Matériaux pour la Géologie de la Suisse

GEOPHYSIQUE
No 21

Publiés par la Commission Suisse de Géophysique
Organe de la Société Helvétique des Sciences Naturelles,
subventionnée par la Confédération

GEOMAGNETIC AND GRAVIMETRIC STUDIES OF THE IVREA ZONE

Études géomagnétiques et gravimétriques
de la zone d'Ivrée

Geomagnetische und gravimetrische
Untersuchungen der Zone von Ivrea

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En Commission
chez Kümmerly & Frey, Geographischer Verlag, Berne
1984

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Printed in Switzerland by Paul Attinger S.A., Neuchâtel

Preface

The present publication, entitled "Geomagnetic and Gravimetric Studies of the Ivrea Zone", is Report No. 21 of the "Contributions to the Geology of Switzerland - Geophysical Series". It contains seven papers on the most recent work carried out in the Ivrea Zone by the Swiss Geophysical Commission.

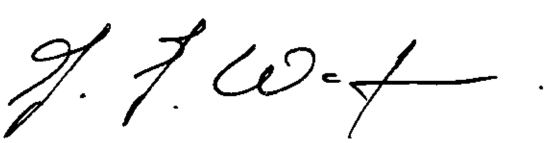
The Ivrea-Verbano Zone at the southern border of the Western Alps in northern Italy has for some time been considered as representing an important prototype structure which permits insight into the middle and lower continental crust. For that reason there is continued interest worldwide to study this anomalous region in more detail with all available techniques.

About 35 years ago Swiss geophysicists started to investigate the pronounced magnetic anomaly west of Locarno, on the northern side of the Lago Maggiore. It soon became clear that this anomaly was part of a much more extended regional disturbance of the Earth's magnetic field located in the inner arc of the Western Alps. Ever since the interest in the Ivrea problem has been kept alive, in particular by Professor Ernst Niggli (Bern) who already in 1946 had pointed out the relation between the positive gravity anomaly and the rock sequence exposed in the Ivrea Zone. He also initiated the first international symposium on the "Zone Ivrea-Verbano" in 1968, which was followed by a second symposium ten years later with Ernst Niggli acting as Honorary President.

The Swiss Geophysical Commission is greatly indebted to the authors of the various contributions in this publication and to all those who have helped in carrying out the extensive measurements in numerous field campaigns. The editors would like to dedicate this volume to Professor Ernst Niggli in recognition of his continued efforts to promote detailed studies of the Ivrea Zone.

Special thanks for financial support are due to the Swiss Federal Office of Education and Science, the Swiss National Science Foundation, the Swiss Academy of Natural Sciences, the Swiss Federal Institute of Technology and, in particular, to the University of Geneva which has contributed substantially to the present project.

On behalf of the Swiss Geophysical Commission



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November 1984

Summary

This volume on "Geomagnetic and Gravimetric Studies of the Ivrea Zone" contains seven reports on recent investigations in the Ivrea-Verbano Zone by Swiss geophysical groups.

The first two papers summarize the geology and the geophysics of that zone. The first paper by R. Chessex and J.-J. Wagner, "On the Geology of the Southern Border of the Western Alps", introduces the reader to the geology of the main structural units of the inner arc of the Western Alps. The second paper entitled "Geophysical Studies of the Ivrea Zone - A Review -" by J.-J. Wagner gives an overview of the most recent geophysical activities in the fields of explosion and laboratory seismology, gravity, geothermics and paleomagnetism.

The next four papers are devoted to the magnetic anomaly associated with the Ivrea Zone. A regional study by J.-J. Wagner, E. Klingelé and R. Mage entitled "Regional Geomagnetic Study of the Southern Border of the Western Alps - The Ivrea Body -", which covers an area of 7000 km^2, defines the major magnetic field disturbances between the localities of Cuneo to the south and Locarno to the north. An interpretation based on the "two and a half-dimensional modelling" method is discussed. In order to have a better understanding of the sources which cause the magnetic anomalies the magnetic properties of the various outcropping rocks have been measured in the laboratory; the data obtained by J.-J. Wagner are reported under the title "Petrophysical Properties of the Ivrea Zone and Adjacent Areas". E. Klingelé, P. Finckh and N. Deichmann in their paper entitled "Detailed Survey of the Locarno Magnetic Anomaly, Switzerland" consider the northern end of the magnetic anomaly caused by the Ivrea Body; this survey has been carried out both on land and on the Lago Maggiore. The work by H. Schwendener, dealing with "The Ivrea Magnetic Anomaly in the Valle d'Ossola and Valstrona Area, Northern Italy" illustrates the good correlation of the magnetic anomalies with the local geology.

Finally, the last paper by E. Kissling entitled "Three-Dimensional Gravity Model of the Northern Ivrea-Verbano Zone" presents a very interesting and careful study of the positive gravity anomaly due to the Ivrea Body which complements the magnetic interpretations.

Although this volume contains much new geophysical information on the southern border of the Western Alps further investigations with the same methods will still be necessary. In particular, it is hoped that detailed seismic reflection work will help to delineate more fully the structural elements of the Ivrea-Verbano Zone.

Table of Contents

I
ON THE GEOLOGY OF THE SOUTHERN BORDER OF THE WESTERN ALPS

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On the Geology of the Southern Border of the Western Alps

1. Introduction

The southern border of the Western Alps is of great interest to many earth scientists because there one finds outcrops of large parts of intermediate and lower continental crust and also of upper mantle material. Before going into more details it is useful to outline the general geological setting.

It is possible to subdivide the Swiss Alps and the adjacent area into a number of large domains, whose composition, structure and evolution differ in many aspects and present large contrasts. The main subdivisions are essentially based on the character of the Mesozoic covers but the older eruptive, metamorphic and sedimentary rocks also exhibit important distinct characteristics.

Along a profile of interest for us (through the Western Alps, on the border between Switzerland and Italy), one distinguishes, from the NW to the SE, or from the exterior towards the interior of the Alpine arc, the Helvetic, the Penninic (partially of oceanic character), the Austroalpine and the Southern Alpine domains. The latter two are the subject of our investigations (Fig. 1).

The Austroalpine domain is represented by the Sesia-Lanzo Zone, a fragment of Permo-Carboniferous and older continental basement which formed the southern margin of the oceanic Penninic-Piémontais domain. This zone and also the Dent-Blanche nappe, which has a similar character, are likely to correspond to the lower Austroalpine nappes of eastern Switzerland (Grisons). This Austroalpine basement is mainly made up of crystalline rocks which have undergone effects of Alpine metamorphism, especially the eo-Alpine phase in the Upper Cretaceous. For more details on the Penninic-Austroalpine boundary see Trümpy (1975).

The Southern Alps are separated from the domains mentioned above (Alps in a restricted sense) by major sutures (e.g. the Insubric Line), the evolution of which is still debated. The facies of the Austroalpine and Southern Alpine formations possess many similar features, both domains are parts of the so-called "Apulian (or Adriatic) promontory" or microplate which very likely belongs to the African plate. However, their structures differ strongly in the sense that in the Southern Alps the effects of Alpine orogeny are very weak and Alpine metamorphism is not found. The basement of the Southern Alps is mainly composed of the Ivrea-Verbano and Strona-Ceneri Zones. The Ivrea-Verbano Zone which forms the major part of the studied area, is limited towards the NW by the Insubric Line and to the SE by the Strona-Ceneri Zone.

2. The Ivrea Zone

The Ivrea Zone, or more precisely the "Diorito-Kinzigitic Zone of Ivrea-Verbano", was recognized and defined by Franchi (1905). It is the object of intensive and detailed investigations particularly since two international symposia have been dedicated to it (First Symposium Zone Ivrea-Verbano, 1968, Bull. suisse minéral. pétrogr., **48,** 1968, and Second Symposium Ivrea-Verbano, 1978, Proceedings, Mem. Scienze Geologiche Univ. Padova, **33,** 1978–9). Recent and fundamental contributions by Zingg and Schmid (1979), Zingg (1980), Hunziker and Zingg (1980) and Zingg (1983) contain most of the significant references. A large part of our geological data comes from their studies.

The basement of the Southern Alps, W and SW of Lago Maggiore, is formed by the two zones of Strona-Ceneri and Ivrea (Fig. 2). The Strona-Ceneri Zone, which is the southernmost part of the basement complex consists mainly of migmatites, gneisses and micaschists belonging to the amphibolite facies. These rocks are intruded by Permian granites (Baveno granite, etc.), covered discordantly by Permian volcanics (porphyrites) and by Mesozoic sediments.

The Ivrea Zone, located between the Strona-Ceneri Zone to the SE and the Canavese and Sesia-Lanzo Zones to the NW, outcrops in the shape of an arc approximately 180 km long, stretching from the vicinity of Ivrea in the SW to Locarno in the NE. Its maximum width is about 20 km.

This zone exhibits a subvertical series of pelitic and mafic rocks with intercalations of carbonaceous and ultramafic rocks. The composition and the high degree of metamorphism in the granulite facies, indicate that it is a segment of the deep crust.

In the central part of this zone, metabasites and metapelites alternate more or less regularly. However, in the NE and in the SW, mafic rocks are dominant forming the so-called "Basischer Hauptzug" or "Mafic Main Formation".

The metapelites correspond essentially to rocks known under the names of kinzigites (amphibolite facies) and stronalites (granulite facies). The ratio of garnet to biotite grows steadily with the increase in the intensity of the metamorphism. Simultaneously one observes a

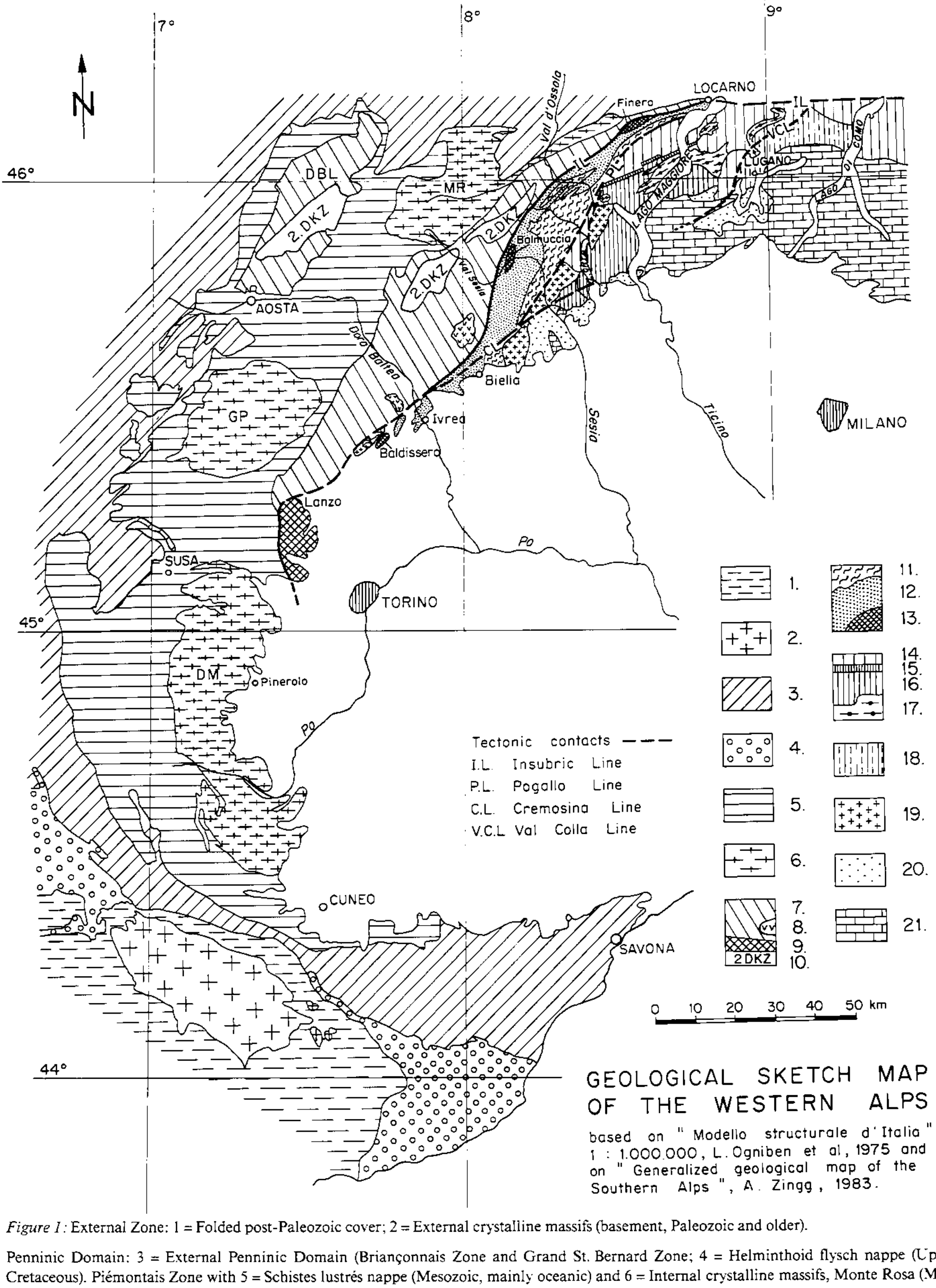

Figure 1: External Zone: 1 = Folded post-Paleozoic cover; 2 = External crystalline massifs (basement, Paleozoic and older).

Penninic Domain: 3 = External Penninic Domain (Briançonnais Zone and Grand St. Bernard Zone; 4 = Helminthoid flysch nappe (Upper Cretaceous). Piémontais Zone with 5 = Schistes lustrés nappe (Mesozoic, mainly oceanic) and 6 = Internal crystalline massifs, Monte Rosa (MR), Gran Paradiso (GP) and Dora Maira (DM).

Austroalpine Domain: 7 = Sesia Zone s.str. and Dent Blanche nappe (DBL); 8 = Tertiary intrusives; 9 = Ultramafics (Lanzo); 10 = "Second Diorito-Kinzigitic Zone" and "Valpelline Series" in DBL (2nd DKZ).

Southern Alps: Ivrea Zone; 11 = Paragneiss; 12 = Mafic rocks; 13 = Ultramafic rocks. Strona-Ceneri Zone; 14 = Gneiss unit; 15 = Amphibolites; 16 = Schist unit; 17 = Orthogneisses. Val Colla Zone; 18 = Gneisses, schists, phylonites. Post-Variscan rocks; 19 = Permian intrusives; 20 = Permian volcanics; 21 = Permo-Mesozoic sediments.

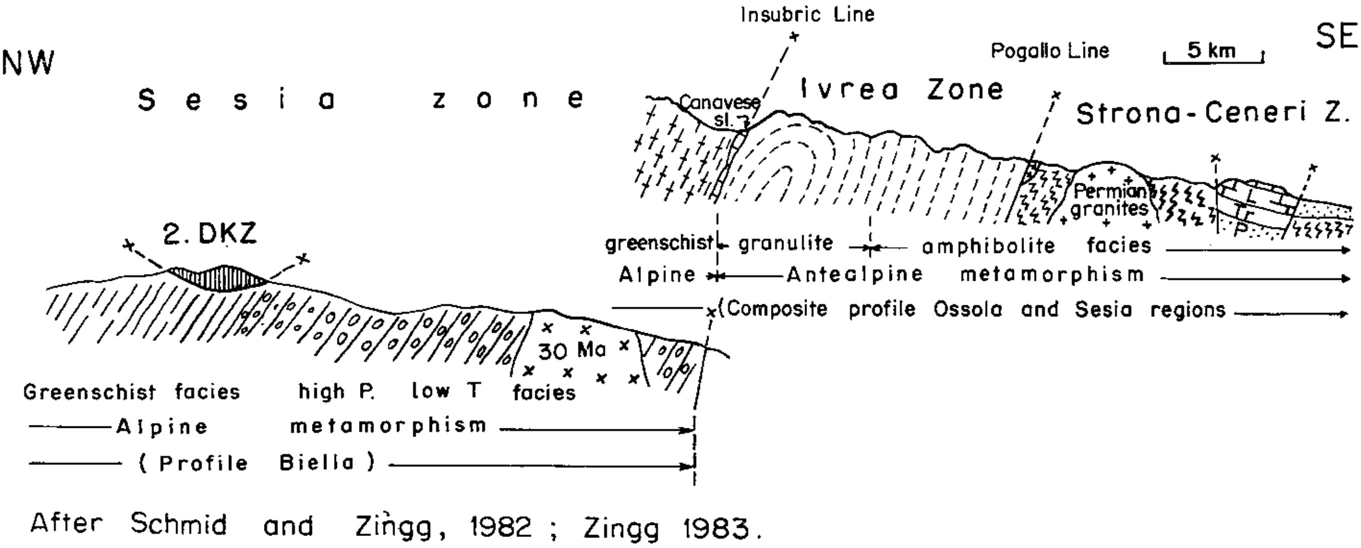

Figure 2: Schematic NW-SE geologic cross section through the Insubric Line and the adjacent units (Sesia-Lanzo Zone on the NW side and Ivrea and Strona-Ceneri Zones on the SE side).

progressive decrease of the water content related to the partial anatexis which supposedly must have been responsible for the degranitization of these rocks. It is nevertheless doubtful that the liberated fluids migrated into the adjacent Strona-Ceneri Zone which represents a higher crustal level (Zingg, 1983).

The predominantly mafic and associated ultramafic rocks have probably been intruded into the deep-lying (at more than 20 km depth) pelitic series. The relation between the intrusion and the metamorphism can be questioned but since the material came from the upper mantle it provided additional heat (Zingg, 1980).

The intensity of the metamorphism increases progressively from the SE to the NW following the direction of the Insubric Line and grading from the amphibolite to the granulite facies. This transition is visible in several of the transverse valleys, e.g. in the Valle d'Ossola and Valstrona. Locally the regular metamorphic zonation is obliterated by synmetamorphic intrusion of the Mafic Main Formation. In the Val Sesia, for example, the mafic magmatic parageneses are only partially re-equilibrated in the metamorphic conditions of the amphibolite-granulite facies. It is also important to mention that the pressure decreases from the NE to the SW, parallel to the strike of the regional structures; it is explained by the axial dip of the Ivrea Zone.

The Ivrea and Sesia-Lanzo Zones contain a few ultramafic massifs, mainly made up of lherzolite. Nicolas (1984) describes three groups (Fig. 1): The feldspar lherzolite (Lanzo massif), the spinel lherzolite (Baldissero and part of Balmuccia) and the granulitic peridotite (Finero). The largest ultramafic massif is that of Lanzo (Fig. 1); it outcrops at the internal limit of the Sesia-Lanzo Zone. Most likely it was emplaced during the Mesozoic in the vicinity of the plate boundary separating Central Europe and the Southern Alps. The other massifs are found near the Insubric Line. Their origin and their history are not fully understood up to now. The exact age is still in doubt because their metamorphism and emplacement are complicated; it seems nevertheless certain that they are pre-Alpine. Some of the lherzolites, initially the garnet lherzolites, could have been derived from an oceanic lithosphere modified during subduction. Spinel lherzolites were then emplaced at the mantle-crust boundary during the Caledonian orogeny. At the same time, and perhaps also later during the Variscan (Hercynian) orogeny, a part of the ultramafics in the Ivrea Zone has been metamorphosed into the granulite and amphibolite facies. The Finero massif with phlogopite and hornblende peridotites, visible in the NE of the zone, has undergone this evolution. Several structural studies emphasize these complications (Lensch, 1968; Steck and Tièche, 1976; Kruhl and Voll, 1970).

The geological, petrological and isotopic data do not allow to derive a unique model for the age and the evolution of the Ivrea Zone. For the time being, the model proposed by Hunziker and Zingg (1980) seems to be the preferable one. Recently Laubscher and Bernoulli (1982) attempted to organize the main lines of the complicated evolution of the Ivrea Zone in terms of depth, temperature and time (Fig. 3).

The highest metamorphism corresponding to the highest temperature and pressure conditions, are found in the amphibolite facies in the south and in the granulite facies in the north; they date to the Ordovician (between 400 and 500 Ma). This is shown by the whole rock Rb-Sr dating on paragneisses and migmatites. The emplacement of the Mafic Main Formation could be more or less contemporaneous with the metamorphism. However, one has to note that the geotectonic environment of this epoch is not well-known. The sedimentation of the pelitic series could have taken place during the Upper Precambrian or the Lower Paleozoic.

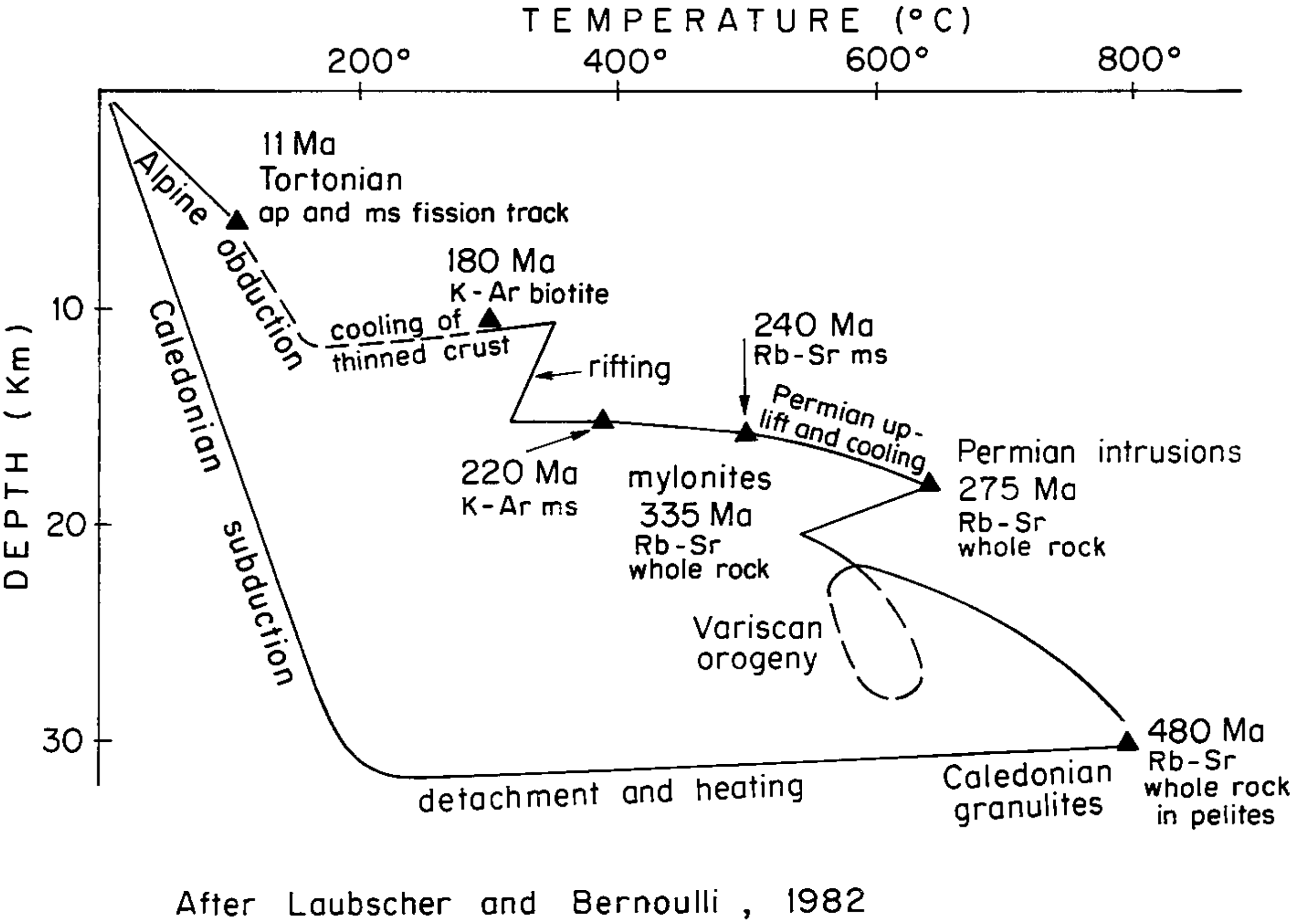

Figure 3: Depth, temperature and time diagram. A first attempt by Laubscher and Bernoulli (1982) to summarize the evolution of the Ivrea Zone.

During the period separating this regional metamorphism from the Variscan orogeny the Ivrea Zone lay at depth, in a more or less horizontal position. The various radiometric ages obtained by different methods on a variety of rocks and minerals show that the Ivrea Zone and the NW part of the Strona-Ceneri Zone cooled much more slowly than the main part of the latter zone. The lack of correspondence between the radiometric ages and the limits of that zone may be due to the fact that these limits are partly defined by recent faults.

The Variscan orogeny has given rise to prograde and retrograde metamorphism essentially in the greenschist and possibly in the amphibolite facies. It is probable that the crustal contamination of the phlogopite peridotite from Finero has taken place during this event. In the Permian, if one accepts the U-Pb ages obtained on zircons and monazites (Köppel and Grünenfelder, 1978/79), the Ivrea Zone was still at great depth whereas the Strona-Ceneri Zone had moved to a much higher structural level.

An important problem is the age and the emplacement mechanism of the Ivrea Body into its present position; is the structure of Variscan or Alpine age ?

Up to now no unequivocal answer has been given to this problem, in particular since the history of the major fault lines limiting the Ivrea Zone is still poorly known. This relates to the Insubric Line which separates the Ivrea Zone from the Sesia-Lanzo Zone and the so-called "Root Zone" to the NW, to the Pogallo Line which separates the Ivrea Zone from the Strona-Ceneri Zone to the SE and to the Cremosina Line located south of the Pogallo Line (Figs. 1 and 2).

Of these different faults, the Insubric Line or Tonale Line (east of Locarno) is the most important one, and many studies have been devoted to it. The only common conclusion derived from them is that the Insubric Line has had a major influence. It forms the southern limit of the large Penninic nappes and the so-called "Root Zone", and also of the Alpine metamorphism. The vertical displacement is certainly important and it is possible that the mechanism has been that of a wrench fault (Laubscher and Bernoulli, 1982). If some movements of it are late and post-metamorphic, others—more difficult to prove—must be early Alpine or even pre-Alpine.

The interpretation of the Pogallo Line is also controversial. Boriani and Sacchi (1973) concluded that it was a

Paleozoic synmetamorphic fault. Hodges and Fountain (1984) postulate that the Pogallo Line was a Late Triassic to Early Jurassic low-angle normal fault with up to 15 km of stratigraphic throw, juxtaposing upper crustal (Strona-Ceneri) and intermediate crustal (Ivrea) rocks. Its present steep dip was only recently attained, namely during a Middle Oligocene-Miocene episode of backfolding and high-angle (Insubric) faulting. However, let us point out that several authors have suggested that the entire crustal section was already perpendicularly upright by Permian time !

3. Sesia-Lanzo Zone

The Sesia-Lanzo Zone (Figs. 1 and 2) is one of the main structural units of the internal Western Alps. It has an elongated form, 90 km long by 25 km wide, extending in a SW-NE direction from the river Stura di Lanzo, near Torino, to the Val d'Ossola where it narrows and finally ends near Locarno. It consists of continental crust attributed to the Austroalpine domain and comprises mono- and poly-metamorphic rocks of variable compositions. It is characterized by the development of a paragenesis of the high-pressure eclogite and blueschist facies. The Sesia-Lanzo Zone is considered as the NW margin of the South Alpine plate, also named the Insubric plate.

The internal limit of the Sesia-Lanzo Zone is defined by the Canavese tectonic line which separates the former from the narrow Canavese Zone and from the Ivrea Zone. The Canavese Zone is a complex tectonic scar (Aubouin *et al.,* 1977). At the southern edge of the Sesia Zone one finds the lherzolitic massif of Lanzo. This ultramafic complex is separated from the Gran Paradiso massif and its cover, consisting of "schistes lustrés" with embedded ophiolites (Penninic domain) by the Viu-Locana (imbricated structure) zone.

According to Nicolas (1974) the Lanzo massif is the exposed top of a slice rooted in the upper mantle. It has been wedged between the South Alpine and the Central European plates during the Alpine orogeny; geophysically it belongs to the Ivrea Zone, i.e. the South Alpine plate. The Lanzo massif exhibits Alpine metamorphism and tectonic effects in its western part.

Compagnoni *et al.* (1977) have interpreted the Sesia-Lanzo Zone as a composite Austroalpine nappe which can be subdivided into two tectonic elements:

(1) An upper element which possesses a lithological and a tectonic identity and is known in the literature as the "Second Diorito-Kinzigitic Zone" (2nd DKZ). Its origin is located north of the Ivrea Zone.

(2) A lower element which comprises the complex of the eclogitic micaschists and the complex of the Minuti gneisses.

The various "klippen" belonging to the upper element are formed by rocks whose lithology and metamorphism are pre-Alpine; they are similar to those of the Ivrea Zone. The ultramafics are only represented by a small harzburgite massif cut by a few pyroxenite dykes (Upper Artogna Valley).

In the lower element the mafic rocks are more frequent in the eclogitic-micaschist complex than in the Minuti gneisses.

The Sesia-Lanzo Zone has been subjected to the two main Alpine metamorphic episodes. A first eo-Alpine phase of high-pressure type in the internal and southern parts of the zone is dated Upper Cretaceous. One observes the development of eclogites and glaucophane schists on pre-Alpine mafic rocks. A second phase, termed meso-Alpine, younger than the thrusting, developed mainly a paragenesis in the greenschist facies.

4. Acknowledgments

We are grateful to the Swiss Geophysical Commission for financial support. We would like to thank André Zingg for providing us with preprints of his work in the Ivrea Zone and for his comments. We also thank Marc Vuagnat for the critical reading of the manuscript. Ronald J. Veitch helped us to improve the English. Jacqueline Berthoud typed the text and Pierre Zbinden drew the figures.

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II
GEOPHYSICAL STUDIES OF THE IVREA ZONE
– A REVIEW –

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Geophysical Studies of the Ivrea Zone
– A Review –

Introduction

During the last decade new explosion seismic, gravimetric, geomagnetic (ground and paleomagnetic surveys) and geothermic studies have been carried out in the Central and Western Alps.

The southern border of the Western Alps, in particular the Ivrea and Strona-Ceneri Zones which exhibit upper mantle and lower to intermediate continental crust, has fascinated many earth scientists and particularly geophysicists working on different aspects of mountain building. These studies have concentrated on two aspects:

(*a*) The geophysical signature related to the collision between the European and the African plates in the region of the Alps.

(*b*) The rocks outcropping in the Ivrea Zone seem to be suitable for a modelling of the intermediate to lower crust.

This review is not exhaustive but serves to draw attention to several interesting contributions to both aspects mentioned above. The geomagnetic studies will not be presented here because most of the papers in this volume are related to them.

Explosion and Laboratory Seismology

Most of the recent results obtained from seismic refraction studies are given by Ansorge *et al.* (1979) and by Mueller *et al.* (1980). They investigated a crustal cross section oriented NW-SE which extends from the Simplon/Monte-Rosa area to the southern tip of the Lago Maggiore (see Fig. 3 by E. Kissling, this volume).

This section shows that crossing the Insubric Line coming from the NW a sharp velocity jump from 5.8 to 7.4 km/s is encountered extending to a depth of more than 10 km. This high-velocity zone overlies a zone of extremely low velocity (about 5 km/s). Seismic reflection observations indicate that the high-velocity zone is limited towards the NW by the NW-dipping fault surface of the Insubric Line, and to the SE by an eastward dip. Further SE of Lago Maggiore, below Sesto Calende, one finds another type of crustal structure with a low-velocity zone (5.4 km/s) in the thin upper crust (between 6 and 10 km depth) overlying a rather uniform deeper crust with 6.3 km/s. The Moho is found at 35 km depth.

The seismic structure northwest of the Insubric Line is very different from the structure southeast of the Ivrea Zone; this could be interpreted as the seismic expression of the contact zone between the European and the African plates.

The Sesia-Lanzo and the Ivrea and Strona-Ceneri Zones were used to model the upper mantle and the lower crust.Based on a field and a laboratory investigation Peselnick *et al.* (1974) demonstrated velocity anisotropy in mantle peridotite. They measured compressional P velocity under confining pressures of up to 1.5 kbar at room temperature, on samples from the Lanzo lherzolitic massif. A velocity anisotropy of about 7%, independent of pressure up to several kbar, was observed. The velocities under 1 to 2 kbar ranged between 7.3 and 7.9 km/s for a mean density of 3.2 g/cm^3. An amount of serpentinization of 14% seems to represent the "mean serpentinization" of the Lanzo massif. The seismic anisotropy data have the highest value in the direction of the peridotite flow line defined by the olivine fabric. The mantle anisotropy has so far been mainly investigated for the oceanic lithosphere (Francis, 1969).

A systematic laboratory study of seismic velocities has been carried out by Fountain (1976). The measurements were made on rock samples from the Ivrea and Strona-Ceneri Zones under confining pressures of up to 10 kbar. Some of the results are shown in the diagram of Figure 1 which gives the P velocity distribution on a NW-SE cross section. The ultramafic complexes near the Insubric Line have velocities of up to 8.5 km/s.

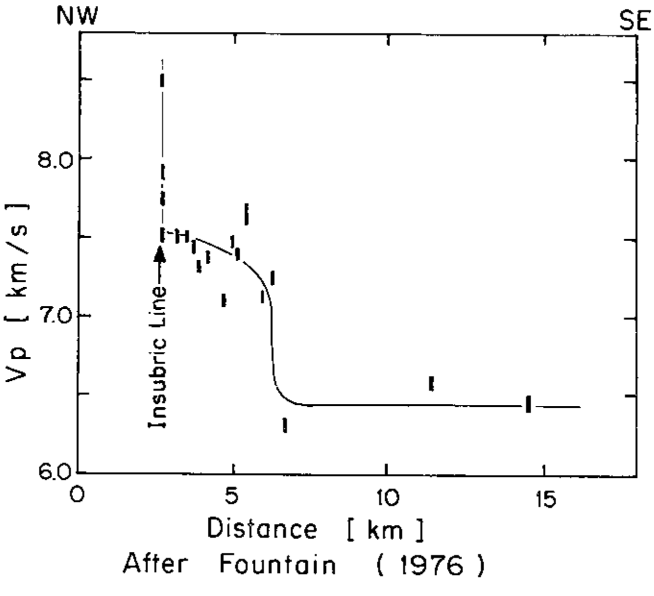

Figure 1: Profile through the Ivrea and Strona-Ceneri Zones of laboratory-measured compressional wave velocities obtained under confining pressures ranging from 6 to 10 kbar.

Moving to the SE along the section the values decrease abruptly to 7.5 km/s which is related to the granulite-amphibolite facies transition zone. The velocity decreases again abruptly to 6.45 km/s for the kinzigite gneisses. If the seismic velocities of rocks from these zones determined in the laboratory are compared to the known crustal velocity structure of the area, strong evidence is found—as Fountain (1976) claims—that the studied sequence represents a nearly complete cross section of the continental crust. This may be helpful in elucidating the structure of other crustal areas, especially since deeper crustal investigations using the reflection seismic method have been initiated recently (Oliver, 1982). With this powerful method one is in the position to trace reflectors from the visible surface geology down into the crust, but where this is not possible synthetic seismograms must be used in the interpretation. Hale and Thompson (1982) used Fountain's (1976) P velocities and densities and Schmid's (1967) geological cross section for the layer thicknesses to generate synthetic seismograms for reflectors in the deeper crust. Their simulation exhibits seismic laminations as actually seen in observed reflections from the lower crust. It is highly probable that with systematic deep seismic crustal reflection investigations currently under discussion the Ivrea Zone will be chosen as one of the prime targets, since it can be considered as an exceptional laboratory in nature.

Gravity

The most important contribution in this field are the new gravity anomaly maps of the Western Alps by Guillaume and Guillaume (1980): A Bouguer map calculated for the standard density of 2.67 g/cm³ which takes into account the terrain effect up to 166.7 km, and an Airy isostatic gravity map with a compensation depth of 30 km and a density contrast of 0.6 g/cm³.
The Bouguer map from which a sector is reproduced covering the anomalous Ivrea Zone (Fig. 2) clearly shows the positive gravity values reaching 60 mgal and more. As mentioned by the authors the anomalies are not strictly parallel to the surface geology. A major E-W shift in the anomaly is visible near Varallo; this observation could possibly be related to a major transverse crustal effect in the Alps. The fluctuations in the positive values could be explained by variations in depth to the top of the Ivrea "perturbing" body.

Geothermics

Although less often mentioned, geothermal data such as heat flow and heat production are of considerable importance in the study of a collision area. 26 heat flow determinations using a 2 meter probe (Haenel, 1974) were made in lakes of Northern Italy. From these measurements 18 are of direct interest in the study of the Ivrea and Strona-Ceneri Zones. Their location is shown on the map in Figure 3 which includes also two values obtained in boreholes (Coleretto near Ivrea and Chezallet near Aosta), and finally a value from the Mont Blanc Tunnel. The mean heat flow for the lakes in the Southern Alps is 64.1 mW/m² ± 9.5 mW/m² which is reduced by an uplift and denudation correction to 43.0 mW/m² ± 7.0 mW/m². The correction is of the order of 33% of the measured value. Finckh (1976) has also made heat flow determinations in some of the northern Italian lakes (as e.g. Lago Maggiore), but with a 12 meter long probe. His results give much higher heat flow values. The discrepancy between the different results raises the question of the reliability of heat flow data. In a critical assessment Haenel (1979) indicates that in lake measurements errors of up to ± 20% have been estimated. It is, furthermore, difficult to compare results because different investigators have only estimated some of the parameters, such as thermal conductivities and sedimentation rates, or have used different corrections.

Therefore, rather than comparing both sets of data, only Haenel's data (1974) will be used. Examining the map (Fig. 3), it seems clear that near the town of Ivrea the borehole data are of the same magnitude as the Lake Sirio and Lake di Viverone data; this permits us to define a relative heat flow minimum in the area which could be associated with the Ivrea Zone or the "Ivrea Body". Both to the west and to the east of the Ivrea Zone the values are higher, a little greater than 80 mW/m² west of the Sesia-Lanzo Zone and between 60 to 80 mW/m² in the Strona-Ceneri Zone and further east.

Höhndorf (1975), in an attempt to calculate the temperature field of the area, determined the heat production of samples from the Ivrea Zone. The histogram in Figure 4 recapitulates these data. One sees that the porphyrites and the granites have the highest values, while the amphibolites are an order of magnitude lower and the ultramafics give only a negligible contribution.

Höhndorf *et al.* (1975) calculated stationary thermal models for the "Ivrea Body" using heat flow and heat production (A) data available at that time. Figure 5 presents a compilation of some of their results. The geometry of the model (Fig. 5A) is based on the classical seismic interpretation (see e.g. Berckhemer, 1969). The model presented here has a uniform thermal conductivity of k = 2.5 W/m·K (Fig. 5C), but the authors have also used a model with a variable conductivity with depth. Regardless of the model used the calculated heat flow values are not affected fundamentally. Figure 5B exhibits the range of fluctuations for the theoretical surface heat flow. Model 1c of Höhndorf *et al.* (1975) shows that west of the Ivrea Zone the Moho (M_W) lies at 50 km depth and has a theoretical temperature between 800 and 1300 °C; east of the "Ivrea Body" the Moho (M_E) lies at only 30 km and the calculated temperature there is between 500 and 800 °C (Figs. 5A and 5C). The authors conclude on the basis of the theoretical temperature distributions that the low-velocity layer west of the "Ivrea Body" could be in a partially molten state if one assumes wet granitic material. As this model is rather complex, one should be careful before reaching definite conclusions. It would be useful to compare these results with data from the Central Alps (Rybach *et al.*, 1977).

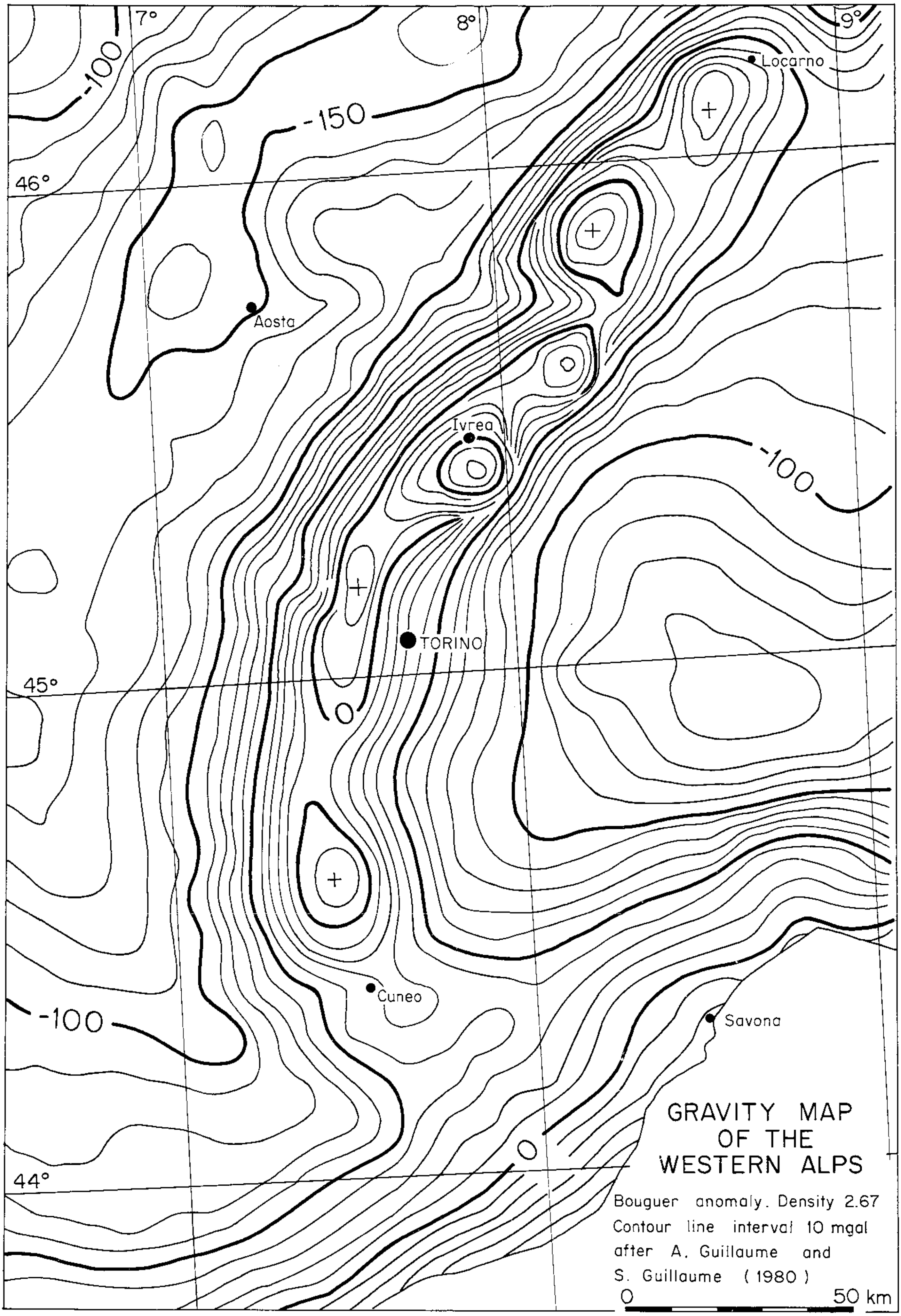

Figure 2: Bouguer gravity anomaly map of the Western Alps for a density of 2.67 g/cm³ and a terrain effect calculation up to 166.7 km. The positive "highs" correspond to the geophysical Ivrea anomaly.

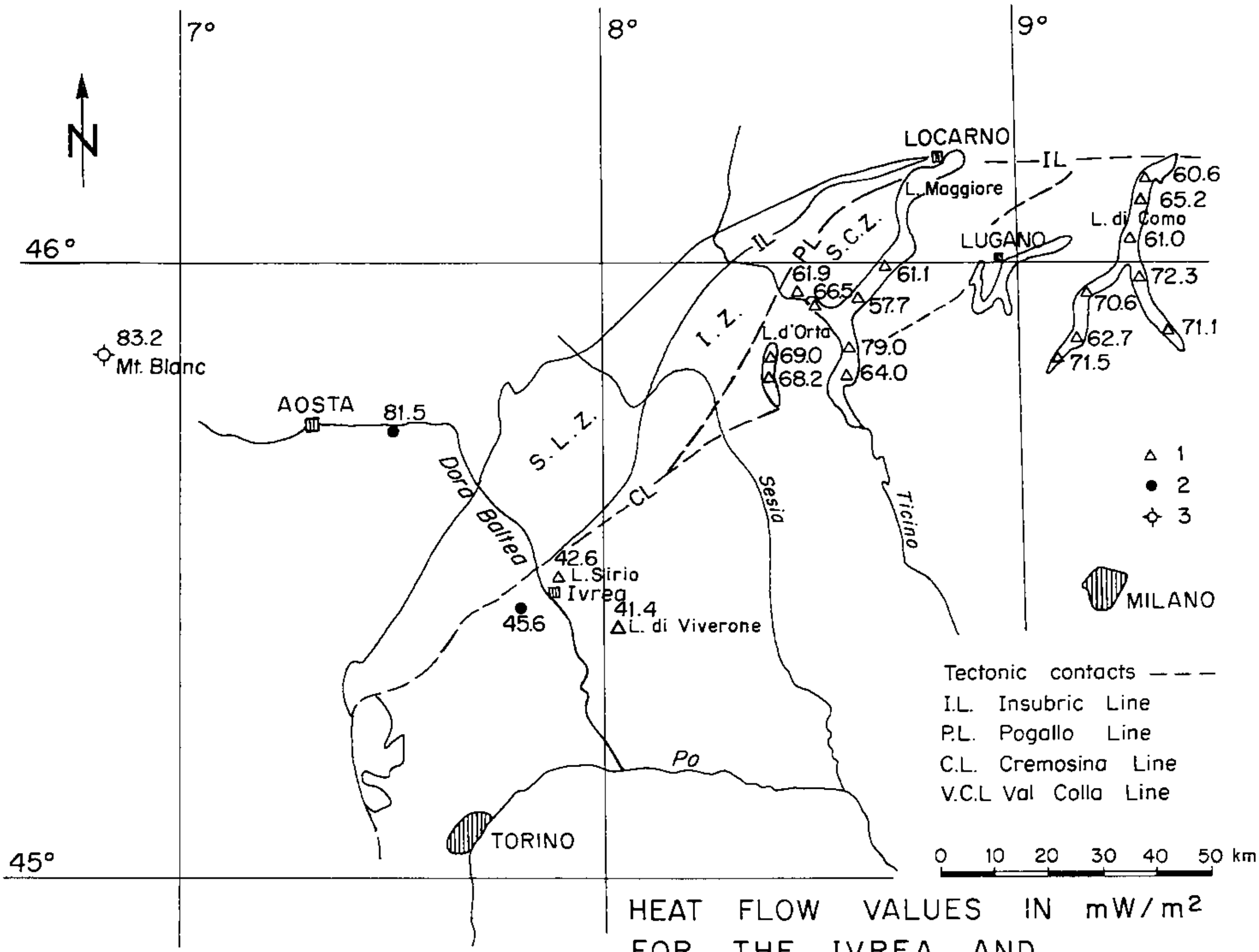

Figure 3: Heat flow values for the Ivrea and Strona-Ceneri Zones. Determinations from 1 = Lake; 2 = Borehole; 3 = Tunnel.

Paleomagnetism

Several studies dealing with the Sesia-Lanzo Zone and the Ivrea and Strona-Ceneri Zones have been published. They all deal with rocks located south of the Insubric Line and, therefore, have escaped the effects of Alpine metamorphism. They have, however, been affected by Alpine tectonics. Furthermore, pre-Permian rocks were subjected to the complex thermal history of the region.

Heller and Schmid (1974) sampled four valleys cutting the Ivrea Zone (V. Cannobina, V. d'Ossola, V. Sesia and V. Sessera) and examined the various rocks (ultramafics and metapelites). Most samples were found to carry a stable magnetization. The most difficult problem throughout this area is to find appropriate references to make the necessary geological corrections to the in-situ magnetization directions. Using the layering as a reference plane the authors suggest that the zone was already steeply dipping during the acquisition of the magnetization and that it has been subsequently deformed. The directional data of these pre-Permian metamorphites indicate a regional anti-clockwise rotation with respect to "stable Europe".

Heiniger (1979) investigated the Permian volcanics (porphyrites) which discordantly cover the basement rocks in the Strona-Ceneri Zone; the sampling sites are in the region of Arona (SW of Lago Maggiore) and the "porphyry district" of Lugano and Ganna. In general alternating field and thermal demagnetizations revealed a stable component. The author mentions that in some places (e.g. in the eastern part of the Lugano district) the tectonic movements have affected the relative position of the volcanics and it, therefore, is not possible to re-establish their original position. The consistent directions determined from samples of the better sites suggest that the Southern Alps have been rotated anti-clockwise by about 50° relative to "stable Europe" since the early Mesozoic. In fact, these Permian paleopoles correspond closely to the Permian part of the African polar wander path.

Paleomagnetic investigations in the Sesia-Lanzo Zone are associated with the late magmatic history of Tertiary age. Andesitic and lamprophyric dikes (Oligocene) located NW of the town of Ivrea exhibit stable remanent directions after alternating field cleaning (Lanza, 1977). They cluster around two directions

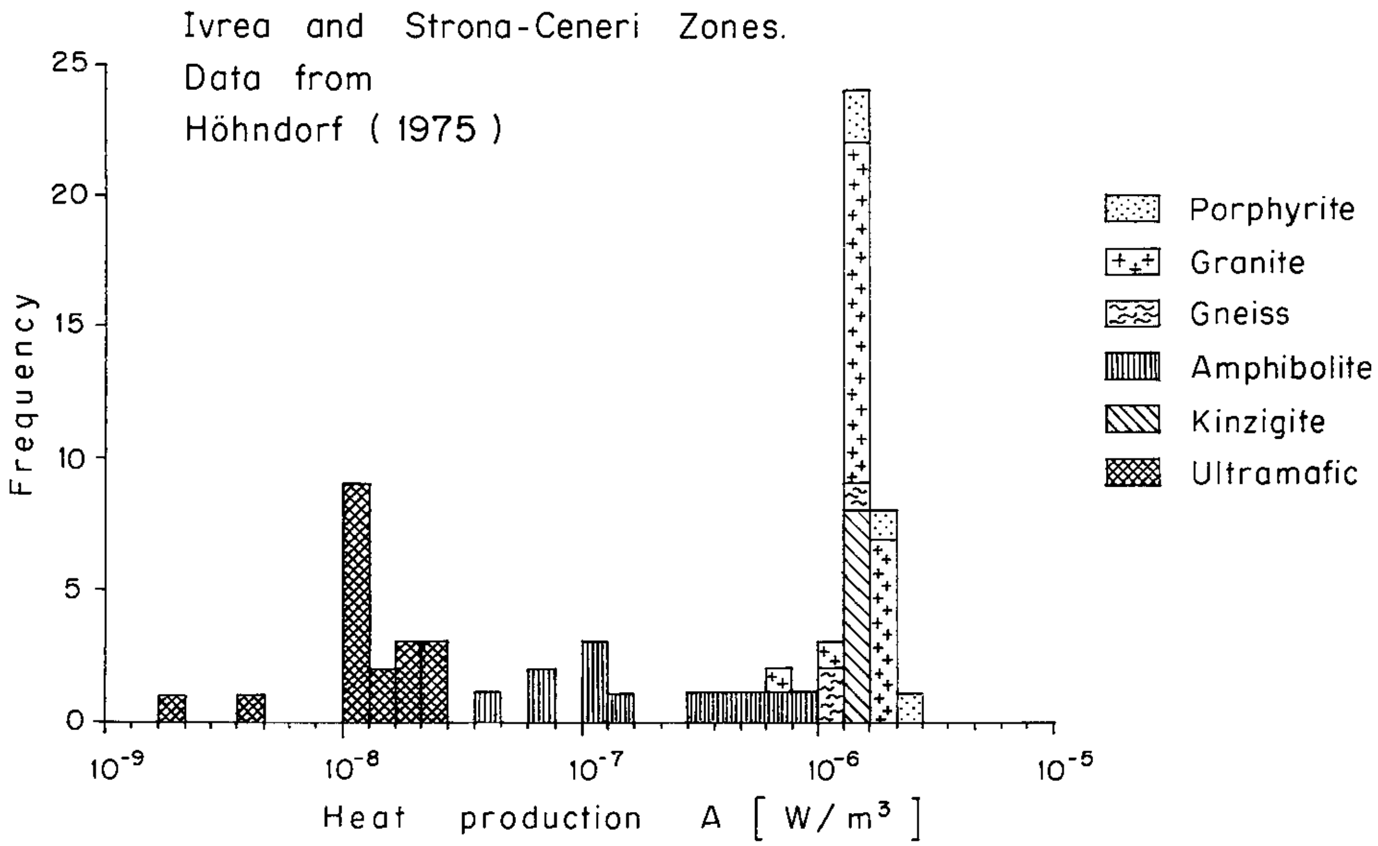

Figure 4: Heat production (A) of various rocks from the Ivrea and Strona-Ceneri Zones.

related to samples from the SE and from the NW. The author indicates that on the basis of geological evidence these two directions are related to tectonic movement (folding about a subhorizontal axis striking north to northeast). Lanza (1978) studied in detail a thin area sandwiched between the Ivrea Zone and the Sesia-Lanzo Zone, known as the andesitic cover of this latter zone. Samples came from the northwest and west of the locality of Biella. It is important to notice that the remanence has a stable behaviour and furthermore gave a positive conglomerate test; it would seem then to be primary. The mean in-situ direction is $D = 135.9°$, $I = -2.9°$, $\alpha_{95} = 8.8°$, which is in agreement with an andesitic site result from Heller and Schmid (1974), namely $D = 129°$, $I = -1°$, $\alpha_{95} = 14°$. These latter authors restored the result for the horizontal position and obtained a direction which is similar to that of the Oligocene granitic Bergell massif. Provided all this andesitic magmatism is of similar age, one could use these results to decipher the regional geological rotations of the internal dikes of the Sesia-Lanzo Zone and of the andesitic cover. Lanza (1978) concluded that after the Middle Oligocene the Sesia-Lanzo Zone was folded about a subhorizontal axis; on the other hand Heller and Schmid (1974) deduced that their andesite (near Biella) indicates an anti-clockwise rotation. Such tectonic corrections need to be verified using rocks from other geologic formations.

Most of these studies raise the problem of the applicability of the paleomagnetic method in complex areas, such as the Alpine system. Lowrie (1980) stated that "... the usefulness of paleomagnetic data as a means of associating the region with a parent supercontinent and/or of deducing its tectonic history becomes severely restricted". It is, therefore, very necessary to make such studies in close association with a structural geologist.

To conclude on an optimistic note the major achievement of these studies is the paleomagnetic demonstration that in the Southern Alps the Paleozoic directions—although they are fairly scattered—correspond to African directions (Lowrie, 1980) and this result allows amongst other geological evidence to relate the Adriatic promontory to the African plate. There also exists evidence for anti-clockwise rotations of up to 25° for the Tertiary with respect to "stable Europe" which are related to Alpine orogeny.

Acknowledgments

I. Hedley and R. Veitch kindly revised the English. Many thanks go to Jacqueline Berthoud for typing the manuscript and to P. Zbinden for drawing all the figures.

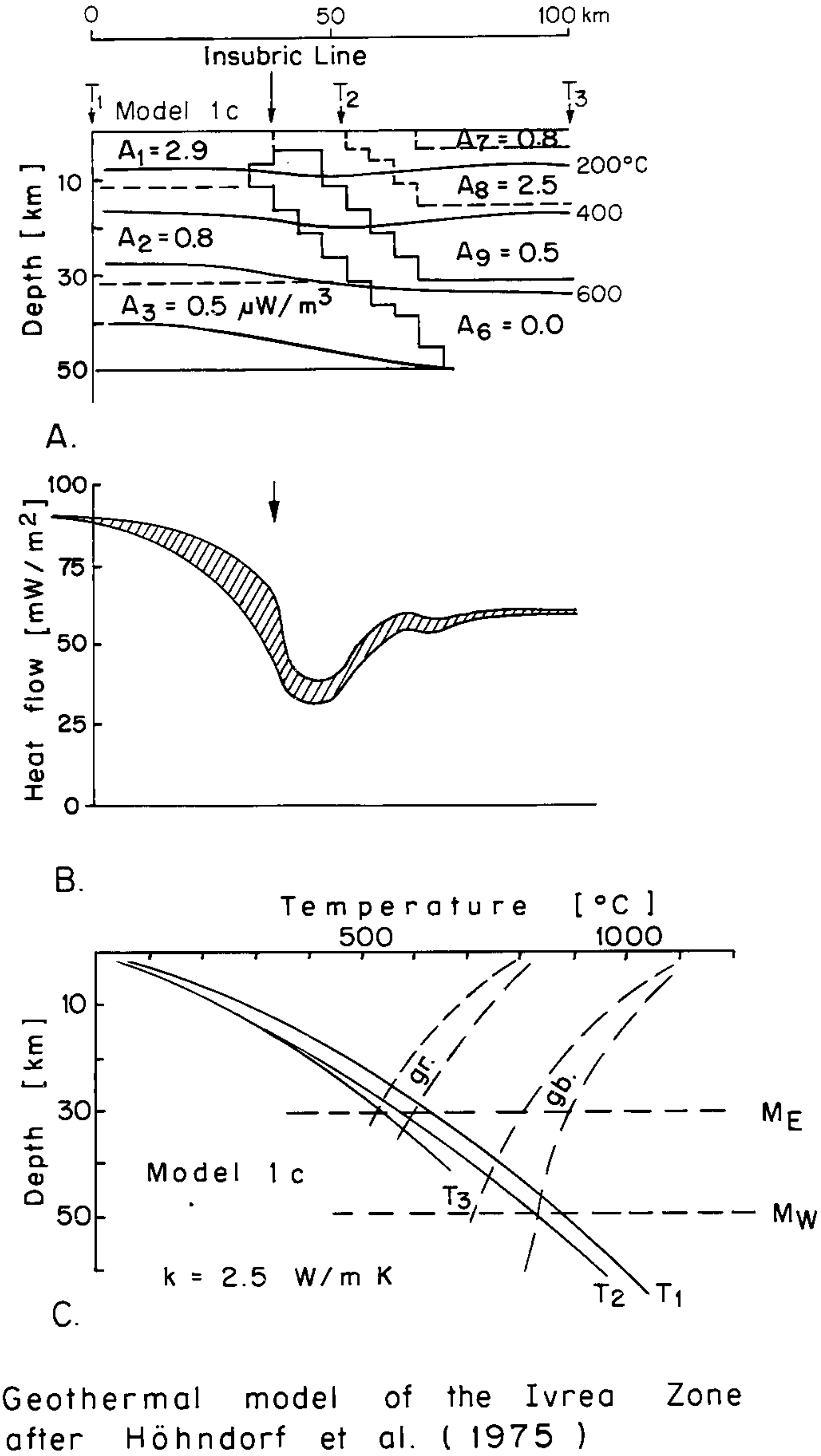

Figure 5: Geothermal model of the Ivrea Zone.

A: Crustal model 1c with heat production values ($A_1 \ldots A_9$, in µW/m³) for the different layers.

B: Range of the calculated heat flow for the various crustal models.

C: Temperature-depth profiles at T_1, T_2, T_3 indicated in Fig. 5 A. Range of melting points for granitic (gr.) and gabbroic (gb.) rocks. M_E and M_W are the Moho depths east and west of the "Ivrea Body", respectively.

k = thermal conductivity.

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III
REGIONAL GEOMAGNETIC STUDY OF THE SOUTHERN BORDER OF THE WESTERN ALPS – THE IVREA BODY –

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Regional Geomagnetic Study of the Southern Border of the Western Alps – The Ivrea Body –

1. Introduction

Since 1972 an extensive geomagnetic ground survey (total field intensity) has been carried out in the southern border region of the Western Alps (Webel and Wagner, 1973; Wagner *et al.*, 1978) with the aim of improving our knowledge of the magnetic counterpart of the well-known Ivrea positive gravity anomaly (Vecchia, 1968) and the anomaly of high seismic P velocity located in the upper part of the crust (Berckhemer, 1968). To avoid confusion, it should be pointed out that the geophysical Ivrea anomalies have a much larger extension than the (geological) Ivrea Zone (IZ) as defined by the petrologists (see Chessex and Wagner, this volume). Due to the rugged topography the field work which covers an area of approximately 7000 km^2, was mainly carried out along valleys which are more or less perpendicular to the Alpine arc (Fig. 1). The basic data set corresponds to 944 total field measurements taken by students of Geneva University during their diploma work. This set is used to produce a regional total field anomaly map which will subsequently be interpreted qualitatively and quantitatively.

2. Previous Investigations

Weber *et al.* (1949) were the first to detect a strong magnetic anomaly west of Locarno during a survey of vertical and horizontal components, which they related to the geological zone of Ivrea. It was only after the stimulus given by the First Symposium on the Zone of Ivrea-Verbano (1968) that further magnetic surveys were undertaken in this area. Albert (1974) measured the vertical component between Torino and Finero in 1969/70, and showed that the anomaly found previously extends further to the southwest close to the city of Ivrea. A few combined total magnetic field and gravity field profiles distributed from south of Biella to the north of Cuneo have been investigated by Lanza (1975). The area south of Cuneo has been studied by Froidevaux and Guillaume (1973, 1979); their field map indicates that the Ivrea anomaly seems to disappear there.

3. New Geomagnetic Survey

Three types of proton magnetometers have been used in the new survey; the basic work was carried out with a Varian M-49A. With the improvement in electronic components the newer magnetometers became lighter and had a greater autonomy of operation. We completed the survey with a Geometrics G 826 and a Scintrex MP-2 magnetometer. The latter allowed us to work for 13 days without changing the batteries.

Measurement method

Measurements of the total field intensity were made mostly along profiles with the stations 1-2 km apart. Stations were chosen for their accessibility, remoteness from magnetic disturbances, and homogeneity. At each station five sets of five readings each were taken at the corners and at the center of a 10 meter square. If these readings varied by more than 10 nT the station was abandoned and a new attempt was made nearby. This technique gives a precision of $\pm$ 3 nT.

For most of the survey we used only one magnetometer in the field, and as each profile was very long, it was decided to use the looping method for the measurements (Fig. 2) in order to correct for the diurnal variation. During each field season we established a complete diurnal variation record so that a reference curve (Fig. 3) was available for the total field data.

As the total magnetic field measurements were taken over several years, we had to adjust our data for secular variation. From a comparison with several field stations we adopted a yearly increase of the field of 25 nT. This is also the value given by Fischer and Schnegg (1978) in the new map of the total intensity geomagnetic field for Switzerland. Therefore all our data have been recalculated for July 1, 1980 (Epoch 1980.7).

The measured field ranges from 45000 nT to 48000 nT, with a mean value around 46300 nT.

4. Geomagnetic Anomaly Field

A reference field was subtracted from the measured values to bring out the regional anomaly field. The International Geomagnetic Reference Field 1975 (IGRF 75) was used. From the obtained values (see e.g. in Fig. 4) one sees that this theoretical field is not applicable to our Alpine area because it systematically gives values which are too high. To avoid such a bias, a linear reference field was computed for the longest N-S measured profile (Domodossola-Asti) by a least-squares regression method. This calculated field is nearly parallel to the IGRF 75, but shifted by 260 nT and, therefore, one can take this value as a constant difference which has subsequently been subtracted from IGRF 75 (Fig. 4).

It is interesting to note that reference values calculated on the basis of MAGSAT 3/80 data (Langel *et al.*, 1980) are approximately 160 nT lower than those of IGRF 75. Thus the former model would give an improve-

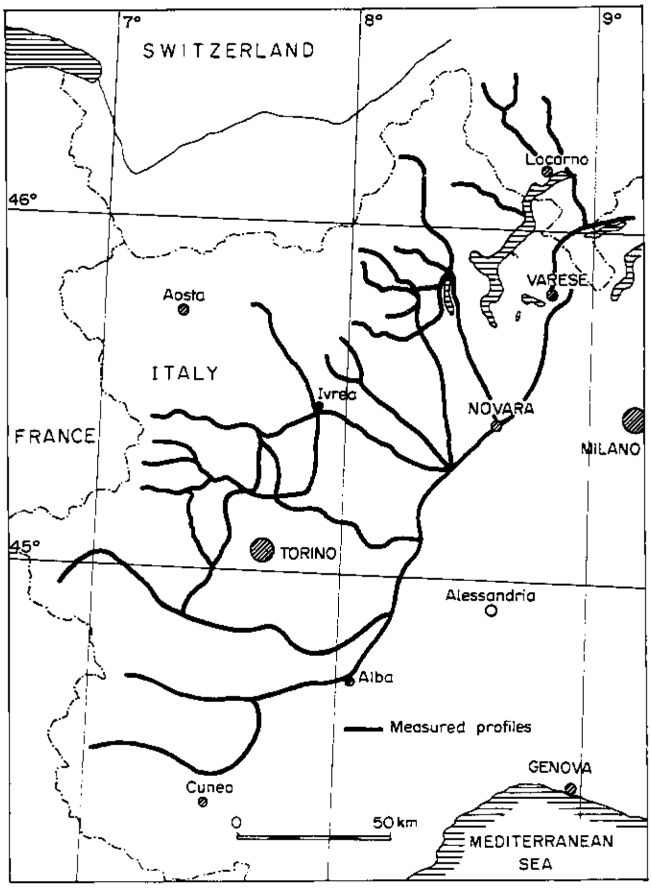


Figure 1: Distribution of the geomagnetic profiles in the southern border region of the Western Alps.

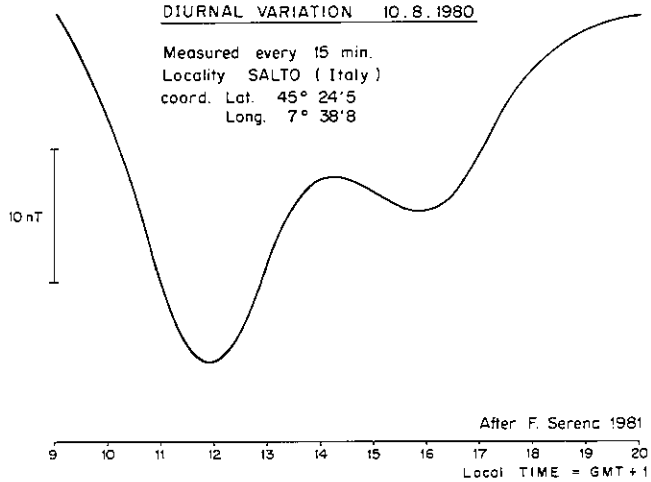


Figure 3: Example of the diurnal variation of the total geomagnetic field in the area of the field work.

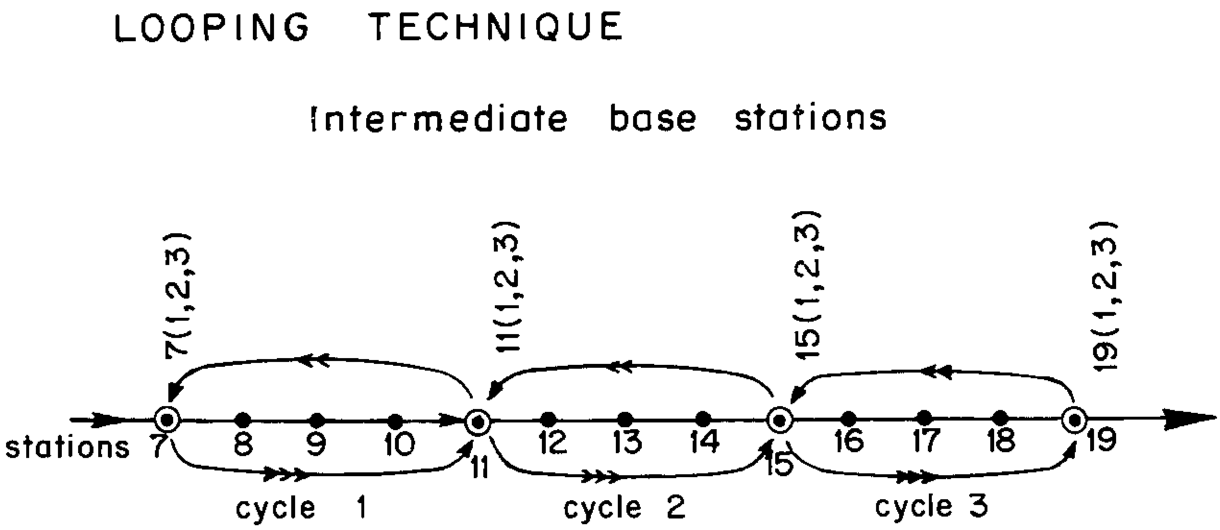


Figure 2: Measurement technique along profiles to obtain diurnal variation using only one magnetometer.

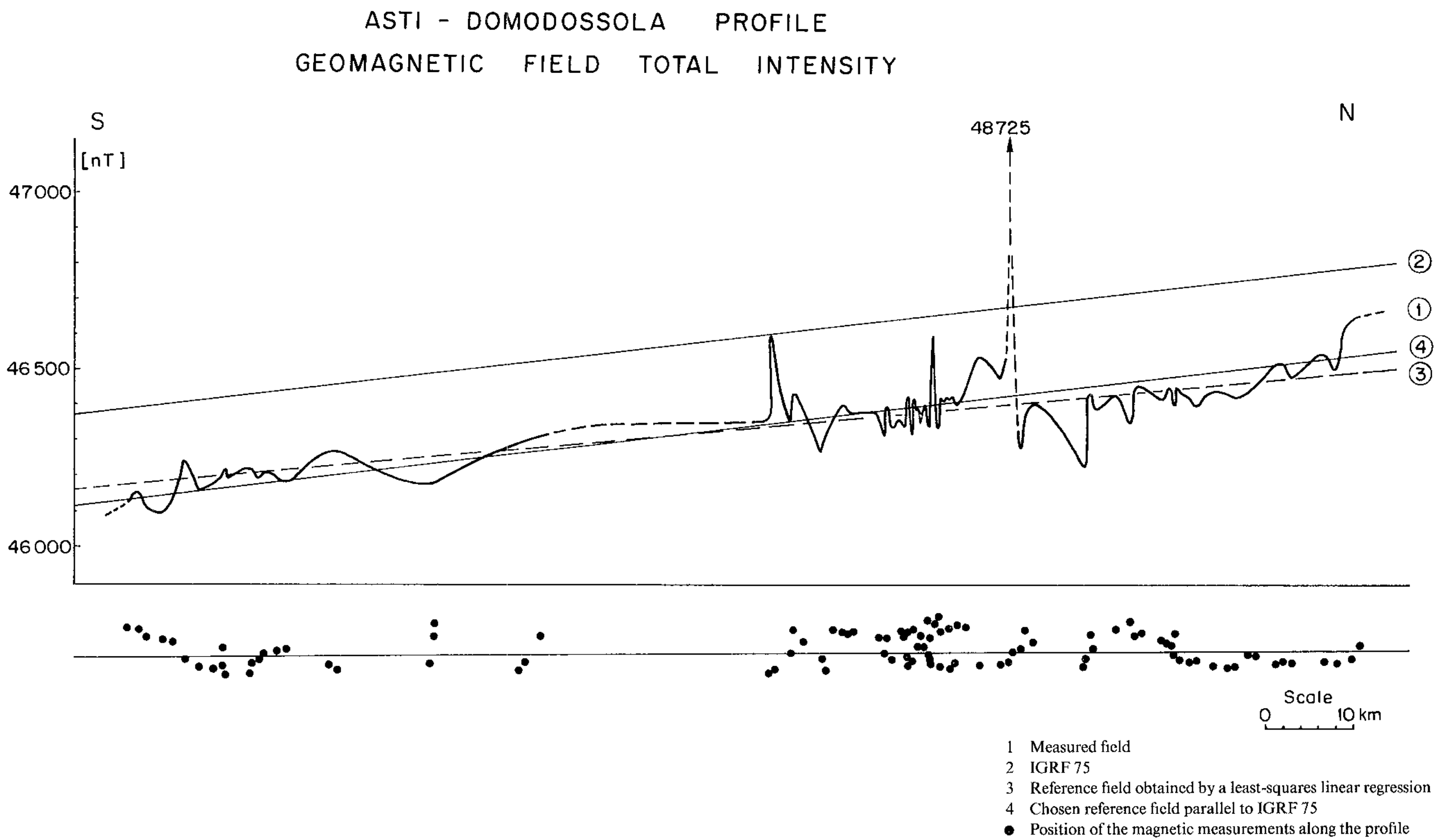


Figure 4: Profile of the total geomagnetic field between Asti (in the south) and Domodossola (in the north) used to define the regional field.

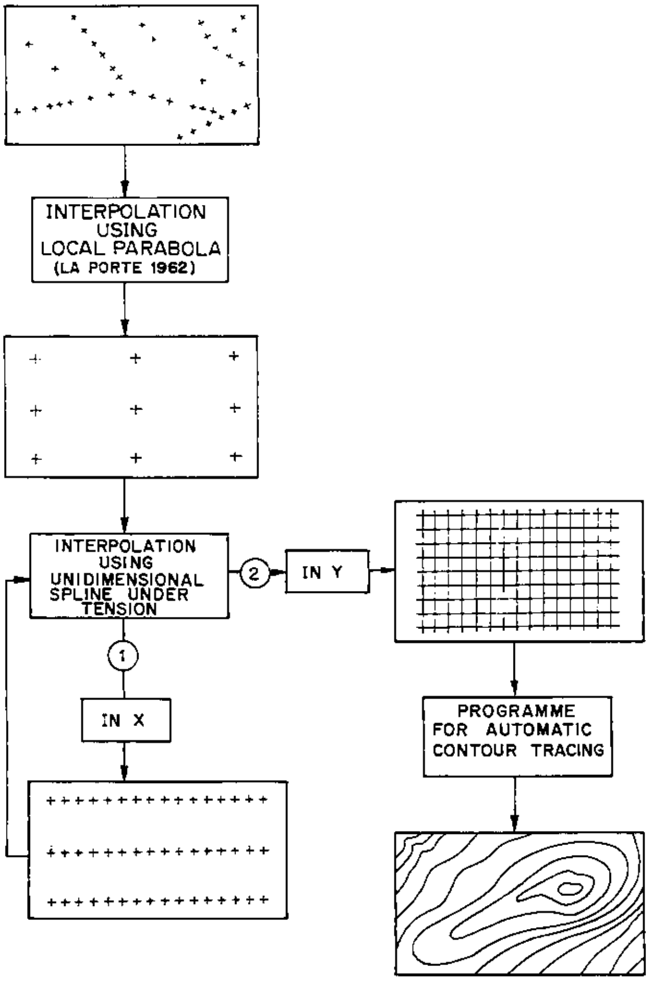


Figure 5: Flow chart illustrating the different steps to achieve automatic contour tracing.

ment, but there still remains a difference of 100 nT compared to the estimated reference field.

Contouring of anomalies

Two problems arise for the drawing of isolines in our area: the first one is the non-uniform distribution of the measurements which are mainly on non-equidistant profiles, the second one is due to the very large and rapid local variations of the anomalous field.

Under these conditions it is very difficult to manually trace the contours. Therefore we decided—since in this investigation we were mainly interested in the gross structure of the perturbing bodies—to draw maps with smoothed anomalies. This allows an interpretation in terms of simple models. A computerized approach is best adapted to solve this problem.

In the present case the contouring has been done in three steps (Fig. 5). In the first one a large-scale grid was calculated with squares having a side which is slightly smaller than the distance between the profiles. To this end the method described by La Porte (1962) was used: The experimental points inside a circle of radius R_o centered on the point to be interpolated are approximated by a second-order polynomial of the type

$$F(x, y) = \alpha_0 + \alpha_1 x^2 + \alpha_2 x + \alpha_3 y + \alpha_4 xy + \alpha_5 y^2$$

in a least-squares fit procedure.

Before performing this operation a weighting procedure is used based on the term $1/R^2$ in order to reduce the effect of distant values. The weight attributed to a point P_i is (Fig. 6)

$$W_i = \left(\frac{R_o^2 - d_i^2}{d_i^2 + \eta^2}\right)^2,$$

where d_i is the distance between the center of the circle and the point P_i and η is a smoothing factor.

The second step allows the refining of the initial grid to obtain a much finer one needed for a good-quality tracing with the computer plotter. To save computing

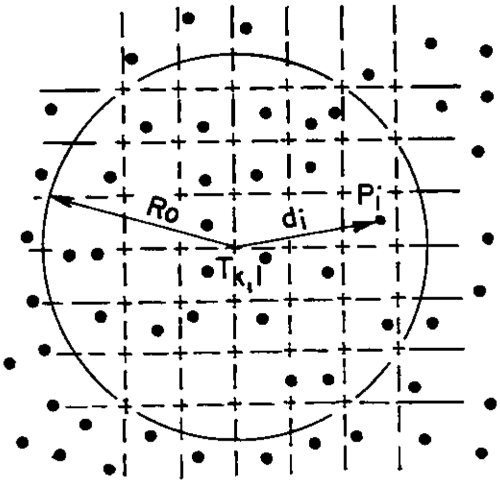
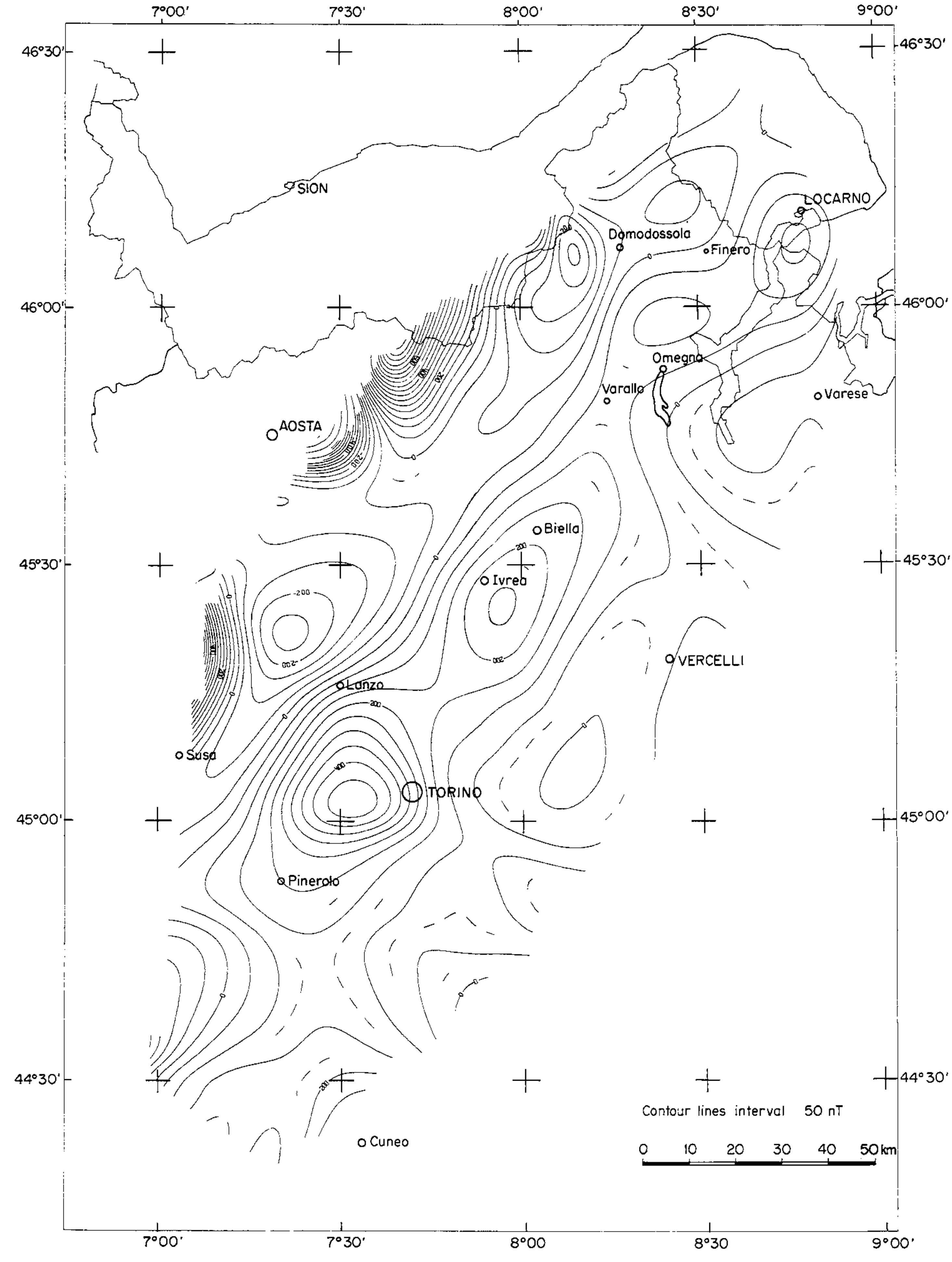


Figure 6: Data selection to compute the data grid.

time, the interpolation is done first line by line on the initial grid. One then obtains a rectangular grid with the smallest dimension equal to 1/K times the original grid size, coinciding with the horizontal axis. Secondly, one proceeds to an interpolation column by column on the previously obtained intermediate grid. This twofold unidimensional interpolation uses a spline under tension whose variations of the stress factor allows an interpolation ranging from a broken line to a classical bi-cubic spline.

Finally this grid is used to produce the isolines which are chosen to give well-defined and clearly visible anomalies.

The fine grid has a size of M (K-1) · N (K-1), where M and N are the dimensions of the large scale grid, and K is the refinement factor. Two maps of the anomalous magnetic field for the geophysical Ivrea area have been produced with smoothing factors of η = 0.25 and η = 0.50. Both maps exhibit a large regional magnetic anomaly which—if side effects to the northwest are disregarded—is oriented SW-NE, extending from Pinerolo to Locarno (see Figs. 7 and 8).



IVREA MAGNETIC ANOMALY MAP

$\Delta T = T_m - (T_{IGRF75} - \delta T_{adj.})$

Figure 7: Magnetic Ivrea anomaly map traced with a low smoothing factor, $\eta = 0.25$.

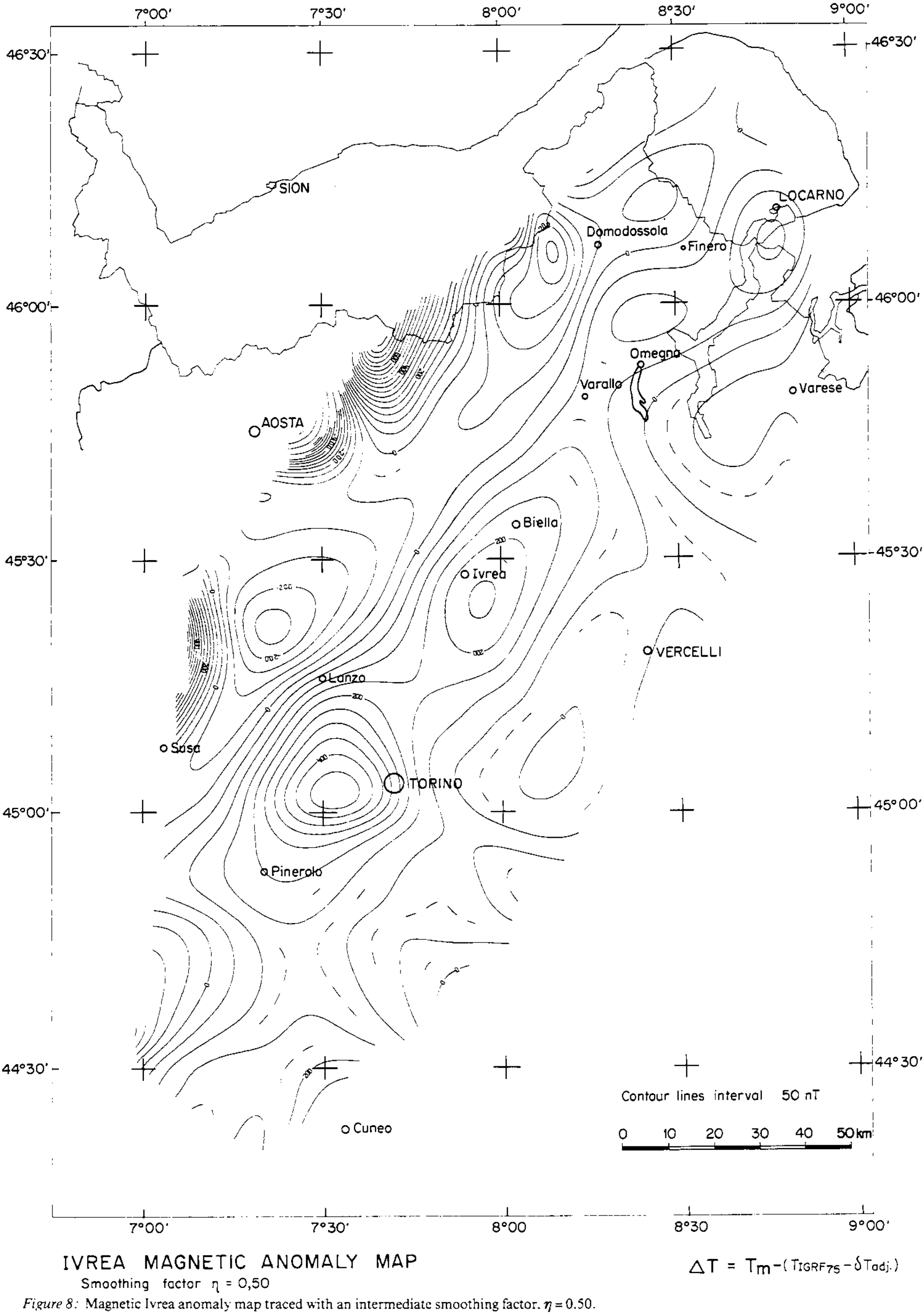


Figure 8: Magnetic Ivrea anomaly map traced with an intermediate smoothing factor. $\eta = 0.50$.

Description of the magnetic anomaly maps

The magnetic Ivrea anomaly consists of a steep and narrow zone of "highs" running always slightly to the southeast of the Insubric Line. An interesting point is that the distribution of the anomaly follows the general trend of the broad regional geology. In fact, between Locarno and south of the locality of Ivrea the positive part of the magnetic anomaly lies mainly on the geological Ivrea Zone. Further south it is more difficult to correlate this positive anomaly with the geology due to the Quaternary cover. A strong positive anomaly appears west of the city of Torino reaching 650 nT (see map in Fig. 7). Although this appears to be a continuation of the magnetic Ivrea anomaly it seems to have a different aspect and should be interpreted as an independent or at least a different body. It should be noted that this particular anomaly is located SSE of the Lanzo ultramafic massif.

5. Tentative Quantitative Interpretation

This interpretation is based on the magnetic Ivrea anomaly map computed with a smoothing coefficient of $\eta = 0.25$ (Fig. 7), because it shows—with more details—the various anomalies.

The main regional anomaly mentioned previously is marked by a few, more or less extended "highs" located SW of Locarno, NW of Omegna and SE of Ivrea. The Torino-Lanzo anomaly is not considered in our interpretation for reasons already mentioned. The three anomalies are separated by local "lows" of the order of 125 nT. It is important to point out that the northwestern zero line is almost parallel to the axis of the maxima. Although the southeastern zero line exhibits a rather complicated behavior it is possible to see a tendency of the zero contours to diverge from the axis of the maxima as one goes from the northeast to the southwest. This means that magnetically speaking the main body should be wider in the region of Ivrea as compared to the Locarno area.

On the other hand, a recent gravity Bouguer anomaly map published by Guillaume and Guillaume (1980) shows a very good coincidence between the gravity "highs" of the positive Ivrea anomaly and our magnetic positive anomalies. This coincidence confirms the hypothesis of the authors cited, namely that these gravity maxima are due to the depth variations of the top of the body. A sketch model (Fig. 9) illustrates these deductions; it has been used as a guideline for the quantitative interpretation. For the inversion a computer procedure has been developed which permits the calculation of a body in 2 1/2 D. It is based on the algorithm suggested by Talwani (1965). This procedure allows the modelling of any elongated structure by a combination of bodies with constant cross section. The effect can be computed either along a profile or on points distributed on an arbitrary surface.

In fact, the first model computed was a slab dipping towards the SE and thickening with depth; its shape had been inspired by the seismic and gravity results. Then by a trial-and-error method this initial body was modified to fit the experimental magnetic data. As it is very difficult to know how the magnetic parameters vary with depth (e.g. magnetic susceptibility) the simplest satisfactory solution was adopted. Figure 10 gives the geographical extension and the various cross sections of the body and also its computed magnetic anomaly. For the calculations a constant susceptibility of $3 \cdot 10^{-3}$ G/Oe was chosen.

Discussion

The computed model (Fig. 10) shows a poor fit at the western flank of the magnetic Ivrea anomaly. It is suggested that this is related amongst other reasons to two main effects:

(*a*) The adoption of a homogeneous magnetic body may be questioned on the basis of the geological structure at the surface and the petrology. These suggest that one should use horizontal susceptibility variations perpendicular to the extension of the body.

(*b*) Along the western flank of the Ivrea anomaly there exists a series of strong magnetic anomalies correlated with the serpentinized part of the Alpine ophiolites. They reach more than −1000 nT and therefore could interfere with our main anomaly.

Another important feature is the location of the Omegna anomaly which has been modelled by shifting the top structure towards the NW. This displacement suggests a major SE-NW trending fault.

Finally, this model has been computed with a susceptibility which, based on surface investigations, corresponds mostly to serpentinized ultramafics and to

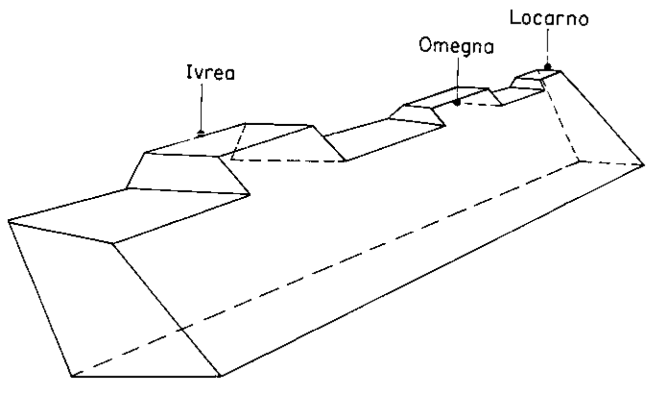


Figure 9: Sketch of the magnetic Ivrea body.

amphibolite. This raises the question as to which rock type could explain the nature of the magnetic body. If it is mainly ultramafic, it means that the serpentinization process took place at a great depth, otherwise there would not be enough magnetite to produce the observed anomaly. The magnetic body has been modelled only in terms of an induced magnetization, the remanent part has been neglected. It is important to remember that the magnetic body differs in shape from the gravity body, all dense rocks being not necessarily magnetic.

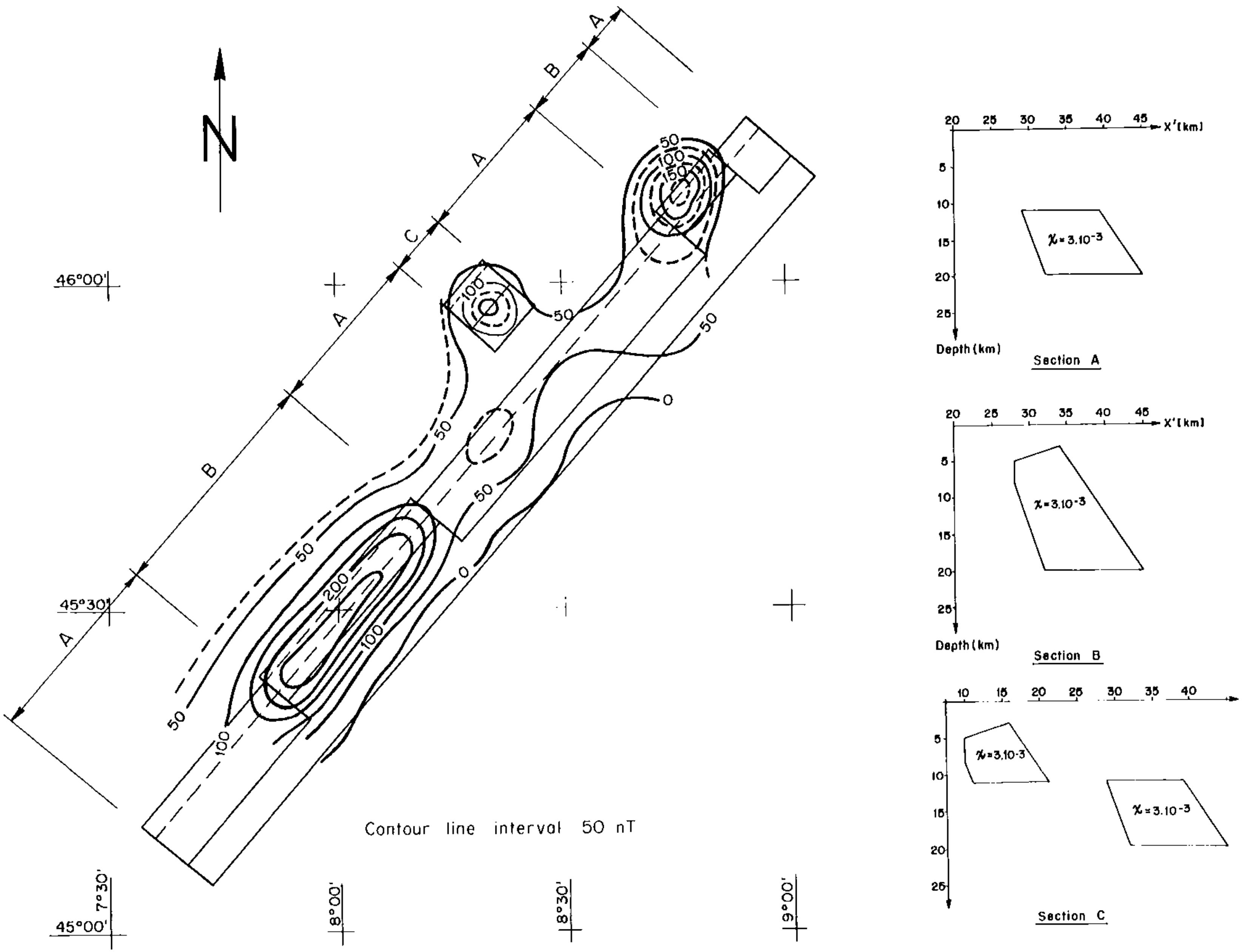


Figure 10: Adopted model of the magnetic Ivrea body and its theoretical anomaly. Magnetic susceptibility $\varkappa = 3 \cdot 10^{-3}$ G/Oe. Compare with the map in Figure 7.

Acknowledgments

This work has been carried out with the enthusiastic cooperation of research students from Geneva University: S. Webel-Bovet, A. Espinosa, Cl. Gallay, Ph. Néri, N. Spycher, G. Rochat and F. Serena. We thank them all for their contribution. We would also like to thank P. Zbinden for carefully drawing all the figures and J. Berthoud for patiently typing all the different versions of the manuscript. I. Hedley kindly revised the English. The field work was supported by the Swiss Geophysical Commission.

Contribution No. 484, ETH-Geophysics, Zürich, Switzerland

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IV
PETROPHYSICAL PROPERTIES OF THE IVREA ZONE AND ADJACENT AREAS

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Petrophysical Properties of the Ivrea Zone and Adjacent Areas

Introduction

A knowledge of the physical properties of rocks is of primary importance for the geological interpretation of geophysical field studies. As the rocks of the Ivrea Zone and of its neighbour to the east, the Strona-Ceneri Zone (see Chessex and Wagner, this volume) represent large parts of the upper mantle and of the lower to intermediate continental crust, these two regions present a unique chance to study the evolution of physical parameters with depth. However, a certain caution is necessary:

(*a*) The Ivrea and Strona-Ceneri Zones are not a complete continuous section; a part is missing at their common border which corresponds to the Pogallo Line.

(*b*) As one is able to trace the history of the area back to the Caledonian orogeny, it underwent transformation which is not necessarily representative of a "normal-type" deep geological section.

In this study of the magnetic and gravity anomalies special attention is paid to the magnetic properties and to the densities of the rocks encountered in the Ivrea geophysical anomaly area. Other properties relevant for the general interpretation, such as seismic velocities (Fountain, 1976) and heat production (Höhndorf, 1975) are summarized in Wagner (see second paper in this volume).

Magnetic Properties

For the magnetic interpretation it is necessary to make assumptions about possible magnetic sources. Each source is characterized by a resultant magnetization and by its geometry. This geometry may be limited at depth by the effect of the geothermal gradient on the magnetic source; the limit is defined by the Curie temperature T_c of the magnetic minerals (e.g. for magnetite, $T_c = 585\ ^{\circ}C$) and by the local geothermal gradient.

Usually the magnetic properties of rocks are controlled by oxide minerals in the ternary system FeO-TiO_2–Fe_2O_3. Magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3) and the low-titanium titanomagnetites have the strongest magnetizations. Hematite (α-Fe_2O_3) and the titano-hematites have weaker magnetizations. The iron sulfide pyrrhotite (FeS_{1+x}) can also give rise to magnetic anomalies.

The resultant magnetization J of rocks is the sum of the induced magnetization (J_i) and the remanent magnetization (J_r)

$$J = J_i + J_r$$

$$J_i = \chi \cdot T \qquad \chi = \text{magnetic susceptibility}, \quad T = \text{local inducing field}$$

The importance of the remanent magnetization varies with its type. To ease the comparison one uses the Koenigsberger ratio defined as:

$$Q_n = \frac{J_r}{J_i} = \frac{J_r}{\chi \cdot T}$$

Usually for continental magnetic surveys $Q_n < 1$ and, therefore, one can neglect the remanent magnetization; this "rule" however has to be controlled each time.

It is noticeable that if the susceptibility is only deduced from the geomagnetic field survey and not by "in situ" or laboratory measurements, and if the remanence of the rocks is not negligible, the determined susceptibility is apparent; its value is

$$\chi_a = \frac{J_r + \chi \cdot T}{T} \quad \text{(Vacquier, 1972)}$$

χ_a is maximum if the induced and remanent magnetization have the same direction.

Sampling and Measurement Techniques

As this study covers the geophysical anomaly area, samples have been taken on outcrops located in the Strona-Ceneri Zone, in the Ivrea Zone, in the Sesia-Lanzo Zone and in the Gran Paradiso Massif.

These representative samples were collected in the field either as cores with a portable drill or as hand samples and then cored in the laboratory. Not all hand samples were oriented. All cores were of 2.5 cm in diameter and were cut to a length of 2.2 cm. 580 specimens have been subjected to various magnetic measurements.

Initial susceptibilities have been measured with a DIGICO bulk susceptibility meter and with a BISON bridge (Model 3101) for the strong samples. The instruments were calibrated with paramagnetic salts and rare earth oxides. Remanent magnetization has been obtained with a DIGICO computerized spinner magnetometer (Molyneux, 1971). The thermomagnetic behaviour in a high magnetic field (up to 10 kOe) and the Curie temperatures were determined with a translation balance.

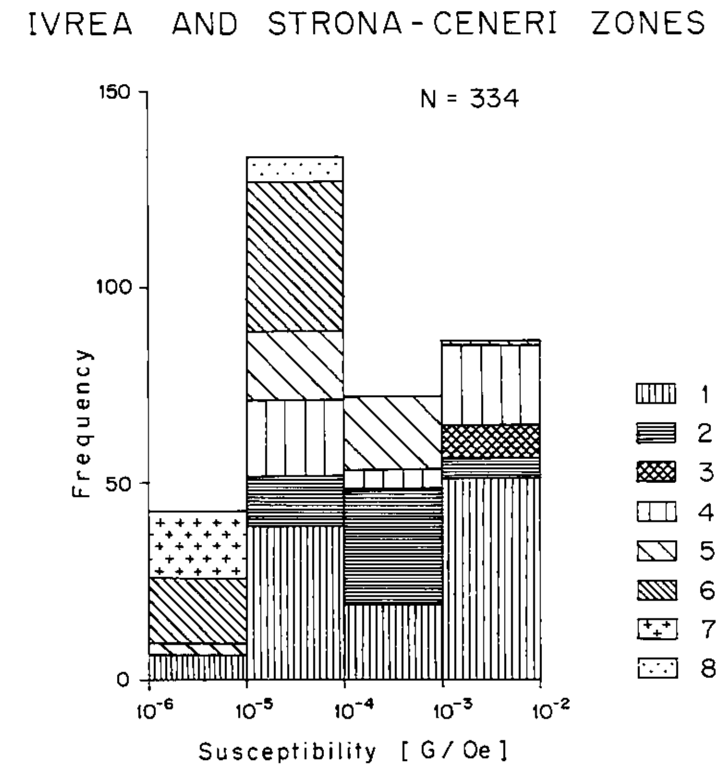

Figure 1: Histogram of susceptibility for the rocks of the Ivrea and Strona-Ceneri Zones:
1 = Amphibolites, 2 = Peridotites, 3 = Serpentinites, 4 = Metagabbros, 5 = Kinzigites, 6 = Stronalites, 7 = Permian granites, 8 = Porphyrites (Permian volcanics).

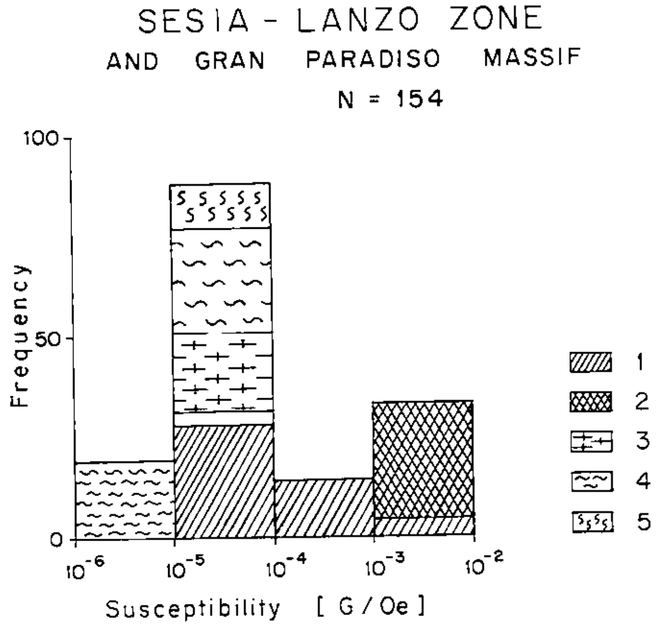

Figure 2: Histogram of susceptibility for the rocks of the Sesia-Lanzo Zone and the Gran Paradiso Massif:
1 = Greenschists ("Prasinites"), 2 = Serpentinites, 3 = Granites, 4 = Minuti Gneisses, 5 = Schists.

Susceptibility

Over the variety of geological "units" sampled the susceptibility ranges from 10^{-6} to 10^{-2} G/Oe (see histograms in Figs. 1 and 2).

For the Ivrea and Strona-Ceneri Zones (Fig. 1), the amphibolites and the metagabbros exhibit a bimodal distribution with a peak between 10^{-5} and 10^{-4} G/Oe and another peak between 10^{-3} and 10^{-2} G/Oe. All other rocks show relative maxima which lie between

10^{-3} and 10^{-2} G/Oe for the serpentinites
10^{-4} and 10^{-3} G/Oe for the peridotites
10^{-5} and 10^{-3} G/Oe for the kinzigites
10^{-5} and 10^{-4} G/Oe for the stronalites
and the porphyrites
10^{-6} and 10^{-5} G/Oe for the granites

In the Sesia-Lanzo Zone and in the Gran Paradiso Massif (Fig. 2) – although the variance of values is as large as the one for the previous zones—rocks with high susceptibility are mainly represented by serpentinites. All the others, i.e. greenschists, granites, Minuti gneisses and schists, range mostly between 10^{-5} and 10^{-4} G/Oe.

Natural Remanent Magnetization (NRM)

For all specimens examined the NRM varies from 10^{-7} to 10^{-3} G, but from a statistical point of view the most common values are between 10^{-5} and 10^{-7} G (Figs. 3 and 4); of the more magnetic samples amphibolites, serpentinites, a few gneisses and porphyrites can be taken as representative. The analysis of the NRM directions shows that most of them have a large dispersion; the radius of the cone of 95% confidence level around the mean direction (α_{95}) is greater than 15° (Heller and Schmid, 1974; Rochat, 1981). In general the carriers of the magnetic remanence have a low coercivity as given by the median destruction field (MDF) value deduced from the alternating field demagnetization. The MDF is often lower than 150 Oe. The only rock with a very high coercivity is the Permian porphyrite; this has also been noticed by Heiniger (1979).

Koenigsberger Ratio Q_n

The majority of the specimens measured have a Koenigsberger ratio below one (Figs. 3 and 4), ranging from a hundreths to a few tenths; this implies that in general the magnetic anomalies are controlled by the induced magnetization. The rocks exhibiting a Q_n

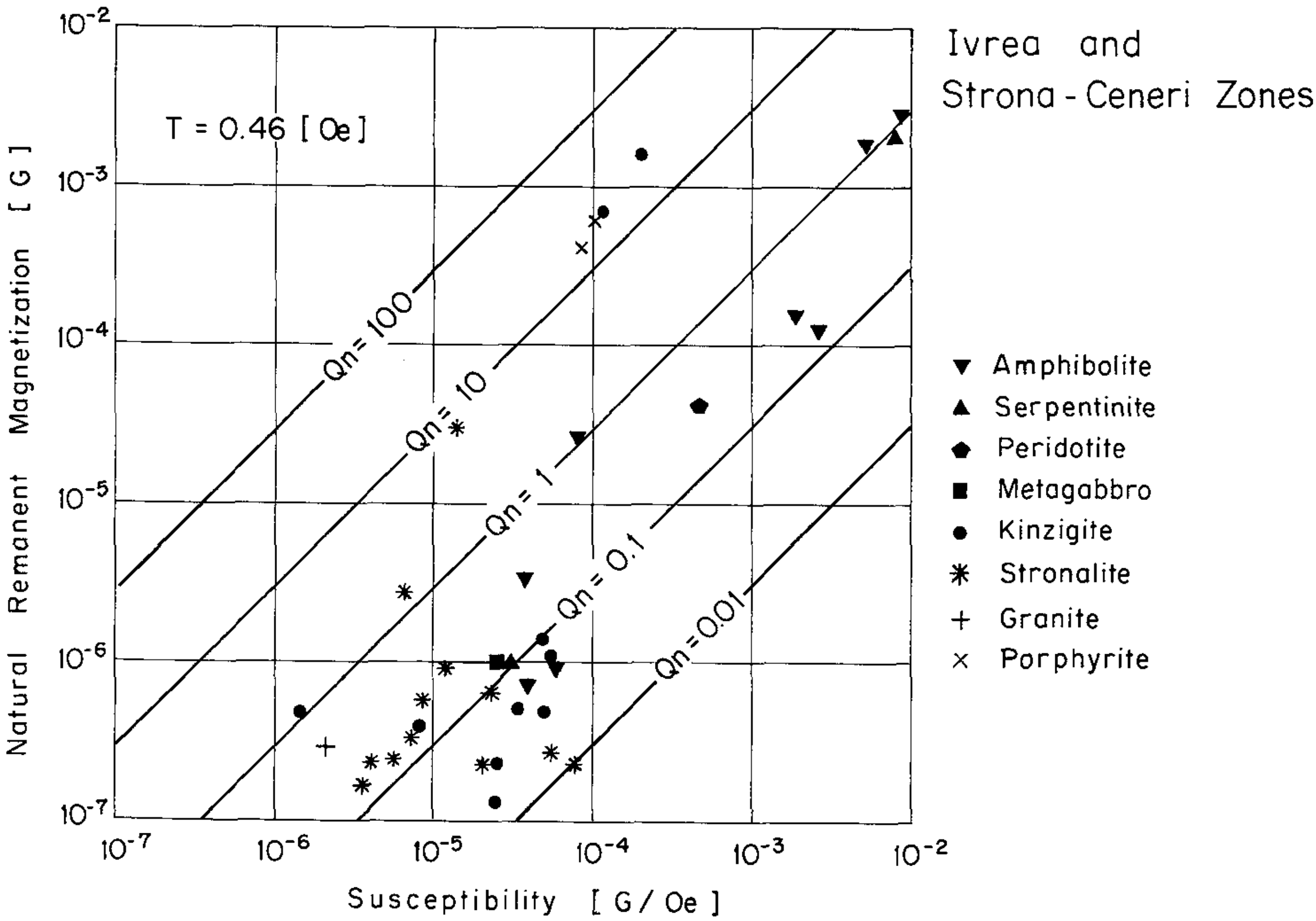

Figure 3: Natural remanent magnetization versus susceptibility diagram showing the variation of the Koenigsberger ratio Q_n for the local geomagnetic field in the rocks of the Ivrea and Strona-Ceneri Zones. Each symbol represents a value based on 1 to 11 specimens.

factor more or less equal to or greater than one are represented by amphibolites, serpentinites, kinzigites and porphyrites for the Ivrea and Strona-Ceneri Zones, and by serpentinites, Minuti gneisses, greenschists and schists for the Sesia-Lanzo Zone and the Gran Paradiso Massif.

Curie Temperature

Amphibolite, serpentinite, peridotite and metagabbro have been investigated for their thermomagnetic behaviour during heating and cooling and for their Curie temperature (T_c). The amphibolite (Fig. 5a) behaves in a completely reversible manner with a T_c near 585 °C characteristic of pure magnetite. The serpentinized peridotite (Fig. 5b) shows an irreversible behaviour; the magnetization after cooling is significantly lower. The heating curve has a final T_c near 585 °C and also another one (T_s) around 420 °C indicating a different magnetic phase which could be related to the development of the serpentinization. The phlogopite-peridotite thermomagnetic characteristic (not shown) is strongly influenced by its paramagnetic component; the presence of a little magnetite is detected by its Curie temperature. The metagabbro measured is essentially paramagnetic.

From these investigations it becomes clear that the magnetite is the most important magnetic mineral in the sampled outcrops. Similar results have been obtained by Wasilewski and Fountain (1982).

Bulk Density-Susceptibility Relation

A bulk density-susceptibility diagram is helpful to correlate magnetic and gravity interpretations, and it also permits one to analyse magmatic differentiation trends, or alteration phenomena (Henkel, 1976). The relations may be represented by different fields in a simple diagram (Fig. 6).

Bulk densities have been measured on specimens by the Archimedes method. The diagram has been traced for the most typical rocks.

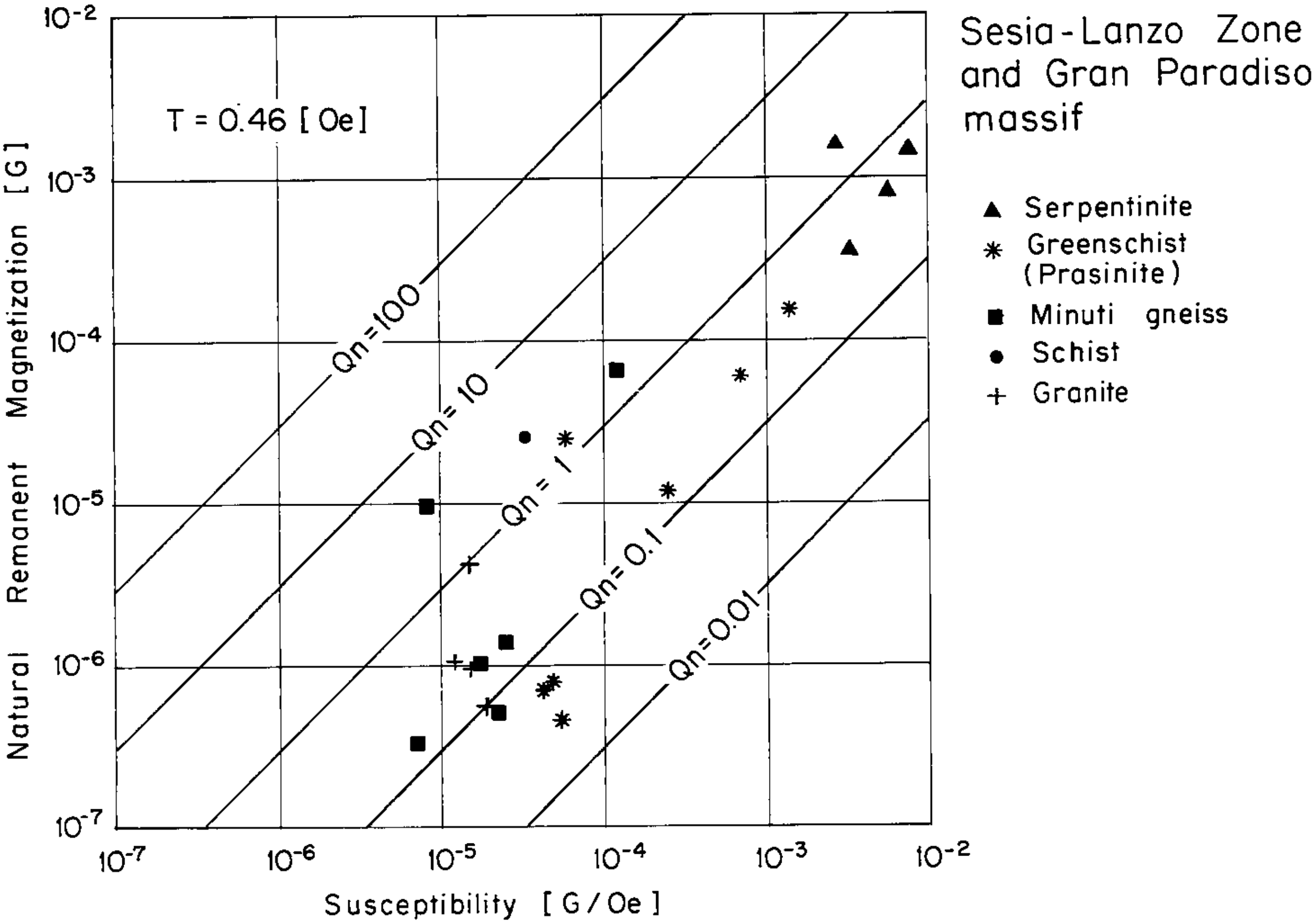

Figure 4: Natural remanent magnetization versus susceptibility diagram showing the variation of the Koenigsberger ratio Q_n for the local geomagnetic field in rocks from the Sesia-Lanzo Zone and the Gran Paradiso Massif. Each symbol represents a mean value based on 2 to 11 specimens.

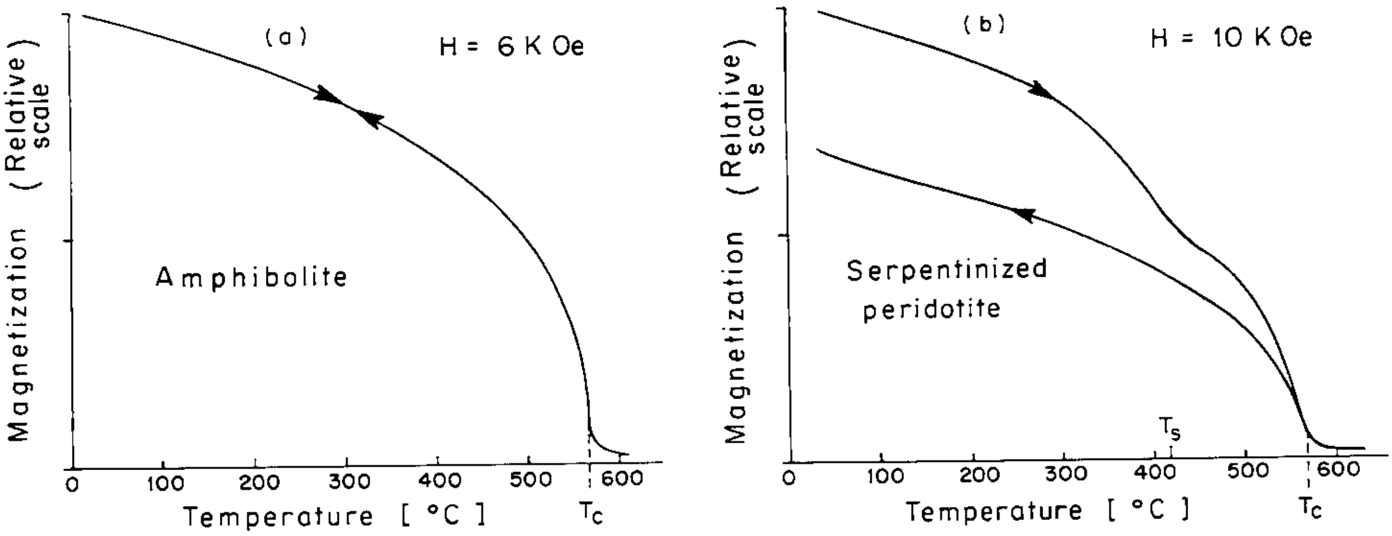

Figure 5: Thermomagnetic curves during heating and cooling. The magnetization is measured in arbitrary units.

(*a*) Completely reversible behaviour for an amphibolite specimen.
(*b*) Completely irreversible behaviour for a serpentinized peridotite.

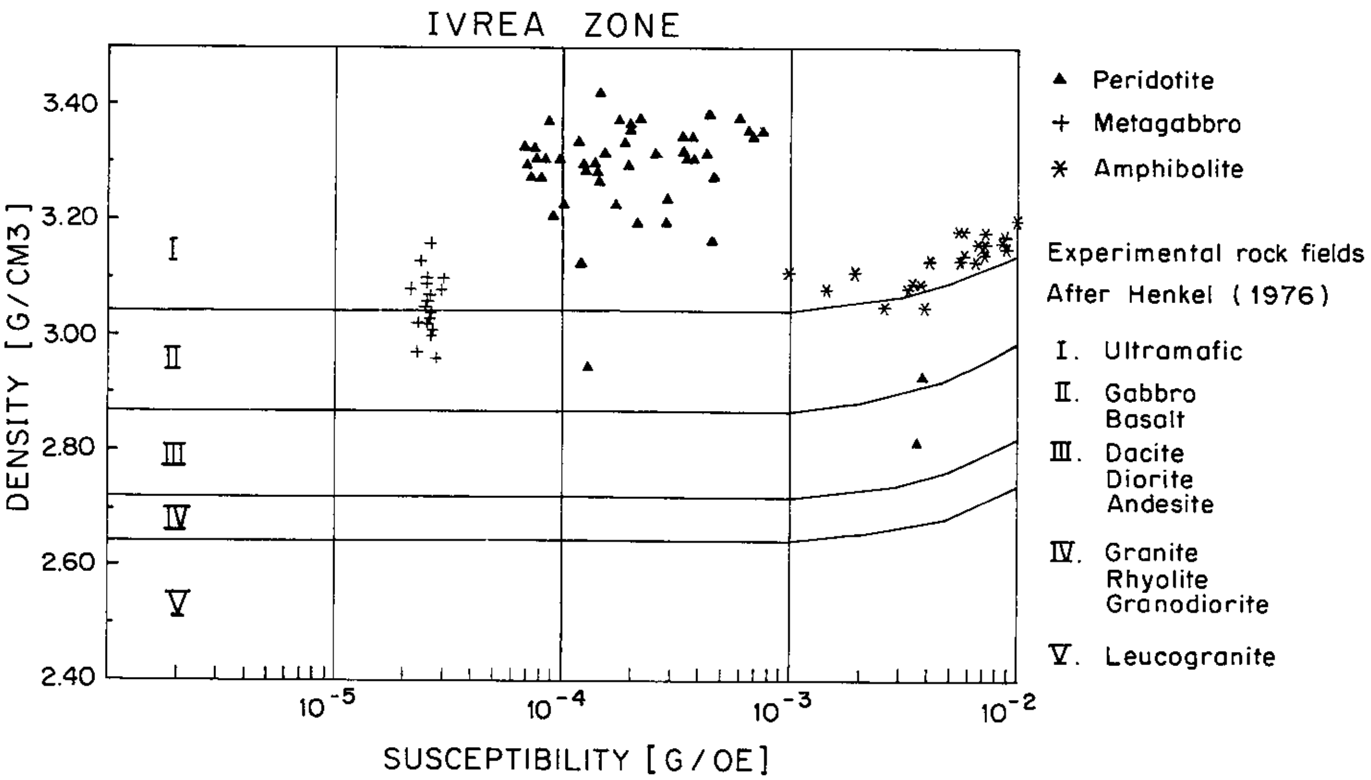

Figure 6: Susceptibility versus density diagram for rocks of the Ivrea and Strona-Ceneri Zones.

It demonstrates that the metagabbros and the amphibolites have nearly the same densities, but their susceptibilities are very different, namely between 10^{-5} and 10^{-4} G/Oe for the former and greater than 10^{-3} G/Oe for the latter. Peridotites which are rather fresh and have a density around 3.3 g/cm^3 are not strongly magnetic if one excludes the serpentinized ones, where the susceptibility is greater than 10^{-3} G/Oe but with a lower density (e.g. 2.8 g/cm^3).

Discussion

Based on all these various magnetic properties and from the intensity of the main Ivrea total field magnetic anomaly, serpentinites and amphibolites are the most likely candidates for the magnetic sources. Their susceptibility $> 10^{-3}$ G/Oe makes it possible to model the Ivrea magnetic body. If the intensity of its magnetization can be simulated with values coming from outcropping rocks, the type of magnetic source at depth is open for discussion.

If one admits as a first-order approximation that the measured susceptibilities at the surface correspond to those of the deeper crust then the magnetic anomalies have a maximum source depth given by the Curie temperature or Curie isotherm of the order of 20 km for a normal geothermal gradient (30 °C/km). In this case the amphibolites which are related to the lower crust (Mueller, 1977) have not only the "right" susceptibility $> 10^{-3}$ G/Oe, but also a density which suits the gravity modelling (see Kissling, this volume).

From the data shown in Figure 6, the peridotites are denser and have a lower susceptibility, but since the ultramafic rocks are easily serpentinized they can reach the appropriate susceptibility and density. The development of the serpentinization process gives rise to a decrease in density and an increase in susceptibility. This latter phenomenon is explained by Saad (1969) that during serpentinization the iron atoms are released from the silicate structure of the paramagnetic olivine and pyroxene and are oxidized to form magnetite. This is well documented on the basis of data published by Logachev and Zajarov (1978). The histogram in Figure 7 shows the susceptibilities for fresh and serpentinized ultramafics (peridotites, pyroxenites and dunites). They demonstrate that the secondary process of serpentinization has increased the susceptibility. With the formation of magnetite by oxidation the rock also acquires a chemical remanent magnetization (CRM) which will also contribute to the increase of the resultant magnetization. The CRM can be very stable.

It is also interesting to note that faults in the ultramafic rocks facilitate serpentinization and are—as a consequence—detectable through their signatures in the form of high narrow magnetic anomalies (see Schwendener, this volume).

If one advances the hypothesis that partly serpentinized ultramafics are the main magnetic sources at depth in the crust, then one should ask at what depth does the serpentinization process take place and, if it develops in the deeper crust, where does the necessary water come from ?

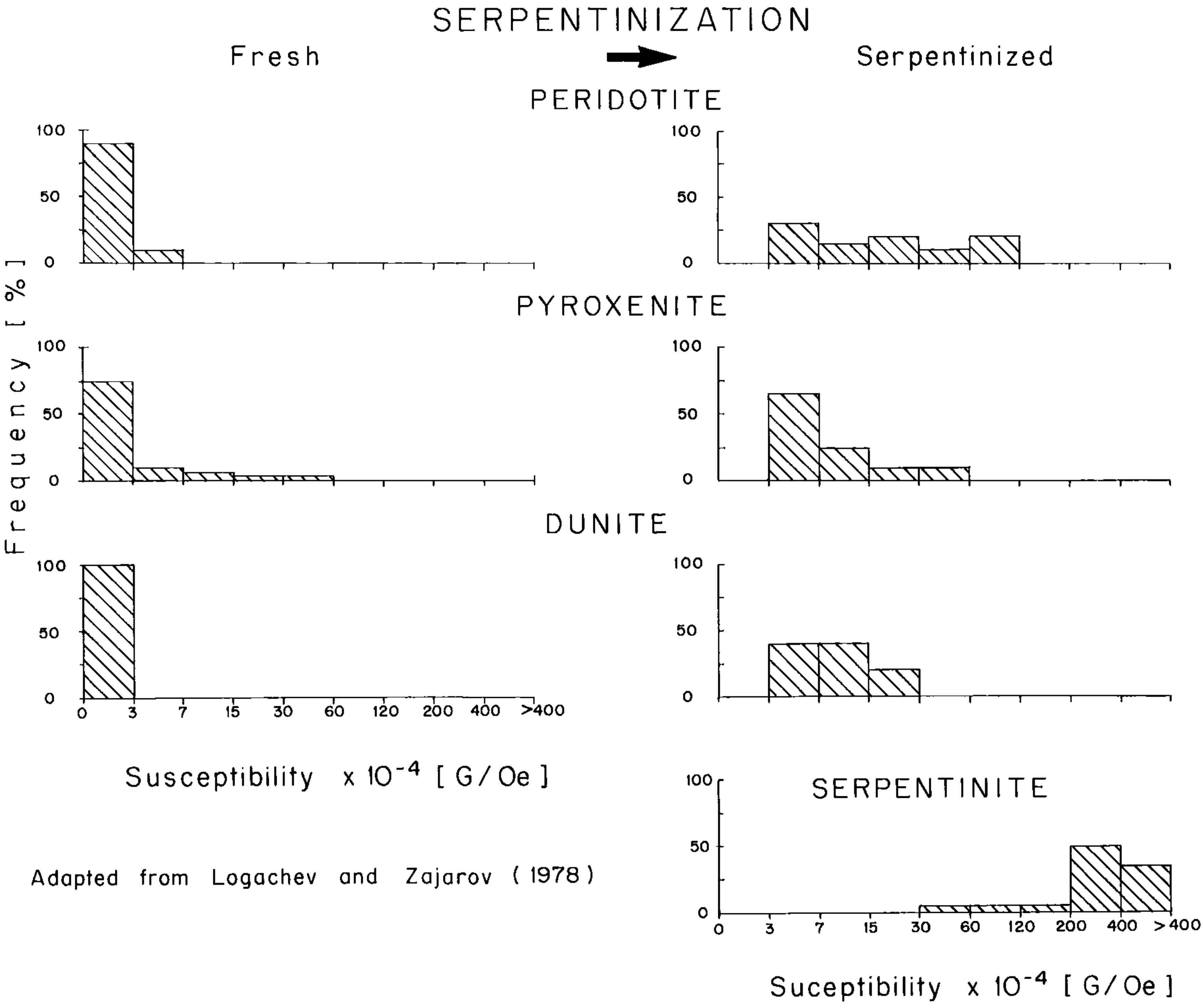

Figure 7: Variation of the susceptibility value with the serpentinization process for peridotite, pyroxenite and dunite samples. For comparison the results for serpentinite are also shown.

Finally, another interesting point should be considered: the evolution of the susceptibility with temperature. Dunlop (1974) has presented experimental data of single-domain magnetite (0.04 μm) particles exhibiting a thermal enhancement of the magnetic susceptibility (Hopkinson effect) of up to a factor of 3 at 550 °C. This effect seems to be less pronounced for multi-domain grains. In some cases a regional contribution from such an effect in terms of a deep-seated thin sheet could be considered.

In conclusion, these experimental results suggest that the main Ivrea anomaly is most likely created by serpentinized ultramafics and by amphibolites; both exhibit adequate susceptibilities for the magnetic model and densities suitable to contribute—amongst other rocks—to the corresponding gravity model.

Acknowledgments

The author thanks I. Hedley for improving the English. J. Berthoud and P. Zbinden are thanked for typing the text and drawing the figures. The Swiss Geophysical Commission financed the field and laboratory work; the Swiss National Science Foundation subsidized the magnetic laboratory equipment. All their contributions are gratefully acknowledged.

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V
DETAILED SURVEY OF THE LOCARNO MAGNETIC ANOMALY, SWITZERLAND

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Detailed Survey of the Locarno Magnetic Anomaly, Switzerland

1. Introduction

The magnetic anomaly of Locarno is well known to geologists and geophysicists since the early part of this century and coincides with the eastern end of the positive gravity anomaly associated with the Ivrea body.

In the region west of Locarno, between the Centovalli and the Lago Maggiore, already in 1944 and 1945, horizontal and vertical magnetic intensities were measured by Weber *et al.* (1949). At that time these authors postulated a fundamental connection between the magnetic anomaly and the mafic and ultramafic complex of the Ivrea Zone, where, in some parts, a very strong magnetization of these rocks was determined. In 1964, additional magnetic investigations were undertaken by M. Wyss and J. Kienle (unpublished diploma theses) in the region north of Brissago, where numerous strong local anomalies were found, which were interpreted to have been induced by lightning.

Similar investigations by Webel and Wagner (1973), along 12 profiles between Cuneo and Locarno, confirm the coincidence of the magnetic anomaly with the mafic complex of the Ivrea Zone. This anomaly can be subdivided into two parts:

1. A regional anomaly with intensities ranging from −300 nT to +300 nT (1 nT ≙ 1 γ), induced by the magnetic Ivrea body itself.
2. Several short-period anomalies with peak values of 1200 nT, which could be caused by dikes or similar structures.

Susceptibility measurements on rock samples from the Locarno region gave values of about 10^{-3} G/Oe for the mafic and ultramafic rocks, indicating that these could be the cause of the magnetic anomaly.

The regional coincidence of the magnetic and gravity anomalies, together with the presence of mafic and ultramafic rocks, suggests the possibility of a quantitative interpretation of the magnetic anomaly. In order to obtain a complete picture of its size and to allow the rejection or smoothing of very local anomalies, which could distort the overall aspect of the geophysical problem, it is necessary to map the anomaly in great detail. Thus, during the period 1978 to 1982, additional field measurements of the total magnetic field as well as laboratory measurements of the magnetic properties of selected rock samples from this region were carried out with the help of students of the Swiss Federal Institute of Technology. These investigations can be subdivided into three phases. The first phase, during the summers of 1978 and 1979, consisted of a preliminary mapping of the most intensive part of the anomaly situated on the northern shore of Lago Maggiore. The second took place in the summers of 1979 and 1980, where mainly the region south of the Lago Maggiore was mapped and where samples for susceptibility measurements were taken. From 1978 to 1980 a total of 1400 stations were measured on land. In autumn 1982, finally, the gap in the lake-covered part of the anomaly was closed with a nautical survey along grid lines with a total length of 400 km.

2. Geographic Situation

The region investigated is located in the rectangle between 8° 15′ E and 8° 45′ E longitude and between 45° 05′ N and 46° 10′ N latitude. It is bounded to the north by the river Melezza, to the east by the river Maggia, to the south by the 1000 m contour line on the northern slope of Monte Gambarogno and to the west by the Swiss-Italian border. A major part of this region is covered by the northern end of Lago Maggiore at an average elevation of 193 m above sea level, whereas the surrounding mountain summits reach elevations exceeding 1500 m above sea level.

3. Geological and Petrographic Situation

The region discussed here lies mainly in the Hercynian crystalline basement of the Southern Alpine complex, which is limited to the north by the Insubric Line. Further north, the gneissic roof zone of the Pennine nappes is found, which forms the northern boundary of the region considered (Bernoulli, 1980). Of relevance for the magnetic anomaly, however, are the rocks of the Hercynian basement, which, in this region, can be subdivided into two major zones. For more geological and petrographical details on the Ivrea-Verbano and Strona-Ceneri Zones see the paper by Chessex and Wagner in this volume.

4. Land Measurements

Total magnetic field measurements were carried out on land with a proton magnetometer at a station spacing of nominally 50 m. For each station, 5 measurements were made at the corners and in the center of a square of about 4×4 m. This procedure allows the determination of the reliability of the central value: whenever the corner values exceeded the central value by more than ± 50 nT, additional repeated measurements were made at this station, in order to determine whether the large variations were caused by a very local anomaly or

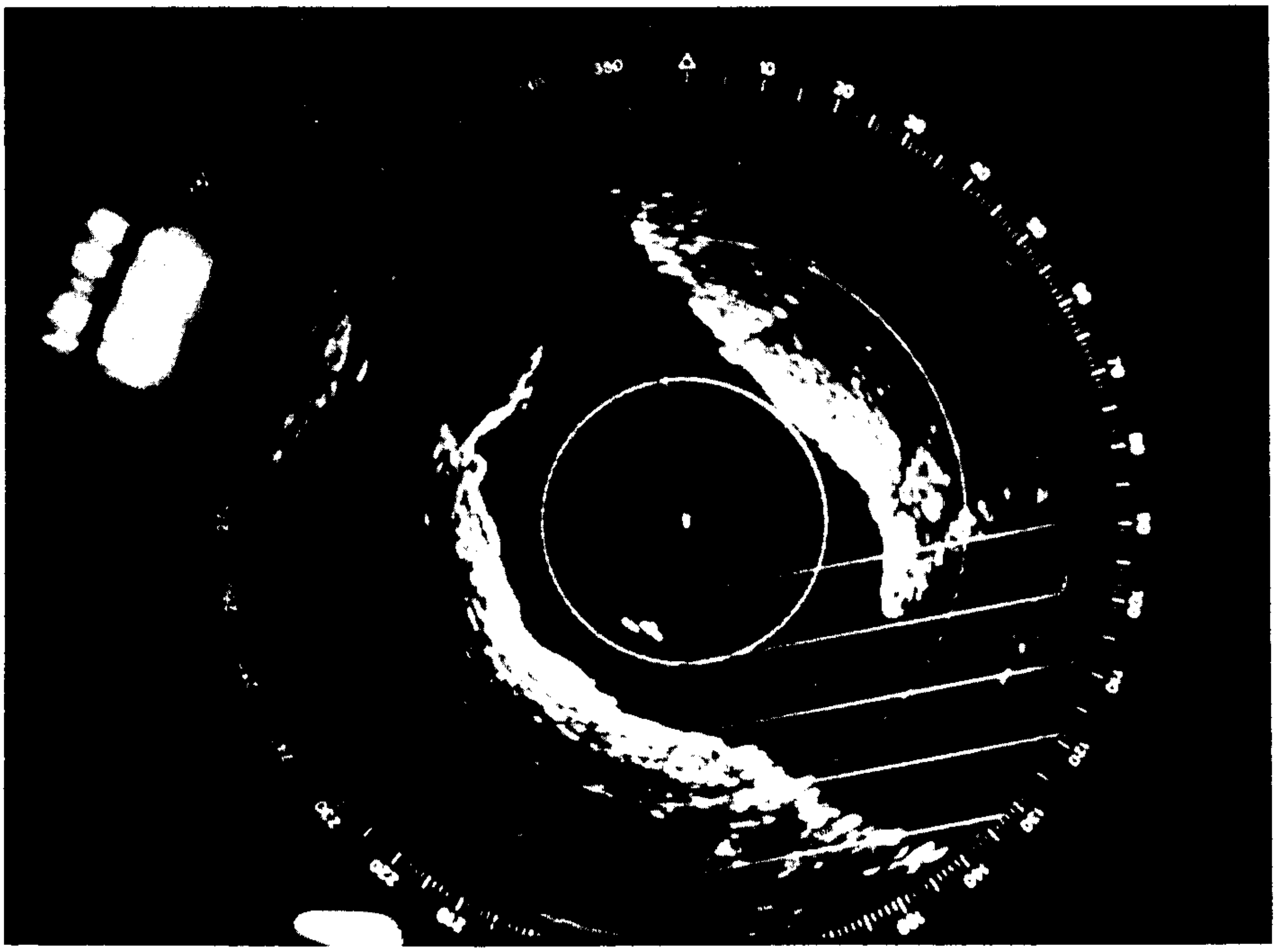

Figure 1: Photograph of the radar screen used for boat positioning during the lake survey.

whether the station was subjected to a magnetic disturbance. If the measured values fluctuated in time, the larger scatter was interpreted as a magnetic disturbance, and, if limited to a single station, the measurement was discarded. If several subsequent stations were similarly disturbed, the average of at least 5 measurements at each station was recorded. Dense vegetation and steep topography made it impossible to measure elsewhere than along footpaths or trails, which are thus delineated on the topographic map by the station positions (indicated by the fine dots in Fig. 2).

With the chosen configuration, anomalies of a wavelength larger than 150 m can be recognized. In areas of strong magnetic gradients, this configuration was changed to a station spacing of 10-20 m, thus increasing the resolution of short-wavelength anomalies, usually associated with mafic slabs or larger blocks.

5. Lake Measurements

The measuring procedure on the lake was adapted from that employed in aeromagnetic surveys (Klingelé, 1985). Measurements were made at intervals of 3 seconds, along straight north-south trending lines spaced at 500 m from each other. The sensor, coupled to a precession magnetometer with a resolution of 1 nT, was towed behind the boat at a distance of 30 m. The measured values of the magnetic field were recorded together with time and profile label on digital magnetic tape as well as in analog form on a paper chart recorder. The measurements were run from the ETHZ-owned research vessel «THETHYS», a 24-foot inboard cabin cruiser. Electric power for the measuring instrumentation has been provided by a 24 V/60 A alternator which is driven by the boat engine and which charges a 100 Ah lead-acid buffer battery. Profiling speed was held at an effective speed of 15 km/h.

The boat is equipped with a radar for instantaneous navigation and for following a predetermined course during foggy or hazy weather. A camera is mounted above the radar's viewing unit, thus allowing to photograph the radar screen during one full revolution of the beam, which corresponds to an exposure time of about 2 seconds. A digital LED clock affixed to the viewing screen is included in the photographs, thus providing the correlation between the magnetic measurement and the boat's position. Such a photograph is reproduced in Fig. 1, showing the distinct radar reflections from the lake shore and from the two islands of Brissago. The dot at the central cross-hair indicates the ship's position relative to the lake shores and the slightly clearer line upwards from this dot indicates the ship's heading. The angular subdivision on the circumference is not related to the azimuth and is only used for navigational purposes. The equidistance of the three concentric rings and of the parallel straight lines corresponds to a horizontal distance of 2 and 1 km, respectively.

During this survey, such photographs were taken at one minute intervals synchronized to the minute marks on the magnetic record. Later, the negative film was projected onto a transparent base map in appropriate enlargement and the radar image was adjusted to match the map's shore lines. The central cross-hair marks the boat's position at the corresponding time. The accuracy of this procedure for the size of this particular lake basin is about ±20 m. Similarly, the positions of particular events, such as ends of lines or course changes, were fixed by additional photographs.

The positions in the lake determined in this manner are shown in Fig. 2 as dots, and the ship's course is represented by the connecting straight lines. The shores of the northern end of Lago Maggiore are shown as almost continuous lines, interrupted only at river inflows.

6. Data Reduction

The numerous single-point magnetic field measurement values from the Locarno region obtained over several years and with different methods and instruments were processed together with the lake survey in order to obtain a map of the total magnetic field and subsequently of the residual field of this region. The procedure can be subdivided into 4 steps: (1) correction for diurnal and secular variations, (2) computation of the grid of the total magnetic field, (3) computation of the regional magnetic field and its anomalies and finally (4) cartography. The last point shall not be described here in further detail.

(1) *Correction for diurnal and secular variations*

A base station with a paper recorder was set up in the vicinity of the survey during the measurements. The recorded variations were then digitized and, after linearisation, utilized for corrections. Assuming the diurnal and secular variations to be the same over a zone with a radius of about 150 km, the correction for diurnal variations and the data reduction to the chosen reference epoch of 1978.5 is given as

$$F_p(a) = F_p(t) - F_s(t) + \underbrace{F_s(m) - F_o(m) + F_o(a)}_{\text{constant term}}$$

where:

$F_p(a)$ = Value of the mean magnetic field at point P for year $\underline{a}$

$F_p(t)$ = Measured value of the magnetic field at point P and time t

$F_s(t)$ = Measured value of the magnetic field at the base station at time t

$F_s(m)$ = Value of the mean magnetic field at the base station during the survey period

$F_o(m)$ = Value of the mean magnetic field at observatory O during the survey period

$F_o(a)$ = Value of the mean magnetic field at observatory O during year $\underline{a}$

The values of $F_o(m)$ and $F_o(a)$ were obtained from the Magnetic Observatory at Neuchâtel (Switzerland), and the assistance of P. A. Schnegg is gratefully acknowledged here.

(2) *Total field grid computation*

In a first step the region of interest was subdivided into three zones, namely the area to the north of the lake, the area to the south and the lake itself. In each of these zones, an independent grid with square meshes of 50×50 m was established; the three grids have a common origin and were unified later in the final map.

The interpolation method used is described in the paper by Wagner, Klingelé and Mage, of this volume.

(3) *Computation of the regional magnetic field and its anomalies*

Based on the International Geomagnetic Reference Field (IGRF 75), the regional normal field was computed for the corners of a grid of 1 km mesh width, covering an area considerably larger than that of interest here. This coarse grid was fitted by a least-squares procedure giving the coefficients of a first-order polynomial in x and y, permitting it to be interpolated at the point of the finer grid derived from the data. The residual field was then obtained by subtracting this normal field from the measured total field at these points. At first sight, this procedure may seem complicated, but the linear interpolation employed is computationally considerably faster than the alternative expansion into spherical harmonics of 13th degree.

Figs. 3 and 4 show the resulting maps of the total magnetic field and of the residual anomalies, respectively. Both reveal two anomalies of high intensities (1220 nT and 1050 nT, respectively) with non-rectilinear axes and a shift with respect to each other, suggesting a complex geometry of the disturbing body.

7. Susceptibility Measurements

Since a quantitative interpretation is impossible without at least an approximate knowledge of the magnetic susceptibility of the rocks in the region, about 90 representative rock samples were collected in the zones showing strong anomalies. These samples were cut to cylinders of 2.54 cm diameter and 2.25 cm length, and their susceptibility was determined using an induction balance UEF-KLY 1 at the Geomagnetism Laboratory of the ETH Institute of Geophysics in Zürich. Fig. 5 shows the results of these measurements in the form of histograms on ultramafic rocks, kinzigites and mafic samples, respectively.

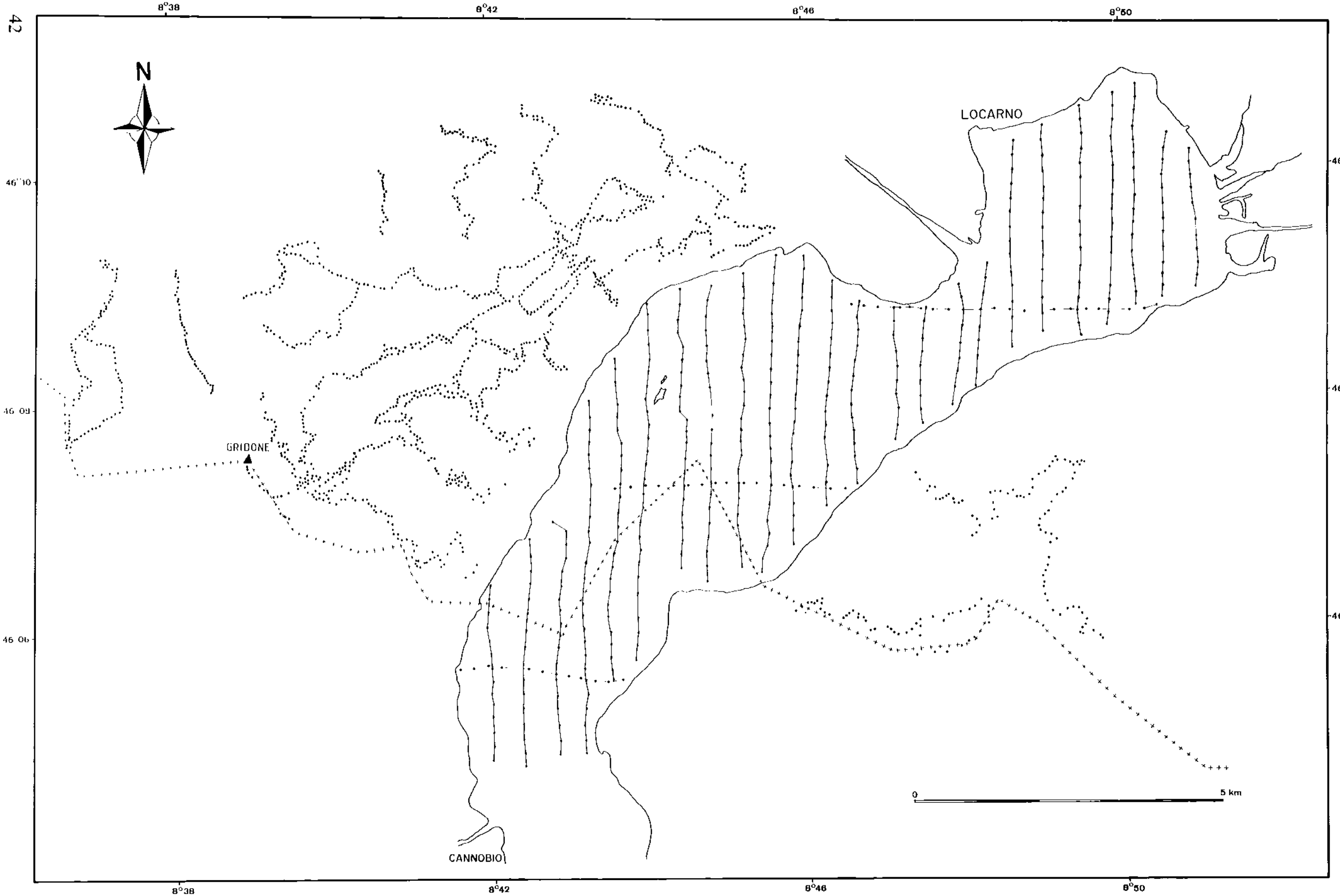

Figure 2: Location map of magnetic field measurements. Dots indicate land-based stations. Dots connected by straight lines mark points of photographic positioning and the boat's course during the lake survey. Small plus signs represent the Swiss-Italian border.

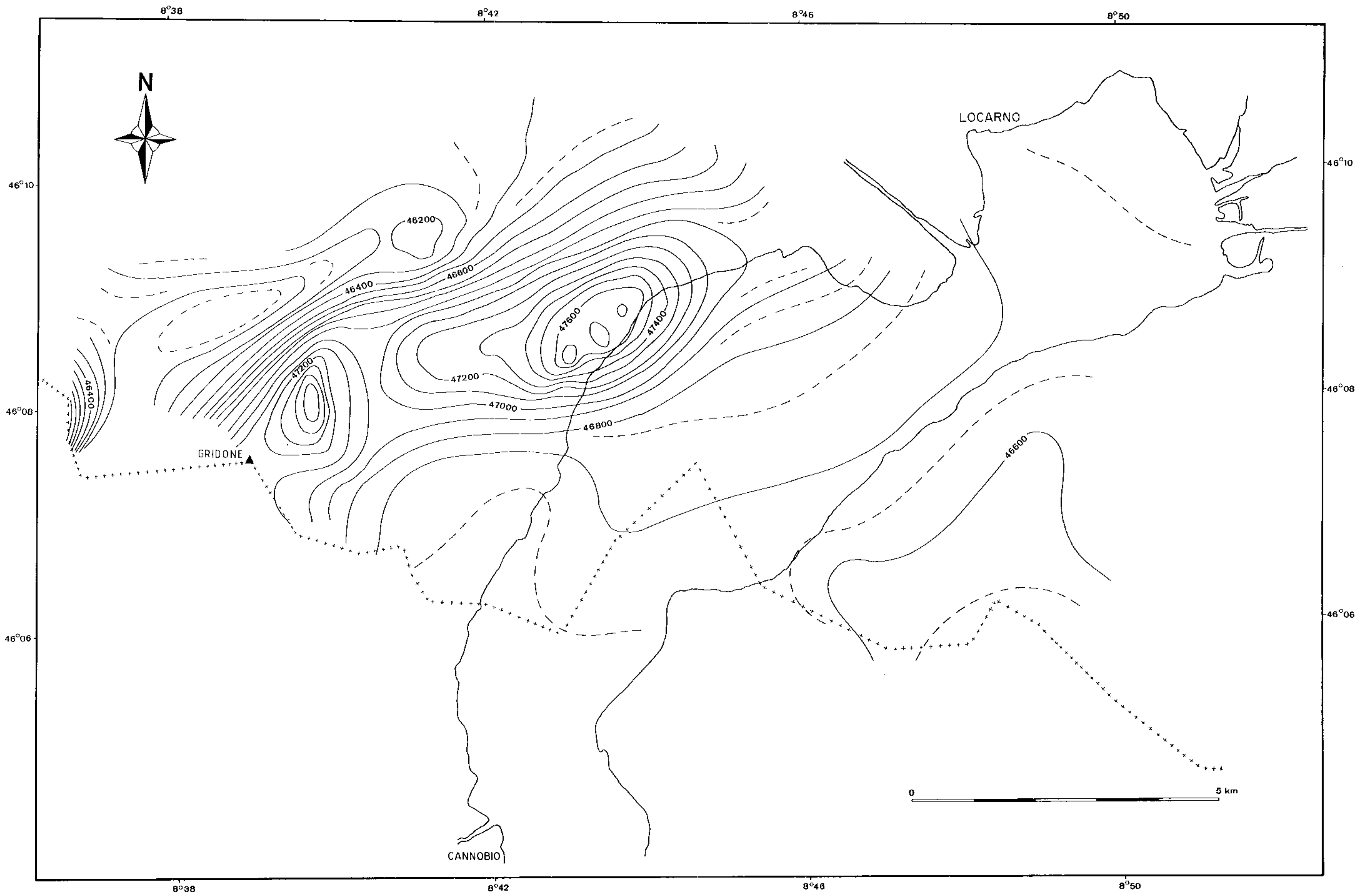

Figure 3: Map of the total magnetic field of the Locarno region after diurnal and secular corrections for the epoch 1978.5 based on ground measurements.

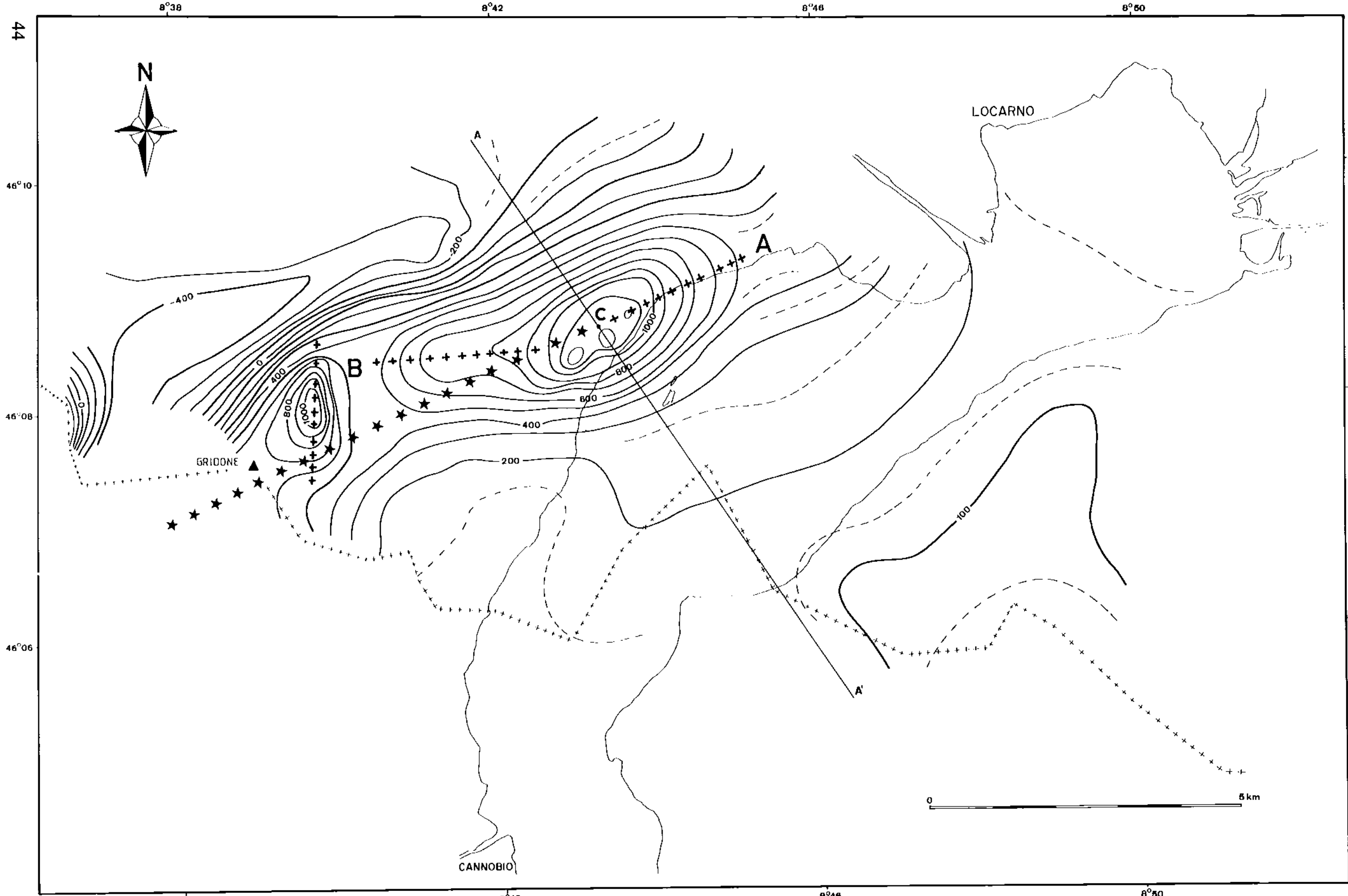

Figure 4: Map of residual magnetic anomalies of the Locarno region. Heavy plus signs indicate the axis of the principal anomalies. Star symbols indicate the axis of the aeromagnetic anomaly. Straight line between A and A' indicates the position of the interpreted profile.

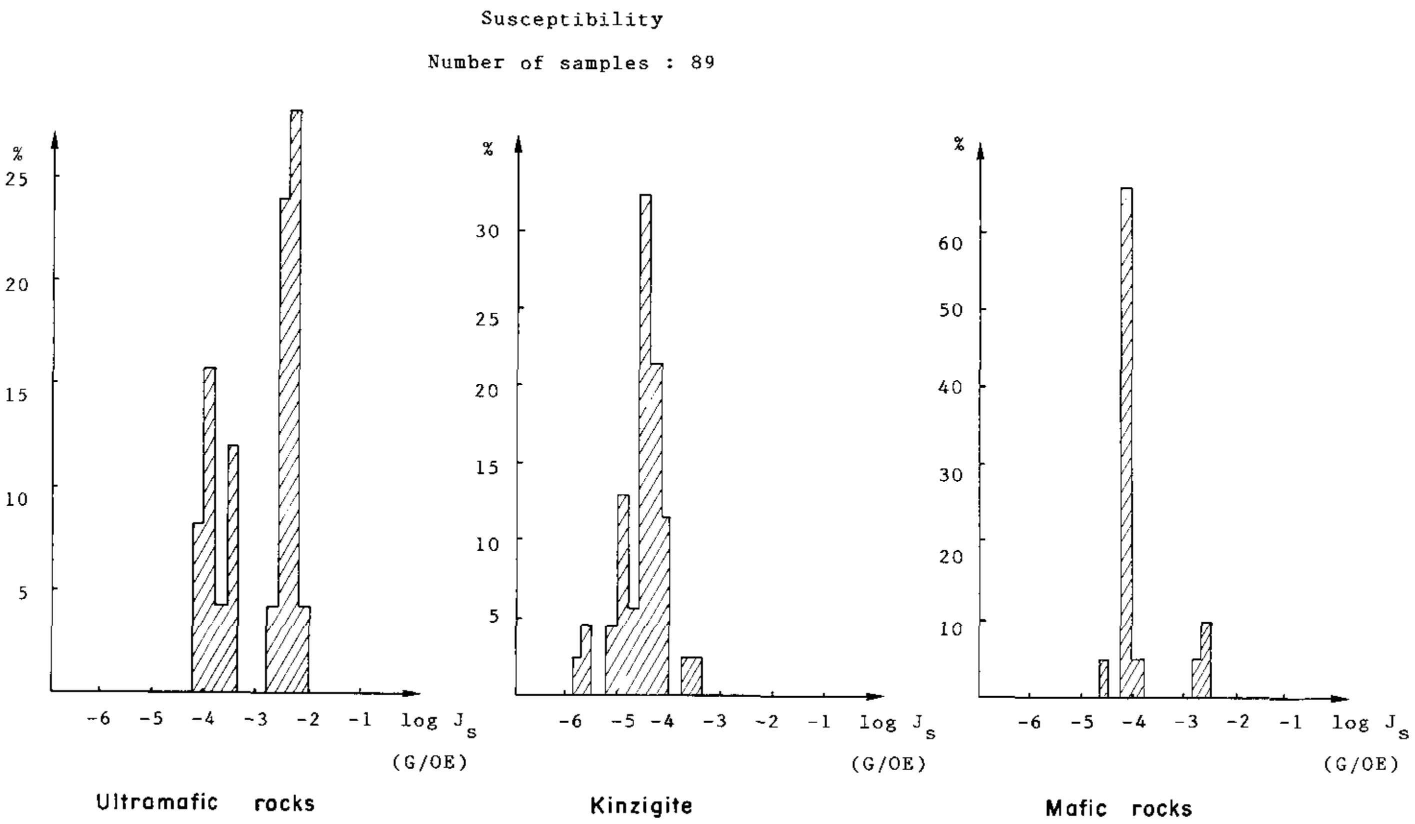

Figure 5: Susceptibility histograms for ultramafic, kinzigitic and mafic rocks sampled in the study area.

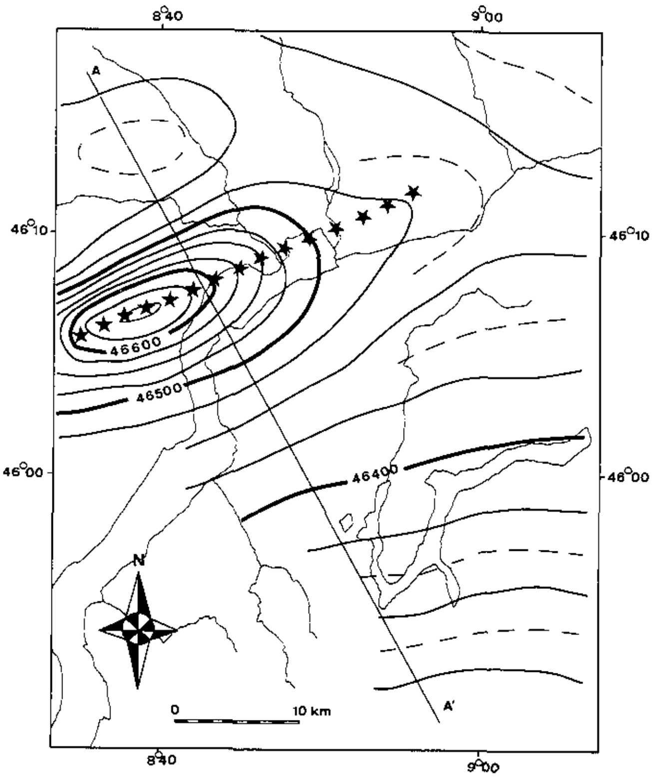

Figure 6: Section of the aeromagnetic map of Switzerland (from Klingelé, 1982) showing the axis of the anomaly (stars) and the position of the interpreted profile (A - A′).

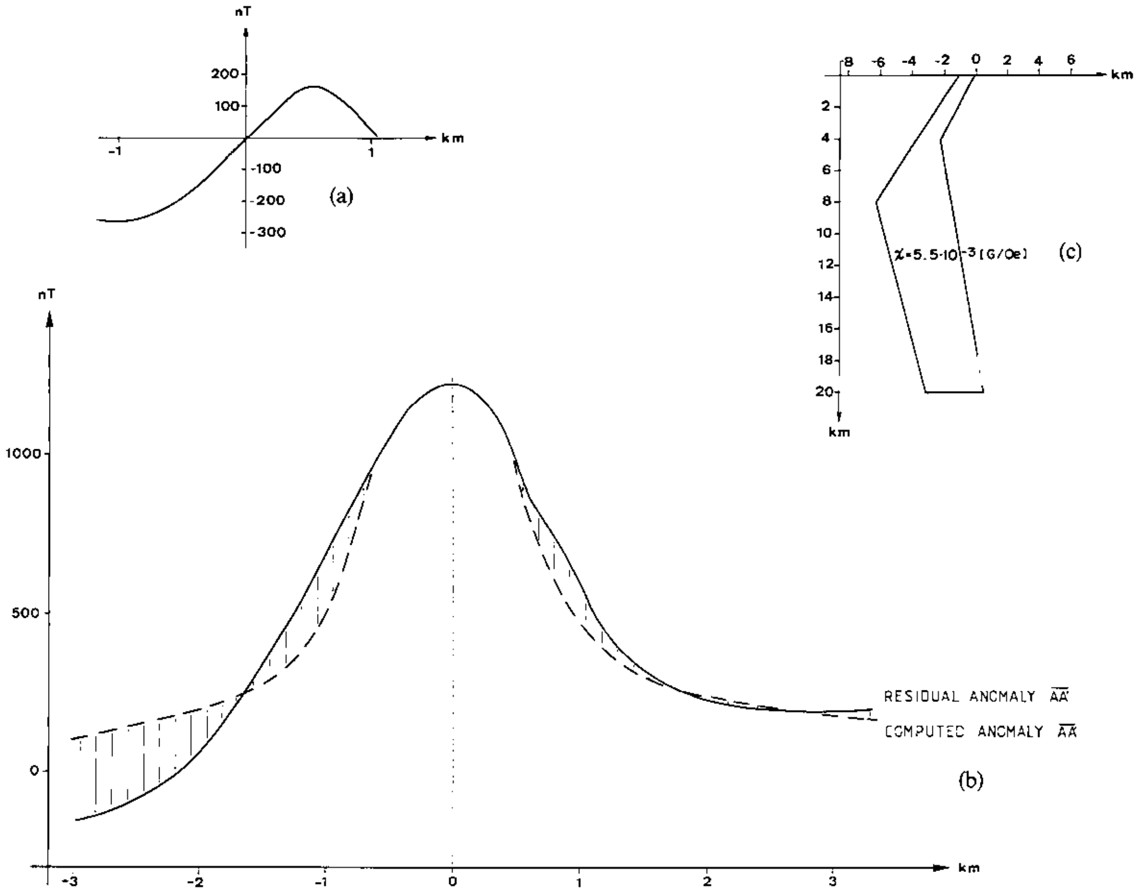

Figure 7 (a): Model of the disturbing body, based on the ground survey.
Susceptibility contrast = 5.5×10^{-3} G/Oe.
(b): Computed and measured residual anomaly along line A - A′ in Fig. 4.
(c): Difference between the northern part (left side) of the two curves in Fig. 7b.

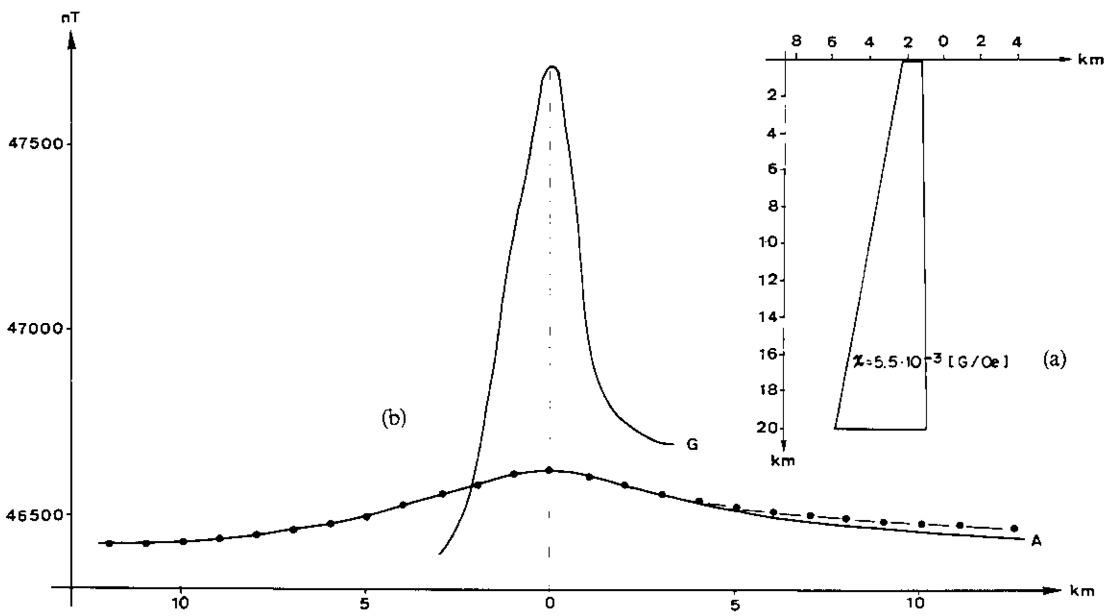

Figure 8 (a): Model of the disturbing body based on the aerial survey.
Susceptibility contrast = 5.5×10^{-3} G/Oe.
(b): Total field anomaly (thick line A) and calculated anomaly based on the aerial survey along line A - A′ in Fig. 6.
Thin line G represents the total field anomaly measured on the ground.

8. Interpretation

A closer look at the map of the residual anomalies (Fig. 4) clearly reveals the existence of two main anomalies, whose positive axes are at an angle of about 90° to each other. The western anomaly of about 1000 nT suggests from its north-south orientation, which is in contradiction to the strike of the known geological structures, and from the absence of a negative lobe, the presence of a body with high remanence. Therefore a quantitative interpretation of this anomaly is not attempted in this paper.

The eastern anomaly, with an overall WSW-ENE orientation of its positive axis, is bent in its western part, which is probably due to the influence of the strong anomaly to the west. The general trend of this anomaly must be compared to the results obtained from the aeromagnetic survey. Fig. 6 shows the total field anomaly as revealed by the aeromagnetic survey in the same region (Klingelé, 1982). The axis of this anomaly, delineated by stars, is superimposed onto the anomaly derived from ground measurements shown in Fig. 4. This comparison clearly shows that the general trend of the anomaly based on ground measurements is the same as the one resulting from the aeromagnetic survey. Thus, interpretations of the two anomalies should give similar results.

Based on the method given by Talwani and Heirtzler (1959), both data sets were interpreted along a profile perpendicular to the principal axis of the anomaly, indicated by the straight line from A to A′ in Figs. 4 and 6. This method consists of a curve-matching procedure, in which the interpreter must minimize the differences between a calculated anomaly and the measured one, by varying the susceptibility contrast and the dimensions of one or more disturbing bodies of infinite extent in the direction perpendicular to the interpreted profile. The theoretical number of solutions is infinite, but can be constrained within reasonable limits by geological, tectonic and petrophysical considerations. The results obtained reveal that the anomaly can be explained by an almost vertical body of mafic to ultramafic composition, having the form of a slab broadening with depth.

The model derived from the ground measurements is shown in Fig. 7a together with the corresponding theoretical curve superimposed on the measured residual anomaly (Fig. 7b), and with the difference between the two. The somewhat larger discrepancy between the two curves in the northern part (Fig. 7c) suggests the existence of a protuberance on the disturbing body, having a width of a few hundred meters at most.

Figs. 8a and 8b show the solutions for the airborne survey and the corresponding model calculations. The resulting differences in shape between the disturbing bodies obtained from the airborne and from the ground-based interpretations are relatively small and can basically be attributed to the smoothing effect of the aerial survey, which was flown at an altitude of 5000 m. Note that the best-fitting susceptibility contrast in the models is the identical value of 5.5×10^{-3} G/Oe for both models. In the aerial survey no indication is found for the western anomaly, which is clearly present in the ground-based survey and, consequently, the modelled form of the disturbing magnetic source is somewhat simpler. Fundamentally, both surveying methods yield comparable results, but the ground-based survey has a higher resolution.

9. Acknowledgments

The authors gratefully acknowledge the assistance and support of their colleagues, collaborators and of several graduate students at the Institut für Geophysik of the ETH Zürich. Prof. St. Mueller critically read this paper and made a number of helpful suggestions for its improvement. Mrs. E. Hirzel and J. Berthoud typed several versions of the manuscript for which we are indebted to them.

Contribution No. 485, ETH-Geophysics, Zürich, Switzerland.

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VI
THE IVREA MAGNETIC ANOMALY IN THE VALLE D'OSSOLA AND VALSTRONA AREA, NORTHERN ITALY

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The Ivrea Magnetic Anomaly in the Valle d'Ossola and Valstrona Area, Northern Italy

1. Introduction

The rocks of the Ivrea Zone and the adjoining Strona-Ceneri Zone to the southeast (see Chessex and Wagner, this volume) consist of material originating from the upper mantle and from the lower to intermediate continental crust. To elucidate the fine structure of the regional magnetic anomaly that is generated by these rocks (see Wagner, Klingelé and Mage, this volume, and Albert, 1974), a high resolution survey of the total magnetic field has been performed along three profiles. The profiles are situated on the northeastern and southwestern flank of the Valle d'Ossola and in the Valstrona. The profiles are about 20 km long, perpendicularly to the strike of the Ivrea Zone.

2. Magnetic Measurements

The measurements of the total magnetic field were carried out in the year 1977 (Schwendener, 1978) with a SCINTREX MP-2 proton-precession magnetometer. This instrument provides a resolution of 1 nT. The average spacing between the stations in the Ivrea Zone is 50 m. It was reduced down to 20 m in regions of high magnetic anomalies. Outside of the Ivrea Zone one station was measured every 250 m. At each station 5 values were sampled. They are situated at the center as well as 5 m to the north, south, east and west of it. This allows to have control on the local horizontal gradients of the total magnetic field. Investigations on the precision of the data gave mean errors of $\pm$ 2 nT in

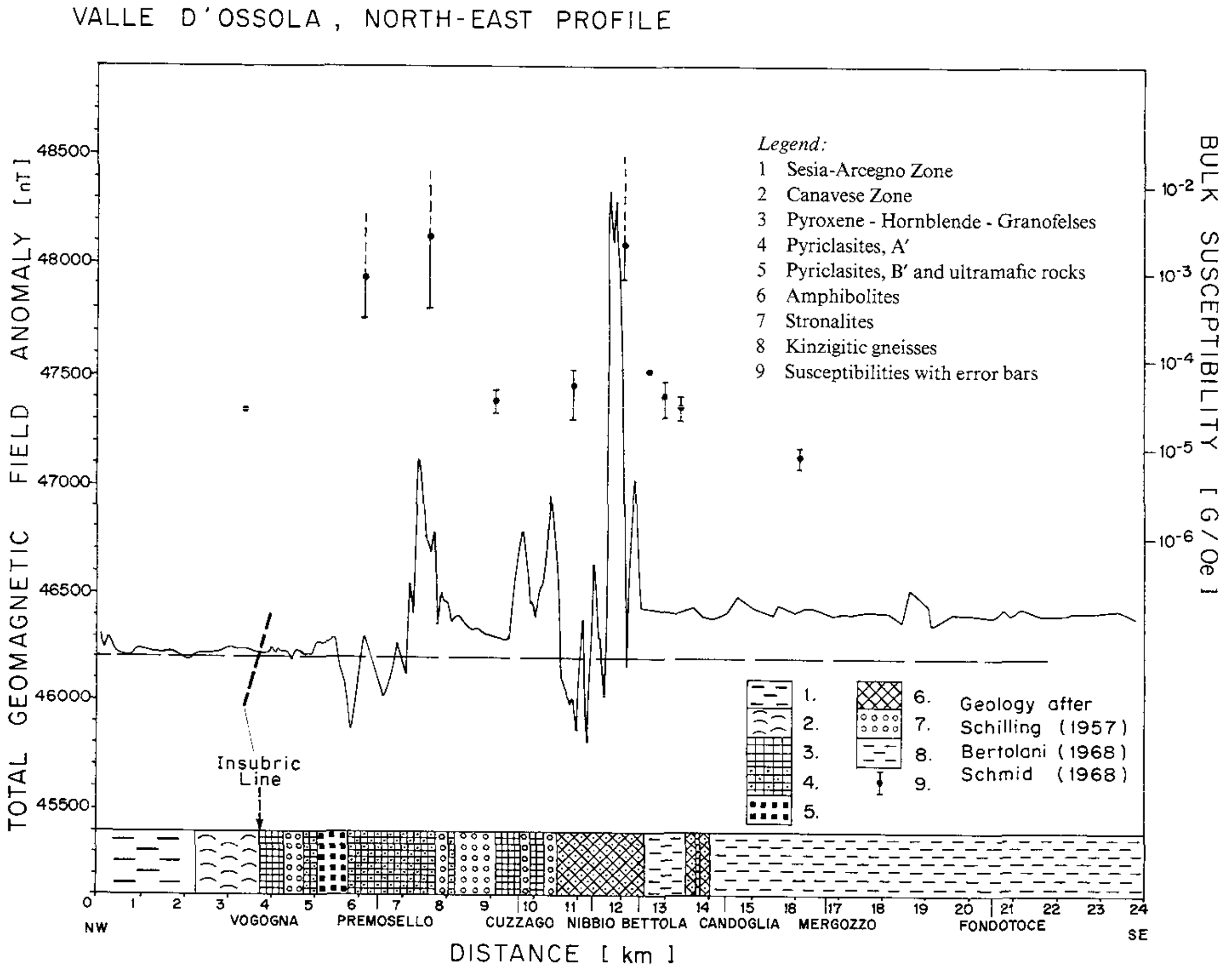

Figure 1: Total magnetic field along a profile across the northeastern flank of the Valle d'Ossola, together with a simplified geological section (after Schmid, 1968).

regions of no anomalies and ± 6 nT when high anomalies were present. To eliminate the diurnal variations, the total magnetic field was recorded with a base station operating in the surveyed area.

3. Reduction of the Observations

After the reduction of the diurnal variations, corrections were made for the change in altitude and latitude. The corrections were calculated for 1977 with the help of the values of IGRF (International Geomagnetic Reference Field) 1975.
No corrections for topographic effects were made.
The three measured profiles are shown in Figs. 1, 2 and 3 together with simplified geological sections.

4. Susceptibilities

On a series of rock samples, drilled on the northeastern flank of the Valle d'Ossola, magnetic bulk susceptibilities were measured with a "GEOFYZIKA KLY-1" kappa-bridge.

The susceptibilities range from $8 \cdot 10^{-6}$ G/Oe in the rocks of the Strona-Ceneri zone to $3 \cdot 10^{-3}$ G/Oe in the amphibolites of Nibbio and $6 \cdot 10^{-3}$ G/Oe in the pyriclasites of Premosello. They are plotted together with the magnetic profile across the northeastern flank of the Valle d'Ossola (Fig. 1).

5. Discussion of the Magnetic Profiles

For the following discussion the nomenclature of rocks has been adopted from Schmid (1967). The three

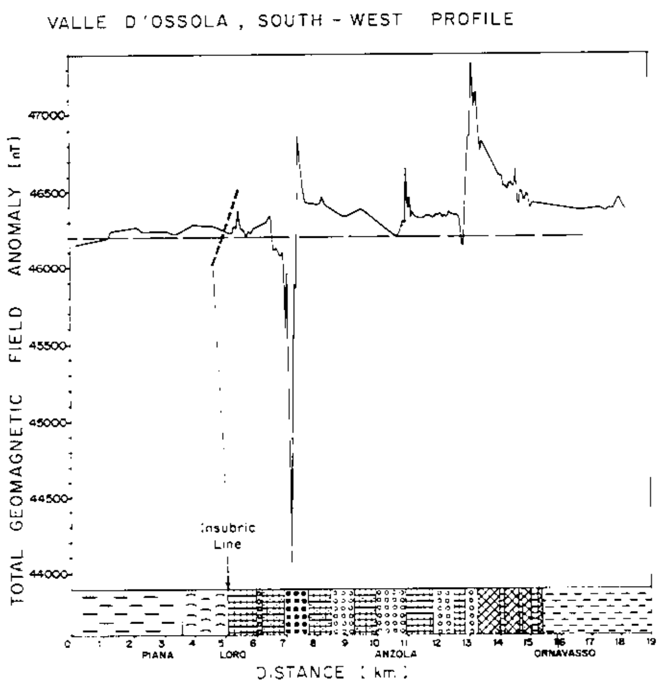

Figure 2: Total magnetic field along a profile across the southwestern flank of the Valle d'Ossola.

presented profiles show clearly, that the magnetic anomaly generated by the Ivrea Zone consists of a series of local anomalies of 0.2 to 2.0 km in width with amplitudes of up to 2000 nT. They can be correlated very well with the mafic and ultramafic rocks of the Ivrea Zone. On the Valle d'Ossola northeastern profile (Fig. 1) the first local anomalies occur 2 km southeast of the Insubric Line in the pyriclasites of Premosello, which also possess high susceptibilities. The field remains quiet in the region of the stronalites (northwest of Cuzzago) and is again strongly anomalous in the area of the pyroxenites and amphibolites between Cuzzago and Bettola. A similar situation is found for the southwestern profile in the Valle d'Ossola (Fig. 2). The strong local anomalies were measured in the region of the pyriclasites and amphibolites whereas the field remains rather undisturbed in the region of the more intermediate stronalites.

While form and size of the local anomalies in the two Valle d'Ossola profiles differ significantly, they occur in the same petrological units. This indicates that the amount of magnetic minerals is likely to change, which could be due to different amounts of serpentinization (see Wagner, this volume). Their presence, however, remains restricted to the same units (pyriclasites and amphibolites).

This statement is corroborated additionally by the Valstrona profile (Fig. 3), where only one outcrop of mafic rocks is present (amphibolites, southeast of Rosarolo). The only strong local anomaly on this profile is clearly correlated with this unit. The ultramafic rocks (peridodite) near Campello Monti cause only weak local anomalies as expected from their lower susceptibilities (see Wagner, this volume).

A continuous increase of the total magnetic field intensity (150-200 nT) from the northwest to the southeast can be observed on all the three profiles. This regional anomaly has been interpreted with a two-dimensional model consisting of a southeastward-dipping plate of 15 km thickness with a susceptibility of 0.001 G/Oe (Schwendener, 1978). The cross section of this plate is in accordance with the three-dimensional gravity model (Kissling, this volume).

6. Acknowledgments

The author gratefully acknowledges the assistance and support of his colleagues, collaborators and of several graduate students at the Institut für Geophysik of the ETH Zürich. Prof. St. Mueller critically read this paper and made a number of helpful suggestions for its improvement. Mrs. E. Hirzel and J. Berthoud typed several versions of the manuscript for which I am indebted to them.

Contribution No. 486. ETH-Geophysics. Zürich, Switzerland.

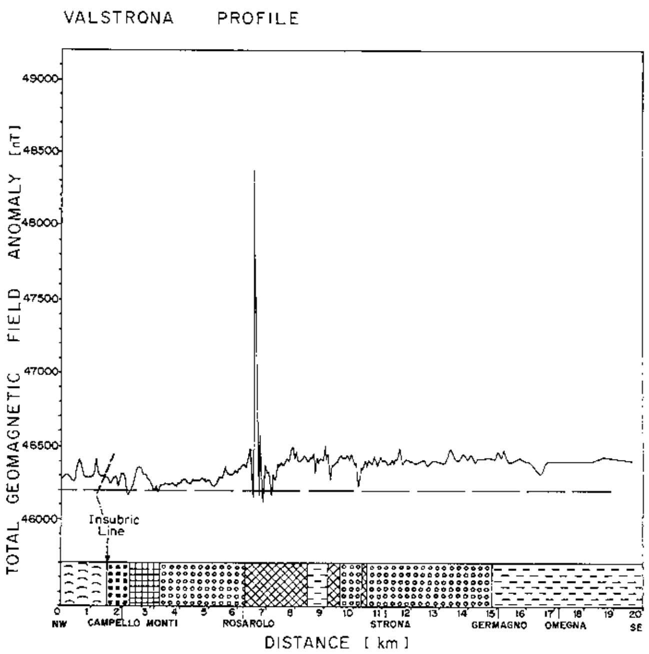

Figure 3: Total magnetic field along a profile in the Valstrona.

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VII
THREE-DIMENSIONAL GRAVITY MODEL OF THE NORTHERN IVREA-VERBANO ZONE

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Three-Dimensional Gravity Model of the Northern Ivrea-Verbano Zone

1. Gravity and Seismic Data

The interpretation of the new Bouguer map of Switzerland (Klingelé and Olivier, 1980) by a model of the crustal and upper mantle structure in the Central Alps requires the consideration of the gravity effect of the Ivrea body. For this purpose the results of a gravity survey (Kissling, 1980) in the northernmost part of the Ivrea-Verbano Zone have been incorporated into the Bouguer map of Switzerland (Fig. 1). The high station density of this map (in average one station per 16 km^2 in the Alps) allows three-dimensional gravity modelling for the Central Alps as well as for the northern Ivrea-Verbano Zone. Because this recent gravity survey was restricted to the north of the Val Sesia (Fig. 1), gravity information for the southern part of the Ivrea body must be taken from the small-scale Bouguer map "Schwerekarte der Schweiz und der angrenzenden Gebiete", a compilation of data from Bouguer maps of Italy, France, Germany, Austria and Switzerland published previously (Kahle *et al.*, 1976).

Reinterpretation of older seismic data as well as new refraction lines in the vicinity of the northern Ivrea-Verbano Zone led to a cross section from the Valais to the Po plain (Fig. 3) by Ansorge *et al.* (1979). This reinterpretation is most useful for a three-dimensional gravity model because its cross section is mainly based on refraction lines that run parallel to the main tectonic units though situated slightly to the northeast of the Ivrea body.

2. Geologic Model Constraints

Several large-scale geologic maps of the northern Ivrea-Verbano Zone have been published in the last two decades. While the maps of Bertolani (1968), Boriani and Sacchi (1973) as well as that of Steck and Tièche (1976) supplied specific information for near-surface geometry of the Ivrea body the geologic map of Schmid (1967 and 1968) has been used for most of this study (see also Chessex and Wagner, this volume).

It is interesting to note that the main tectonic lineament of the area, the Insubric Line (IL) which showed large horizontal and vertical displacements during the Late Tertiary (Laubscher, 1971) presently shows remarkable seismic quiescence (Mayer-Rosa and Mueller, 1979).

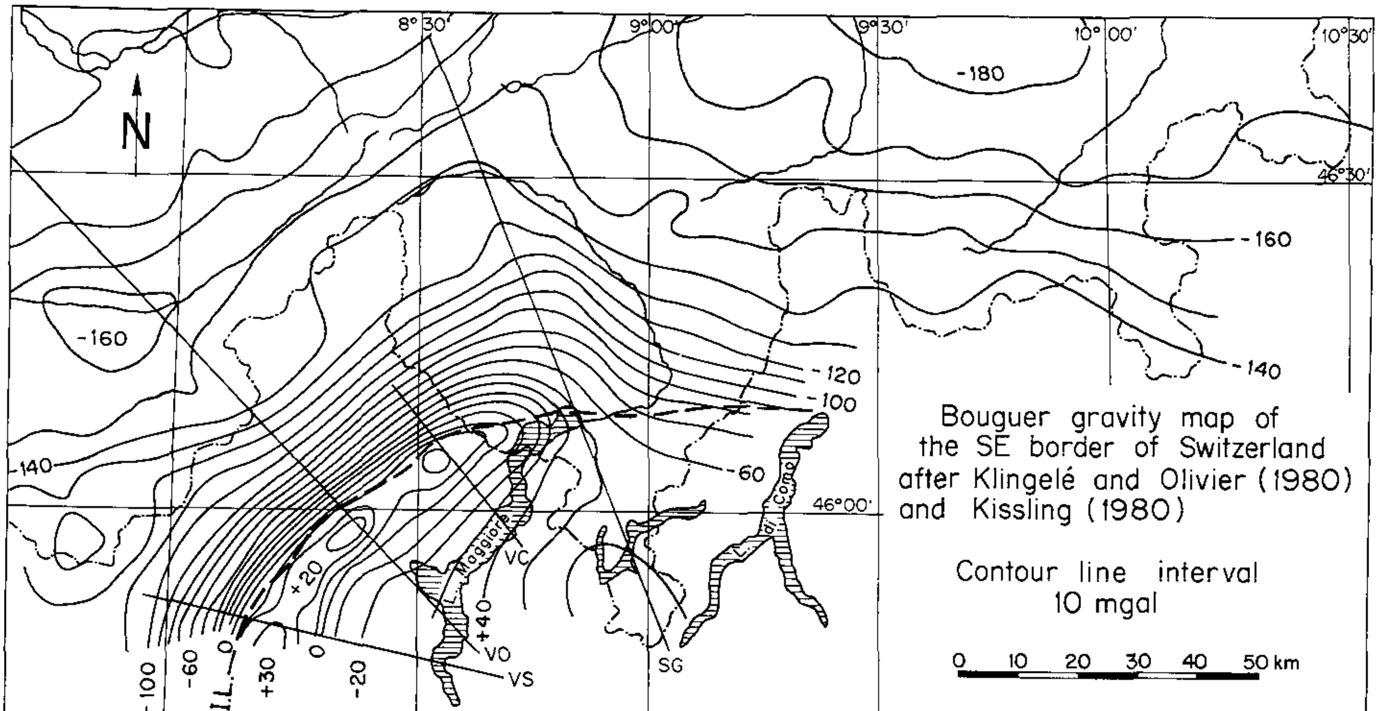

Figure 1: Bouguer map of the southeastern border of Switzerland (in mgal) after Klingelé and Olivier, 1980 and Kissling, 1980. Location of gravity profiles in the northern Ivrea-Verbano Zone:
VS = Val Sesia profile, VO = Valle d'Ossola profile,
VC = Val Cannobina profile, SG = Swiss Geotraverse.

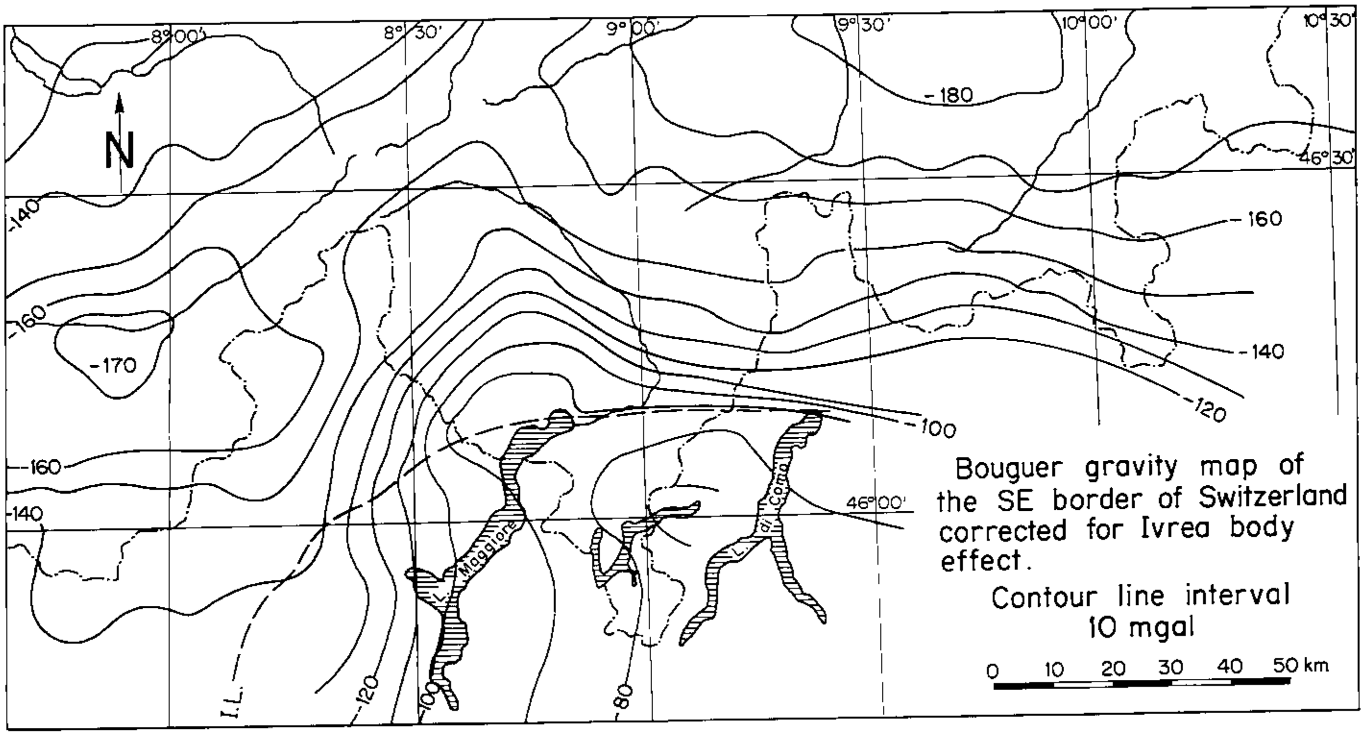

Figure 2: Bouguer map of the southeastern border of Switzerland (in mgal) after the removal of the gravity effect caused by the Ivrea body.

In the area under consideration, the Insubric Line is exposed over a vertical range of 2000 m showing a dip of about 50° in Val Sesia with a steady tendency to higher angles toward north (60° in Valle d'Ossola, subvertical near Locarno-Bellinzona, see Gansser, 1968).

To the southeast the Ivrea-Verbano Zone is bordered by the Strona-Ceneri Zone, locally separated from each other by faults (Schmid, 1968). The density and the velocity up to pressures of 10 kbar for many of the rock types of these zones were measured by Fountain (1976). To obtain information about the two-dimensional distribution of the near-surface density within the Ivrea-Verbano Zone and the surrounding areas some 100 samples (each between 3 and 10 kg) have been collected. The bulk density was measured under wet and dry conditions in the laboratory using the principle of Archimedes (accuracy in our case: +/− 0.01 g/cm^3). The results are shown in Fig. 4. While bulk densities higher than 3.0 g/cm^3 are common for many ultramafics, a rock complex of this size with an average surface density over 3.0 g/cm^3 is unique in Europe. It is also worth noting that these high densities are associated with several rock types. Using the names introduced by Schmid (1967), four groups of rock types may be distinguished:

a. Ultramafic rocks with densities up to 3.20 g/cm^3,

b. Stronalites and basic rocks with densities between 2.95 and 3.10 g/cm^3,

c. Kinzigites with densities 2.70 – 2.90 g/cm^3, which form some kind of intermediate layer between the Ivrea-Verbano and Strona-Ceneri Zones,

d. The schists and gneisses of the Strona-Ceneri Zone, which scatter widely about an average density of 2.65 g/cm^3; values as low as 2.45 g/cm^3 have been found locally, and within the Strona-Ceneri Zone there are several batholiths (for example the granite of Baveno) that show a density of 2.67 g/cm^3.

Since the stronalites, the mafic rocks (mainly amphibolites), and kinzigites are well mixed over a broad area, they may be treated as one single layer as far as density is concerned. This layer then has an average positive density contrast of 0.35 g/cm^3 on the surface and shall be referred to as the main Ivrea body. The density distribution shown in Fig. 4 suggests the southeastern border of the so-defined Ivrea body lying within the Ivrea-Verbano Zone paralleling its boundary to the Strona-Ceneri Zone. While the fine lamination of the mafic and intermediate rocks of the Ivrea-Verbano Zone allows the simplification to a single layer of an average density around 3.0 g/cm^3, the ultramafic rock complexes within this body have to be accounted for separately in the gravity model. These complexes have an average surface density which exceeds that of the main Ivrea body by 0.05 – 0.15 g/cm^3. Because all of the larger ultramafic rock complexes lie close to the Insubric Line (Schmid, 1968), the very strong horizontal gravity gradient in this area (Fig. 1) is partly due to

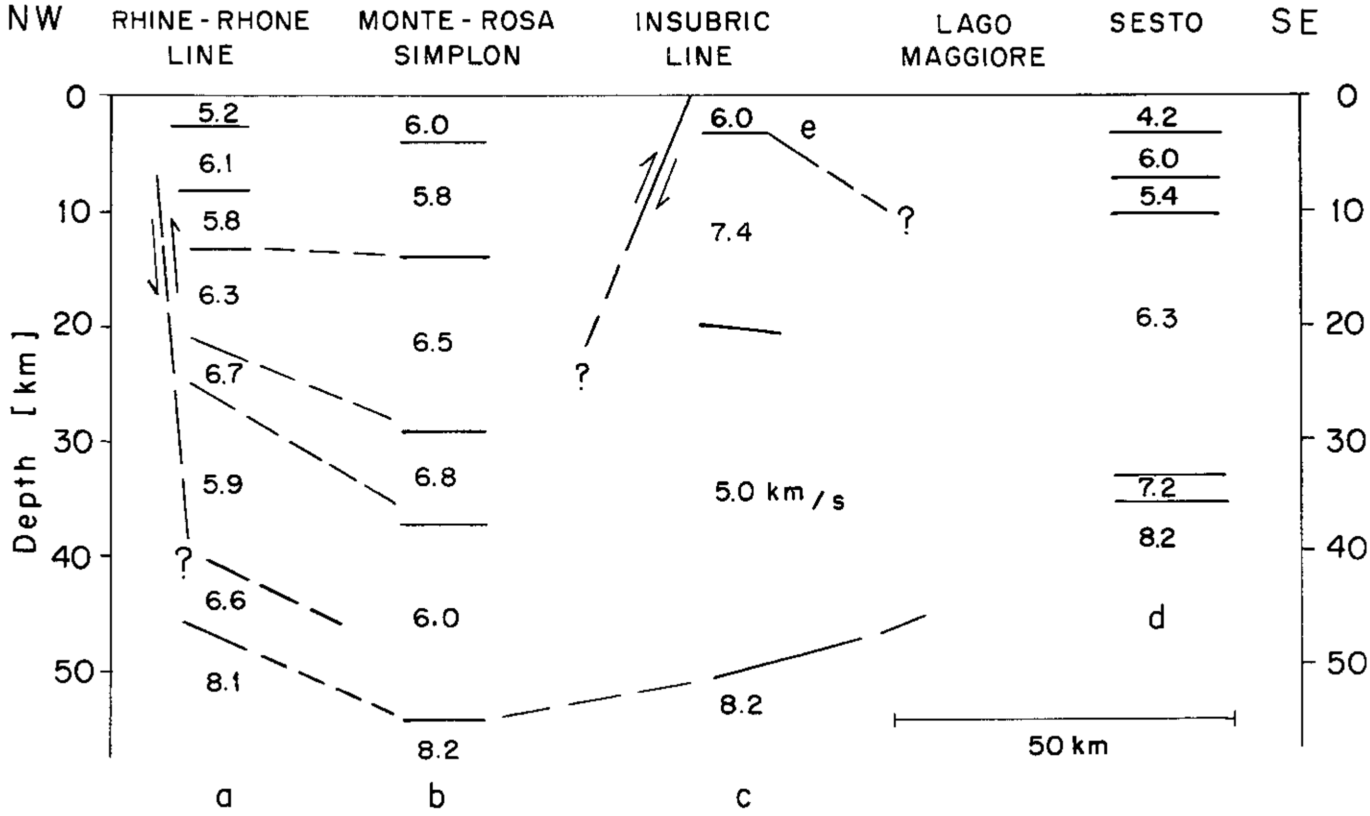

Figure 3: Seismic cross section from the Valais to the Po plain. a, b, c, d: after Ansorge *et al.*, 1979; e: after Fuchs *et al.*, 1963.

anomalies of short wavelength superimposed on the main gravity effect of the Ivrea body as a whole.

3. Three-Dimensional Model of the Ivrea Body

The southern section of the Ivrea body must not be neglected while modelling the section north of Val Sesia. For this reason the three-dimensional modelling of both the gravity and seismic data in the southern Ivrea-Verbano Zone was necessary. Despite the sparse geophysical data in the southern Ivrea-Verbano Zone and the masking sediments of the Po plain, the errors associated with the model calculation of the northern Ivrea body are quite small. We only need to know the gravity effect of the southern part of the Ivrea body in the area north of Val Sesia while the same model anomaly has to fit the known gravity field in the whole southern area. Of course, we therefore cannot gain any new information about the shape of the southern part of the Ivrea body. The model used in this study for the southern Ivrea-Verbano Zone, a uniformly eastward-dipping plate with a positive density contrast of 0.35 g/cm^3, is but one out of several different possibilities.

The procedure of modelling the northern part of the Ivrea body follows four steps:

1. Recalculation of near-topographic corrections (with a radius of up to 2.5 km from the gravity station). This correction (using average densities according to the distribution shown in Fig. 4) was done only for gravity stations having more than 50% of their near-topographic area within the Ivrea-Verbano Zone. For higher precision (better than +/− 2 mgal; 1 mgal = 0.00001 m/sec^2) this should be done for all stations within 2.5 km of the Ivrea-Verbano Zone. However, the errors due to both the uncertainty in station elevation and the effects of the unknown Quaternary sediments in the valleys, where most stations are located, are of the same order of magnitude.
2. Outlining the top of the Ivrea body and the enclosed ultramafic rock complexes according to the geologic maps and the distribution of surface rock densities (Fig. 4).
3. Introduction of seismic model informations. This includes the data (Fig. 3) from Ansorge *et al.* (1979), P-wave velocities of the Ivrea body (German Research Group: Reporter Berckhemer, 1968 and Giese, 1968), the thickness and structure of the crust in the surrounding area (Mueller *et al.*, 1980) and the velocity-density relationship of Woollard (1975) and Christensen and Fountain (1975).
4. Calculation of the gravity effects for different models that fit the above constraints and comparing the results with the measured anomaly. The model calculation was done using a FORTRAN program (Kissling, 1980) following the method proposed by Goetze (1976).

Most of the recently acquired gravity data lie along three profiles, each of which runs more or less perpendicular to the local strike of the Ivrea-Verbano Zone

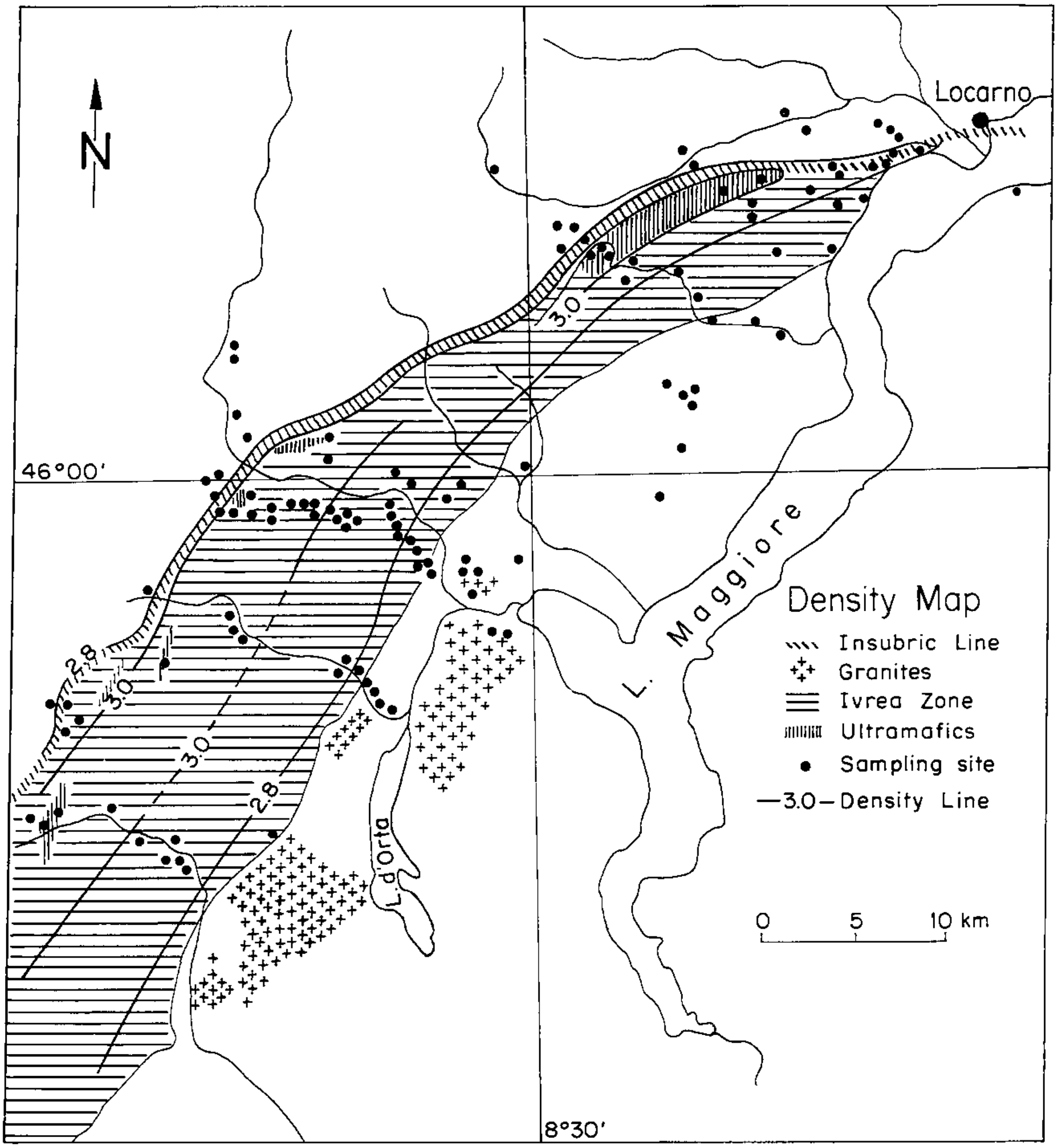

Figure 4: Map showing the bulk density distribution of surface rocks in the Ivrea-Verbano Zone.

(Figs. 4 and 5). The Swiss Geotraverse Basel – Chiasso, the easternmost profile which does not cross the Ivrea-Verbano Zone but runs only a few kilometers east of Locarno, still shows a contribution of about +40 mgal which must be ascribed to the Ivrea body (Kissling *et al.*, 1983). The different gravity anomalies along these three profiles (Fig. 5) require a change in shape of the Ivrea body from Val Sesia to Locarno as illustrated by the three cross sections (in addition to the cross sections of the northeastern and southern ends of the model) in the three-dimensional model of the northern Ivrea body shown in Fig. 6.

4. Discussion

While discussing the proposed model of the northern Ivrea body, it is important to keep in mind that the goal of the study was to find the simplest model fitting the geologic, gravimetric and seismic data. Because of the intrinsic non-uniqueness of any gravity modelling the main interest in such model calculations is to separate the most tightly constrained geometric model parameters (those for which a slight change results in a significant difference in the computed field) from the model parameters for which a whole family of solutions could be valid.

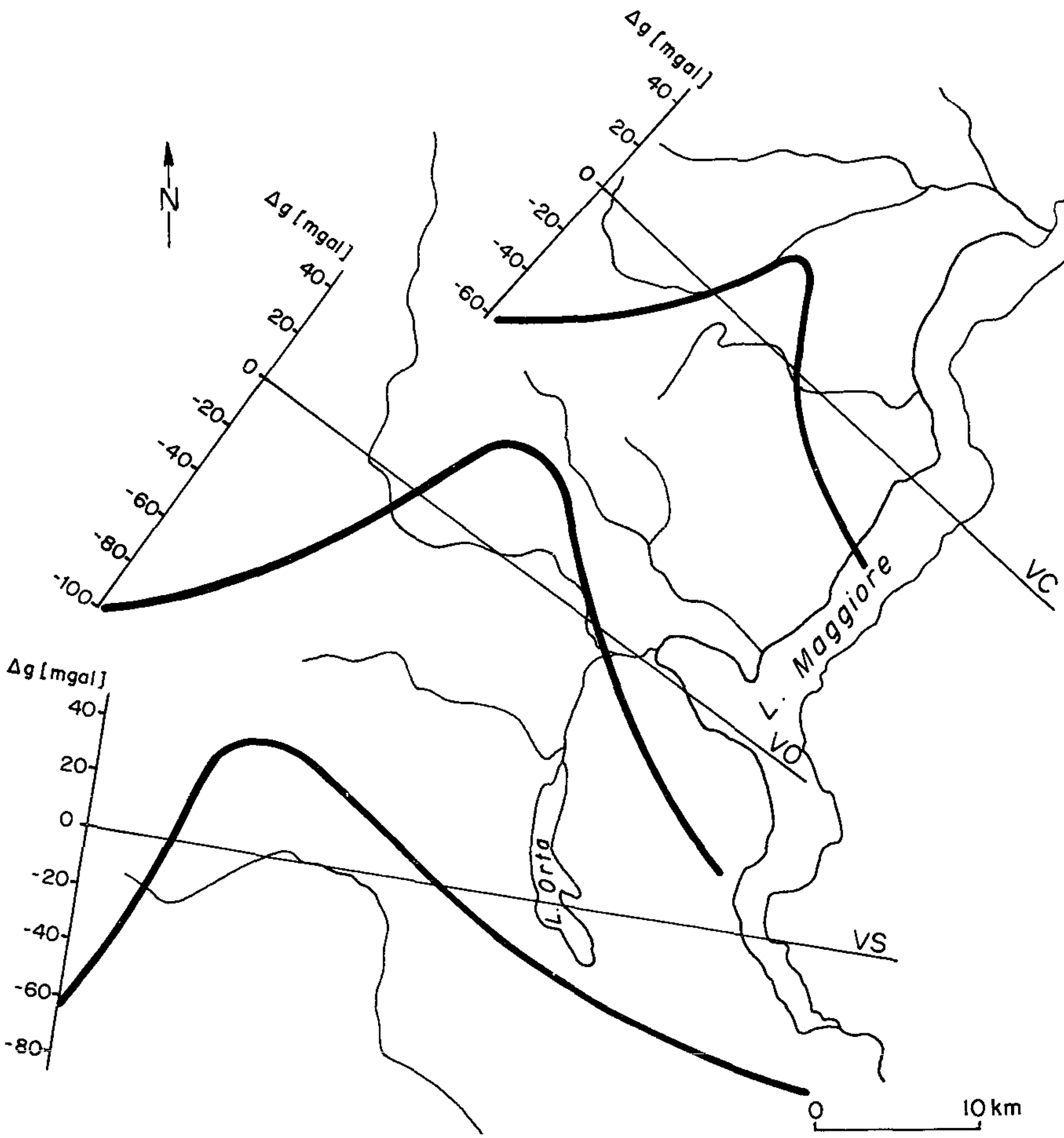

Figure 5: Comparison of three gravity profiles across the northern Ivrea-Verbano Zone. VS = Val Sesia, VO = Valle d'Ossola, VC = Val Cannobina, △g = Bouguer anomaly (in mgal).

The model calculations indicate that two of the most tightly constrained parameters are: (1) the dip (Fig. 6) of the Insubric Line (i.e. the northern and western boundary of the Ivrea body to a depth of at least 10 km) and (2) the main shape of the body as an eastward to southward dipping plate of about 15 km thickness. Although the gravity information about the deeper part of the crust is somewhat questionable, it is quite clear that the entire Ivrea body lies within the Southern Alps being separated from the main Alpine arc by the deep-reaching Insubric Line. Furthermore this gravity modelling suggests, but certainly does not prove, that the Ivrea body may reach down to the depth of the crust-mantle boundary ("Moho"). The maximum depth is an important aspect of any Ivrea model because many geophysical interpretations (see, for example, Hale and Thompson, 1982) rely on a model first given by Giese (1968) that clearly connects lower crust and even upper mantle of the Southern Alps with rocks seen at the surface within the Ivrea-Verbano Zone. Although the ultramafic rocks represent most likely upper-mantle material it is still unclear if we really may see a "Moho" while walking across the Zone of Ivrea-Verbano. The continuous sequence extending

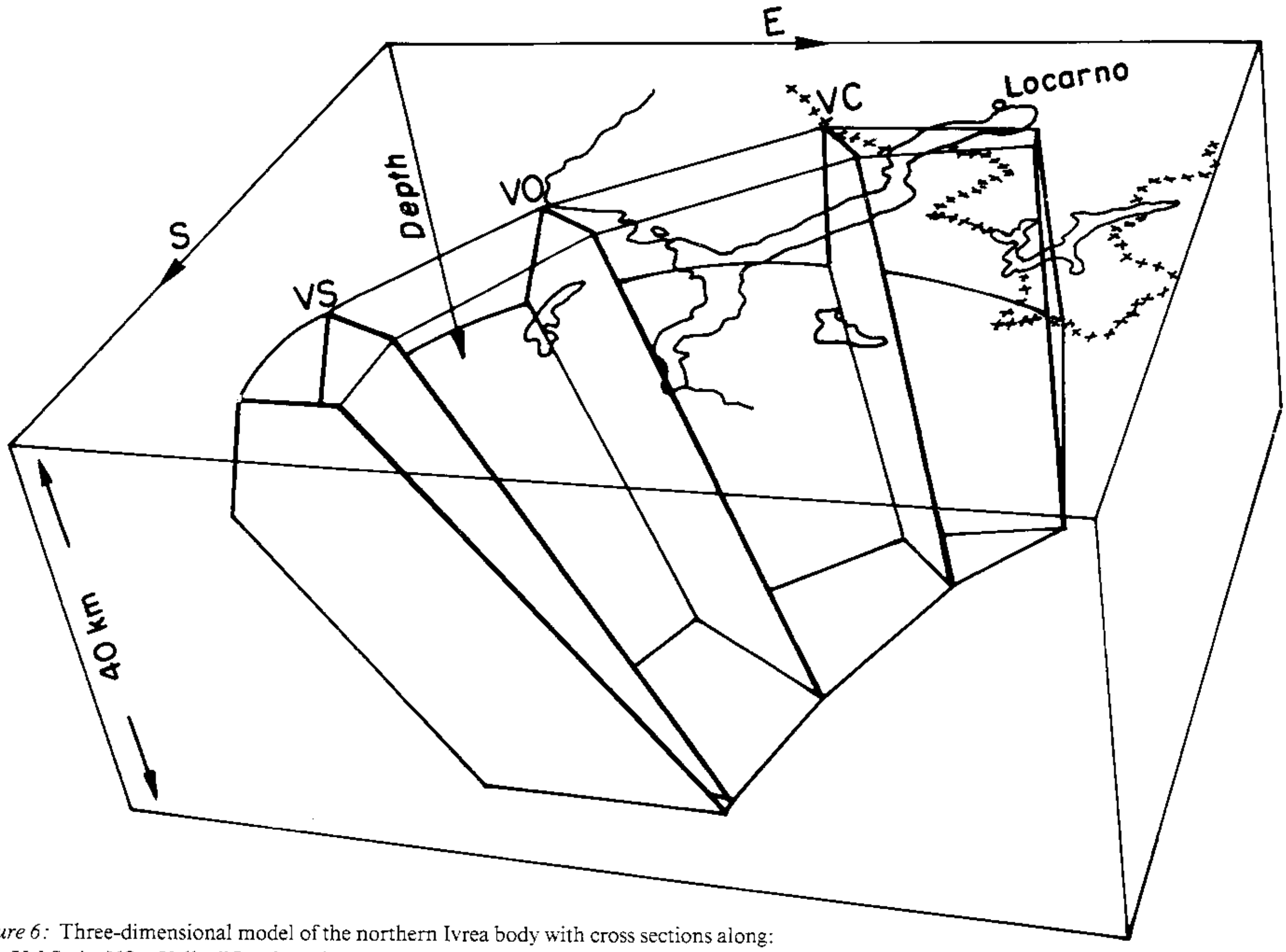

Figure 6: Three-dimensional model of the northern Ivrea body with cross sections along: VS = Val Sesia, VO = Valle d'Ossola, VC = Val Cannobina.

from the Permo-Mesozoic sediments across the gneissic and granitic Strona-Ceneri Zone to the intermediate and basic rock layers of the Ivrea-Verbano Zone might very well represent a complete cross section through the upper and middle into the lower continental crust (Mehnert, 1975; Mueller, 1977 and 1978). But the position of the isolated and compositionally distinct ultramafic rock complexes within the mafic part of the Ivrea-Verbano Zone remains questionable because they might have been peeled off from a deeper part of the Ivrea body. Furthermore, the lack of seismic information in the eastern part of the Ivrea-Verbano Zone extending to Moho depths makes it impossible to even try tracing this first-order discontinuity from below the Po plain up into the Ivrea body.

If the high-density rocks of the Ivrea-Verbano Zone were already within the upper crust before the beginning of the Alpine orogeny as the petrographic data suggest (see Schmid, 1968 and Proceedings of the Second Symposium Ivrea-Verbano, 1978/79) two questions arise: (1) how was the Ivrea body formed, and (2) how is it supported in the crust (it must be noted that it is isostatically undercompensated; see Isostatic Anomaly Map of Switzerland, Klingelé, 1979; Klingelé and Kissling, 1982)? Answers to these questions would provide additional information on the main problem discussed here: what was and what is the Ivrea-Verbano Zone? Does it really represent a cross section through the continental crust?

In a simplified view the Ivrea body has the shape of an eastward dipping plate. The tectonic activity (Laubscher, 1970) along the Insubric Line during the Alpine orogeny may account for the change in shape of the Ivrea body near the surface and at its northern end (Fig. 8).

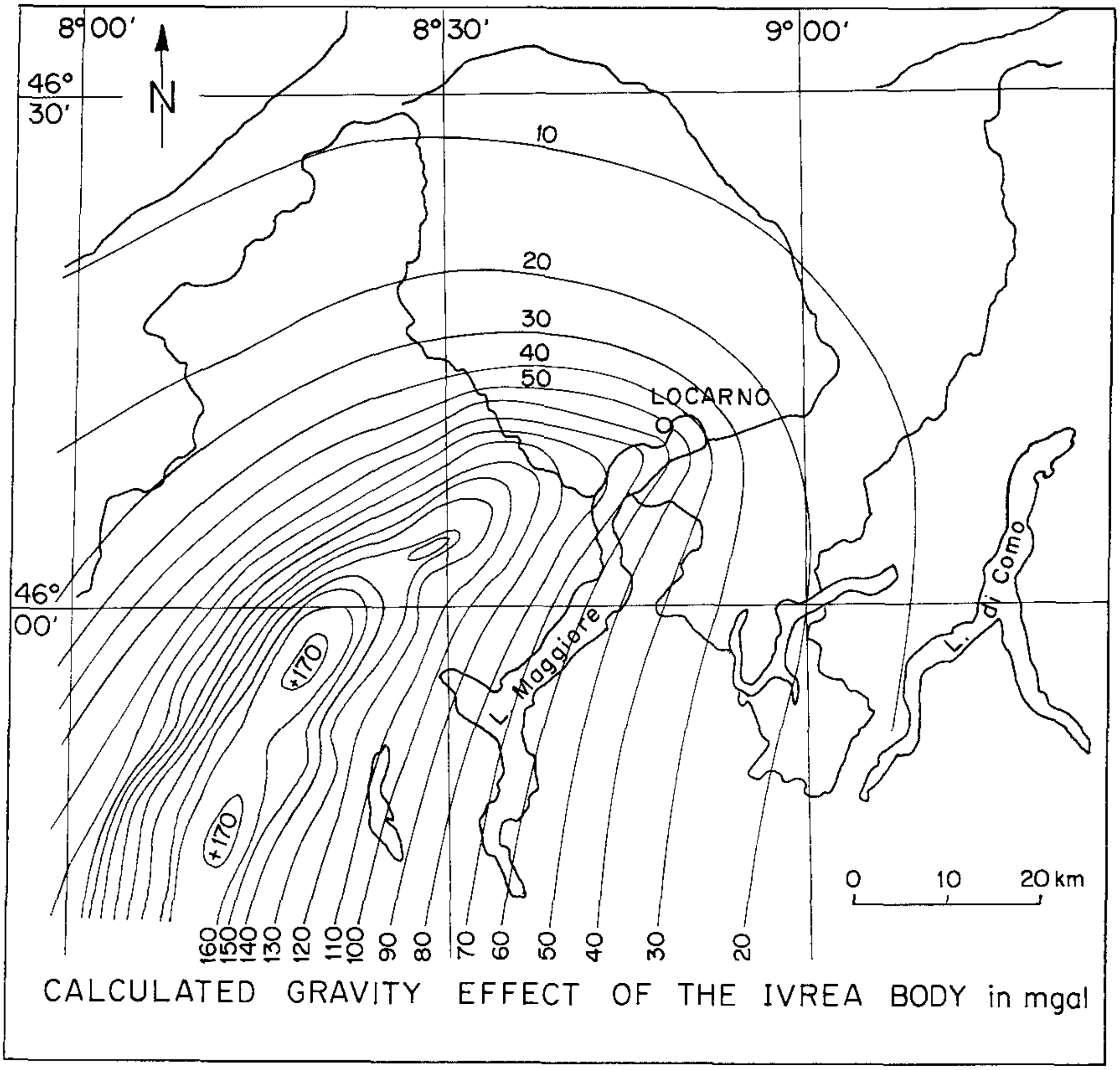

Figure 7: Calculated gravity effect of the Ivrea body (in mgal).

Subtracting the gravity effect of the Ivrea body (Fig. 7) from the Bouguer gravity map (Fig. 1), one gets a corrected Bouguer map of the southeastern part of Switzerland, supposedly without the Ivrea anomaly (Fig. 2). A residual gravity anomaly ranging from −80 to −130 mgal in the Canton of Ticino, seems to represent a remaining part of the Ivrea effect. Taking a closer look, this anomaly covers a broad area mostly outside of the Ivrea-Verbano Zone. It is formed by a strong gravity gradient some 20 km north of the Ivrea body and by a smooth gravity high reaching towards Locarno from the east-southeast. Both of these features extend at least some 50 km towards the east, where it has been recognized in a survey recently undertaken by Meyer (1982) and Schwendener (1983). Therefore, any interpretation of this remaining gravity anomaly in the Canton of Ticino by a change in the Ivrea model would suppose a northern and eastern continuation of the Ivrea body underneath the Central Alpine root zone in the north and underneath the Strona-Ceneri Zone in the Southern Alps. While the first is most unlikely, the latter could mean a connection of the gravity high in the region of Verona (Italy) with the Ivrea-Verbano Zone. This would lead to a simple explanation for the gravity field in northern Italy as proposed by Mueller and Talwani (1971).

On the other hand, there is no geologic evidence for this interpretation (i.e. an eastern continuation of the Ivrea body), and the refraction seismic profiles in the Southern Alps (Ansorge *et al.*, 1979) show no intracrustal layer between Monte Ceneri and the Bergamasc Alps that could be interpreted as a deep-lying Ivrea body. Furthermore, the gravity study in this area by Schwendener (1983) indicates that the local positive anomaly in the Canton of Ticino (Fig. 2) is part of a

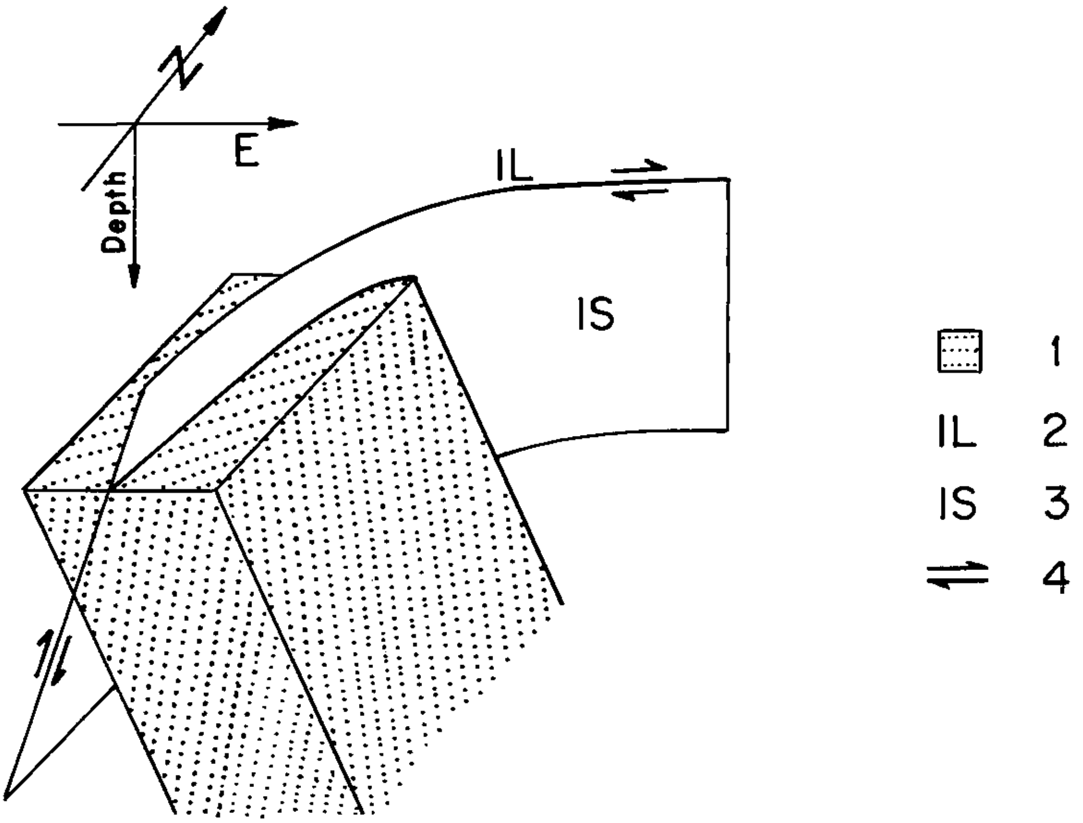

Figure 8: Structural sketch of the Insubric Line:
1 = rocks of the Ivrea body, 2 = Insubric Line, 3 = surface of tectonic movement, 4 = sense of displacement.

pronounced, but locally varying change in gravity from the Central to the Southern Alps. This is caused by a distinct change in the depth to Moho and crustal structure over the area of the Insubric Line. Because the seismic information about the crustal structure in the Canton of Ticino is sparse (Mueller *et al.*, 1980), and since there might be a few local anomalies involved in this remaining gravity field (Fig. 2), an eastern and northern continuation of the Ivrea body s.s. cannot be proved.

Although there had already been a number of geophysical surveys in the southern part of the Ivrea-Verbano Zone, the importance of this rock complex for the understanding of the structure of the crust and uppermost mantle clearly justifies additional and more detailed seismic and gravimetric investigations. In terms of interpretation of the Ivrea body as a cross section through the continental crust it would be most useful to know more about its internal structure.

5. Acknowledgments

The author is very grateful to St. Mueller (ETH Zürich) and to D. P. Hill (U.S. Geological Survey, Menlo Park, California) for critically reading the manuscript and offering helpful suggestions for its improvement. Sincere thanks for many stimulating discussions are due to the author's collaborators at the Institut für Geophysik of the ETH Zürich, especially to E. Klingelé, H. Schwendener and J. Ansorge. I also wish to acknowledge with gratitude the field excursions led by R. Schmid (ETH Zürich). I am indebted to H.-P. Boller (Zürich) for the steady help during the field work and to Mrs. E. Hirzel and J. Berthoud for typing the manuscript. The preparation of this manuscript has been supported by the Swiss National Science Foundation, Grant No. 82.998.082.

Contribution No. 487, ETH-Geophysics, Zürich, Switzerland.

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Achevé d'imprimer sur les presses
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