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Anomalous directional behaviour of the real parts of the induction arrows in the Eastern Alps: tectonic and palaeogeographic implications

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Abstract
The electromagnetic induction pattern in the Eastern Alps is characterised by a (continuous) large-scale zone on which the real parts of the induction arrows show anomalous directional behaviour. This zone extends from the Penninic Domain of Eastern Switzerland (Graubünden) probably into the Carpathian ranges. A coarse mesh of a Magnetotelluric (MT) and Geomagnetic Deep Sounding (GDS) station in the Alps of Graubünden and Valais (Western Switzerland) indicates that this electromagnetic anomaly is restricted to the Mesozoic sediments of the North Penninic Bündnerschiefer-facies that begins in Eastern Switzerland and extends towards the east beneath Austroalpine, South Penninic and Southalpine units. Striking similarities in position and arrangement between this zone and the magnetic signature in the Eastern Alps are found. The analysis of the GDS data with the method of the Hypothetical Event Analysis (HEA) shows that current channelling affects the electromagnetic fields in this zone and causes the anomalous direction of induction arrows. Based on the combined interpretation of GDS data from the Eastern Alps and West Hungary together with our recent data from Switzerland, the following geological implications are discussed: i) a spatial decoupling of induction processes from the upper to the lower crust; ii) a lower crustal conductive structure caused by the indentation of the Northern Adriatic promontory or terrane; iii) the eastward continuation of the Bündnerschiefer-facies at least to the tectonic window of Rechnitz.

Key words *EM induction – geomagnetic deep sounding – conductivity anomaly – Eastern Alps*

1. Introduction

The results presented in this study are mainly based on GDS data from the Penninic Alps of Switzerland (Schnegg, 1998; Gurk, 1999), the Eastern Alps (Berktold *et al.*, 1976; Berktold, 1978; Bahr, 1992) and from the Transdanubian conductivity anomaly in West Hungary (Adam *et al.*, 1972, 1990). This compilation uses available geomagnetic observations from various research groups and the more recent studies from Switzerland. Generally, Swiss data comprise the entire magnetic and magnetotelluric transfer function set covering a period range from $T = 1\text{-}300$ s. This period range was thought to be sufficient with respect to induction processes in many of the typical rocks of the Penninic Alps. On the contrary, data from other parts of the Alps are (with exception) solely accessible as real induction arrows covering a standard period range of $T \geq 1200$ s. Thus, imaginary parts of the magnetic transfer function are not the subject of this paper. Most of the conclu-

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sions drawn in this study are based on the magnetic distortion hypothesis for two-dimensional conductive structures. Since this distortion model is independent of the signal period, the maps displaying real induction arrows of different period ranges are justified. All presented real induction arrows point towards more resistive regions. A list of the data used for the compilation is given in table I.

In the past 20-30 years, several geomagnetic deep soundings have been carried out to investigate the electrical conductivity distribution in the transition zone Molasse Basin/Calcareous Alps and below the Hohen Tauern and Zillertaler Alps. Only a small increase in electrical conductivity, however, was found below the Hohen Tauern and below the upper valleys of the rivers Drau and Rienz. Nevertheless, Berktold (1978) already marked this region from the Zillertaler Alps to the Hungarian border that delineates a portion of the large structure (fig. 1) on which we focus in this paper. As the number of stations was too small, no detailed information could be given about the extension and the depth range of these local conductivity anomalies. Besides the MT/GDS site ENZI (Bahr, 1992) in the Grossvenedigermassiv of the Hohen Tauern (fig. 2a) and several short periodic measurements in the Gailtaler Alps (Adam, 1995; Adam *et al.*, 1992, 2000), no further induction studies have been conducted in the Eastern Alps.

2. Geological outlines

The North Penninic basin (fig. 2b) is a subbasin in the northern part of the Mesozoic Thetys ocean. Remnants of the Eastern North Penninic basin are preserved in the Alps of Eastern Switzerland as low metamorphic Mesozoic

Table I. List of data used for the compilation of induction arrows in fig. 1.

Key	Region	Reference
I)	Northwest Italy I	Bozzo and Meloni (1989) Meloni *et al.* (1989) Di Mauro *et al.* (1998)
II)	Rhinegraben and Jura of Swabia D, F	Richards *et al.* (1980) Tezkan (1986) Menvielle and Tarits (1986) Blundell *et al.* (1992)
III)	Molasse D	Berktold (1978) Blundell *et al.* (1992)
IV)	Eastern Alps and West Hungary D, A, H	Berktold (1978) Wallner (1977) Adam *et al.* (1972) Adam *et al.* (1992) Adam (1995) Blundell *et al.* (1992) Bahr (1992) Bahr (personal communication)
a)	Jura Mountain (Ajoie),CH	Gurk (personal communication)
b)	Penninic Alps of Valais, CH, I	Schnegg (1998)
c)	Penninic Alps of Graubünden CH	Gurk (1999)

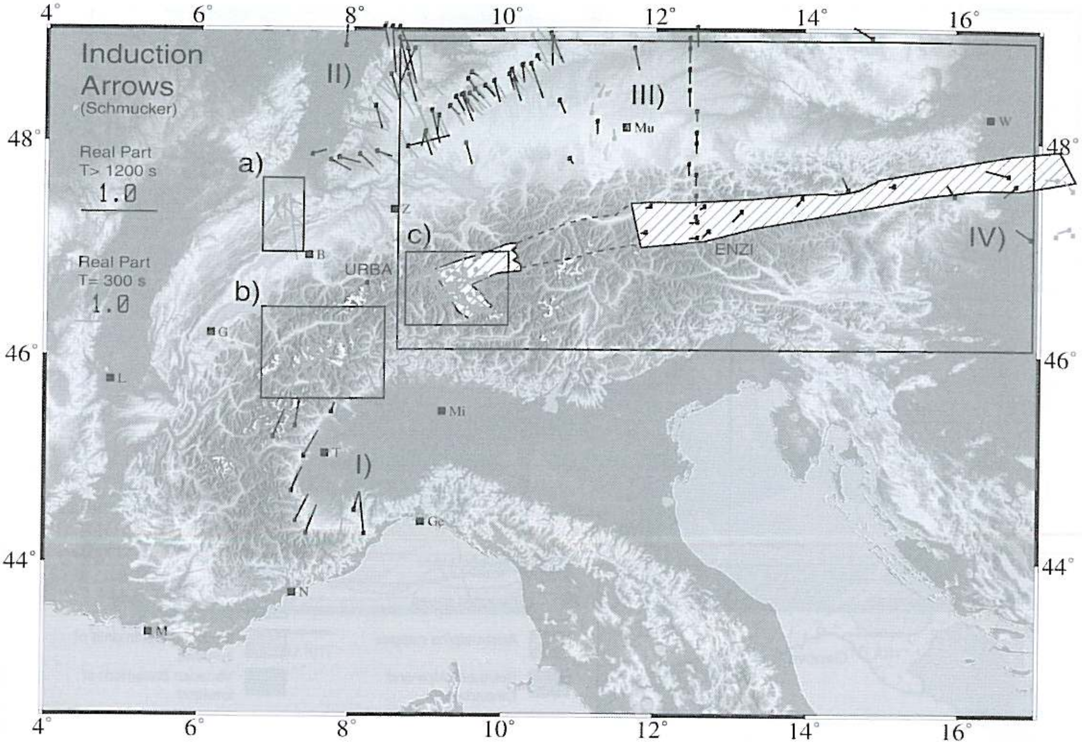
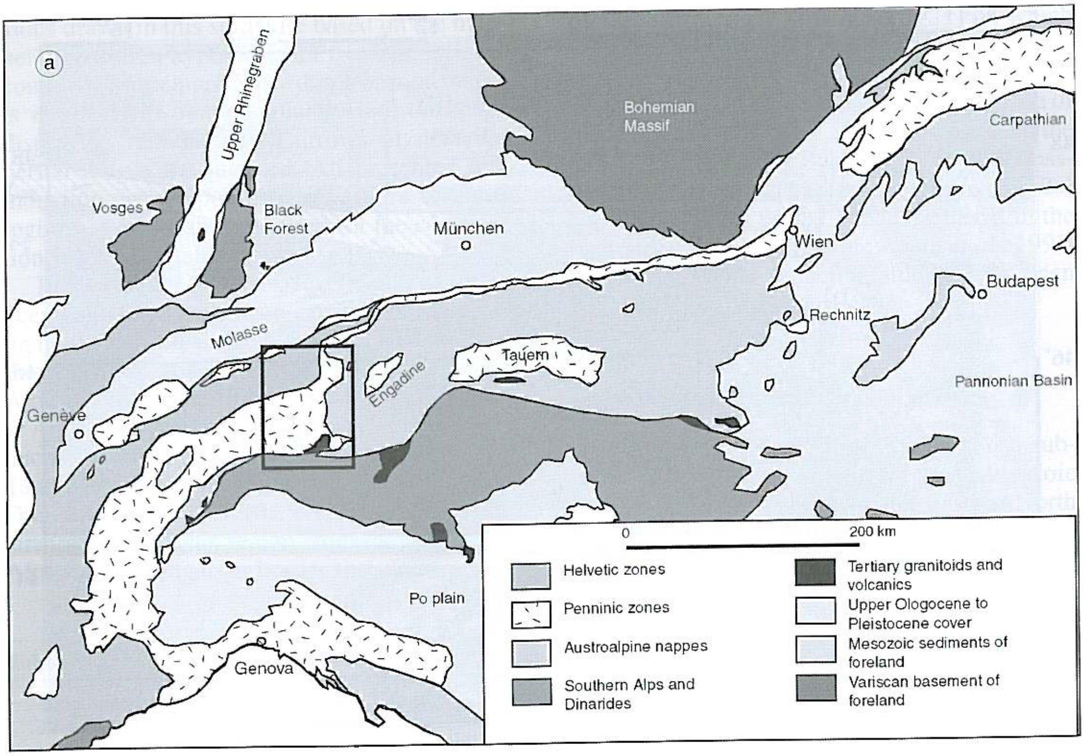


Fig. 1. Compilation of real part induction arrows (T = 300 s and T > 1200) from the orogenic belt of the Alps. The data refer to several European Research Groups (listed in table I). The striped area marks zone of anomalous directional behaviour (and anomalous amplitude) of real induction arrows. The dotted line marks the area of presumed anomalous directional behaviour of real induction arrows. Mi = Milan; T = Turin; Ge = Genova; L = Lyon; N = Nice; M = Marseille; G = Geneva; B = Bern; Z = Zürich; Mu = München; W = Wien.

Bündnerschiefer sediments (fig. 3b) and associated basaltic rocks which formed approximately 140-170 Ma ago (Steinmann and Stille, 1999). The Bünderschiefer are sited between the Helvetic units below and the Middle Penninic, South Penninic and Austroalpine units above (fig. 2a,b). It is controversially discussed whether the North Penninic basin can be interpreted as an isolated marginal basin which was completely underlain by thinned continental crust (Weissert and Bernoulli, 1985), or as a partial oceanic basin which was replaced towards the east by the South Penninic ocean in a large «en-echelon» structure (Trümpy, 1988). A third solution is proposed by Stämpfli in which the oceanization of the North Penninic basin was already complete (Stämpfli and Marchant, 1997).

Geochemical data (Steinmann and Stille, 1999) show that the North Penninic basalts are directly derived from a depleted mantle source and are overlain by 2.5 km thick series of siliclastic-turbiditic Bündnerschiefer sediments. Compared to the South Penninic oceanic basalts, which were covered by a reduced series of pelagic sediments, the North Penninic realm was not so far evolved in oceanization.

Towards the east, the Bünderschiefer-facies become covered by Middle Penninic, South Penninic and Austroalpine units. They are thought to reappear (fig. 2a) in the tectonic windows of Engadine, Tauern and Rechnitz, although they



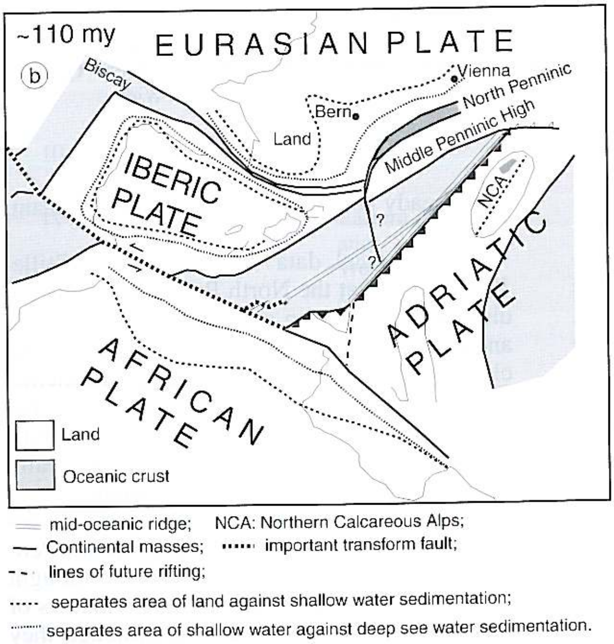
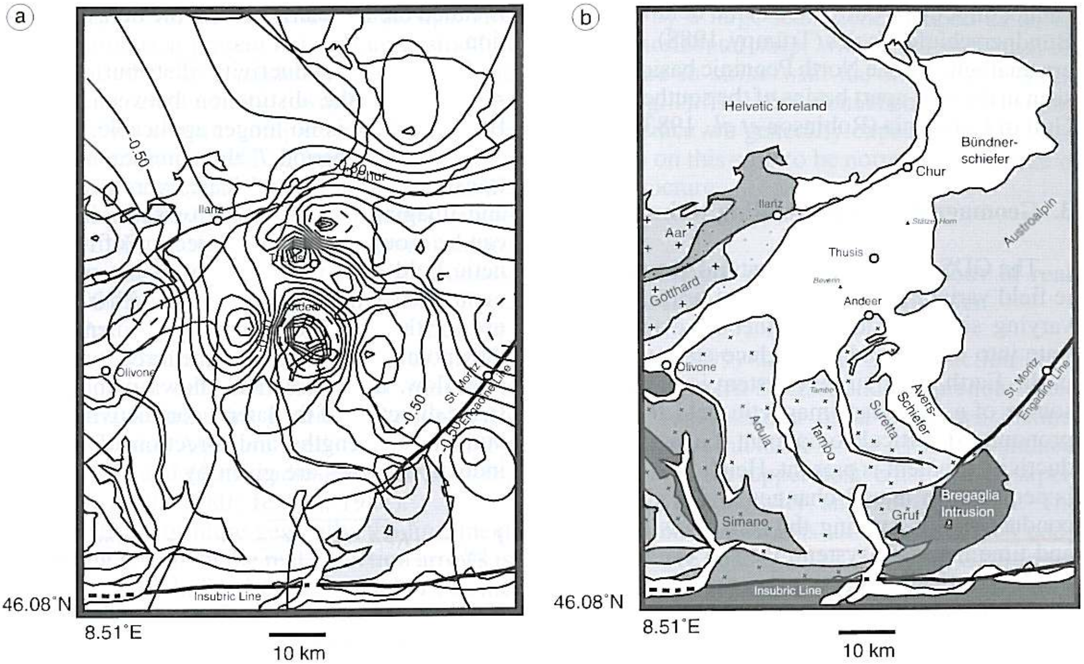


Fig. 2a,b. a) Sketch map of the Alps and surrounding areas. Redrawn after Trümpy (1988). b) Palaeogeographic reconstruction of the Western Mediterranean in late Lower Cretaceous time. Redrawn after Frisch (1979).



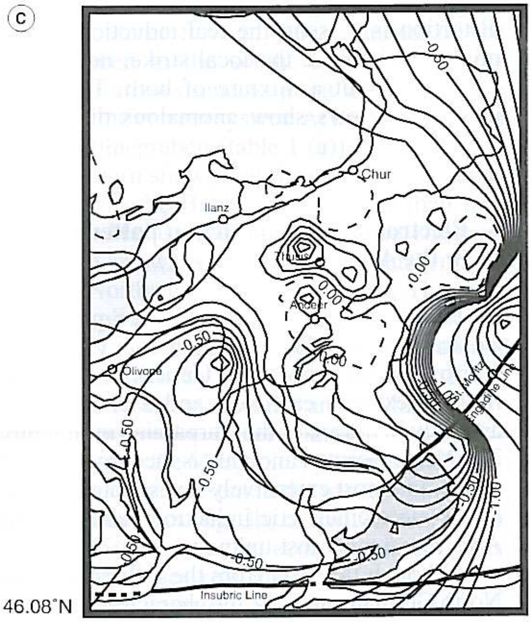


Fig. 3a-c. Hypothetical event maps (real part) of the anomalous vertical magnetic field in Graubünden (Eastern Switzerland) for the periods $T = 4.7$ s (a) and $T = 126$ s (c). For these maps we assumed a regional horizontal magnetic field of 1 nT with an azimuth of 45° from north. Current concentrations are indicated by the spatial gradient of the vertical magnetic field. The different anomaly pattern for shallow (a) and deep penetrating electromagnetic waves (c) shows decoupling of induction processes, vertically and horizontally (Gurk, 1999). b) Simplified tectonic map of the Graubünden MT/GDS survey area. For location see box in fig 2a.

cannot directly be correlated in the field with the Bündnerschiefer-facies (Trümpy, 1988). A modern analogue for the North Penninic basin can be seen in the pull-apart basins of the southernmost Gulf of California (Robinson *et al.*, 1983).

3. Geomagnetic deep sounding technique

The GDS technique uses natural geomagnetic field variations $\boldsymbol{B}_p$ as source of primary time varying signals. Electromagnetic waves penetrate into the ground and induce eddy currents in the Earth. This current system is in turn the source of a secondary magnetic field $\boldsymbol{B}_S$ with a pronounced vertical component if a lateral conductivity gradient is present. Hence, the method is sensitive to lateral changes in the electrical conductivity. Assuming the subsoil as a linear and time invariant system, we can use the secondary vertical component as the response of the local system to the inducing homogeneous primary field (Wiese, 1962):

$$B_{S_z}(f,\boldsymbol{r}) = A(f,\boldsymbol{r})\cdot B_{P_x}(f) + B(f,\boldsymbol{r})\cdot B_{P_y}(f).$$

$A(f,\boldsymbol{r})$ and $B(f,\boldsymbol{r})$ are the complex transfer functions in GDS, while $B_{S_z}(f,\boldsymbol{r})$, $B_{P_x}(f)$ and $B_{P_y}(f)$ are respectively the vertical and horizontal components of the geomagnetic field in the frequency domain and $\boldsymbol{r}$ is the vector to the local observation point.

Since we probe the subsurface with a time varying magnetic field of decreasing frequency, the skin effect yields transfer functions that are related to different propagation depths of the electromagnetic wave. The longer the signal period, the deeper the penetration of the electromagnetic wave into the subsoil of unique conductance. For a true 2D conductivity structure with a (regional) strike direction chosen along the x-axis and, $\sigma = \sigma(y,z)$, the transfer functions A and B are *composed* out of two de-coupled main components:

– The component of the transfer function whose electrical field is parallel to the structure is called the E-Polarisation of the transfer function.

– The component of the transfer function whose electrical field is normal to the structure is called the B-Polarisation of the transfer function.

For a 3D conductivity distribution ($\sigma =$ $= \sigma(x,y,z)$), the distinction between E- and B-Polarisation is no longer applicable.

At a given period T, the complex magnetic transfer functions A and B are expressed as real and imaginary induction arrows. Such arrows can be thought of as the projection of the magnetic field on a plain tangent to the measurement point at the surface. Their length is a measure for the lateral conductivity gradient. Since they point perpendicular to the direction of current flow, their direction allows mapping the strike direction of the lateral conductivity distribution. The lengths and direction of the real induction arrows are given by

$$L_{\text{real}} = \sqrt{ReA^2 + ReB^2}, \quad \theta_{\text{real}} = \arctan\left(\frac{ReB}{ReA}\right).$$

The local superposition of an anomalous magnetic field on the regional magnetic field causes a magnetic distortion (Ritter and Banks, 1998). The anomalous field is generated by the spatial deviation of the uniform regional currents through or around a local anomaly. If magnetic distortion is present, the real induction arrows might not indicate the local strike, nor the regional one, but a mixture of both. Thus, real induction arrows show anomalous directional behaviour.

4. Electromagnetic induction pattern in the Alps

Two predominant anomalies are present in Central Europe (Wybraniec *et al.*, 1999): the North German anomaly (Untiedt, 1970) that roughly extends east-west and a conductivity anomaly in the arc of the Carpathian mountains. The North German anomaly is the largest one in extent and most extensively investigated whereas the electromagnetic induction pattern in the Alps remains almost unknown.

Although far away from the influence of the North German anomaly, the characteristic South direction of the real part of the induction arrow will not generally change towards and within

(Schnegg, 1998) the Western/Central Alps. This observation is at present not well understood. It might result from a gradually decrease of the subsurface conductivity towards the south or result from a more complex structure of the external magnetic field (Schmucker, 1999). In Southern Germany, a predominant southeast direction of the real part induction arrows can be observed. Berktold (personal communication) suspects an additional conductivity anomaly (900-9000 S) within the Northern Phyllite Zone of the Post Variscian cover in front of the Mid-German Crystalline High (Blundell *et al.*, 1992) to cause this azimuth. Real part induction arrows that exhibit this general direction north of the Central Alps are well documented by several MT and GDS studies (Berktold, 1978; Richards *et al.*, 1980; Tezkan, 1988).

The strike, or more generally, the lineament indicating feature of the real induction arrows is well illustrated in fig. 1 (see also table I). In the Western Alps, their directions assume the alpine arc (table I (b)). In the Upper Rhinegraben area (table I (II)) they are influenced by a current channelling effect caused by high resistive Variscan basement rocks of the Vosges and Black Forest at both sides of the graben driving an electric current flow in the sediments of the Rhinegraben to the south. Consequently, the induction arrows tend to point away from the centre of the current system. At the southern end of the Rhinegraben (table I (a)), the induction arrow pattern shows that the current flow tends to leak into the Bressegraben rather than into the Swiss Molasse. Another important effect on induction arrows is present at the southernmost sites in Northwest Italy (table I (I)). The very large amplitude of these induction arrows is caused by the «coastal effect» – due to a high lateral conductivity contrast between the extreme low resistive seawater and the high resistive onshore rocks. Large contrasts in conductivity between the Mesozoic Sediments and crystalline rocks are present in the western and eastern Penninic Alps (fig. 3b) of Switzerland (table I (b,c)). Similar to the «coastal effect», this contrast increases real induction arrow amplitudes locally up to $L_{\text{real}} > 1$.

Contrarily, the electromagnetic induction pattern in the Central and Eastern Alps is dominated by a large-scale zone, shaped as an almost horizontal strip, where real induction arrows are in strike with the structure, pointing SW (fig. 1). This directional behaviour is anomalous since we generally expect real induction arrows on this strip to be normal to the strike of this structure.

5. Anomalous directional behaviour of real induction arrows in Graubünden

Gurk (1999) states that EM induction processes in Eastern Switzerland are predominated by the superposition of at least two distinct conductive structures – the (local) Bündnerschiefer in the uppermost crust and a super-regional conductivity anomaly at depth. The deeper anomaly forms an edge in which eddy currents are concentrated. Studying GDS transfer function with the Hypothetical Event Analysis (Banks and Beamish, 1984; Ritter and Banks, 1998), the 3D current concentration in the investigation area is found to be characteristic in distinct period bands and tectonic regions. The displayed current concentration shows a spatial de-coupling of induction processes, almost independent from the chosen direction of the hypothetical event. For short periods (T = 1-10 s), induction and/or current channelling is related to Mesozoic sediments and their internal inhomogeneities. For periods longer than $T = 100$ s, induction and/or current channelling is limited to the Austroalpine and Penninic basement (fig. 3a-c).

The particular geometric constellation of both structures evokes magnetic distortion (independent of signal period) in Graubünden: real induction arrows on the Bündnerschiefer point SW in an (anomalous) strike direction, whereas outside this structure, the real parts of induction arrows point towards SE. Locally, magnetic distortion increases the amplitude of real induction arrows on the Mesozoic Avers-Schiefer sediments (fig. 3b).

The concept of magnetic distortion expects to find anomalous directional behaviour on the *continuation* of the Mesozoic Bündnerschiefer as long as the geometric relation between local and regional conductive structures are valid

(Gurk, 1999). Since the MT/GDS survey of the Penninic Alps of Valais (Schnegg, 1998) (Western Switzerland) do not show magnetic distortion, the prolongation of the Bündnerschiefer-facies should be found towards the east. Hence, the anomalous direction of induction arrows is a tool to map this distinct facies beneath the Austroalpine and South Penninic units.

6. Similarities between the induction pattern and the magnetic signature in the Eastern Alps

Striking similarities between the elongated zone of anomalous directional behaviour of real part induction arrows and the magnetic signature of the Eastern Alps are present.

Heinz reports three main types of magnetic anomalies in the Eastern Alps (Heinz, 1989; Heinz and Seiberl, 1990):

– «Marginal» types of short wavelength and high amplitudes connecting the Penninic system of the Engadin window to the Rechnitz-Bernstein, situated along the northern margin of the Austroalpine thrust sheet;

– «Large scale structures» extending from the Engadin window into the Carphathian ranges;

– Anomalies associated with basement structures north of the Alps.

The «marginal» types (fig. 4) are addressed to ophiolithic remnants of the South Penninic ocean whereas «large scale structures» are associated with remnants of a North Penninic ocean domain (Heinz and Seiberl, 1990). Arrangement

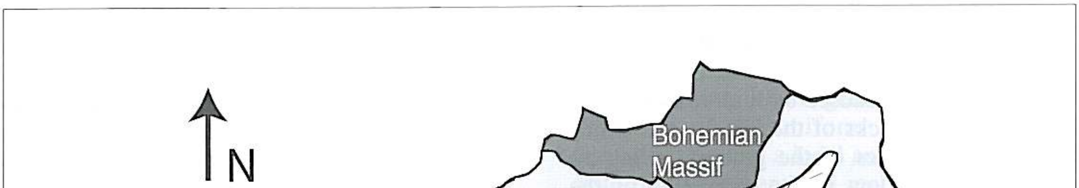


Fig. 4. Simplified tectonic map of Austria with magnetic anomaly pattern (black) of marginal type (high gradient, short wavelength). Modified after Heinz (1989).

and position of the induction anomaly correspond to the «marginal» type and «large scale structure» anomalies of the total magnetic field. The former anomaly is restricted to the North Penninic Bündnerschiefer-facies and is not caused by ophiolithic rocks. Obviously, all anomaly types are connected via the geodynamic history of the Eastern Alps (fig. 2b).

After initial rifting during the Triassic, the oceanic crust was developed in the South Penninic ocean since the early Jurassic. These events were largely controlled by the opening of the Central Atlantic (Laubscher and Bernoulli, 1977). The actual arrangement of the paired anomalies is the result of later tectonic activities. The opening period of the South Penninic basin was followed by the development of a southward dipping subduction zone on its southern margin, implying the almost simultaneous opening of a North Penninic ocean and southward motion of the Middle Penninic High (Briançonnais) (Ratschbacher and Frisch, 1988). The consumption of the Southern Penninic oceanic crust and the subsequent first «continent-continent» collision completed this period (Middle Cretaceous to early Upper Cretaceous). A second «continent-continent» collision took place as the consequence of the subduction and consumption of the Northern Penninic basin which was presumably completed in the late Eocene (Frisch, 1981). The southern rim of stable Europe collided with the welded Middle-Penninic-Southern Penninic-Austroalpine complex. During this event, the Bündnerschiefer-facies in Graubünden was 30 km subducted and finally uplifted and exposed. Remnants of the South Penninic were tilted, uplifted and partly exposed by erosion (Heinz, 1989), forming the sources of the «marginal» anomaly signature.

7. Conclusions

«Large scale» magnetic anomalies and the elongated zone of anomalous directional behaviour of the induction arrows are of North Penninic origin. Both structures terminated at west (Graubünden) and extend towards east (Bernstein/Rechnitz) (Heinz, 1989).

From this reason, we confirm the conclusion drawn by Heinz that the North Penninic basin terminats at west and is opens at east (Heinz, 1989; Heinz and Seiberl, 1990). Consequently, the Northern Penninic ocean was not directly dependent on the history of the Central Atlantic. Several studies support this model (Frisch, 1977; Frisch, 1979; Schmid *et al.*, 1990).

Furthermore, the continuation of the North Penninic Bünderschiefer-facies beneath Austroalpine and South Penninic units at least to the Rechnitz window can be deduced from the GDS observation.

The origin of the deep conductive structure (fig. 3c) that is responsible for the anomalous directional behaviour remains unknown. Gurk (1999) proposes a stacked lithosphere in the Eastern Alps to justify a conductivity anomaly at depth. The enhanced conductivity might result from highly mineralised fluids as reported from springs of the Scuol-Tarasp/Inn valley. Here water reaches conductivities up to 15000 μS/cm (0.65 $\Omega \cdot$m) at $T = 5.6°$ (Bissig, 1997). The analysis of their CO_2 content shows isotopic significance that is typical for thermo-metamorphic reactions in carbonates from the crust (Wexsteen, 1988). Arthaud gives a general model for fluid transport and escape of brines in the Western Alps (Arthaud and Dazy, 1989). This model has a strong association with the tectonic setting in the Graubünden area. Therefore we suspect the presence of brines generated by dehydration at depth to be tectonically trapped along the northern limitation of the stacked lithosphere system, created by the indentation of the Northern Adriatic promontory or terrane. Hence the current concentration at depth could delineate the transition between the European and Adriatic lithospheres. From a speculative point of view, the stacked lithosphere might also result from the remnant of the Middle Penninic High.

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