The European Geotraverse Project:
a major European scientific venture

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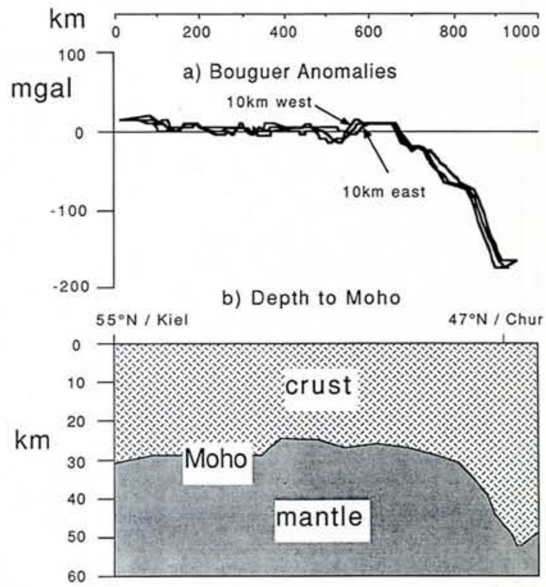

Fig. 3 — Comparison of gravity (Bouguer anomaly) profiles with seismically determined Moho depths. a). Three gravity profiles, a central profile coincident with the trace of the Moho depths of (b) and two parallel profiles, each 10 km east and west of the main profile (data from Ref. 5). b) Depth to Moho from refraction seismic results (data from Ref. 4). Gravity anomalies due to crustal sources can be seen in the variation among the three Bouguer anomaly profiles. Anomalies due to mantle sources (mainly the depth to the Moho) are evident from the long-wavelength downward trend which begins near Lake Constance and dips steeply under the Alps evidenced by all three traces.

Part II

In Part I, published in the June 1987 issue of *Europhysics News*, the aims and organization of the "EGT" were described and an introduction given to seismic research methods.

Another application of refraction seismic data is to map the depth to the Moho as shown in Fig. 3b. The data for this figure have been gathered from many small experiments over the last twenty years [3]) and the position of this profile was drawn to coincide with a nearly north-south 1000 km profile from Kiel to Genoa (the EUGEMI experiment) that was recorded in September-October 1986. This experiment was a success, involving more than 20 large explosions and over 200 operators; the data are still being processed. The new results, however, do not alter the general features shown in Fig. 3 which illustrates a relatively "flat" Moho under much of central Europe and a relatively deep Moho under the Alps. Changes in the depth to Moho are also mirrored in changes in the long-wavelength gravity anomalies [4]) (gravity methods will be discussed in more detail below). On comparing Figs. 3a and b, a parallel thickening of the upper crust and downward trend in the gravity anomaly curve is clearly evident. Both these effects are due to the large mass of crustal material of the Alps (see also Fig. 5 where this profile is continued). A slight upward bulge in the Moho near Kassel (Federal Republic of Germany) at 400-500 km along the profile is not apparent in the gravity profile. To explain this it is useful to remember that gravity is a potential field, integrating density effects over a wide three-dimensional area whereas refraction seismics measures travel times of the "velocity field" along a two-dimensional profile. Seismic data are directly affected by the discontinuous nature of the materials through which the signal passes, whereas the potential field of gravity is continuous at all points. Short wavelength gravity effects are sensitive to "nearby" crustal anomalies which are difficult to resolve with the large-scale refraction seismic method. But the density effects of these crustal anomalies can mask the Moho topography as in Fig. 3a. In contrast, the crustal anomalies are "transparent" to the refraction seismic experiments that provided the data for Fig. 3b and resolved km-scale variations in the depth to the Moho.

With increased resolution through either reflection seismic profiles or denser station spacing in refraction experiments, the crustal density anomalies apparent in the gravity profiles can also be seismically determined. Indeed, recent seismic profiles from the southern and central parts of the Federal Republic of Germany that cross each other yield a 3-dimensional picture indicating widespread lateral heterogeneity within the crust. Other seismic results from different regions demonstrate that indeed heterogeneity characterises much of the crust beneath central Europe.

Electromagnetic Methods

Electromagnetic surveys measure natural or artificially generated electrical fields at or near the Earth's surface. These fields are strongly influenced by the presence of conductive layers in the crust. Although electromagnetic surveys are commonly used to detect mineral resources or ground water occurrence, sensitive instruments with large arrays and complex analytical methods can also detect deeper-lying conductive layers in the crust and to depths of over 400 km in the mantle.

There are three principal methods to measure fluctuations in the Earth's electromagnetic field: magnetometer arrays or magnetovariational sounding (MV), magnetotelluric profiles (MT), and frequency soundings (FS). In MV techniques, three orthogonal components of the time-varying magnetic field are recorded by magnetometers arranged in a two-dimensional array. Sources for the magnetic field are currents in the magnetosphere and ionosphere with field strengths ranging from a few to several thousand nT and periods from 1 min to 1 day. MV arrays of up to a thousand km length yield information about the areal distribution of electrical conductivity and delineate crustal and upper mantle conductivity anomalies.

Natural fluctuations in currents that run through the Earth are utilised in the magnetotelluric (from Latin *tellus* = earth) method (MT). The horizontal component of the electric field and the horizontal and vertical components of the magnetic field are measured simultaneously as a function of frequency.

* We apologize for the mistaken reference to the University of Zurich in Part I.

Analysis of the results yields impedance as a function of frequency which is then inverted to give resistivity as a function of depth.

FS methods use powerful magnetohydrodynamic generators as electromagnetic signal sources. One such generator, located on Rybachy Island off the northern shore of the Kola Peninsula, feeds a current pulse of 10-20 kA or several subsequent pulses of 0.5-1.2 kA via a 7 km long cable into the Barents Sea. Since the current tends to flow around the island, both magnetic and electric dipole fields are generated. Telluric and associated magnetic fields have been measured at distances of 350-500 km from the source and have been used to estimate conductivity structures in the Baltic Shield [5]).

In the *crust* high-conductivity layers may indicate the presence of aqueous fluids (water as ions or solutes) or conductive material (graphite, magnetic and hydrated minerals, sulphur in combination with other volatiles, or iron). Porosity of rocks and salinity of fluids are also factors that affect resistivity in the crust, although usually to a lesser degree than those just mentioned. Zones of high conductivity are normally interpreted either as mineralised layers produced by precipitation after fluid flow in fractured rock or as fluids present along major thrusts or fractures.

Beneath the crust, in the *upper mantle*, temperature and fluid phases in association with partial melting are the critical parameters. Temperature is related to conductivity both theoretically (through the semiconduction equation) and practically (in the correlation of conductivity with heat flow as found by surveys in the central European rift system). The transition from the lithosphere to the asthenosphere is poorly understood; it is neither a simple chemical change (as at the Moho) nor a density transition (as the 440 km boundary), but rather a temperature effect. One consequence of this temperature difference is that the lithosphere is cooler and therefore more rigid than the underlying asthenosphere.

Fig. 4 shows the results of a magnetotelluric study [6]) carried out in the region of the central segment of the EGT which illustrates some of the information attainable by MT methods. This profile crosses a clearly defined geological division between two zones of the Hercynian (Variscan) mountain system. Called the Rhenohercynian and Saxothuringian zones (labeled RH and SX in Fig. 4), these regions are well-known from surface exposures, but little is understood about their significance in the evolution of the European lithosphere. Interest in the nature of these zones is high and several methods are now being focussed on their properties at depth. The zones with pattern in Fig. 4 are regions of low resistivity (*ca.* 10 Ωm), the white areas have high resistivity (*ca.* 1000 Ωm). There are three conducting layers:

1) at about 10 km depth (*i.e.* beneath Münsterland),

2) in the upper/middle crystalline crust (the irregular band at about 20 km depth), and

3) the layer below 50 km depth.

The shallowest layer confirms the presence of widespread and thick sedimentary basins over much of northern Ger-

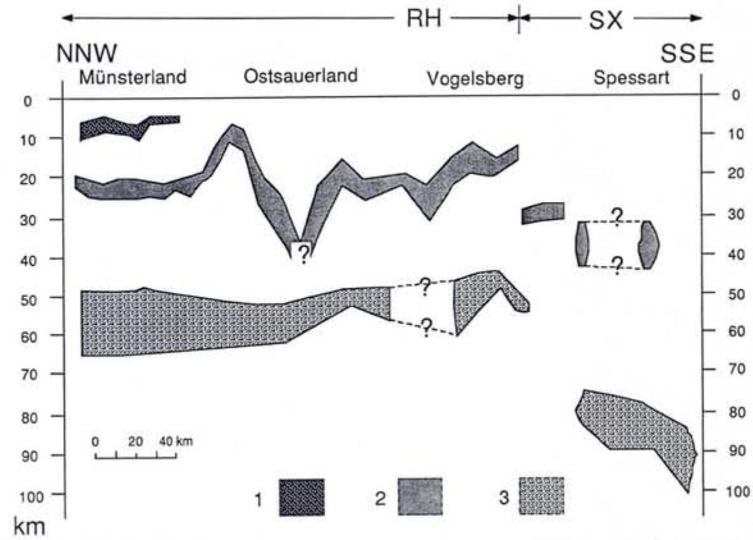

Fig. 4 — Resistivity/depth profile across the Rhenish Massif (Federal Republic of Germany). Patterns: 1: resistivities in the range 3-9 Ωm; 2: resistivities in the range 2-189 Ωm; 3: resistivities in the range 1-262 Ωm; resistivities in the surrounding material ranges from 10-14000 Ωm. The uppermost zone is probably due to water saturated basin sediment, the middle zone may signify ancient fracture planes, and the lowermost zone could be due to thermal effects at the top of the asthenosphere (data from Ref. 7).

many. Sediments are usually channels for ground water and this characteristic is reflected by the low-resistivity of layer 1. Of particular interest are the two deeper layers which coincide in depth and extent with seismic low-velocity zones that have been found in this region. If associated with fluids, the zone should indicate low seismic velocity; if associated with mineralised layers or high-pressure metamorphism (mylonitisation), the zone may be seismically detected as high-velocity layers. As mentioned above, some high-velocity seismic reflectors in the upper crust have been proposed as mineralised or mylonite layers along which large blocks of the continental crust may have moved. Thus detection of zones of high conductivity through magnetotelluric methods not only supports the seismic identification of these layers, it also provides confirmation of their geologic significance. The deepest zone of low-resistivity (layer 3) is usually called the "conductosphere" and may correspond to the asthenosphere which is expected at this depth. Seismic results have not yet penetrated to this depth; it is hoped that, as for FENNOLORA, the forthcoming EUGEMI results may provide information on upper mantle velocities to compare with the electromagnetic data.

In addition to the horizontal differentiation, another important observation from the data of Fig. 4 is the clear evidence for a deep-seated vertical boundary beneath the surficial exposure of the Rhenohercynian/Saxothuringian boundary. Vertical reflectors are notoriously difficult to resolve through seismic methods. The confirmation by electromagnetics of the importance of this geological boundary is itself a valuable result; that it appears to continue through the "conductosphere" (asthenosphere) is an unexpected discovery that awaits data from other sources better to understand it.

Gravimetric and Geodetic Methods

Gravity measurements provide another important parameter that reveals information about the deep density structure of the crust and upper mantle. After correction for topography (normally calculated to a radius of 167 km from the measurement site using an average density of crustal material of 2670 kg/m^3), for elevation ("free air" correction), and for the effect of earth tides (since gravity measurements are now accurate to better than ± 10 μgal (100 nm/s^2) and maximum amplitudes of earth tides are about 250 μgal), the resultant gravity measurements are compared to a standard reference model

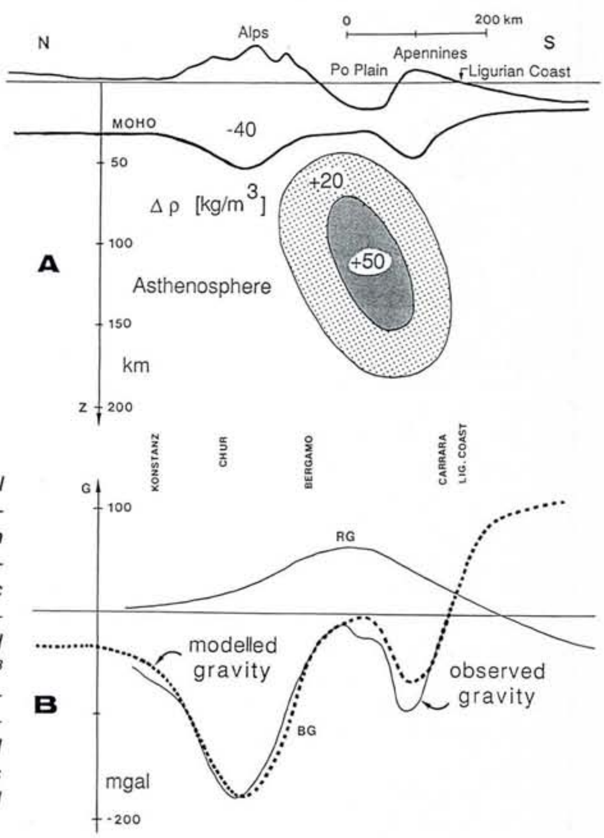

Fig. 5 — Geodynamic model across the Alps. A "gravimetric topography", Moho depth (thick line), and model of deep-seated, dense lithospheric body within the asthenosphere. Numbers (−40, +20, and +50) are densities in kg/m^3 relative to that of the asthenosphere. B observed and modelled Bouguer anomaly (BG) and residual gravity (RG) curves (gravity data from Ref. 7 and density model from Ref. 9).

and called "Bouguer anomalies". Large *negative* Bouguer anomalies indicate missing mass at depth, large *positive* Bouguer anomalies indicate the presence of a deep, extra-dense mass. Negative Bouguer anomalies in a region with normal crustal densities indicate that crustal rocks must continue to abnormal depths as was seen in Fig. 3a in the region of the Alps.

The wavelength of the Bouguer anomaly curve along a given profile is proportional to the depths of the anomaly source. Short and intermediate wavelength Bouguer anomalies provide information about the upper crust (*i.e.* sedimentary basins and density variations in the depth range 1-5 km). Large wavelength gravity anomalies usually reflect changes in depth to the Moho. As stated in the discussion of Fig. 3a, gravity is a potential field and gravity data integrate density effects over a wide region. Long wavelength Bouguer anomalies can be corrected for surficial densities where these are known or estimated and data so corrected are called "residual" gravity. The residual gravity provides information on effects of anomalous bodies located in the lower crust and upper mantle.

Fig. 5 illustrates the gravity behaviour under the southern segment of the EGT. This north-south profile is an extension to the south of Fig. 3. The top line shows the topography of the crystalline basement along a profile extending from Lake Constance to the Ligurian coast and transecting the Alps, the Po Plain, and the northern Apennines. This is not a precise outline of the surface of the Earth, but the surface as seen by a gravity meter, a kind of geologic X-ray. Dense, massive bodies (the Alps with granites, gneisses, and limestones) are opaque, but sediments, such as in the Po Plain, are relatively "transparent". The thick black line marks the seismically determined transition of the crust to the upper mantle (the Moho) as determined by seismic methods. The Alps evidence a large negative Bouguer effect implying that deep under the normal crust there are "roots" of the same material that forms the surficial part of the mountain range. Another region where negative Bouguer anomalies are found is near large sedimentary basins such as the Po Plain which also can be seen to give a negative dip to the Bouguer anomaly curves in Fig. 5b. Positive Bouguer anomalies are encountered in northern Italy where they indicate a buried volcanic arc internal to the Apennines and updoming of the upper mantle beneath the Ligurian Sea. The observed Bouguer anomaly curve in Fig. 5b stops at the Ligurian Coast near Carrara, Italy, but shows clearly the positive trend towards the south.

Further analysis and modelling of detailed gravity data [7]) which form the basis for Fig. 5 yield evidence for a deep density anomaly dipping into the asthenosphere. In Fig. 5b, the lower thin and broken thick lines are the observed and modelled Bouguer anomaly (BG) curves and the upper thin line is the residual gravity (RG) curve. The residual gravity was produced by taking into account all known near-surface effects, such as the sediments of the Molasse Basin to the north of the Alps and of the Po Plain south of the Alps. Seismic refraction and reflection data, information from boreholes, and results of geoelectric soundings were used to define the geometry and the density distributions of these near-surface structures. After the crustal effects were eliminated, a large, long-wavelength positive anomaly is evidenced by the residual gravity curve in Fig. 5b. Three-dimensional modelling [8]) and a least-squares inversion technique were applied to this data and the result indicates a deeply buried, dense body in the upper mantle under the southern margin of the Alps. One model of this structure [9]) is shown in the lower part of Fig. 5a. The centre of this dense body lies southwards of the maximum topography and the minimum Bouguer values due to the Alps and their crustal root. Although this model is still very primitive, lacking independent data from other sources (seismic tomography, precise geodetic levelling, and heat flow among others), it appears that this deep, dense body is a slab of continental lithosphere, partially subducted in the African/European plate collision, which is now lying in a near-vertical position under the southern Alps.

Further south, the EGT crosses Corsica and Sardinia. These two pieces of old (Hercynian) European continent have provided clues to a very dynamic and, in a geological sense, recent past. Similarity of rocks on Corsica and Sardinia with those from southern France supports the view that these islands were once part of the European continent. About 21 Ma ago, they began rifting away from Europe. Magnetic anomalies charted by airborne surveys and the findings of palaeomagnetism (a method based on the record of the direction of the Earth's ancient magnetic field which is contained in some rocks and can be used to reconstruct the movements of parts of the Earth's crust) indicate [10]) that first Corsica alone, then Corsica and Sardinia together, rotated counterclockwise at a relatively fast rate of 30 mm/a. Fig. 6 illustrates this process. Rifting had ceased by 18 Ma ago when Corsica and Sardinia arrived at their present position leaving the Provençal Basin in their wake. This movement could be related to an early stage of the same process that created the central European rift. However, in contrast to central Europe, Corsica and Sardinia were not hindered by complex intra-continental stresses and could completely separate from the rest of the continent. They thus provide a striking example of the horizontal movement of lithospheric blocks and the creation of oceanic basins.

Additional Evidence

To interpret adequately seismic, magnetic, and gravimetric results and synthesise them into models of the evolution of continents, many other methods must also be applied that have not yet been mentioned. These include the measurement of *recent crustal movements* to obtain a picture of the acting stress field through precise geodetic levelling and remote sensing. Accurate gravity data demand precise geodetic measurements (for positioning and elevation) and thus these two methods are closely related. Another valuable method is *geothermics* which can identify temperature anomalies. High heat flow values which indicate active geologic processes, for instance, in volcanic areas, rift zones, and newly forming

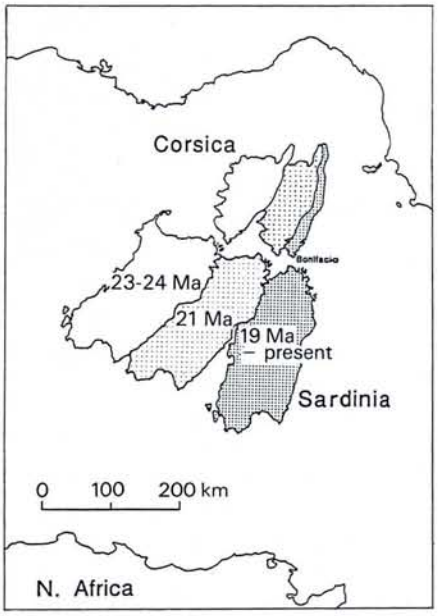

Fig. 6 — Rotation of Corsica and Sardinia. The positions are shown at the beginning of the drifting, at the end of the first step, and in the present situation (data from Ref. 10). Both aeromagnetic and geochronologically-dated palaeomagnetic results were used to constrain the timing and extent of movement.

ocean basins where mantle material is close to the surface. *Geochemistry* is important in gaining direct knowledge of the composition of the lower crust and upper mantle through chemical analysis of xenoliths, mantle and deep crustal material brought up in volcanoes. *Geochronology*, which uses precise analyses of ratios between radioactive isotopes and known decay rates for age dating, can help piece together the puzzle of superposed mountain building events. There are several cases where rocks of ancient mountains have been weathered down and the resistant minerals redeposited as sediments only to become involved again in younger mountain building events. One example of this is shown in Pb-U isotope data from zircons (a very hard zirconium silicate oxide) that were originally formed in mountain building 3700 Ma ago, subsequently eroded, and then redeposited in sediments which were caught up in the Hercynian orogeny dating from 400-230 Ma ago [11].

Geological field studies, aeromagnetics, geothermics, and palaeomagnetism combined to provide the crucial evidence for the rotation of Corsica and Sardinia. Although this rotation is now an accepted part of the geological evolution of the western Mediterranean, this result and others have created more questions than they have answered. How and when did the rifting from the European continent take place? What processes in the asthenosphere and lithosphere trigger rifting and drive the mechanism of plate movement? What is the nature of the layers and zones detected by the electromagnetic and seismic methods? What keeps the Alps rising when a deep density anomaly lies below their roots? The present EGT programme will not be able to answer these difficult questions, but the large amount of data obtained from many different methods, the organisational structures, and the human resources for evaluating, analysing, and integrating these data into a unified whole, together provide a fertile ground out of which answers may one day arise.

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