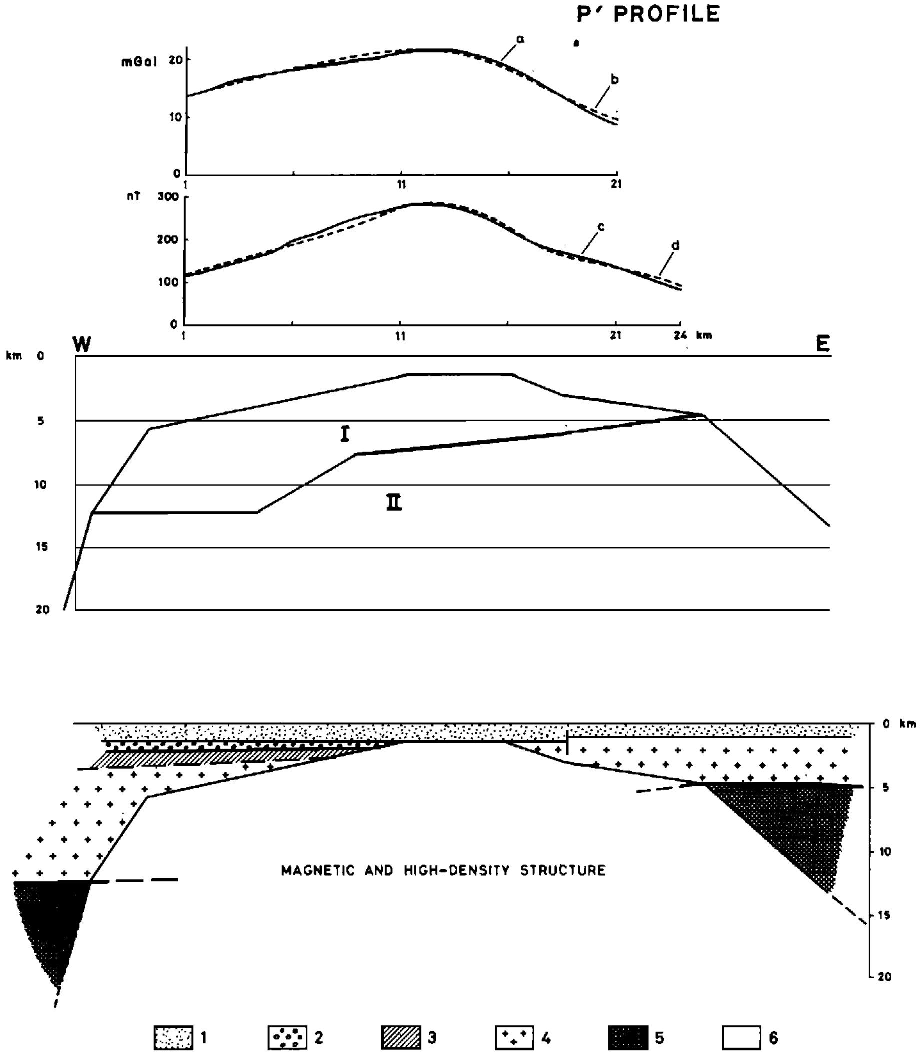



FIG. 7. P′ profile: modeling example of MAPB (located on Figure 6). a = Bouguer anomaly; b = gravity effect of modeling; c = aeromagnetic data; d = magnetic effect of modeling; I: $\Delta X = 0.0016$ SI units, $\Delta\rho = 0.12$ g/cm$^3$; II: $\Delta\rho = 0$, $\Delta X = 0.0016$ SI units.

Explanation of lithologies:
1 = sedimentary rocks.
2 = Permian.
3 = undifferentiated Brioverian and Paleozoic.
4 = granite.
5 = basement (nonmagnetic and dense).
6 = magnetic and high-density structure; from Ménichetti and Guillen (1983).

(Menichetti and Guillen, 1983; Menichetti, 1984). As shown in Figure 7, a positive gravity anomaly is related to the magnetic anomaly. Inversion has been performed for different pairs of density and susceptibility contrasts using an initial model obtained by direct interactive modeling. It has been assumed that the structure is an intrabasement intrusion with homogeneous magnetization from its upper surface to the Curie depth (about 20 km). We assume also that its density contrast decreases with depth. This last assumption probably involves an increase with depth of the density of surrounding formations (granitic units overlying a denser series of unknown nature).

To arrive at a suitable solution for this inversion, the density contrast (at the top of the structure) would vary from 0.1 to 0.25 g/cm$^3$, and the susceptibility contrast between 0.016 and 0.032 (SI). The top of the structure is between 1.8 km (nearly outcropping at the top of the basement) and 4 km deep, according to the chosen density-susceptibility pair. One of these solutions is shown in Figure 7; for this solution, the top of the structure crops out at the top of the basement.

In the center of the Paris basin, the gravity anomaly related to the MAPB is much smaller and partly masked by various intrabasement heterogeneities (granite batholiths, for example). The maximum depth of the magnetic structure has been found to be great, up to 8 km (Le Mouel, 1969). So the whole magnetic body can probably lie inside the lower dense unit (unit 5 in Figure 6), and thus no gravity effect is observed.

## CONCLUSION

Geophysical synthesis allowed preparation of a map of the lithology and structure of the pre-Triassic basement of one of the most important French sedimentary basins, the Paris basin. It is now possible to sketch the hidden continuation of the principal Caledonian and Variscan units under the sedimentary cover (Autran, 1980).

A preliminary hypothesis for the structural evolution of the Paris basin and of the Magnetic Anomaly of the Paris Basin (MAPB) can be suggested. Prior to emplacement of leucogranitic eohercynian units extending from the Vosges to the Armorican massif (dated at 340 m.y. in its outcropping part), a tensional phase (rifting) allowed intrusion of mafic rocks, which explains the MAPB. Later, a compressional phase with sinistral strike-slip faults, well known in the Central massif (Sillon Houiller fault, dated at 280 m.y.), occurred with a major overthrust mainly in the northern part of the Paris basin. At the same time the intrusion of granitic bodies marked a new magmatic event along the MAPB axis. Later vertical displacements controlled sedimentation from Permian to Tertiary time. These displacements can be observed on the faults bordering the MAPB (Debeglia and Debrand–Passard, 1980). Subsidence was the dominant tectonic movement up to Mio–Pliocene time.

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