

# Report on data availability

## CHPM2030 Deliverable D1.2

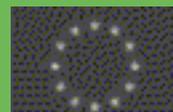
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## CHPM2030 DELIVERABLE D 1.2

### REPORT ON DATA AVAILABILITY

#### *Summary:*

This report aims to provide a brief overview of four major ore districts in Europe, namely in SW England, southern Portugal, NW Romania and central and northern Sweden. It is completed with a survey of existing boreholes in the European countries, where temperatures at depth in excess of 100°C are observed. The report includes descriptions of the geological settings, and on-going efforts in geophysics in seeing deeper and increasing resolution for detecting mineralized zones at depth, as well as attempting to estimate their geothermal potential.

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## Extended summary

This report is a condensed compilation and evaluation of five reports on available data for the development of orebody enhanced geothermal systems, i.e., the CHPM technology at upper crustal depths in suitable ore districts of Europe. It will serve as a basis for research on a new type of facility for *Combined Heat, Power and Metal extraction* (CHPM). The five reports, written by individual working groups from the United Kingdom (UK), Portugal, Romania, Sweden and the European Federation of Geologists (EFG) are attached here in original form as appendices 1.2.1 to 1.2.5. They mainly comprise geological, geophysical and geochemical data on and descriptions of mineralized areas in these countries. The EFG report presents a European inventory of drill holes with temperatures in excess of 100°C, availability of data for these holes, and any metal enrichments having been encountered at depth.

The target areas in the specified countries belong to three large metallogenic provinces in Europe: the Precambrian Fennoscandian Shield province, as for Sweden; the late Paleozoic Variscan province, as for SW England and southern Portugal; and the Mesozoic-Cenozoic Alpine province, as for NW Romania. In these provinces prospective zones suitable for the CHPM technology should be evaluated.

Much is already known about the geology, mineralisation, fluids and the geothermal potential of the ore districts, discussed in this report. However, the knowledge often is restricted to the upper 1 000 m of the crust or less. Locally, where deep drilling has been performed, the conditions may be evaluated to greater depths. The availability of data has significant implications regarding the accuracy of modelled conditions in an enhanced geothermal system (EGS) at greater depths. Therefore, the structural information and the knowledge of the physical state of the upper crust need to be enlarged considerably in order to meet the goals of the CHPM project.

## 0 Preface

This report describes what is already known about the geology, mineralisation, fluids and the geothermal potential of the areas of interest. It is one of the first deliverables of the CHPM2030 project - an EC-funded Horizon2020 project which aims to develop a novel and potentially disruptive technology that can help satisfy European needs for energy and critical metals in a single interlinked process. Working at the frontiers of geothermal resources development, minerals extraction and electro-metallurgy, the project aims to convert ultra-deep metallic mineralisations into *orebody-enhanced geothermal systems (EGS)*. It will serve as a basis for the development of a new type of facility for *Combined Heat, Power and Metal extraction (CHPM)*.

The project will help providing new impetus to geothermal development in Europe by investigating previously unexplored pathways at low-TRL. This will be achieved by developing a roadmap in support of the pilot implementation of such system before 2025, and the full-scale commercial implementation before 2030. It will include detailed specifications of this new type of future EGS facility (CHPM).

In the technology envisioned, the metal-bearing geological formation will be manipulated in a way that the co-production of thermal energy and metals will be possible. Four geographical areas have been chosen for assessment based on pre-existing data and potential for CHPM development in mineralised areas in the United Kingdom (UK), Portugal, Romania and Sweden. This report summarises information relevant especially to these four countries, but even for other European regions.

The CHPM project aims to provide proof-of-concept for the following hypotheses:

1. The composition and structure of orebodies have certain favourable characteristics that could be used to our advantage when developing an EGS.
2. Metals can be leached from orebodies in high concentrations over a prolonged period of time and may substantially influence the economics of EGS.
3. The continuous leaching of metals will increase system's performance over time in a controlled way and without the need to use high-pressure reservoir stimulation, minimising the potential detrimental impacts of both heat and metal extraction.

## 1 Introduction and outline of work

This report is a condensed compilation and evaluation of five reports on the availability of data of some of the European ore districts for the development of enhanced geothermal systems. These reports were written by individual working groups from the UK, Portugal, Romania, Sweden and the European Federation of Geologists (EFG) and are attached here as appendices 1.2.1 to 1.2.5. Their basic structure was initially agreed upon by the different working groups. Subsequent work has shown however that for practical reasons the original layout could not be preserved in all details and some headings have been merged, deleted or renamed and others have been added. Still, as far as possible, we have tried to fit the contents of the national reports into the original structure and to keep its headings and sub-headings.

The reports from the UK, Portugal, Romania and Sweden mainly comprise geological data on and descriptions of mineralized areas in these countries. The EFG report presents a European inventory of drill holes with temperatures in excess of 100°C, availability of data for these holes, and whether any metal enrichment have been encountered at depth.

In this report we summarize and focus on data availability; for actual data, descriptions and conclusions we refer to the individual working group reports (appendices 1.2.1 to 1.2.5). We will also attempt to draw some conclusions on how the available information may be used to predict geological and physical conditions relevant to the present task at greater crustal depths.

### 1.1 Country specific issues

Specific conditions or issues for each country in question have been noted in a few cases (see appendices). As far as we understand, nothing that may be critical to the present task has been put forward.

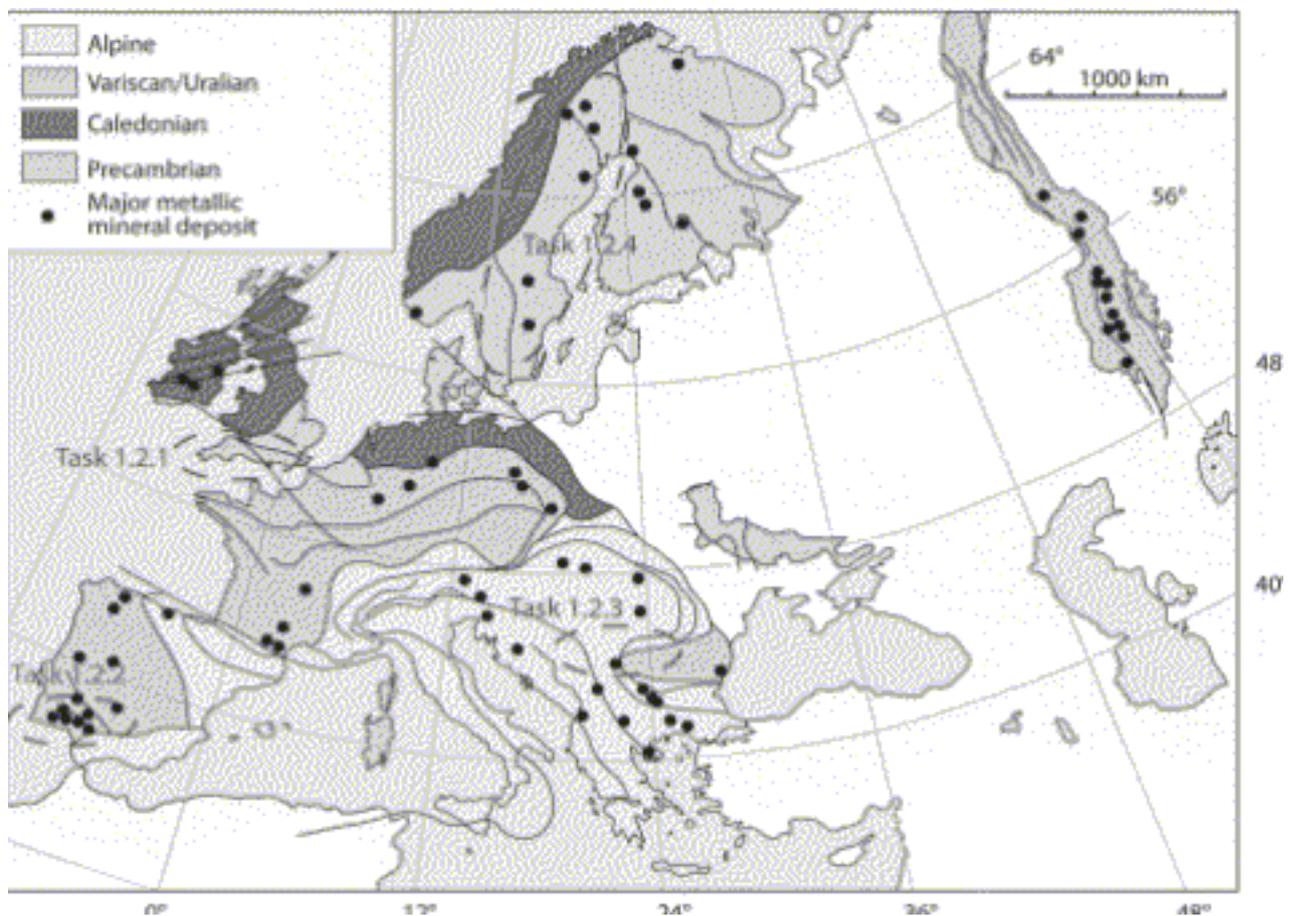
### 1.2 Goals

Our understanding of the formation of ultra-deep metallic mineral deposits is limited. Current 3D metallogenic models typically focus on the upper 3 km of the crust. Mineralisation below this depth has been of limited interest due to the challenges of extracting it with conventional mining and at reasonable costs. The objective of this task is to highlight and categorize previously reported studies of the uppermost crust of the Earth, e.g., from prospecting, deep drilling, and geophysical surveys, integrating the outcomes of recent predictive models. We need to investigate the possible extension of current metallogenic models to greater depths, and to understand knowledge gaps and limitations that have to be overcome in order to confidently identify target sites for a future CHPM facility. Targeting sites will be the subject of the forthcoming task 6.2. Special attention has to be paid on the relationship between mineralisation, deep seated faults and fault-zone/fracture geometry and the structural setting of deposits. Deep seated faults and present and past tectonic conditions have an impact on deep fluid flow. Hence, they may affect both local heat flow and the geometry and composition of an ore deposit. The results of previous European research (like, e.g., ProMine, Eurogeoresource) should be assessed and updated with information covering the target depth.

## 2 Previous research and available data

The particular reports of the five working groups (see appendices) present available geological, geophysical, drilling and other data related to mineralized areas in the European countries, with special focus on England, Portugal, Romania and Sweden (figure 1). Some of the reports also provide accounts of geological conditions, but varying in detail and extent.

It is tried to sum up information and accessibility about data and sources even in tabular form. The report by the British Geological Survey (BGS; Appendix 1.2.1, chapter 10) contains a summary and table of their data holdings. British data are freely or openly available. In most cases, however, they only reflect conditions down to 600 to 1 000 m, or less.



**Figure 1.** Major ore deposits of Europe (after Weihed 2015), with the mining areas and their available data described in tasks 1.2.1 to 1.2.4 indicated (see appendices 1.2.1 to 1.2.4), i.e., in the Southwest of England, Southern Portugal, Northwestern Romania and Central and Northern Sweden

The reports from Portugal and Sweden (Appendix 1.2.2 and 1.2.4) include tables on databases held by their national geological surveys, i.e., LNEG, and SGU. All of these data are accessible, either directly or on request. In Appendix 1.2.5 we provide information on existing boreholes within Europe, where temperatures of more than 100°C were measured and mineralisations being found. It should be noticed that all kinds of data in accordance with INSPIRE in general are free of charge.

## 2.1 Geology and geophysics, including drilling

The report from the BGS (Appendix 1.2.1) focuses on conditions in south-west England, i.e., connected to six large granitic plutons in Cornwall, and contains a description of the geology, tectonic evolution and physical properties of this area. Data exist in form of regional geological maps (1:50 000 scale) by the BGS. Several comprehensive reviews on the geology are available as well as reports on geochronology, isotopes and fluid inclusions. Wells for geothermal studies within a HDR project have been drilled in the 1980s down to c. 2 600 m, but the majority of boreholes drilled for temperature measurements is less than 100 m deep.

The Iberian Pyrite Belt (IPB) in Portugal and Spain constitutes an intensely mineralized part of the crust, and has consequently been the subject of several studies as noted in the report from Portugal (Appendix 1.2.2). The studies include general geological syntheses and evaluations of stratigraphy, volcanism, structure and regional metamorphism, ore-related alterations, and facies architecture of the ore-bearing volcano-sedimentary complex (VSC). Exploration drillings for metal deposits down to more than 1 500 m have been performed in the IPB.

The report from Romania (Appendix 1.2.3) contains an extensive and detailed account of the tectonic evolution and the geology of the country, specifically of the Bihor mountains, the Beius basin and the Banatitic Magmatic and Metallogenic Belt (BMMB). It largely summarizes the relevant geological, geophysical and other data for this task. As in the case of England, wells for geothermal studies have been drilled in the Beius basin down to almost 2 600 m with the hot water used locally for heating purposes.

The report from Sweden (Appendix 1.2.4) focuses on data availability. References are given to the most recent geological descriptions, geophysical investigations and published papers. Sweden has four ore-bearing districts: Bergslagen, the Skellefte field, northern Norrbotten and the Caledonides, of which the first three ones are dealt with in the report. Geological maps with descriptions by SGU at 1:50 000 and 1:250 000 scales are available for most parts of these districts. Drilling down to almost 6 800 m has been performed in central Sweden and some tens of exploration boreholes are reaching more than 1000 m in depth.

A short summary of the present knowledge and data of the above named ore districts, i.e., in the form of keywords only, is given in tables 1 and 2. Figure 2 provides a general overview on major ore deposits in Europe, based on the ProMine databases (Weihed 2015, Cassard et al. 2015).

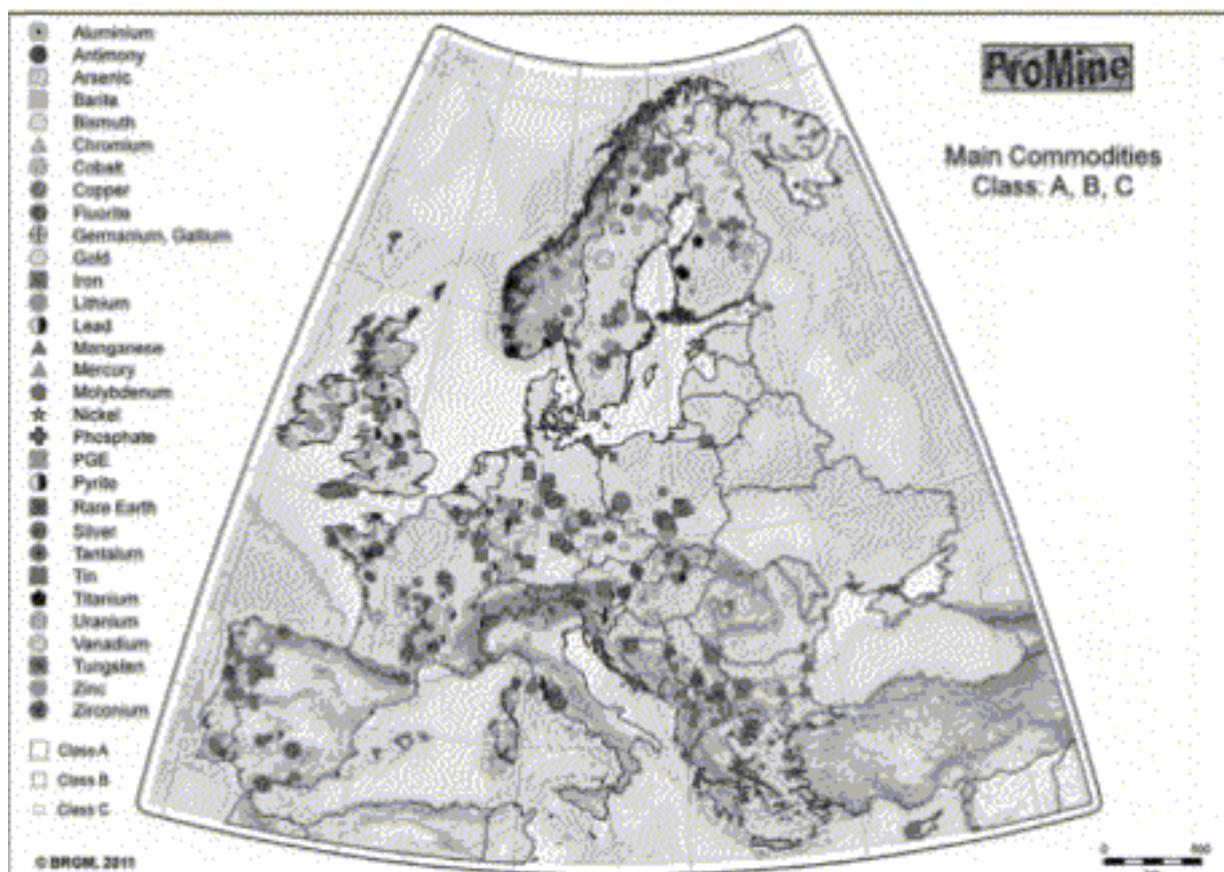
## 2.2 Geometry and composition of ore deposits

The style of mineralisation in the areas of investigation, i.e., south-west England, the IPB of Portugal, the BMMB of Romania and three mining districts of Sweden are described in the individual reports in Appendix 1.2.1 to 1.2.4.

### 2.3 Structural evolution, deep-seated faults and fracture zones, their alignment

Structural data and the structural evolution as well as data on the present stress field (measured stress and directions) are documented for south-west England in Appendix 1.2.1. Similar data were acquired in the IPB (Appendix 1.2.2), where structures and structural evolution have been evaluated by means of detailed geological mapping, drilling and geophysical soundings. This information has been utilized in 3D-modelling, particularly in areas with known mineralisations.

An extensive account of the tectonic and structural evolution in Romania and surrounding countries is given in Appendix 1.2.3, while the situation in Sweden is discussed in Appendix 1.2.4 and relevant publications noted there.



**Figure 2.** Main ore deposits of Europe, with their major ore content and size (class A, B, C) indicated, according to the ProMine database (after Cassard et al. 2015).

### 2.4 Hydraulic properties, deep fluid flow

Most data on crustal fluids in the European countries discussed here are available from uppermost levels, usually extending down to a few 100 m depth. Data down to several 1000 m depth are fairly uncommon. In general, the hydraulic conductivity and the magnitude of the fluid flow are very low at deep levels.

CHPM2030 Areas – Mining Region		Geology / Geophysics				EGS Potential According to Present Knowledge - Regions of Interest				
Mining Region (Country)	Geology Setting / Age	Tectonics	Mineralisation / Mining Depth	Hydrogeology	Geophysics / Boreholes	5 km Models	Temperature	Heat Flow	EGS local (y)	EGS Potential
South-west England (Cornwall, UK)	Variscan / assoc. felsic magmatism	Granitic plutons; NW-SE trending fault structures	Pre- (Au-Sb), post- (Zn-Pb-Ag), and granite (Sn-W, Sn-Cu) related ore bodies; mining depth ~ 790 m	large reservoir of saline, thermal waters	very limited deep geophysical data, 0 to < 1000 m, most boreholes < 600 m		Measured 90 °C (max.) at 2000 m; model: 185 - 220 °C at 5000 m depth	Locally in excess of 110 mWm <sup>-2</sup>	HDR proj. in 1980s, depth 2.5 km, discontinued	Medium
Portuguese Iberian Pyrite Belt (Nevés Corvo)	1800 m - Volcano-sedimentary/Paleozoic (Variscan)	Folding and shearing, strike slip faults	1000 m/massive sulphide, stockwork	Fissural/low productivity, volcanic and sedimentary rocks	Gravity, magnetics, seismics, TEM, drillholes < 1300m	combined model	c. 130 °C at 5000 m	> 85 mWm <sup>-2</sup>	None	Medium
Bihar Mountains, Beius Basin (Apuseni Mountains, Romania)	Sanatitic Magmatic-Metallogenic Belt: granodiorite-granitic batholith/Mesozoic (Alpine)	Strike slip faults, NW - SE oriented, owing to batholith intrusion, having allowed the infiltration of metasomatic fluids.	Skarns with Cu, Pb, Zn, Ag, Au	karst, volcanic, plutonic rocks, short re-charge times	Magnetic -, gravity maps; 3 Beius basin drillholes < 2790 m		80 - 90 °C at 3000 m	> 90 mWm <sup>-2</sup>	Beius: Installed 27 MW, reserv 52 MW <sup>1</sup>	Medium
Fennoscandian Shield (Sweden):										
Bergslagen	Svecofennian/felsic magmatism/1.9 Ga	Folding and shearing	Mining depth Zinkgruvan 1130 m, Garpenberg 1250 m	Crystalline bedrock, low permeability	Gravity, magnetics, reflection seismics, Sijon boreholes < 6800 m	combined model	87.5 °C at 5500 m	c. 60 mWm <sup>-2</sup>	None	Low
Skellefte district	Svecofennian/felsic magmatism/1.9 Ga	Folding and shearing	Mining depth Kristineberg 1250 m	Crystalline bedrock, low permeability	Gravity, magnetics, reflection seismics, AMT, MT, drillholes	combined model, Kristineberg (12 km)		50 mWm <sup>-2</sup>	None	Low
Northern Norrbotten	Svecofennian/felsic magmatism/1.9 Ga	Folding and shearing	Mining depth Kiruna 1540 m	Crystalline bedrock, low permeability	Gravity, magnetics, reflection seismics, AMT, MT, TEM, drillholes			51 mWm <sup>-2</sup>	None	Low

15 | Researcher et al. (2019)

Table 1. Summarizing data about some of the ore districts of Europe that are the base for the present report

Country	Geology / Geophysics					EOS Potential (According to Present Knowledge - Regions of Interest)				
	Geology Setting / Age	Tectonics	Mineralisation / Mining Depth	Hydrogeology	Geophysics / Boreholes	5 km Markers	Temperature	Heat Flow	EOS local (t)	EOS Potential
<b>Some European countries, with borehole temperatures in excess of 100 °C reported</b>										
Austria			No mineralisations		c. 100 drillholes					
Belgium					4 holes		> 90 °C at 2 km			
Croatia					c. 1000 holes = 2000 m		< 50 °C / km			
Germany			No data reported		2000 boreholes where temperature > 100 °C					
Greece			No metal enrichments reported		5 boreholes reported where temperature is > 100 °C					
Hungary			No metal enrichments		c. 100 boreholes where temperature is > 100 °C					
Italy			No metal enrichments		694 boreholes					
Luxembourg							> 30 °C at 1.5 km			
Poland			Metal enrichments of various kind in drillholes reported		boreholes exist where temperature is > 100 °C					
Slovenia			Cu, Au		7 boreholes					
Slovak Republic			various metals		3 drillholes					
Slovenia					43 boreholes, but for exploration of hydrocarbons					
Spain			not identified		33 boreholes					
Switzerland										
Iceland										

**Table 2.** Summary of boreholes drilled in some of the European countries where temperature is above 100°C and mineralisations were identified (see even Appendix D1.5).

Hydraulic properties of the upper crust in south-west England are described by using data from structure and stress-field measurements (Appendix 1.2.1). Data from the IBP partly estimated from pumping tests, are briefly discussed in the report from Portugal (Appendix 1.2.2).

An extensive description of the hydraulic properties in the Bihor Mountains and Beiuş basin in Romania is given in Appendix 1.2.3. Hydraulic properties and deep fluid flow in various parts of Sweden are discussed in Appendix 1.2.4. A large number of data were also provided from extensive investigations done at study and research sites of the Swedish Nuclear Fuel and Waste Management Company (SKB), though even here depth is limited.

## 2.5 Fluid composition, brines, meteoric waters

Data on ancient ore-forming fluids (see Appendix 1.2.1) provide some frames on the character of evidently metal-bearing fluids, and could be used for comparison to those on present day systems. Fluids associated with granite-related vein-type mineralisations in south-west England were magmatic in origin. They ranged from c. 280 to 400°C and contained between 5 and 15 wt% NaCl. Post-magmatic vein mineralisations formed from cooler (c. 130°C) but more saline fluids with c. 26 wt% NaCl.

The quality, e.g., of brines and waters at upper crustal levels varies considerably between countries reported here. High values of total dissolved solids (TDS) are usually found at levels below 1000 m depth.

Data on fluids in south-west England are extensive and well characterised in Appendix 1.2.1. The existence of palaeobrines is well understood in the shallow sub-surface, but little is known for depths  $\gg$  200 m. As in all cases when generalizing data, one has to be aware of bias in data owing to where exploration or exploitation of commercially interesting minerals has occurred. There are currently no data available on fluids in the IBP. However, these are expected to be provided in the near future (Appendix 1.2.2). The composition of upper crustal fluids in the Bihor Mountains, Romania, is described mostly by analyses of waters from springs (Appendix 1.2.3). Fluid characteristics from a number of boreholes of various depths in Sweden are described in Appendix 1.2.4. The maximum salinity in waters of 150 000 mg/l was reported from large depth of 5700 m in western central Sweden, with their residence times estimated to hundreds of millions of years (Juhlin and Sandstedt 1989; Juhlin et al. 1998). The Cl-isotope composition of brines from 1000 m depth in coastal areas indicates a residence time of approximately 1.5 Ma (Louvat et al. 1999).

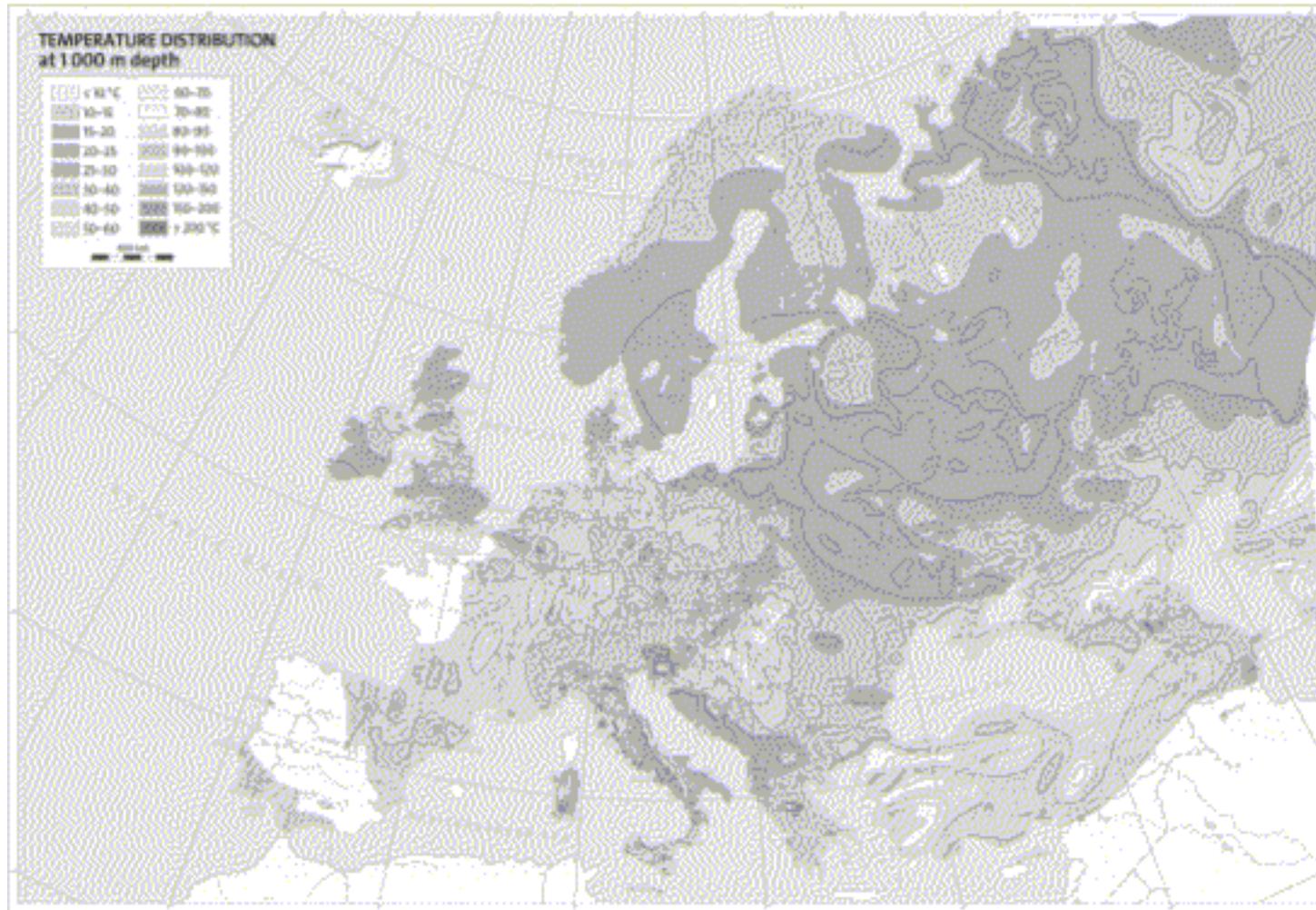
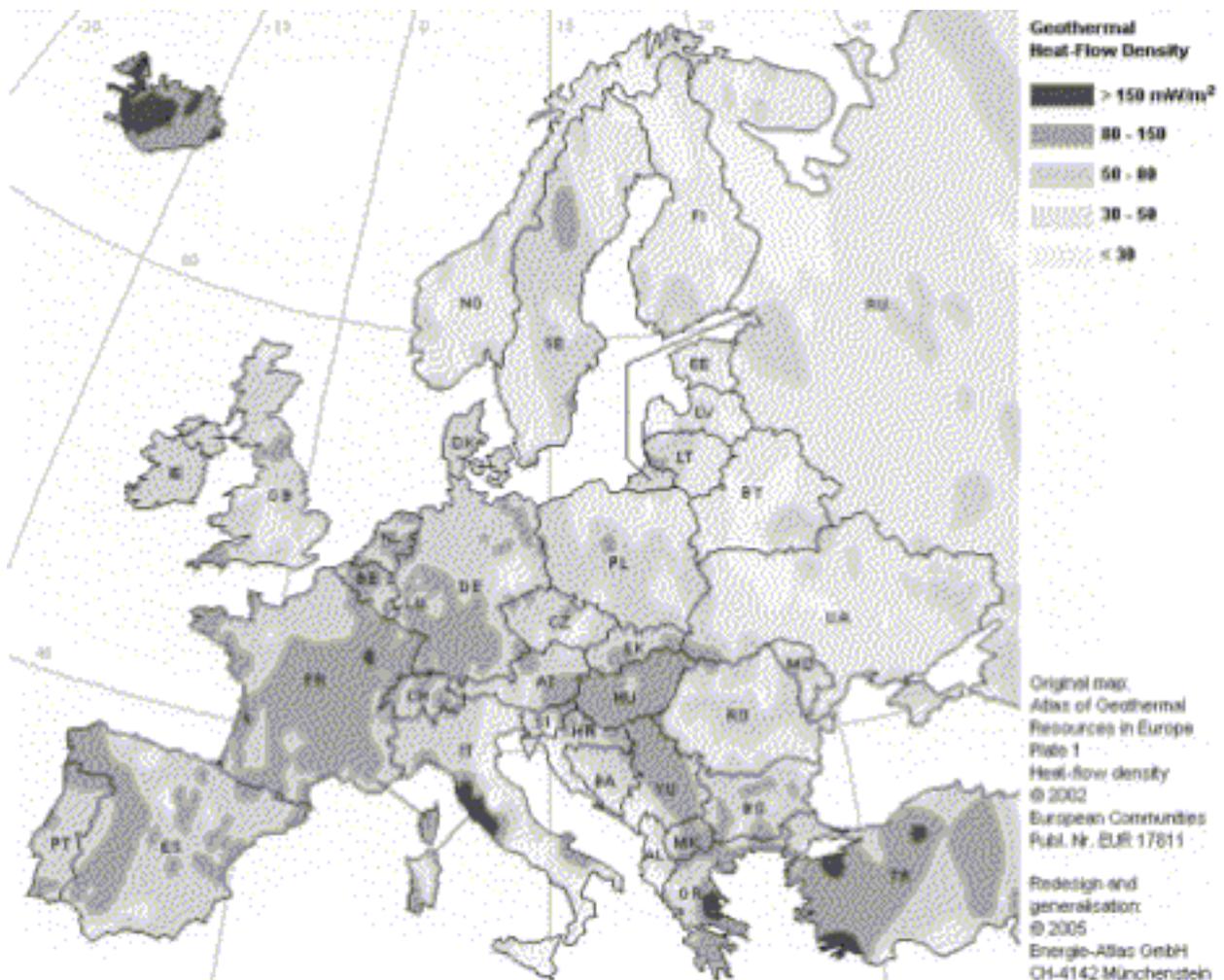


Figure 3. Temperature distribution at 1000 m depth in Europe (Schellschmidt and Hurter 2002)



**Figure 4.** Generalised heat flow density map of Europe, based on the Atlas of Geothermal Resources in Europe (after Hurter and Haenel 2002)

## 2.6 Thermal properties and heat flow

The geothermal heat flow in Europe ranges from less than 30 mW/m<sup>2</sup> to values exceeding 150 mW/m<sup>2</sup> (figure 4). Estimated temperature at 1000 m depth (figure 3) is partly related to the heat production and indicates areas of interest for this project. South-west England and the western part of Romania have relatively high temperatures at 1000 m depth and below.

Heat flow density in south-west England varies from 52 to 120 mW/m<sup>2</sup> as given in Appendix 1.2.1. The temperature gradient from borehole data was calculated to 26 to 35°C/km and temperature at 5000 m depth estimated to 185–220°C.

In the IBP, heat flow density was estimated to 65–85 mW/m<sup>2</sup> and temperature extrapolated to about 130°C at 5000 m depth (Appendix 1.2.2). As for Romania, in the BMMB heat flow density reaches 105 mW/m<sup>2</sup> and temperature at 3000 m depth is 80–90°C. These data and further ones on heat production and thermal conductivity from different parts of Romania are described in Appendix 1.2.3.

A description of data on thermal properties of the uppermost crust in Sweden is available in Appendix 1.2.4. Heat flow in the mining districts is varying between 50 and 60 mW/m<sup>2</sup> and the geothermal gradient is low, around 17°C/km.

Appendix 1.2.5 summarizes information on boreholes in more than 20 European countries, where temperature was reported to be above 100°C and mineralization occurs. In future work these data need to be extended.

## 2.7 Current metallogenic models (2D- and 3D-)

The formation of mineralisations according to their magmatic stage, with primarily tin and copper deposits, is discussed in the report for south-west England (Appendix 1.2.1). Mineralisations of the IPB are volcanogenic massive sulphide (VMS) deposits and described in Appendix 1.2.2.

The most important mineralisations in Romania are associated with the Banatitic Magmatic and Metallogenic Belt (BMMB), a 900 km long and 30 – 70 km wide zone. The Bihor Mountains are a part of this belt and of the Northern Apuseni Mountains and contain ore deposits of brucite, borate and skarn (Appendix 1.2.3). Sweden has an abundance of mineralisations representing most styles of ore-formation (Appendix 1.2.4).

### 3 Identifying target sites for future CHPM

#### 3.1 Extending existing models to greater depth, integrating data down to 7 km

Ore prospecting campaigns in the European countries, e.g., like in Portugal and Sweden, have not only increased by number but even by their depth of investigation. Efforts are undertaken looking deeper into the sub-surface and enhancing resolution for detecting mineralized zones, ore bodies and imaging faults, fracture zones and lithological contrasts. This is not only based on using traditional potential field methods, like gravity and magnetic methods, but also applying deep electromagnetic-, e.g., magnetotelluric (MT) and reflection seismic methods. Because of an often suitable contrast in electrical resistivity between the host rock and the mineralized zone, MT and especially AMT measurements, make it possible to identify such zones, though depth resolution may not be satisfying. Reflection seismics, instead, can provide high-resolution images of the underground and sufficient depth of investigation. For Sweden, several studies where high resolution seismics was used for mineral exploration and site characterization were published, e.g., Juhlin and Palm (1999), Malhemir et al. (2006, 2007, 2009a, b, 2011), Tryggvason et al. (2006), Schmelzbach et al. (2007). The limiting factor in applying high resolution reflection seismic waves, and, in a powerful combination, also electromagnetics (AMT) to screen the sub-surface is the economy of such investigations. Thus, exploration depth is constrained by the accessibility of an ore deposit at depth by direct mining.

Much of the information of the upper crust in SW England relates to the upper 1000 m, except for the Carnmellenis granite, where a HDR project provided better insight into the upper crust (see Appendix 1.2.1). The granite bodies of Cornwall are estimated to be of tabular shape, reaching down to about 3 – 4 km, or even much deeper. But, deep exploration data, in excess of 1000 m in depth are rare. In Romania, for the BMMB not much is reported from deep geophysical studies, beside from magnetic and gravity surveys. However, without additional data from reflection seismics these potential methods suffer from limited resolution in structures and depth.

With the present information available on the sub-surface of the areas under consideration, i.e., from geology, geophysics and boreholes, it is hard to properly extrapolate structures to greater depth. The investigations reported from Sweden (cf. Appendix 1.2.4, fig. 12) show that considerable efforts need to be undertaken in geologically complex areas to properly acquire data, i.e., preferably having 3D- instead of 2D seismic surveys – though again economic issues will limit this precondition.

#### 3.2 Knowledge gaps and limitations

As reported here, geological and geophysical data are in most cases only available for the uppermost c. 1000 m of the crust, but rare further down. Locally, boreholes to greater depths (<c. 3 000 m; in England and Romania) have been drilled, while in Sweden a hole down to almost 6 800 m exists.

This project, CHPM2030, requires the prediction of structures and lithology in complex environments at depth down to about 4–7 km, and estimating temperature, metal content, fluid chemistry and flow in the bedrock. Predicting the stress field, fracture geometry and permeability at depth in the crystalline bedrock is of crucial importance and highly challenging. With the present knowledge and

data available this task is not easy to fulfil. For pilot areas within CHPM2030, further intensive multi-disciplinary studies must be considered, e.g., three-dimensional electromagnetic and seismic surveys, as well as better predictions of temperature, heat flow and permeability at depth. The 3D integration of geological and geophysical results will then better allow for planning and conducting of exploration and possibly later-on production drillings.

## 4 Discussion and concluding remarks

The reports of the four nation-based working groups from the UK, Portugal, Romania and Sweden show that the general geology of the chosen area(s) in each country is well known and documented (appendices 1.2.1 to 1.2.4). In general, this is also the case for existing mineralisations and their styles of formation. A significant amount of data underpins this knowledge base, the majority of which is freely, or openly available. However, there are limitations. The knowledge is often restricted to the upper 1 000 m (or less) of the crust. Locally, where deep drilling has been performed, the conditions may be evaluated to greater depths. The availability of data has significant implications regarding the accuracy of modelled conditions in an enhanced geothermal system (EGS) at greater depths.

Available data from deeper levels are fairly infrequent. Most of the available data originate from governmental organisations which are obliged to provide data. On the other hand, data from mining companies are in many cases considered to be privately owned and not available. Properties and description of metadata (e.g., location, sampling methods), could be limiting factors for interpretation of data.

## Acknowledgements

The compilation of a report on existing data of several mining districts in Europe needs many helpful hands. We acknowledge the support of our colleagues at our home institutions, national universities and mining and exploration companies. Tobias Weisenberger is thanked for critically reading the manuscript.

## References

For practical reasons, we do not duplicate references here; instead, the reader is referred to the references given in the appendices.

## Other sources / Web links

EuroGeoSurveys (EGS), web links there, like, e.g., for Eurare, EuroGeoSource, Minerals4EU, Promine, ThermoMap ([www.eurogeosurveys.org](http://www.eurogeosurveys.org)).



## CHPM2030 DELIVERABLE D1.2 APPENDIX 1.2.1

# REPORT ON DATA AVAILABILITY: SOUTH WEST ENGLAND

### *Summary:*

This report provides an overview of geoscientific data and information relating to South West England, with a particular focus on its geology, structure, stress-field characteristics, mineralisation and previous geothermal research in the region.

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## Executive summary

This report provides a summary of key information available for South West England, which is relevant for development of enhanced geothermal systems in the region. South West England is a geologically complex region with a long and significant history of metal mining, producing primarily tin (c. 2.8 million tonnes) and copper (c. 2 million tonnes). The geology of the region is largely the result of Variscan tectonics and associated felsic magmatism. The current surface expression of the Cornubian Batholith comprises six large granitic plutons. From west to east these are: the offshore Isles of Scilly (120 km<sup>2</sup>), Land's End (190 km<sup>2</sup>), Carnmenellis (135 km<sup>2</sup>), St Austell (85 km<sup>2</sup>), Bodmin (220 km<sup>2</sup>), and Dartmoor (650 km<sup>2</sup>). These granite bodies were intruded into a series of Devonian (410–355 Ma) green schist facies metasedimentary rocks, locally known as 'killas' during the late Carboniferous and early Permian (295–270 Ma). The granites of South West England are texturally and compositionally complex, although broadly they comprise peraluminous, S-type granites of the two-mica variety. They are enriched in elements that include K, F, B, Li, Sn, Th, U and Rb. However, it is their enrichment in K, Th and U that is responsible for their heat-production via radioactive decay.

Mineralisation in South West England is wide-spread and can be broadly divided on the basis of its timing relative to granite emplacement as: (1) *pre-granite* orebodies of the sedimentary-exhalative type, and shear-zone hosted Au-Sb type; (2) *granite-related* mineralisation, comprising greisens and sheeted vein complexes, and polymetallic sulphide lodes and; (3) *post-granite* mineralised Zn-Pb-Ag veins (so called crosscourses).

Fluids associated with granite-related mineralisation are magmatic in origin, and ranged in temperature from about 400°C for Sn-W greisens to about 280°C for Sn-Cu polymetallic lodes, with salinities ranging between 5 and 15 wt% NaCl. Post-granite mineralisation is dominated by Pb and Zn rather than Sn and Cu, and formed from lower temperatures fluids (c. 130°C), with higher salinities of about 26 wt% NaCl. Warm (up to 55°C), high-salinity groundwaters have been found at depths of up to 820 metres depth, primarily issuing from crosscourses and lodes in mines at the northern edge of the Carnmenellis granite. These flows occur in mines in both the granite and in the killas. Some of the crosscourse flows have been discharging for more than 30 years, suggesting that a large reservoir of saline, thermal water exists at depth.

The south-west of England is structurally complex with at least three different episodes of deformation identified. Permeability in the south-west is fracture dominated. Therefore, it is the large NW-SE-trending fault structures that are potentially most important for enhanced geothermal systems in terms of fluid flow. Principal stress orientations are about 30° off parallel from that of the NNW-SSE and ENE-SWS-trending joints sets observed in the Carnmenellis granite. The maximum *in-situ* stress ( $\sigma_H$ ) is about 70 MPa in the NNW-SSE direction, whilst the minimum *in-situ* stress ( $\sigma_h$ ) is about 30 MPa in an ENE-WSW direction.

Previous geothermal research in the south-west of England peaked between the 1970s and 1990s. The south-west region was of interest because of the high heat flows present in the Cornubian granites (c. 115–139 mWm<sup>-2</sup>). These high heat flow values suggest high temperatures (c. 185–220°C) at depths of 5 km or more.

In 1984 an extensive programme of work, funded by the UK Department of Energy (DEn) and the Commission of the European Communities (CEC), was undertaken by the British Geological Survey (BGS) to assess the UK's geothermal potential. Over the same time period (1977–1984) the Camborne School of Mines (CSM) was assessing the feasibility of creating HDR geothermal systems at a test site at the Rosemanowes quarry, on the Carnmenellis granite, in Cornwall. It was assumed that the behaviour and characteristics of a HDR system could be modelled using geochemistry, geophysics and physical properties

testing. Between 1985 and 1989 the Department of Energy and the Commission of the European Communities funded a detailed geochemical investigation of the HDR site at Rosemanowes. These investigations were undertaken by the BGS, the then NERC Isotope Geology Centre (NIGC), the University of Bath (UoB) and CSM. In 1987 an informal working group (the UK Hot Dry Rock Geochemistry Group) was established to align the geochemical programme more closely with the work being undertaken by CSM at the Rosemanowes test site.

In summary a huge amount is already known about the geology, mineralisation fluid history and geothermal potential of South West England. A significant body of data underpins this knowledge base, the majority of which is freely, or openly available. However, there are limitations. For example, much of this data, with the exception of the HDR datasets, only relates to the upper 1,000 m of the crust. This has significant implications regarding the accuracy of modelled conditions in an enhanced geothermal system (EGS) at greater depths. There are also 'gaps' in the data (e.g. very limited deep-geophysical data), and some data sets have not been updated since their creation in the 1970s and 1980s.

## 1 Preface

This report is a published product of the 'CHPM2030' project – an EC-funded, Horizon2020 project which aims to develop a novel and potentially disruptive technology solution that can help satisfy European needs for energy and critical metals in a single interlinked process. Working at the frontiers of geothermal resources development, minerals extraction and electro-metallurgy, the project aims to convert ultra-deep metallic mineralisation into 'orebody-enhanced geothermal systems' that will serve as a basis for the development of a new type of facility for 'Combined Heat, Power and Metal extraction' (CHPM).

The project will help provide new impetus to geothermal development in Europe by investigating previously unexplored pathways at low-TRL. This will be achieved by developing a roadmap in support of the pilot implementation of such system before 2025, and full-scale commercial implementation before 2030. This will include detailed specifications of a new type of future EGS facility that is designed and operated from the outset as a combined heat, power and metal extraction system.

In the technology envisioned, the metal-bearing geological formation will be manipulated in a way that the co-production of thermal energy and metals will be possible. As part of this, we will investigate how fluid chemical conditions can be optimised to facilitate recovery of specific metals, anticipating variable market demands in the future. Four geographical areas have been chosen for assessment based on pre-existing data and potential for CHPM development in mineralised areas in the United Kingdom (UK), Portugal, Romania and Sweden. This report summarises information relevant to the UK.

The project aims to provide proof-of-concept for the following hypotheses:

1. The composition and structure of orebodies have certain favourable characteristics that could be used to our advantage when developing an EGS;
2. Metals can be leached from the orebodies in high concentrations over a prolonged period of time and may substantially influence the economics of EGS;
3. The continuous leaching of metals will increase system's performance over time in a controlled way and without the need to use high-pressure reservoir stimulation, minimising the potential detrimental impacts of both heat and metal extraction.

## 2 Introduction

During the last 50 years geothermal energy research in the UK has been limited, partly due to a lack of high-enthalpy resources, but also because of the availability of cheap fossil fuels during the 1980s and 1990s. Research has focussed on three main aspects: (1) a nationwide appraisal of heat flow; (2) energy generation from hot-brines in deep, hyper-saline aquifers (HSA) and; (3) energy generation from enhanced geothermal systems (EGS) in hot dry rocks (Busby, 2010).

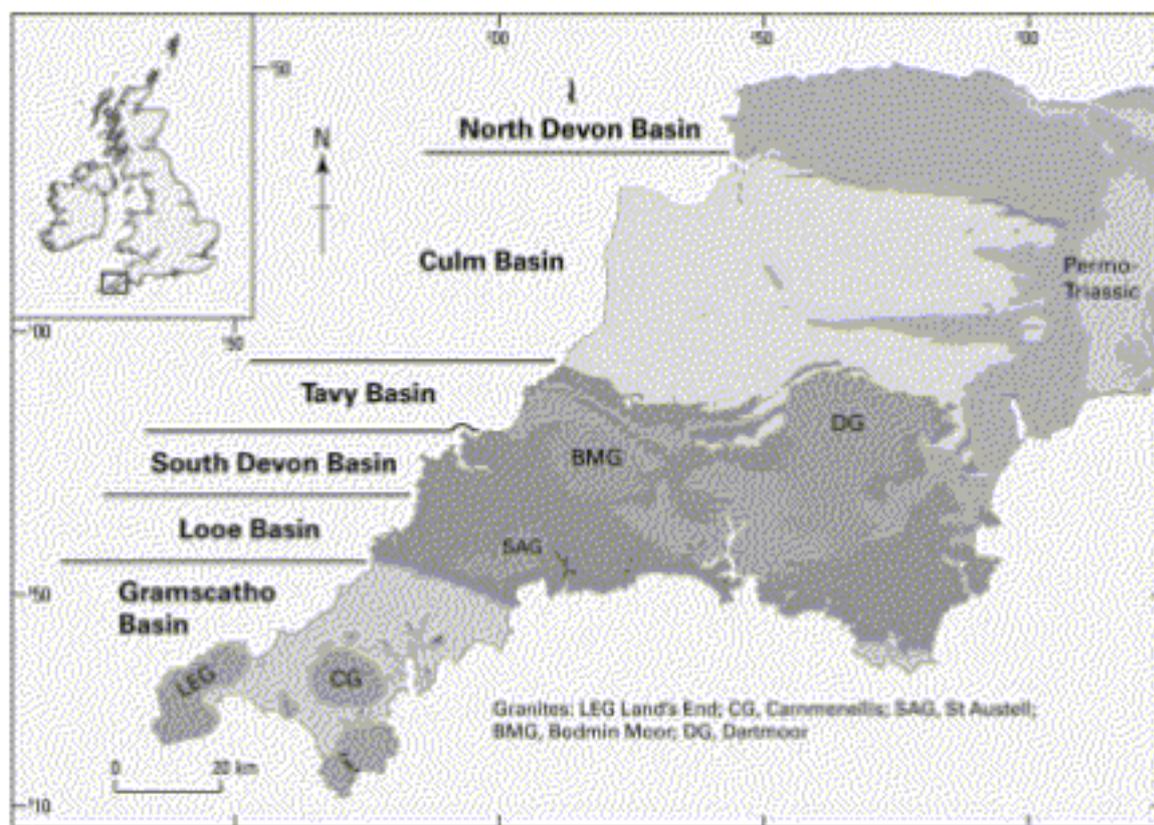
Heat flow measurements (Lee *et al.*, 1987; Downing and Gray, 1986; Rollin, 1995; Rollin *et al.*, 1995 and; Barker *et al.*, 2000) place UK background heat flow at about  $52 \text{ mW m}^{-2}$ , with elevated values associated with buried granites in north-eastern England and radiogenic granites in South West England. The average UK geothermal gradient is approximately  $26^\circ\text{C km}^{-1}$ , although locally it can exceed  $35^\circ\text{C km}^{-1}$ .

The radiogenic granites of South West England were assessed for their HDR geothermal energy potential as part of the HDR project during the 1970s and 1980s. This programme of work was largely undertaken by the Camborne School of Mines to assess the performance of an EGS in the Carnmenellis granite, in South West England. The test site operated a set of deep (between 2–2.5 km) boreholes to assess the feasibility of developing a full-scale commercial HDR system at about 5–6 km depth.

South West England was chosen as a potential pilot study site for the CHPM2030 project because of the large amount of data that are available for South West England, the region's status as a historically important orefield, and because of the history of geothermal research in the region.

### 3 Geology

The geology and metallogensis of South West England is complex and has been the subject of extensive scientific research for more than two centuries. It was during the eighteenth century (c. 1778) that William Pryce first attempted to synthesise the geology, mining practices and metallurgy of the region. A number of important papers followed in the early to mid-nineteenth century (Phillips, 1814; De La Beche, 1839; Henwood, 1843) that sought to explain the role of granite and circulating fluids in the formation of South West England's mineral deposits. This extensive metallogenic province, covering the county of Cornwall and part of the county of Devon from Land's End to Dartmoor, a distance of some 150 km is termed the 'Cornubian Orefield'. Significant advances were made during the twentieth century in understanding the formation of the Cornubian Orefield, with the publication of numerous papers by Dines (1934 and 1956) and Hosking (1950, 1951, 1952, 1964, and 1969). Geoscience research during the past forty years has sought to refine many of the earlier theories and concepts by the application of geochronology (Chesley *et al.*, 1993; Chen *et al.*, 1993; Clark *et al.*, 1993; Clark *et al.*, 1994; and Darbyshire, 1995), isotope studies (Rouse and Colman, 1976; Darbyshire and Shepherd, 1994; and Shail *et al.*, 2003) and fluid inclusion research (Williamson *et al.*, 1997; Gleeson *et al.*, 2000; 2001; Williamson *et al.*, 2000; and Müller and Halls, 2005).



**Figure 1.** Simplified geological map of South West England showing the distribution of sedimentary basins and the location of the granites (re-drawn from BGS mapping data and Shail and Leveridge, 2009)

Regional geological mapping by the British Geological Survey at 1:50 000 scale, and airborne geophysical (i.e. magnetic and radiometric) and remote sensing (i.e. LiDAR) surveys, flown as part of the TELLUS South West project, have further contributed to the geological knowledge base. Comprehensive reviews of the geology

of South West England can be found in Selwood *et al.* (1998), LeBoutillier (2002) and Shail and Leveridge (2009), and references therein.

A brief chronology of major geological events in South West England, from oldest to youngest, includes: (1) The development of a series of middle Palaeozoic (410–345 Ma), east-west trending volcano-sedimentary basins (from east–west these are the: North Devon Basin; Culm Basin; Tavy Basin; South Devon Basin; Looe Basin and; Gramscatho Basin) (Figure 1) that have been inverted, deformed and subjected to low-grade metamorphism (Parker, 1989; Shail, 2014); (2) Variscan continental collision, during the mid-Carboniferous (331–329 Ma), resulted in significant crustal shortening and the development of NNW-trending thrust sheets (Parker, 1989; Shail, 2014); (3) Crustal extension and orogenic collapse during the late Carboniferous and lower Permian that resulted in extensive granitic magmatism (295–270 Ma) and associated hypothermal (300–600°C) Sn-W greisens, and mesothermal (200–300°C) Sn-Cu mineralisation hosted by E-W-trending mineral lodes. Following granite emplacement widespread Pb-Zn mineralisation developed in N-S-trending crosscourses, many of which are re-activated NNW-trending thrust sheets (Parker, 1989; LeBoutillier, 2002; Shail *et al.*, 2014) and; (4) Cyclic periods of uplift, erosion and sedimentation throughout the Jurassic and Cretaceous (Parker, 1989; Shail *et al.*, 2014) resulting in the current landscape (e.g. exposure of granite roof zones at the existing land surface).

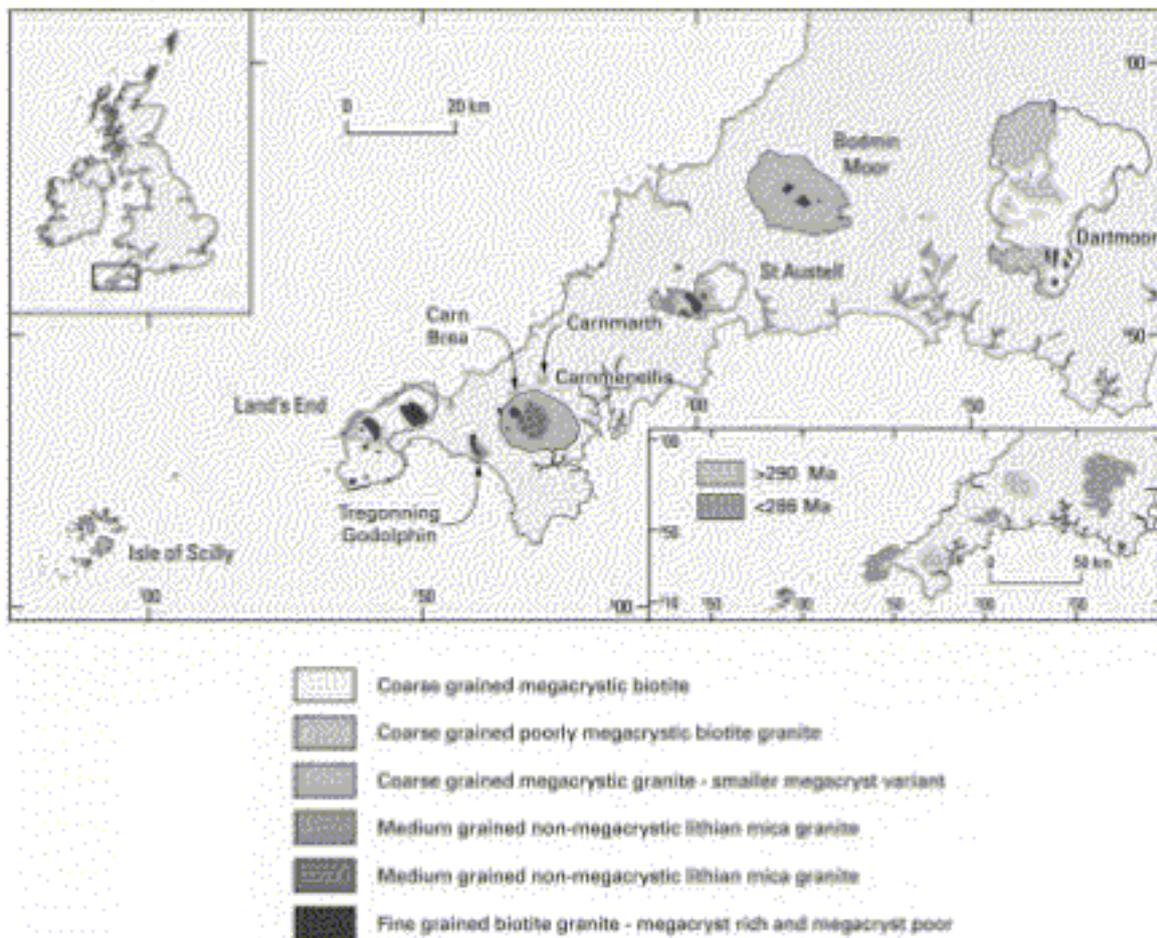
Emplacement of the Cornubian batholith into largely Devonian sedimentary rocks caused large-scale heating and thermal alteration. These metamorphic rocks in South West England are locally known as ‘killas’. Although these rocks are not economically important in themselves, fractures within them host a significant proportion of the region’s mineral deposits (e.g. polymetallic mineral veins, or ‘lodes’). The ‘killas’ comprises a series of Devonian (410–355 Ma), marine deposited sandstones, siltstones, mudstones and rare carbonates that were regionally metamorphosed to sub-green schist facies during the Variscan Orogeny. As a result of granite emplacement, the low-grade regional metamorphism has been locally overprinted by higher-grade contact metamorphism, to produce a series of aluminosilicate and/or cordierite-bearing slates (Selwood *et al.*, 1998).

The current surface expression of the Cornubian Batholith is six large granite plutons. From west to east these are: the offshore Isles of Scilly (120 km<sup>2</sup>), Land’s End (190 km<sup>2</sup>), Carnmenellis (135 km<sup>2</sup>), St Austell (85 km<sup>2</sup>), Bodmin (220 km<sup>2</sup>), and Dartmoor (650 km<sup>2</sup>) (Figure 1). The subsurface extent of the Cornubian Batholith is estimated to be about 250 km in length and has an approximate width of between 40 and 60 km (Willis-Richards and Jackson, 1989; Scrivener, 2006). However, there is uncertainty about the true size of the Cornubian Batholith because current models are based on a small amount of data (e.g. gravity measurements and a very limited number of deep drill holes). Similarly there is some uncertainty about the true thickness and shape of the granite plutons. 2D-gravity modelling of the Carnmenellis, St Austell and Bodmin granites indicates they are tabular bodies with an estimated thickness of between three and four kilometres, whilst the larger Dartmoor pluton is estimated to be about nine kilometres thick (Taylor, 2007). However, seismic refraction data suggest that the depth of the base of the batholith (i.e. its lower contact with the killas) is variable, ranging from about seven and eight kilometres beneath the Bodmin and Carnmenellis granites, respectively, to about ten kilometres beneath the Dartmoor granite (Brooks, 1984; Shail *et al.*, 2014).

Radiometric dating (U-Pb in monazite and zircon) suggests that the extensive granitic magmatism observed in South West England occurred over an about 20-million-year period, between about 293 Ma and 274 Ma, although separate intrusive episodes can be identified in some of the individual plutons (Chen *et al.*, 1993; Chesley *et al.*, 1993; Clark *et al.*, 1994). In terms of age, the plutons can be broadly divided into two groups:

(1) the older (>290 Ma) Bodmin Moor, Isles of Scilly and Carnmenellis granites and; (2) the younger (<286 Ma) Land's End, St Austell and Dartmoor granites (Figure 2).

Compositionally the granites are all peraluminous, S-type granites that are enriched in elements such as K, B, F, Li, U, Th, Sn, Rb and Pb. An interesting feature of Cornubian granites is their high uranium content (with an average of about 12 ppm for all plutons), which is largely controlled by the distribution of accessory minerals such as uraninite and monazite (Chappell and Hine, 2006; Scrivener, 2006). Importantly it is the radioactive decay of uranium, thorium and potassium in the Cornubian granites that is responsible for their high heat production through radioactive decay (Chappell and Hine, 2006).



**Figure 2.** Map showing the principal mineralogical and textural variations in the Cornubian Batholith. It combines subdivision into biotite and lithian-mica granites with a textural scheme based primarily on mean matrix grain size and the size and abundance of alkali feldspar megacrysts – compiled from Exley and Stone (1964, 1982) Stone and Exley (1985), Hawkes and Dangerfield (1978), Dangerfield and Hawkes (1981), Exley *et al.* (1983), Floyd *et al.* (1993), Manning *et al.* (1996), Manning (1998) and Shail *et al.* (2014). In-set map shows the distribution of granite ages: Dartmoor, St Austell and Land's End (in purple) are <286 Ma, whereas Bodmin, Carnmenellis and Isles of Scilly (in yellow) are older (>290 Ma)

The granites of South West England can be categorised mineralogically into three broad groups: (1) biotite granite; (2) topaz granite; and (3) tourmaline granite. However, minor variants also exist, including Li-mica granite and fluorite granite (Exley *et al.*, 1983; Floyd *et al.*, 1993; Manning *et al.*, 1996). Textural variations are also used to distinguish sub-classes of the granites e.g. fine-grained tourmaline granite (Manning *et al.*, 1996) (Figure 2). The older granites (Bodmin Moor, Isles of Scilly, and Carnmenellis) can be distinguished from the younger granites (Land's End, St Austell and Dartmoor) by their texture, composition (peraluminosity), isotopic signature ( $^{143}\text{Nd}$ ) and rare earth element (REE) patterns. These differences may reflect increased mantle-melting and possibly increased amounts of crustal melting during formation of the younger granites, probably in response to higher temperatures in the lower crust. However, it remains unclear why temperatures increased, and if this change was transitional, or an abrupt change in response to a discrete tectonic event (Stone, 1995; 1997; 2000a; 2000b; Shail *et al.*, 2014).

### 3.1 Summary

The region has been studied for more than 200 years and thus a large amount of data exists that describes the relationship between magmatism and mineralisation. Complimentary geological mapping and airborne geophysical surveys have further refined the interpretation of the geological evolution of the region. The abundance of magmatism and mineralisation across South West England warrants its status as a globally significant metallogenic province.

### 3.2 How South West England can positively contribute to the aims of CHPM2030:

- Extensive body of academic literature.
- Good understanding of the geological evolution of the region.
- Continuous digital geological mapping at 1:50,000 scale.
- Complimentary regional datasets (e.g. LiDAR, airborne geophysics, geochemistry, etc.).
- 3D model of the geology at 1:625,000 scale.

### 3.3 Limitations in our current understanding of the geology of South West England:

The majority of the primary data that exists is related to the shallow sub-surface (<1,000 m, and often <200 m). There has also been no regional deep geophysical investigation. As a consequence, this presents uncertainty in terms of extrapolating information and data at surface to any significant depth.

## 4 Fluids

Academic research in South West England during the past 30 years has focussed on the nature of mineralising fluids, and their role in metal transport and ore deposit formation. Fluid inclusion (i.e. fluids trapped during mineral growth) studies have been invaluable in revealing the composition (salinity), temperature and in some cases the pressure of the mineralising fluids. Complimentary stable isotope studies (e.g. O, H, He and S) have also provided useful information on the source of the mineralising fluids (e.g. He signatures suggest a mantle-derived volatile component) (Shail *et al.*, 2003). Studies of shallow groundwaters (down to c. 100 m), as part of the HDR programme have provided insights into water-rock interaction over short time intervals and at shallow depths. Similar studies of deep, thermal spring waters from disused mines provide information on fluid circulation and mixing. When combined these data (e.g. shallow groundwater and mine water composition, and fluid inclusion studies) have enabled important conclusions to be drawn regarding palaeofluid circulation in both the granites and country rocks of South West England (Smedley *et al.*, 1989).

Broadly two dominant fluid types have been implicated in the formation of mineralisation in South West England:

- (1) Moderate to high salinity (NaCl+CO<sub>2</sub>), high temperature magmatic fluids that produced the granite-related mineralisation (e.g. polymetallic Sn-Cu lodes); and
- (2) High salinity (NaCl+CaCl<sub>2</sub>), lower temperature basinal fluids that formed the younger, post-magmatic mineralisation (e.g. crosscourses) (Table 1).

Mineralisation style	Temperature	Salinity	Composition
Greisen <sup>1</sup>	450–350°C	5–10 wt%	NaCl±CO <sub>2</sub>
Polymetallic lode (Sn-Cu) <sup>2</sup>	280–200°C	3–15 wt%	NaCl
Polymetallic lode (Pb-Zn) <sup>2</sup>	c. 220°C	0–5 wt%	NaCl
Crosscourse <sup>2</sup>	c. 130°C	26 wt%	NaCl±CaCl <sub>2</sub>

**Table 1.** Summary of fluid inclusion data for mineralising fluids (Smith *et al.*, 1996<sup>1</sup> and Gleeson *et al.*, 2001<sup>2</sup>).

Stable isotope studies (i.e. Cl, O, H, He and S) on fluids taken from inclusions in the mineralisation have provided useful insights in to the origin of mineralising fluids. For example, isotopic studies of main stage, polymetallic lodes indicate that mineralising fluids were principally magmatic in origin, whilst fluids associated with later crosscourses are distinctly non-magmatic, having a strong sediment-derived fluid signature (Wilkinson *et al.*, 1995; Gleeson *et al.*, 1999; Banks *et al.*, 2000; Shail *et al.*, 2003).

Warm (up to 55°C), high-salinity groundwaters have been found at depths of up to 820 metres, primarily issuing from crosscourses and lodes in mines at the northern edge of the Carnmenellis granite. These flows occur in mines in both the granite and in the killas. Some of the crosscourse flows have been discharging for more than 30 years, suggesting that a large reservoir of saline, thermal water exists at depth (Smedley *et al.*, 1989). These deep spring waters 31–55°C, mildly acidic to neutral (pH 5.4–7.7), and compositionally they are dominated by Na, Ca and Cl (Smedley *et al.*, 1989) (Table 2). Stable oxygen ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta^2\text{D}$ ) isotope studies indicate that these waters are not derived from seawater, but are more likely diluted palaeobrines

which have flowed through crosscourse structures within the granite and killas. Their chemical and isotopic signatures also indicate mixing and dilution by circulation of local meteoric water (Alderton and Sheppard, 1977; Smedley *et al.*, 1989).

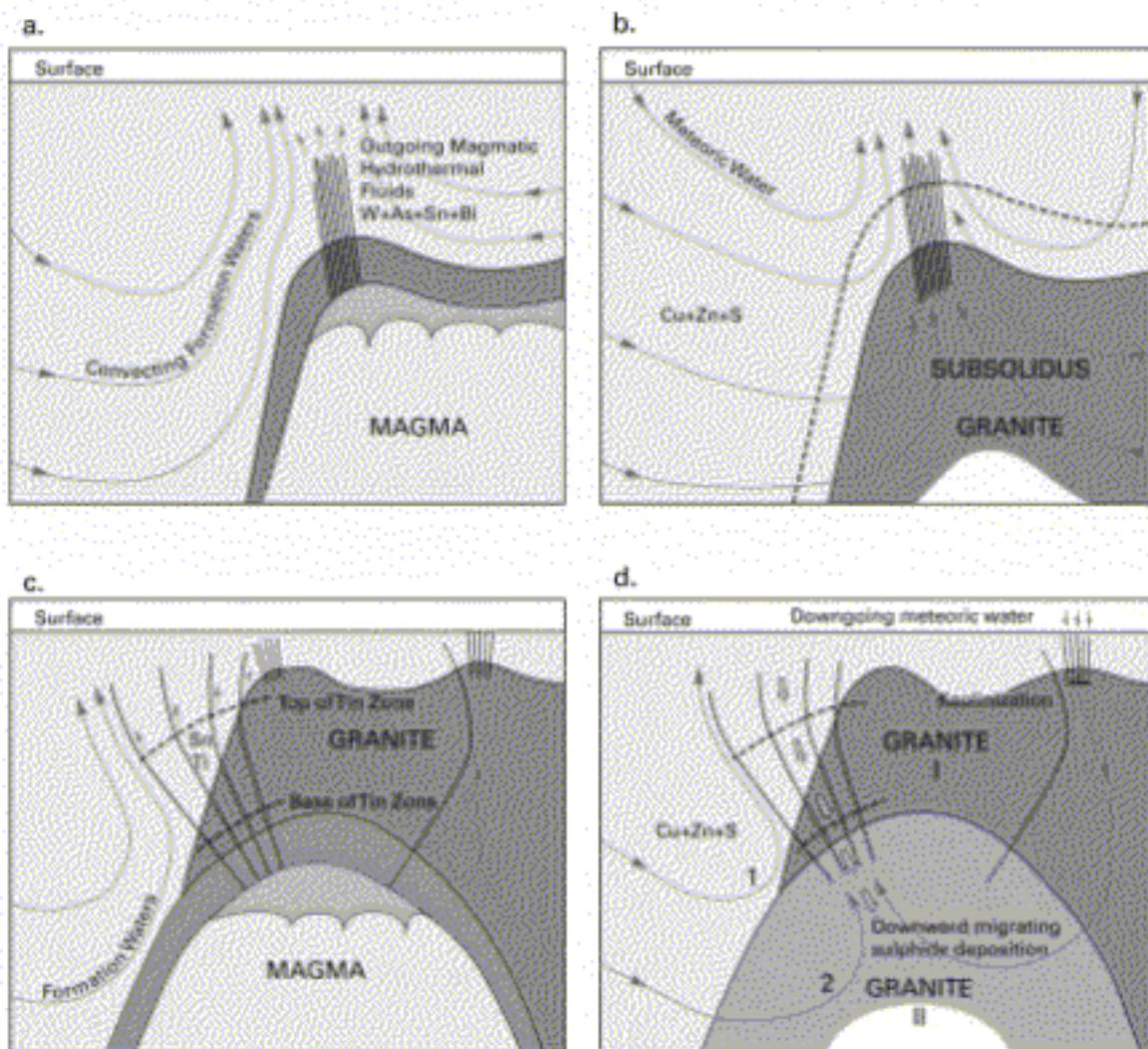
Parameter	South Crofty (420 level)	South Crofty (420 level)	Wheal Jane	Clifford United
Source	Smedley <i>et al.</i> , 1989		Alderton and Sheppard, 1977	
Depth (m)	690	690	198	448
pH	6.79	5.38	7.70	n.r.
Temperature (°C)	45.3	34.3	31.5	52
Total dissolved solids	14,099	10,454	9,934	9,189
Na	3,210	1,890	2,073	2,043
K	138	66.8	127	111
Mg	51.6	94.8	29.5	32
Ca	1,670	1,630	1,326	1,166
Cl	8,750	6,500	6,110	5,628
SO <sub>4</sub>	107	240	118	124
HCO <sub>3</sub>	n.r.	n.r.	23.8	n.r.

**Table 2.** Summary of mine water compositions (n.r., 'not reported')

Low salinity, shallow groundwaters from within the granite and killas show considerable compositional overlap. However, slight differences can be observed in both the major cation (i.e. Ca, Mg, Na and K) and anion (i.e. HCO<sub>3</sub>, SO<sub>4</sub>, Cl and NO<sub>3</sub>) contents of these waters. Granite-related shallow groundwaters are more acidic (pH 4.3–6.9) and are dominated by Na, K and Cl, whilst killas-related groundwaters are more alkaline (pH 4.9–8.0), and have compositions dominated by Ca, Mg and HCO<sub>3</sub>. The higher overall concentration of elements (e.g. Ca, Mg, Cl, etc.) in killas-related groundwaters suggests that the killas is more reactive, or possibly more soluble, than the granite. The abundance of minerals such as calcite, dolomite, chlorite and clays in the killas may account for these higher concentrations by dissolution and precipitation, and ion exchange reactions. Element enrichment and depletion patterns suggest that shallow groundwater compositions are strongly controlled by lithology. For example, granite-related waters typically have higher Ba and Rb contents, which likely reflects dissolution of alkali feldspar (Smedley *et al.*, 1989; Smedley and Allen, 2004).

Previous studies suggest that palaeo-fluid flow in and around the Carnmenellis granite can be divided into four main stages (Figure 3): (1) Expulsion of early magmatic fluids associated with the emplacement of the granite, which led to the formation of sheeted Sn-W greisens in the granite roof zone and overlying metasedimentary rocks. Hydrothermal convection of formation waters starts to occur in response to the thermal anomaly created by the granite emplacement. (2) Copper, zinc and sulphur are leached from the host rocks. Formation waters are drawn down through the granite as the system begins to cool, resulting in

the deposition of Cu-Zn-sulphides in veins. (3) Main-stage, polymetallic lodes are emplaced within the granite roof zone by further expulsion of magmatic fluids. (4) Formation waters start to circulate through the granite in response to cooling of the system, resulting in the deposition of Cu-Zn-sulphides in steeply dipping fissures (Smedley *et al.*, 1989). Post-magmatism basinal brines circulate through N-S-trending structures within the granite and killas, mixing with meteoric waters. These fluids deposited Pb-Zn-rich mineralisation within the so called crosscourse veins (Scrivener *et al.*, 1994; Gleeson *et al.*, 2000; 2001).



**Figure 3.** Schematic diagram illustrating fluid flow regimes in relation to emplacement of the Carnmenellis granite. (a) Expulsion of magmatic fluids forming Sn-W greisens and generation of hydrothermal convection in overlying groundwaters. (b) Leaching of metals and sulphur from the host rocks. Cooling of the system permits meteoric waters to pass down into the granite pluton. (c) Main stage, polymetallic lodes form in the roof zone of the granite pluton by expulsion of magmatic fluids. (d) Meteoric waters circulate through the granite as the system cools. Cu-Zn sulphides are deposited in a series of lodes (re-drawn after Smedley *et al.*, 1989)

## 4.1 Summary

Fluids associated with both Sn-W greisen and Sn-Cu polymetallic lode mineralisation in South West England are primarily of magmatic origin, In contrast fluids associated with post-granite crosscourse mineralisation are distinctly non-magmatic and derived from sedimentary basins, possibly with a local meteoric water component. Saline mine waters (known to extend to depths of at least 820 metres) are considered to be palaeobrines that have been diluted by local meteoric water. These mine waters exploit N-S-trending crosscourse structures in the granite and killas. Active fluid flow and mixing has, and continues to, play an important role in the formation of the Cornubian Orefield.

## 4.2 How South West England can positively contribute to the aims of CHPM2030:

- Mineralising fluids, saline mine waters and shallow ground waters are reasonably well characterised (e.g. by fluid inclusion, stable isotope, geochemical studies etc).
- Significant amounts of data have been generated as part of the HDR programme (e.g. water chemistry, stable isotopes, and fluid inclusions).
- Fluid circulation is reasonably well understood in the shallow subsurface.

## 4.3 Limitations in our current understanding of fluids in South West England:

- Much of the primary data that exists is related to the shallow sub-surface (<1,000 m, and often <200 m). Hence little is known about fluids existing at depths below 1,000 m, both in terms of chemistry and circulation.
- Mine water data are largely restricted to sites concentrated around the Carnmenellis granite.

## 5 Mineralisation

The Cornubian Orefield has a complex, protracted (c. 100 Ma), multi-stage history of polymetallic mineralisation. Mineralisation comprises a variety of styles, ranging from Devonian-Carboniferous syngenetic mineralisation, to recent placer and kaolin deposits. Although historically the south-west region was major metal producer, the Drakelands Sn-W deposit (operated by Wolf Minerals Ltd) is the only active metal mine in South West England. It is hosted within and around a dyke-like body of porphyritic granite, known as the Hemerdon Granite that forms a cupola to the south-west of the main body of the Dartmoor Granite. The deposit is one of the world's largest tungsten deposits containing 35.7 million tonnes at a grade of 0.18% WO<sub>3</sub> and 0.03% Sn (Wolf Minerals, 2015). The Drakelands operation has a production capacity of more than 3,000 tonnes of tungsten concentrate per annum (Wolf Minerals, 2015). There is a long history of mineralisation-related research in South West England, with a particular focus on granite-related hydrothermal tin and tungsten-bearing deposits.

### 5.1 Historical production

Historically, the south-west region was a major metal producer. Mineral deposits in the region were predominantly exploited for tin, tungsten, arsenic, zinc, lead and copper (Dines, 1956; Shail *et al.*, 2014; Burt *et al.*, 2015). Approximate quantities of metal production in South West England are shown in Table 3.

Mineral or metal (Tons)	
Sn metal	2,770,000
Cu metal	2,000,000
Fe ore	2,000,000
Pb metal	250,000
As (as As <sub>2</sub> O <sub>3</sub> )	250,000
Pyrite	150,000
Mn ores	100,000
Zn metal	70,000
W (as WO <sub>3</sub> )	5,600
U ore	2,000
Ag ore	2,000
Ag metal (from sulphide ore)	250
Co-Ni-Bi ores	500
Sb ores	300
Mo metal	Minor
Au metal	Minor
Barite	500,000
Fluorite	10,000
Ochre/umber	20,000
Kaolinite (china clay)	150,000,000

**Table 3.** Estimated total mineral and metal production from South West England. After Dines (1956), Alderton (1993) and South Crofty PLC (1988-1998). Adapted from LeBoutillier (2002)

## 5.2 Mineralisation in South West England

Four main stages of mineralisation have been identified in South West England, forming over about a 100 Ma period between the early Permian and the late Triassic. The mineralisation can be broadly divided on the basis of its timing relative to granite emplacement as:

- (1) *Pre-granite* orebodies of the sedimentary-exhalative type and shear-zone hosted Au-Sb mineralisation;
- (2) *Granite-related* mineralisation, comprising greisens and sheeted vein complexes and polymetallic sulphide lodes and;
- (3) *Post-granite* mineralised Zn-Pb-Ag crosscourses (highlighted in Table 4). Figure 4 provides an overview of the fluid chemistry of these mineralisation styles.

*Pre-granite* mineralisation comprises: (1) stratiform mineralisation that contains sub-economic enrichments in base metals (Scrivener *et al.*, 1989; Scrivener, 2006); and (2) metamorphogenic quartz-carbonate veins that typically contain Sb-As-(Au) (Clayton *et al.*, 1990). The main commodities associated with the early stratiform mineralisation are iron and base metals. Orogenic shear-hosted Au-Sb-Ag mineralisation is limited to basinal argillaceous lithologies with significant volumes of basic volcanic rocks. It is also spatially associated with NNW-trending shear zones (Stanley *et al.*, 1990). Fluid chemistry and structural data indicates that the quartz-Au-Sb veins were precipitated early from CO<sub>2</sub>-rich metamorphic fluids with fluid inclusion homogenisation temperatures (Th) in the range 315–280°C (Clayton *et al.*, 1990).

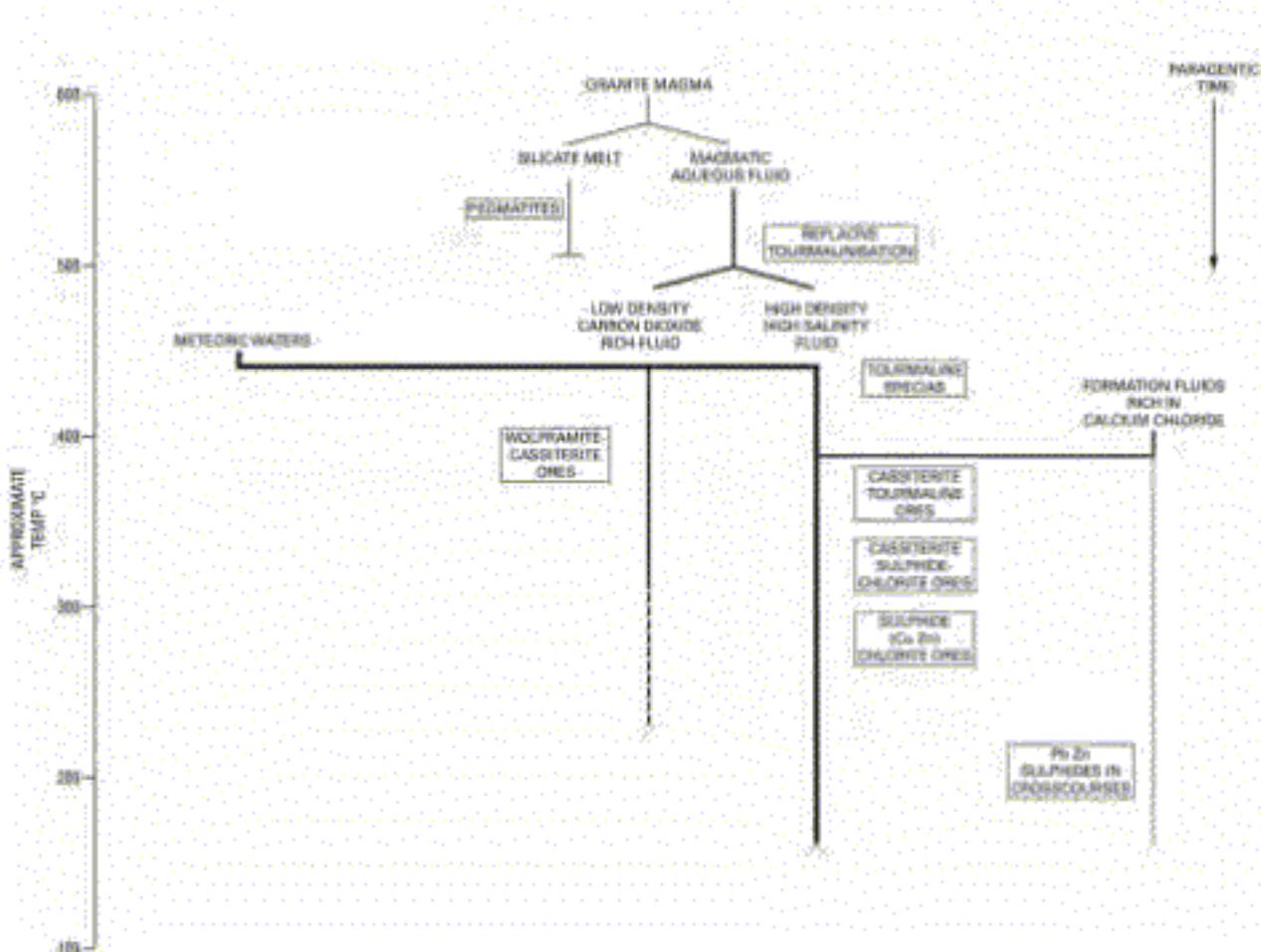
*Granite-related* mineralisation formed largely during the early to mid-Permian. These mineral deposits were historically of the greatest economic importance and were exploited for tin, tungsten, arsenic and base metals. *Granite-related* mineralisation includes skarns and pegmatites, greisens and sheeted vein deposits, and the main-stage polymetallic deposits. Localised skarn deposits have resulted from the thermal alteration of calc-silicate minerals that have been altered by boron-rich fluids (Scrivener 2006). Volumetrically these skarns are insignificant, thus reflecting the lack of carbonate-rich rocks in the region.

Greisen occurrences are restricted in extent, but common immediately adjacent to all plutons, including the Isles of Scilly Granite (Grant and Smith, 2012; Sullivan *et al.*, 2013; Shail *et al.*, 2014). Greisen wall rock alteration is characterised by the development of secondary mica around sheeted veins and in stockworks. It occurs in the granite (endogranite) and the surrounding host rocks (exogranite). Endogranitic greisens occur at St. Michaels Mount (Floyd *et al.*, 1993), Cligga Head (Hall 1971; Jackson and Moore 1977), and Hemerdon (Beer and Scrivener, 1982), while exogranitic greisens occur in the Tregonning and St Austell granites (Dominy *et al.*, 1995). The greisens comprise closely spaced quartz-tourmaline veins up to 0.1 m wide that host wolframite, cassiterite, stannite, arsenopyrite and other sulphides. Fluid inclusions indicate that the greisen-bordered veins were precipitated over a wide range of temperatures (Figure 4). Greisens represent the earliest occurrence of significant fracture controlled magmatic-hydrothermal mineralisation in South West England (Shail *et al.*, 2014). Greisen bordered, sheeted veins and quartz-(feldspar)-wolframite lodes formed within 2–3 Ma of granite emplacement, and overlap with muscovite cooling ages for the host/adjacent pluton (Chen *et al.*, 1993; Chesley *et al.*, 1993).

Pre-granite mineralisation	Main ore minerals				
1) Rifting and passive margin development (early Devonian- Carboniferous) sedimentary-exhalative (SedEx) mineralisation	Haematite	Siderite	Galena	Sphalerite	
2) Variscan convergence and continental collision (late Devonian- Carboniferous) shear zone hosted Au-Sb + base metal mineralisation	Gold	Bournonite	Sphalerite	Chalcopyrite	Tetrahedrite
<b>Granite-related mineralisation</b>					
3) Early post-Variscan extension and magmatism (early Permian)					
a) Magnetite-silicate skarns developed in metabasaltic hosts	Magnetite	Cassiterite			
b) Sulphide-silicate skarns developed in calc-silicate granite hosts	Cassiterite	Arsenopyrite	Pyrite	Chalcopyrite	Pyrrhotite
c) Greisen-bordered sheeted vein complexes	Wolframite	Cassiterite	Chalcopyrite	Sphalerite	Bismuthinite
d) Quartz-tourmaline veins and breccias	Cassiterite	Haematite			
e) Polymetallic sulphide lodes	Cassiterite	Chalcopyrite	Wolframite	Arsenopyrite	Sphalerite
<b>Post-granite mineralisation</b>					
4) Episodic intraplate rifting and inversion (late Permian – Cenozoic)					
a) Crosscourse Pb-Zn ± F, Ba mineralisation	Galena	Sphalerite	Arsenopyrite	Chalcopyrite	

**Table 4.** Summary of mineralisation styles in the South West England (Cornubian) orefield (adapted from Andersen *et al.* 2016).

Polymetallic lodes containing cassiterite and chalcopyrite, and subordinate arsenopyrite, sphalerite, galena and localised wolframite post-date the greisen bordered, sheeted veins. These lodes were historically the main source of tin and copper in the region. The complex structure and mineralogy of these deposits, and their strong spatial association with granite bodies, reflect the protracted magmatic-hydrothermal activity associated with their formation (Scrivener 2006). These polymetallic lodes are generally orientated E-W and developed between 269–259 Ma, although there is a suggestion that this reflects the dating of more than one paragenetic episode (Chen *et al.*, 1993; Clark *et al.*, 1993). These lodes mark the final contribution of magmatic-hydrothermal fluids to mineralisation in South West England (Shail *et al.*, 2014).



**Figure 4.** Overview of the evolution of mineralising fluids in South West England (after Leveridge *et al.*, 1990)

*Post-granite* mineralisation formed by east-west extension during regional extension-driven subsidence in the Permian, which resulted in the formation of north-south-trending fracture systems. Subsequent fracture-controlled ingress of metal-complexing basinal fluids from Permo-Triassic sedimentary successions into the Variscan basement resulted in the stripping of metals from metalliferous source rocks, and the formation of what is known as ‘crosscourse’ mineralisation (Scrivener *et al.*, 1994). This comprises polymetallic veins dominated by lead, zinc and copper, which locally host antimony-bearing minerals. The north-south-trending crosscourse mineralisation postdates the granite related Sn-W-Cu mineralisation by

30–40 Ma (Scrivener *et al.*, 1994). The crosscourse veins were primarily exploited for lead, zinc, silver, fluorite and baryte, typically within Devonian and Carboniferous successions.

In addition to the styles of mineralisation described above, there are a number of less significant types of mineralisation that are not described in this report. These include: syn-granite tourmaline-tin veins (Scrivener 1982; Bromley 1989); tourmaline breccias (London *et al.*, 1995; Müller and Halls 2005); post-granite, low temperature manganese and iron replacement deposits; and gold-carbonate veins (Jackson *et al.*, 1989). Following granite emplacement, descending meteoric water resulted in alteration of feldspar, leading to high levels of kaolinisation in the St Austell and Dartmoor granites. This has not been discussed in this report as it is not metallic mineralisation. However, the following references provide a good overview of this late-stage alteration: Sheppard (1977), Bray and Spooner (1983) and Bristow and Exley (1994).

### 5.3 Summary

The south-west of England is a historically important mining region and has produced a significant range and volume of metals. However, the region is best known for its tin and copper production. Mineralisation in South West England can be categorised into four broad styles that have been related to the timing of granite emplacement (i.e. pre-granite, granite-related, and post-granite). The most significant mineralisation in South West England from an economic perspective is related to magmatic-hydrothermal activity associated with granite emplacement. Importantly a significant, and growing, body of research and data exists on mineralisation in South West England.

### 5.4 How South West England can positively contribute to the aims of CHPM2030:

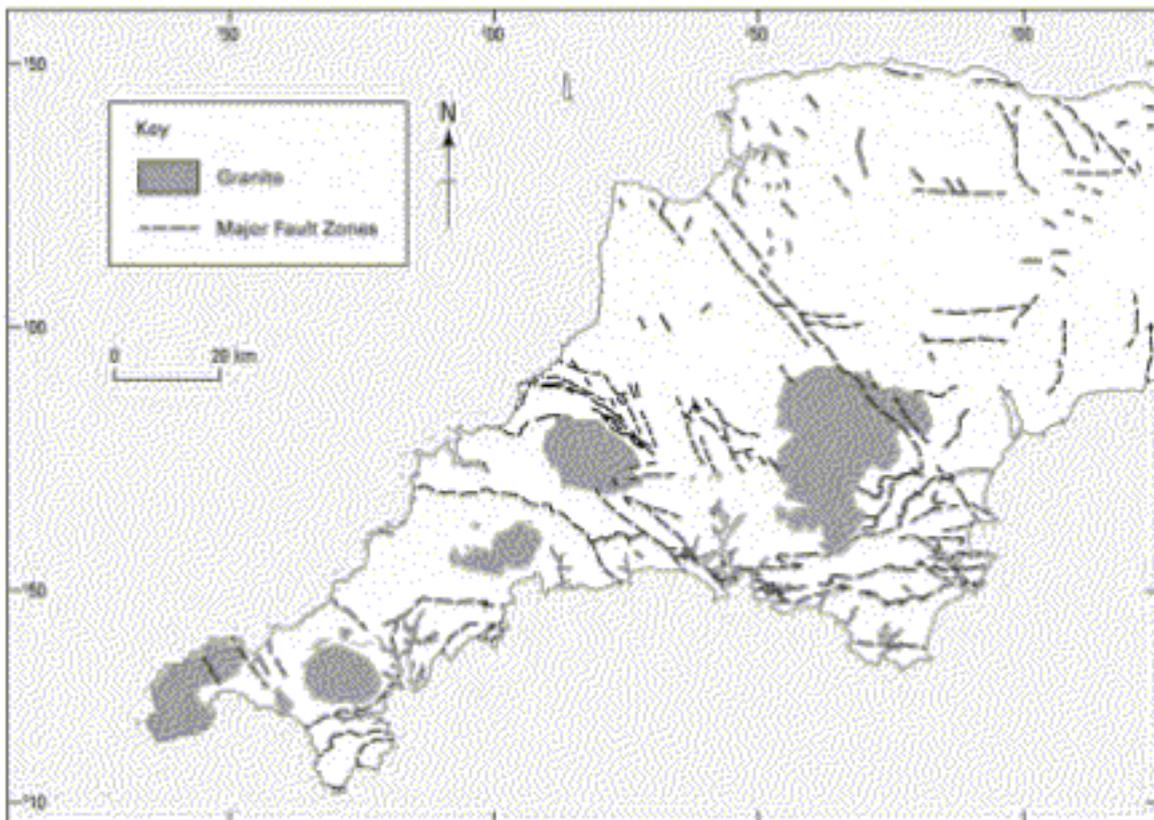
- A large amount of data (e.g. geochronology, fluid composition, mineralogy, geochemistry, etc.) has been generated from ore deposit research in South West England.
- A good understanding is developing of how magmatism, fluids and large-scale structures have interacted to produce economic mineralisation. This data and knowledge has implications for engineered geothermal systems.

### 5.5 Limitations in our current understanding of the mineralisation in South West England:

- There is significant uncertainty about the form and scale of mineralisation below 1,000 m.
- The distribution of data coverage is generally skewed towards areas where economic mineralisation has been exploited or commercial mineral exploration has occurred.

## 6 Structure and stress-field measurements

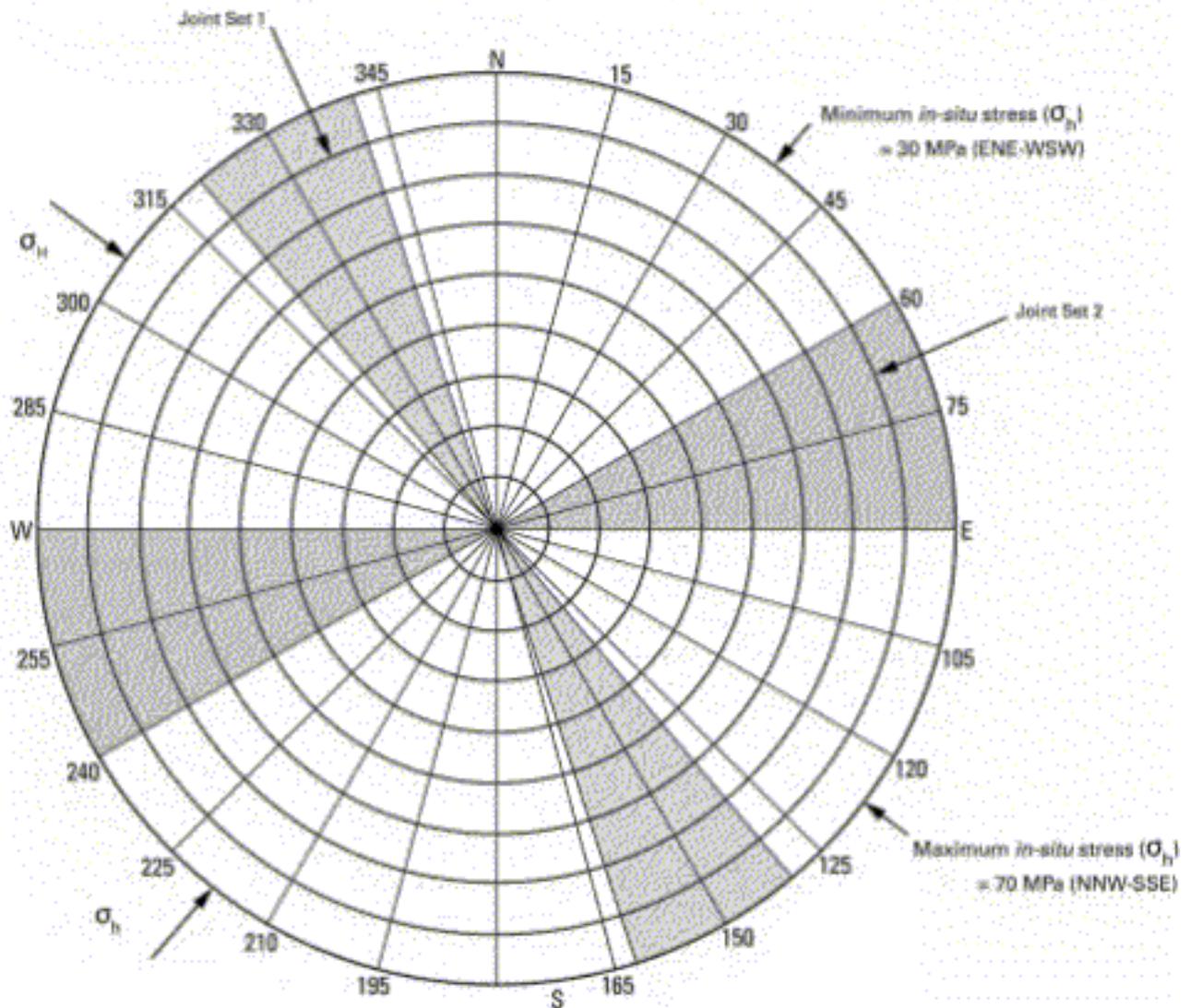
South West England is a structurally complex region whose geological past has been dominated by Variscan tectonics. British Geological Survey mapping, academic research and seismic surveys have led to the identification of three main deformational phases associated with Variscan orogenesis. Two phases are related to crustal shortening ( $D_1$  and  $D_2$ ) whilst the third ( $D_3$ ) is associated with crustal extension during orogenic collapse (Alexander and Shail, 1996; Leveridge *et al.*, 2002). The  $D_1$  deformation event (c. 385 Ma) is characterised by: (1) large-scale (10s km), NW-SE-trending strike-slip faults; (2) a NNW-trending mineral lineation; and (3) E-W-trending folds. Structures associated with the second deformation event ( $D_2$ ) are similar to those formed during  $D_1$ , but  $D_2$  structures are generally more steeply dipping. The  $D_3$  event (c. 305–300 Ma) occurred in response to orogenic collapse and associated crustal extension. It resulted in the development of steep to gently inclined WNW-ESE-trending extensional faults (Alexander and Shail, 1996; Leveridge *et al.*, 2002). Regionally extensive NNW-SSE-trending crosscourse structures formed during the Permian in response to a period of crustal extension (Scrivener *et al.*, 1994; Shail and Alexander, 1997).



**Figure 5.** Map of the distribution of major NW-SE-trending faults and granite bodies in South West England (drawn from BGS mapping data)

In South West England both granite and the killas have inherently poor permeability (Heath *et al.*, 1985). Accordingly, fluid circulation in the region is largely controlled by regional-scale structures (e.g. NW-SE-trending faults) (Figure 5) and fractures (Heath *et al.*, 1985; Bromley *et al.*, 1989; Smedley *et al.*, 1989). Fractures in the granite are primarily the result of magma chamber processes, for example cooling and hydro-fracturing (caused by the movement of magmatic fluids). In contrast fractures in the killas are principally the result of granite emplacement. Local zones of high-fracture density, in both granite and killas,

may also be associated with episodes of late faulting. However, the permeability and connectivity of these fractures, particularly at depth, remains enigmatic (Heath *et al.*, 1985).



**Figure 6.** Principal stress orientation and magnitude in the Carnmenellis granite as determined by *in-situ* hydraulic fracture tests at the Rosemanowes HDR test site (re-drawn from Pine and Batchelor, 1984)

A relatively small number of stress field measurements were made on the Carnmenellis granite, during the 1980s. Both hydraulic fracture tests and overcoring tests were conducted at the Rosemanowes HDR test site at depths of 0–2,000 m and 800 m, respectively. All of the tests were successful in achieving ‘breakdowns’ (i.e. the point at which the fluid pressure is high enough to fracture the rock), in only one of the tests was the hydraulic fracture fully characterised using microseismic monitoring. A series of overcoring tests were also conducted in the South Crofty mine (on the edge of the Carnmenellis granite) at a maximum depth of 790 m. A similar, but unrelated, set of stress field tests (i.e. hydraulic fracturing and overcoring) were carried out at Carwynnen quarry, also on the Carnmenellis granite. Although the hydraulic fracture tests and overcoring were conducted at much shallower levels, 700 m and 34 m, respectively the two studies confirmed the presence of two joint sets in the Carnmenellis granite: one trending NNW-SSE-trending and the other ENE-WSW. The results from both studies show that the *in-situ* stress orientation is about 30° off parallel from

that of the natural joint sets observed in the granite. The studies also demonstrated that maximum *in-situ* stress ( $\sigma_H$ ) is approximately 70 MPa in the NNW-SSE direction, whilst the minimum *in-situ* stress ( $\sigma_h$ ) is about 30 MPa in the ENE-WSW direction (Figure 6). It was found that stress magnitude and orientation at depth are relatively consistent across the Carnmenellis granite, and are fairly consistent with measurements from the rest of the United Kingdom. Importantly it was found that shearing along these natural joints was more likely than dilation, unless very high injection pressures were used (Pine and Batchelor, 1984; Evans, 1987; Cooling *et al.*, 1988; Haimson *et al.* 1989; Turnbridge *et al.*, 1989).

## 6.1 Summary

The south-west of England is a structurally complex region whose geological past has been dominated by Variscan tectonics, which resulted in at least three episodes of deformation. The permeability of rocks (i.e. granites and metasedimentary rocks) in South West England is inherently very low, and as such faults and fractures are locally and regionally important in terms of fluid flow. In particular the presence of large-scale, NNW-SSE-trending crosscourse structures are an important consideration for the design of any EGS system in South West England. However, the permeability and connectivity of these features, particularly at depth, remains enigmatic. Assessment of the stress field in South West England shows it is comparable to other parts of the UK. Two joint sets occur in the Carnmenellis granite and analysis has determined the relative *in-situ* stress orientation and the maximum and minimum *in-situ* stress values.

## 6.2 How South West England can positively contribute to the aims of the aims of CHPM2030:

- *In-situ* stress measurements have been made at depth (up to 2,000 m) in South West England.
- Relative to many other onshore parts of the UK the stress field in South West England is fairly well constrained.
- Consistency in the approach used for making *in-situ* stress field measurements in South West England means the results of different survey are directly comparable.

## 6.3 Limitations in our current understanding of the stress field in South West England:

- Whilst existing data provide a good indication of the stress field in the upper 2 km of crust in South West England, uncertainty about the type of lithologies which occur at greater depth and their structural characteristics means the validity of extrapolating these measurements to the target depths of an EGS system is a consideration.
- Only a small number of deep (specific ~2,000m) stress measurements are available for South West England. This is a particular issue given that significant heterogeneity in stress orientation and magnitude may exist.

## 7 Deep sub-surface temperatures in South West England

### 7.1 United Kingdom overview

Between 1977 and 1994 the UK government funded an assessment of potential geothermal energy resources. This programme considered three main elements: (1) appraisal of heat flow; (2) potential of hot-brines from deep hyper-saline aquifers (HAS) for direct heat production; and (3) the potential of EGS, which included the HDR Programme. A catalogue of sub-surface temperatures, heat flow estimations, thermal conductivity measurements and geochemical data was compiled by BGS (Burley and Edmunds, 1978). It was subsequently updated by Burley and Gale (1982), Burley *et al.* (1984) and Rollin (1987). The findings of this work were summarised by Downing and Gray (1986a, 1986b), BGS (1988), Parker (1989, 1999) and most recently in Barker *et al.* (2000).

A heat flow map (Figure 7) of the UK was generated and subsequently revised (Downing and Gray, 1986a, b; Lee *et al.*, 1987; Rollin, 1995; Rollin *et al.*, 1995; and Barker *et al.*, 2000). The map shows two areas of enhanced heat flow that are associated with the radiogenic granites of South West England (Cornwall) and the buried granites of northern England. Temperatures at 5 km depth were estimated to be as high as 180–190°C in Cornwall, and up to 130–170°C in northern England, but rarely exceeded 95°C elsewhere. The average geothermal gradient is 26°C km<sup>-1</sup> but locally it can exceed  $\approx 35^\circ\text{C km}^{-1}$  (Busby, 2010). The average UK heat flow is approximately 55 mWm<sup>-2</sup>.

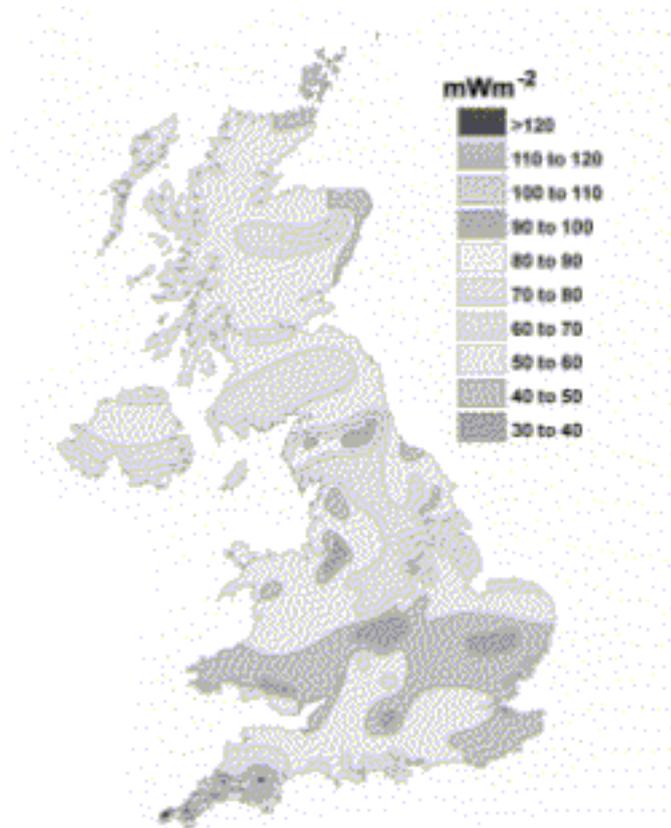
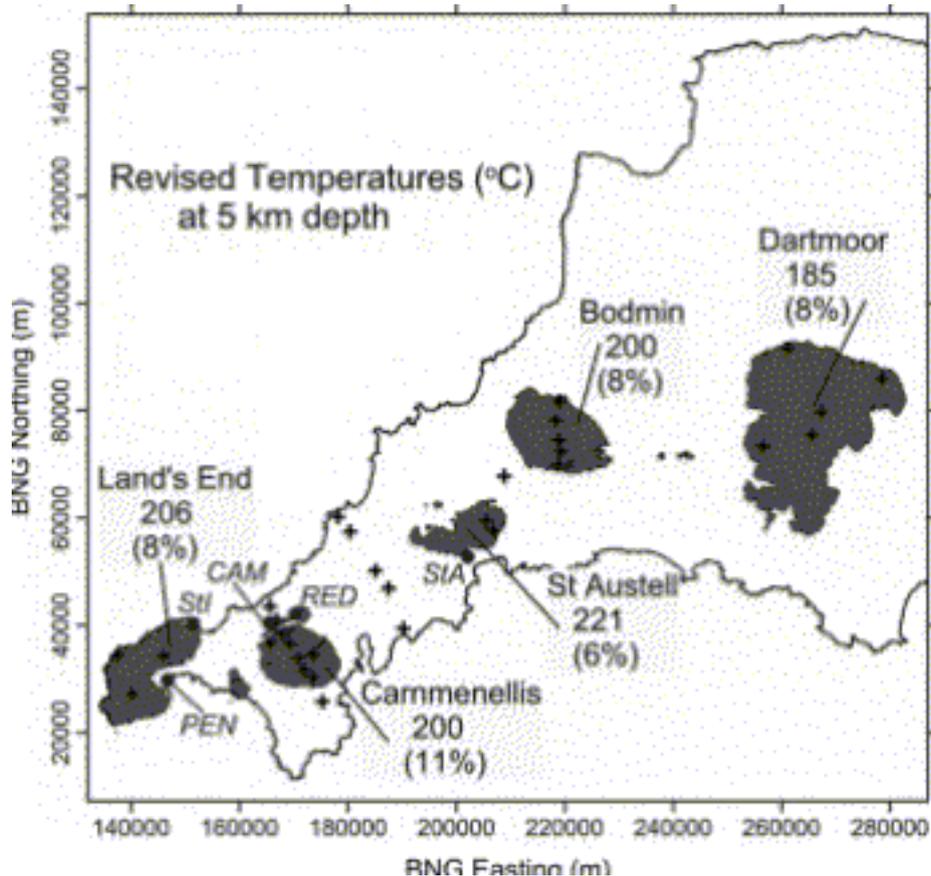


Figure 7. Heat flow map of the UK (after Busby, 2010)

## 7.2 South West England overview



**Figure 8.** Revised estimated granite-related average temperatures (°C) at a depth of 5 km and the percentage increases (in brackets) over previously published estimates. Locations of five towns, are shown in blue; PEN = Penzance; StI = St Ives; CAM = Camborne; RED = Redruth and; StA = St. Austell (after Busby and Beamish, 2016)

Of specific interest to this project are the data for the south-west region of the UK, in particular Cornwall where the geothermal gradient is estimated to be highest. Barker *et al.* (2000) noted that the average heat flow in the Cornubian granites of South West England is  $\approx 120 \text{ mWm}^{-2}$ . Heat production values for the Cornubian granites can be found in Wheildon *et al.* (1981) and Thomas-Betts *et al.* (1989). Beamish and Busby (2016) have re-assessed the quality of these original data sets, and in addition have recalculated the heat flows in accordance with our improved understanding of paleoclimate. This has resulted in revised values that are higher than the original estimates, with the consequence that temperatures at depth are also greater i.e. at 5 km they range from  $\approx 185^\circ\text{C}$  for the Dartmoor granite to  $\approx 220^\circ\text{C}$  for the St Austell granite, (Figure 8) which is an increase of between 6 and 11 per cent. The vast majority of the temperature data comes from shallow wells (about 100 m), with additional data available from some former mines e.g. Geevor mine at about 400 m and South Crofty at about 600 m. As such, these estimated temperatures are based on a model that assumes constant heat production to a depth of 5 km. There are only very limited (historic) temperature data available from depths below 600 m, largely comprising data from the former HDR Project at Rosemanowes Quarry, near Redruth, on the Carnmenellis granite. Here three deep wells were drilled, the deepest being a 2,600 m vertical well, plus several shallow boreholes (300 m). Barker *et al.* (2000) reported that measured temperatures were  $\approx 80^\circ\text{C}$  at 2,100 m depth (in well RH12) and  $\approx 100^\circ\text{C}$  at 2,600 m (in well

RH15). The revised heat flow data from Beamish and Busby (2016) gives slightly higher, estimated, subsurface temperatures of  $\approx 84^{\circ}\text{C}$ , and  $\approx 102^{\circ}\text{C}$  at 2,100 m and 2,600 m, respectively. Unfortunately, UK government funding was withdrawn from the HDR project before it could investigate conditions at 5–6 km, and it closed in 1994. Although its three deep wells are still accessible, it is unclear if any temperature measurements have been obtained since the close of the project. To date no other deep wells have been drilled in the region.

### 7.3 Summary

A significant body of data exists from a British government funded assessment of the potential geothermal energy resources in the UK, over a period spanning three decades. South West England, specifically Cornwall, was estimated to have the highest geothermal gradient in the UK. Temperatures at 5 km depth in the Cornubian granites are estimated to be in the range of  $\approx 185^{\circ}\text{C}$ – $220^{\circ}\text{C}$ . However, it is important to note that these estimates are based on modelled heat flow and heat production. Data from depths of  $>600$  m is very limited, but the measured temperature from one of three deep wells in the Carnmenellis granite was  $\approx 100^{\circ}\text{C}$  at 2,600 m. It is notable that these three well are still accessible.

### 7.4 How South West England can positively contribute to the aims of CHPM2030:

- A significant dataset exists from investigation of the geothermal potential of the UK. However, some of this data may be only available in analogue format.
- Three deep boreholes are still accessible within the Carnmenellis granite, meaning there is potential for new measurements to be taken to validate existing data and new models and estimates.

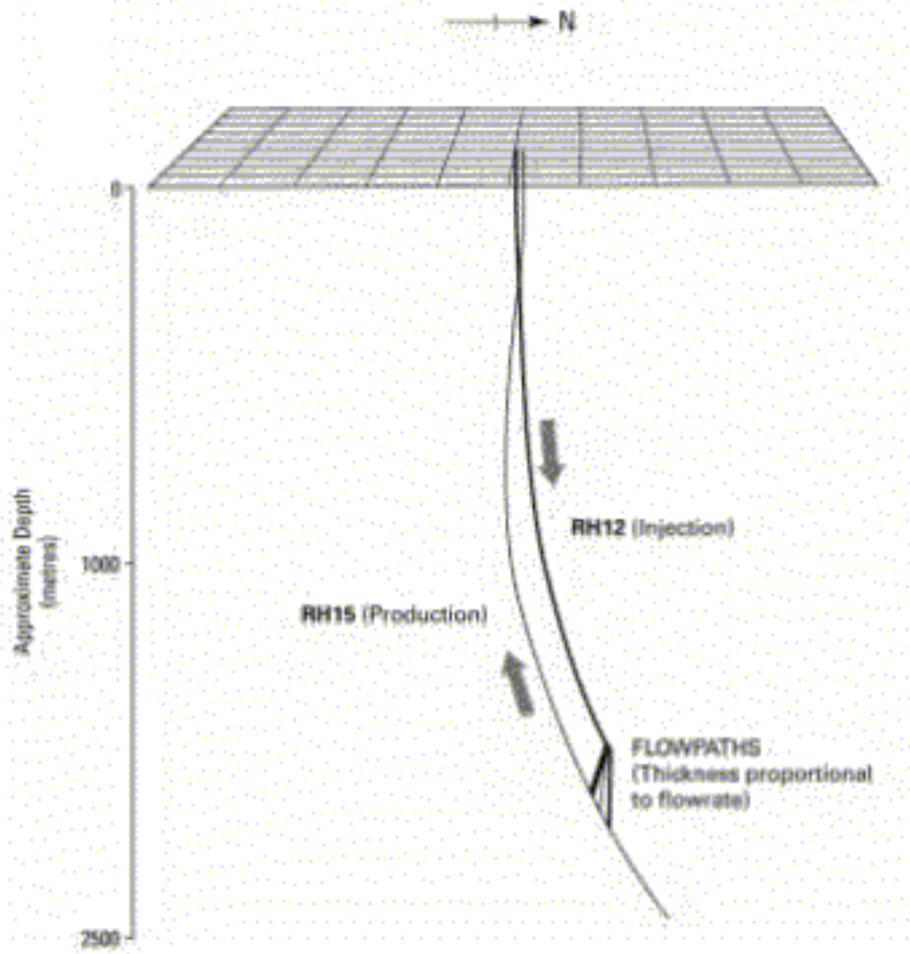
### 7.5 Limitation in our current understanding of deep sub-surface temperatures in South West England:

- Despite a significant body of data there is still significant uncertainty about the temperatures that might exist at the depth of an EGS system as most estimates and models are based on extrapolation of near surface historical data.
- Selected historical data is only available in analogue format.
- The HDR project ceased in 1994, with little associated work taking place during the subsequent 22 years.



1989 the Department of Energy and the Commission of the European Communities funded a detailed geochemical investigation of the HDR site at Rosemanowes. These investigations were undertaken by the BGS, the then NERC Isotope Geology Centre (NIGC), the University of Bath (UoB) and CSM. In 1987 an informal working group (the UK Hot Dry Rock Geochemistry Group) was established to align the geochemical programme more closely with the physical properties and geophysical work being undertaken by CSM at the Rosemanowes test site. The BGS output from this work was series of seven volumes (Edmunds *et al.* 1989; Richards *et al.* 1989; Andrews *et al.* 1989; Smedley *et al.* 1989; Bromley *et al.* 1989; Savage *et al.* 1989 and; Richards *et al.* 1989) that outline the methods and results of geochemical HDR research at the Rosemanowes test site (Edmunds *et al.*, 1989) (Figure 9). Similar outputs (authored by CSM) that describe the physical properties of the HDR system are not held by the BGS.

An overview of the aims and main conclusions of each volume is given below along with a schematic of the HDR system at the Rosemanowes test site (Figure 10). Volumes 1 and 2 (Edmunds *et al.* 1989; Richards *et al.* 1989) are not described here as they are primarily, overview-type documents (Volume 1 provides a synopsis of the other 6 volumes, whilst Volume 2 provides an overview of geochemical results collected as part of the HDR programme). Full details of methods used and results obtained are given in each of the volumes.



**Figure 10.** A schematic diagram showing the configuration of the 2 and 2.5 km test wells at the Rosemanowes HDR test site (re-drawn from Edmunds *et al.*, 1989)

## 8.1 Volume 3: The use of natural radioelement and radiogenic noble gas dissolution for modelling the surface area and fracture width of a Hot Dry Rock system (Andrews *et al.* 1989)

### *Scope of the report*

The movement of natural radioelements (e.g.  $^{226}\text{Ra}$ ) and radiogenic noble gases (e.g.  $^{222}\text{Rn}$ ) in the HDR system was investigated to: (1) characterise changes in reservoir surface area; (2) develop a routine monitoring method for determining  $^{222}\text{Rn}$  in the HDR return fluids; (3) determine the effect of surface mineralisation and physical conditions on  $^{222}\text{Rn}$  flux, and hence upon derived reservoir parameters; (4) estimate the effect of fracture width variation on the radon model; and (5) assess geochemical changes in radioelement chemistry induced by HDR circulation.

### *Conclusions*

- Reservoir surface area showed a general increase as flow tests progressed.
- Tracer transit times of up to 400 hours were observed within fractures.
- Mineralised surfaces, particularly those hosting uranium-rich minerals, dramatically increase the  $^{222}\text{Rn}$  flux of the system.
- Uranium mobilisation occurs in the system in response to fluid circulation.

## 8.2 Volume 4: Fluid circulation in the Carnmenellis granite: hydrogeological, hydrogeochemical, and palaeofluid evidence (Smedley *et al.* 1989)

### *Scope of the report*

Investigation of the hydrogeology and hydrogeochemistry of the Carnmenellis granite helped to explain important processes, such as: (1) granite-water interaction; (2) fluid-flow in granite; and (3) solution-precipitation reactions. Understanding natural fluid flow can be useful to HDR development as it provides an analogue to artificial short-term circulation in the HDR reservoir.

### *Conclusions*

- Groundwater flow in both granite and killas is dominated by fracture permeability; primary permeability in both rock types is low. In particular it is the north-south-trending crosscourse structures that are the most important water-conducting fractures.
- Shallow groundwater compositions show a strong affinity with the local geology and soils. In many cases the element concentrations are very lithology-specific, for example Cl,  $\text{HCO}_3$ , pH, Na, Ca, Mg levels are highest over the killas, whilst Al, Ba and Rb levels are higher over the granite.
- Saline thermal waters discharging in deep mines (depths down to 820 m) are effectively dilute palaeobrine (formed by long-term water-rock interaction) that have mixed with circulating local meteoric waters.

## 8.3 Volume 5: Mineralogy and geochemistry of the Carnmenellis granite (Bromley *et al.* 1989)

### *Aims of the report*

In order to fully understand the geological constraints on HDR reservoir development the geology of the region is considered in detail. In particular the following areas of enquiry are of interest: (1) the spatial variation in the petrological and geochemical characteristics of the granites ; (2) the spatial variation in the nature of the fracture system ,and the character of fracture mineralogy and adjacent wall-rock alteration; (3)

the mechanisms and products of natural fluid-rock interaction under conditions similar to those pertaining in an artificial reservoir, and which might provide useful analogues for reservoir behaviour; and (4) the prediction of geological conditions at depths of 5–7 km in regions where commercial reservoirs may be developed.

### Conclusions

- Rock at depth is likely to be an inhomogeneous mixture of vuggy, pegmatitic granite and magmatic residues (i.e. restite). Thus water-rock interaction would be significantly different from that predicted by experiments on samples of ‘average’ Cornubian granite.
- The ability to drill an inhomogeneous mixture of granite and restite is likely to be very different from that of standard granite alone.
- Localised zones of argillic alteration, associated with crosscourse structures at depth, may hamper drilling operations.
- North-south-trending crosscourse structures are likely to extend to significant depths and as such represent important zones of increased permeability. However, they may also lead to extensive fluid loss from the HDR system.

## 8.4 Volume 6: Experimental investigation of granite-water interaction (Savage *et al.* 1989)

### Scope of the report

Investigation of chemical reactions that take place between circulating fluids and reservoir rock in a HDR system is important because: (1) it provides an indication of the evolution of the physical characteristics of a reservoir under development (e.g. temperature), and (2) it provides information about the potential lifetime of a reservoir undergoing commercial operation. Laboratory experiments were undertaken to evaluate the magnitude and rate of water-rock reactions, including: (1) the surface-area dependant release rate of a variety of chemical component from the Carnmenellis granite under likely *in-situ* conditions at EGS depths; and (2) the investigation of the chemical reaction of Carnmenellis granite with possible circulation fluids.

### Conclusions

- The concentration (by weight) of elements in the output fluid from laboratory experiments was as follows (from highest to lowest):  $\text{SiO}_2 > \text{Ca} > \text{Na} > \text{K} > \text{Fe} > \text{Mn} > \text{Rb} > \text{Li} > \text{Cs} > \text{Sr}$ .
- The relative molar release rates of the elements (from highest to lowest) was:  $\text{SiO}_2 > \text{Na} > \text{Ca} > \text{K} > \text{Fe} > \text{Mn} > \text{Li} > \text{Rb} > \text{Sr} > \text{Cs}$ .
- Changes in pH were only found to affect Al (increased with increasing pH),  $\text{SiO}_2$  (increased with increasing pH) and Fe (decreased with increasing pH).
- Use of dilute surface water as an EGS ‘top-up’ fluid was superior to using seawater, the latter causing potential problematical precipitation of hydrated magnesium sulphate phases.
- Bulk granite dissolution rates vary significantly from  $6 \times 10^{-10} \text{ g m}^{-2} \text{ s}^{-1}$  (expressed as  $\text{SiO}_2$  release) at  $60^\circ\text{C}$  to  $5 \times 10^{-7} \text{ g m}^{-2} \text{ s}^{-1}$  (expressed as Ca release) at  $100^\circ\text{C}$ .
- Individual mineral dissolution rates also vary significantly. Experiments at  $80^\circ\text{C}$  have generated the following estimated rates of dissolution:  $2 \times 10^{-11} - 8 \times 10^{-10} \text{ mol m}^{-2} \text{ s}^{-1}$  (biotite);  $4 \times 10^{-11} - 2 \times 10^{-10} \text{ mol m}^{-2} \text{ s}^{-1}$  (oligoclase);  $2 \times 10^{-10} - 4 \times 10^{-10} \text{ mol m}^{-2} \text{ s}^{-1}$  (labradorite) and;  $1 \times 10^{-15} - 2 \times 10^{-14} \text{ mol m}^{-2} \text{ s}^{-1}$  (tourmaline).

## 8.5 Volume 7: Geochemical prognosis for a Hot Dry Rock system in South West England (Richards *et al.* 1989)

### *Aims of the report*

The geochemical aspects of the design and operation of a commercial HDR geothermal system in granite, in South West England are reviewed and modelled in order to predict: (1) the composition of the circulation fluid; (2) the potential for chemical problems associated with the wells and surface plant (including effluents); (3) the rates of water-rock reactions in the HDR reservoir, and how this might affect hydraulic performance; and (4) the potential use of geochemistry in characterising the performance of the HDR reservoir during and after its creation.

### *Conclusions*

- The most appropriate circulation fluid is predicted to be a mildly-saline, neutral to mildly-alkaline local surface water, with low to moderate total sulphur (20–150 ppm SO<sub>4</sub>) and low to moderate total sulphide (5–10 ppm H<sub>2</sub>S).
- Silica and/or carbonate-based scaling are likely to be the biggest issue for wells and surface plant.
- Predicted arsenic (c. 1 ppm), boron (c. 1 ppm), fluoride (c. 10–20 ppm) and silica (c. 300 ppm) concentrations in the circulation fluid mean they could not be discharged straight into the environment without prior treatment.
- Mineral dissolution is likely to result in widening of fractures (by up to 1 mm over a 25-year lifetime) and thus will have an impact on reservoir hydraulics.
- However, the precipitation of secondary minerals (e.g. zeolites, clays and calcite) as a result of granite-water reactions would also have a potentially negative impact on porosity and reservoir hydraulics.

## 8.6 Summary

The UK HDR geochemistry group was a collaboration between BGS and CSM; it sought to use geochemistry to characterise the behaviour and performance of an engineered geothermal system (EGS). A number of important conclusions were drawn from this work, including: fluid residence time, mineral dissolution rates, surface area modelling, and potential problems related to chemistry (e.g. scaling of surface plant and ‘clogging’ of the reservoir by the development of secondary minerals).

## 8.7 How South West England can positively contribute to the aims of CHPM2030:

- Data associated with the HDR programme is specific to engineered geothermal systems.
- Samples, data and observations gathered as part of the HDR project are derived from boreholes down to about 2.6 km deep. This is currently much deeper than similar boreholes in the UK, and thus provides a useful insight into the deep geothermal environment in South West England.

## 8.8 Limitation in our current understanding of South West England:

- Data and interpretation are specific to the Carnmenellis granite.
- Only a small amount of core material from the original HDR programme is available.
- Significant uncertainty remains in terms of actual conditions that might be encountered in a deep (c. 4–6 km) commercial HDR system (i.e. many of the conclusions are based on predictive models).
- Much of the data are only available in analogue format.

## 9 Data holdings at BGS

The BGS is the world's longest established national geological survey, and is the UK's premier provider of objective and authoritative geoscientific data. It has been gathering geoscience data and information about the subsurface in the UK and other countries for more than 180 years. It is a data-rich organisation with more than 500 datasets in its care, including environmental monitoring data, digital databases, physical collections (e.g. borehole core, rocks and minerals), records and archives. Importantly, a great many of these datasets are openly available, many of which provide complete, seamless UK coverage at a number of scales. Certain other datasets may be subject to confidentiality clauses and/or licencing fees. Information about how to access these datasets can be found here: <http://www.bgs.ac.uk/data/home.html?src=topNav>.

These national datasets are available to the CHPM2030 project, and can provide a very useful starting point to assess CHPM potential in South West England. Many of the datasets cover much of the UK, whereas others are specific to South West England (e.g. geophysical data conducted as part of the TELLUS project (<http://www.tellusgb.ac.uk/>)). Most of the data stored relate to surface exposures or the near-surface environment. Although, the datasets do contain much information about a large number of boreholes and mines, most does not extend below 100 m, and there is limited data below 1,000 m. This places significant constraints on predictions when extrapolating the data to EGS depths (i.e. 4–6 km). The datasets are also of differing ages and levels of detail - reflecting changing national priorities over the past decades. In terms of geothermal development, much of the data are derived from a national programme of work in the 1980s and early 1990s. As a consequence, the data reflect monitoring technology and ideas at that time, and much of the data are in analogue format.

### 9.1 Summary

The BGS maintains a large number of datasets (over 500) that include environmental monitoring data, digital databases and physical collections (i.e. borehole core and rock samples). Many of the datasets offer complete, seamless coverage of the UK at a variety of scales. A good number of these datasets are also freely and openly available.

### 9.2 How South West England can positively contribute to the aims of CHPM2030:

- The BGS holds a large amount of information about the geological, geophysical and geochemical properties of the UK.
- Data coverage for the south-west region is very good.

### 9.3 Limitations in our current understanding of South West England:

- The majority of the data sets only relate to the shallow sub-surface 0–1,000 m).
- Some datasets are incomplete (e.g. rock stress data are restricted in spatial coverage).
- Some datasets are based on old data that have been digitised.

Datasets	Description	Scale	Coverage	Access cost	Link
<b>Hydrogeology</b>					
Depth to groundwater	Spatial model showing depth (m) to the phreatic water table.	1:50,000	Great Britain	15p per km <sup>2</sup>	<a href="http://www.bgs.ac.uk/products/hydrogeology/depthToGroundwater.html">http://www.bgs.ac.uk/products/hydrogeology/depthToGroundwater.html</a>
Hydrogeological maps	Spatial model of aquifer potential based on geological formations.	1:625,000	UK	Free	<a href="http://www.bgs.ac.uk/products/hydrogeology/maps.html">http://www.bgs.ac.uk/products/hydrogeology/maps.html</a>
Permeability	Spatial model showing flow regimes (e.g. fracture flow) and relative flow rates.	1:50,000	Great Britain	10p per km <sup>2</sup>	<a href="http://www.bgs.ac.uk/products/hydrogeology/permeability.html">http://www.bgs.ac.uk/products/hydrogeology/permeability.html</a>
<b>Geophysics and remote sensing</b>					
LiDAR	High-resolution LiDAR digital terrain model (DTM) and digital surface model (DSM).	Resolution information on website	SW England	Free	<a href="http://www.tellusgb.ac.uk/data/home.html">http://www.tellusgb.ac.uk/data/home.html</a>
Airborne magnetics	Airborne survey data showing variation in the magnetic field.	Resolution information on website	SW England	Free	<a href="http://www.tellusgb.ac.uk/data/airborneGeophysicalSurvey.html">http://www.tellusgb.ac.uk/data/airborneGeophysicalSurvey.html</a>
Airborne radiometrics	Airborne survey data for the radioactive isotopes Th, U, and K.	Resolution information on website	SW England	Free	<a href="http://www.tellusgb.ac.uk/data/airborneGeophysicalSurvey.html">http://www.tellusgb.ac.uk/data/airborneGeophysicalSurvey.html</a>
Land gravity	A database of over 165,000 gravity observations.	N.A.	Great Britain	Free	<a href="http://www.bgs.ac.uk/products/geophysics/landGravity.html">http://www.bgs.ac.uk/products/geophysics/landGravity.html</a>
Geophysical borehole logs	An archive of geophysical downhole log data.	N.A.	Various	£30 per hole	<a href="http://www.bgs.ac.uk/products/geophysics/boreholeLogs.html">http://www.bgs.ac.uk/products/geophysics/boreholeLogs.html</a>

**Table 5.** Summary of datasets pertinent to CHPM2030 held by the BGS (continued on next page)

Datasets	Description	Scale	Coverage	Access cost	Link
<b>Geology</b>					
UK3D	A 3D bedrock model of the UK at 1:625,000 scale.	1:625,000	UK	Free	<a href="http://www.bgs.ac.uk/research/ukgeology/nationalGeologicalModel/gb3d.html">http://www.bgs.ac.uk/research/ukgeology/nationalGeologicalModel/gb3d.html</a>
Geological maps	2D lithological and structural mapping (bedrock and superficial).	*1:50,000	UK	**20p per km <sup>2</sup>	<a href="http://www.bgs.ac.uk/products/digitalmaps/DiGMapGB_50.html">http://www.bgs.ac.uk/products/digitalmaps/DiGMapGB_50.html</a>
<b>Boreholes</b>					
Borehole database	A database of over one million records of boreholes, shafts and wells.	N.A.	Great Britain	Free	<a href="http://www.bgs.ac.uk/products/onshore/SOBI.html">http://www.bgs.ac.uk/products/onshore/SOBI.html</a>
Borehole scans	Online access to more than one million borehole logs.	N.A.	Great Britain	Free	<a href="http://www.bgs.ac.uk/data/boreholescans/home.html">http://www.bgs.ac.uk/data/boreholescans/home.html</a>
<b>Physical properties</b>					
Rock stress	Online access to almost 1,000 rock stress measurements.	N.A.	Great Britain	Free	<a href="http://mapapps.bgs.ac.uk/rockstress/home.html">http://mapapps.bgs.ac.uk/rockstress/home.html</a>
Discontinuities	Spatial model of discontinuities in bedrock (e.g. fractures and faults).	1:50 000	Great Britain	**30p per km <sup>2</sup>	<a href="http://www.bgs.ac.uk/products/groundConditions/discontinuities.html">http://www.bgs.ac.uk/products/groundConditions/discontinuities.html</a>
<b>Geochemistry</b>					
Gbase south-west	Geochemical baseline survey of soils and stream sediments.	N.A.	SW England	Free	<a href="http://www.bgs.ac.uk/products/geochemistry/GbaseSWproducts.html">http://www.bgs.ac.uk/products/geochemistry/GbaseSWproducts.html</a>
<b>Minerals</b>					
Britpits	A database of over 180,000 records of active and inactive mine and quarry workings.	N.A.	UK	***£50 per region	<a href="http://www.bgs.ac.uk/products/minerals/BRITPITS.html">http://www.bgs.ac.uk/products/minerals/BRITPITS.html</a>

**Footnotes:**

\* Other scales available (e.g. 1:25,000; 1:10,000; 1:625,000).

\*\* Commercial rate. Free to use via the BGS web-based viewer: <http://mapapps.bgs.ac.uk/geologyofbritain/home.html>

\*\*\* The full dataset comprises fifteen regions.

## 10 Conclusion

This report describes the breadth of information available for South West England, which is relevant to the development of enhanced geothermal systems, except data held by CSM relating to physical properties testing and geophysics at the HDR test site. South West England is a geologically complex region with a long and significant history of metal mining, producing primarily tin and copper. The requirement to better understand the economic mineral potential of the region has resulted in almost 200 years' worth of applied and academic research. These studies have generated a huge volume of data that includes: geological mapping, geophysical and geochemical surveys, and numerous reports and peer-reviewed publications. Another potentially important resource in South West England is geothermal energy. Previous geothermal research in the region peaked between the 1970s and 1990s, and focussed largely on the high heat flows associated with the Cornubian granites. In 1984 this programme of work was undertaken by the BGS to assess the UK's geothermal potential. Over the same time period (1977–1984) the Camborne School of Mines (CSM) was assessing the feasibility of creating HDR geothermal systems at a test site at the Rosemanowes quarry, on the Carnmenellis granite, in Cornwall.

In summary a huge amount is known about the geology, mineralisation, fluid history and geothermal potential of South West England. A significant body of data underpins this knowledge base, the majority of which is freely, or openly available. However, there are limitations. For example, much of this data, with the exception of the HDR datasets, only relates to the upper 1,000 m of the crust. This has significant implications regarding the accuracy of modelled conditions in an enhanced geothermal system (EGS) at greater depths. There are also 'gaps' in the data (e.g. very limited deep-geophysical data), and some datasets have not been updated since their creation several decades ago.

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## CHPM2030 DELIVERABLE D1.2 APPENDIX 1.2.2

# REPORT ON DATA AVAILABILITY: PORTUGUESE IBERIAN PYRITE BELT

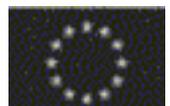
### *Summary:*

This report provides an overview of geoscientific data and information relating south-west Iberian Pyrite Belt, Portugal, with a particular focus on its geology, structure, stress-field characteristics, mineralisation and previous geothermal research in the region.

### *Authors:*

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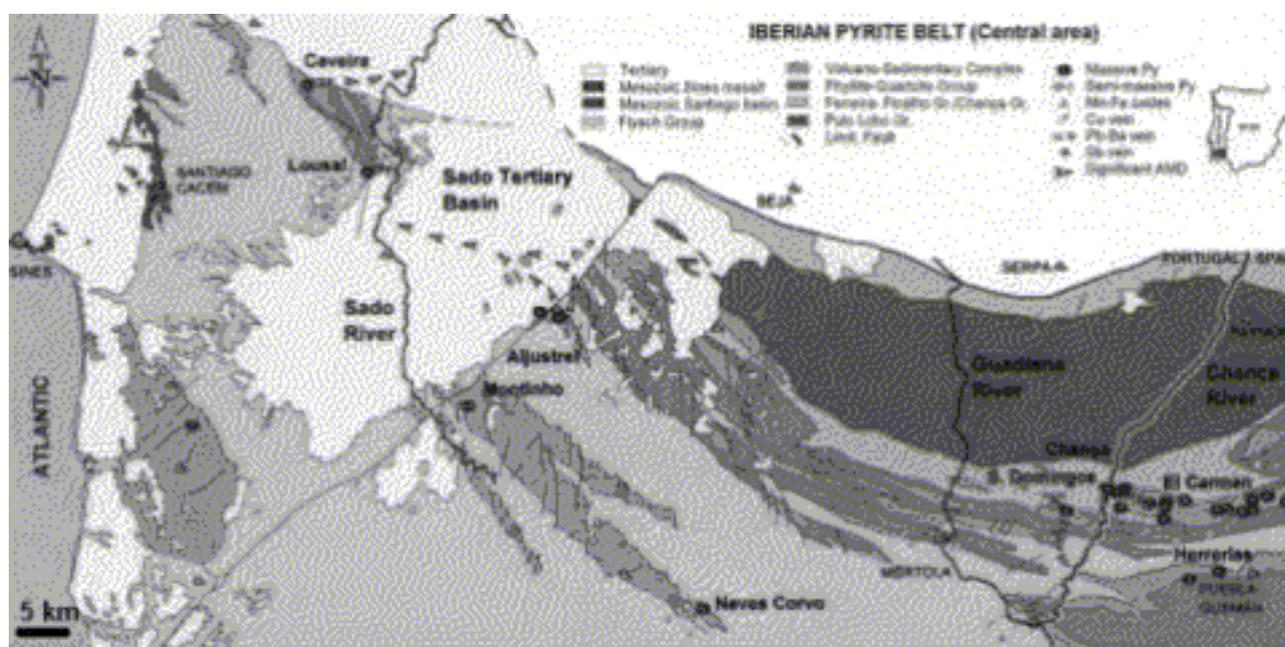
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## 1 Preface

This report was written as part of the CHPM2030 project “Combined Heat, Power and Metal extraction from ultra-deep ore bodies” and studies the ability of the Iberian Pyrite Belt for implementation.

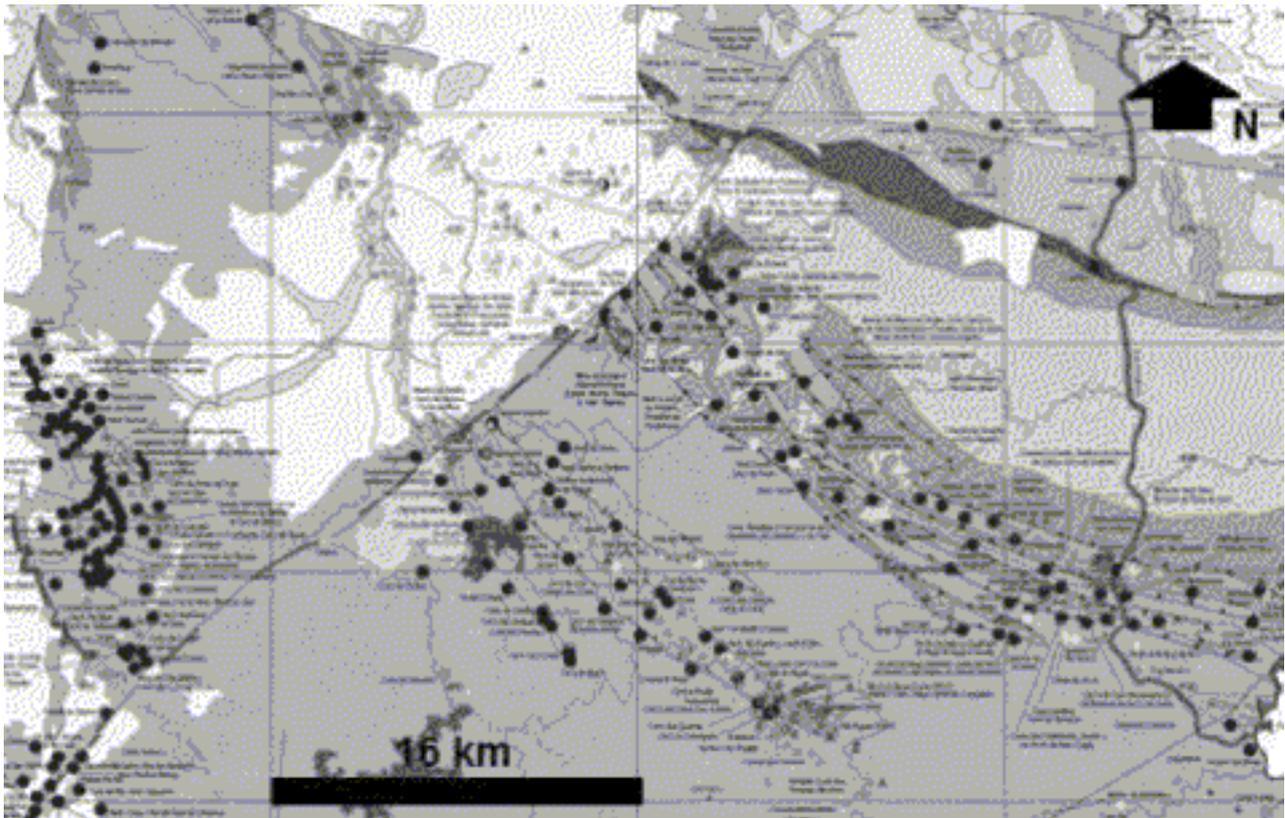
The Iberian Pyrite Belt (IPB) is a Variscan metallogenic province located in the SW of Portugal and Spain that hosts the largest concentration of massive sulphide deposits worldwide (Inverno et al., 2015). It covers about 250 km long and 30–50 km wide (Figure 1) a vast geographical area with particular volcanic and sedimentary sequences of Carboniferous and Devonian ages, identified in the southwest of the Iberian Peninsula (Oliveira et al., 2013). The IPB runs from NW to SE, from Alcácer do Sal (Portugal) to Seville (Spain). Since the 1960’s intense geophysical exploration has been done and discovering new hidden massive sulphide orebodies (like Neves Corvo (Albouy et al., 1981, Relvas et al., 2006, see Figure 1), Las Cruces (Doyle, 1996) and Lagoa Salgada (Oliveira et al., 1998).



**Figure 1.** Location of the central area of the IPB Portuguese sector within the scope of the Iberian Peninsula and main geological groups. Location of the IPB massive sulphide deposits and intense acid mine drainage (Inverno et al., 2015, Abreu et al., 2010). Active mining: Neves Corvo (Somincor-Lundin Mining) and Aljustrel (Almina). Scale (line): 5 km

Due to the large amount of mineral deposits in southern Portugal (Figure 2) and because of the intensive deep mining prospecting, a dense borehole network was created, drilled by mining companies (see example of exploration drill hole distribution in the IPB Portuguese sector in the Figure 3).





**Figure 3.** Central area of the IPB Portuguese sector (ad. Matos and Filipe Eds., LNEG 2013): mineral occurrences – circles: red – massive sulphides, dark purple – Mn, green – Cu, blue – Ba(Pb) and exploration drill holes (triangles). Map grid: 1:25,000 scale maps (16 km x 10 km).

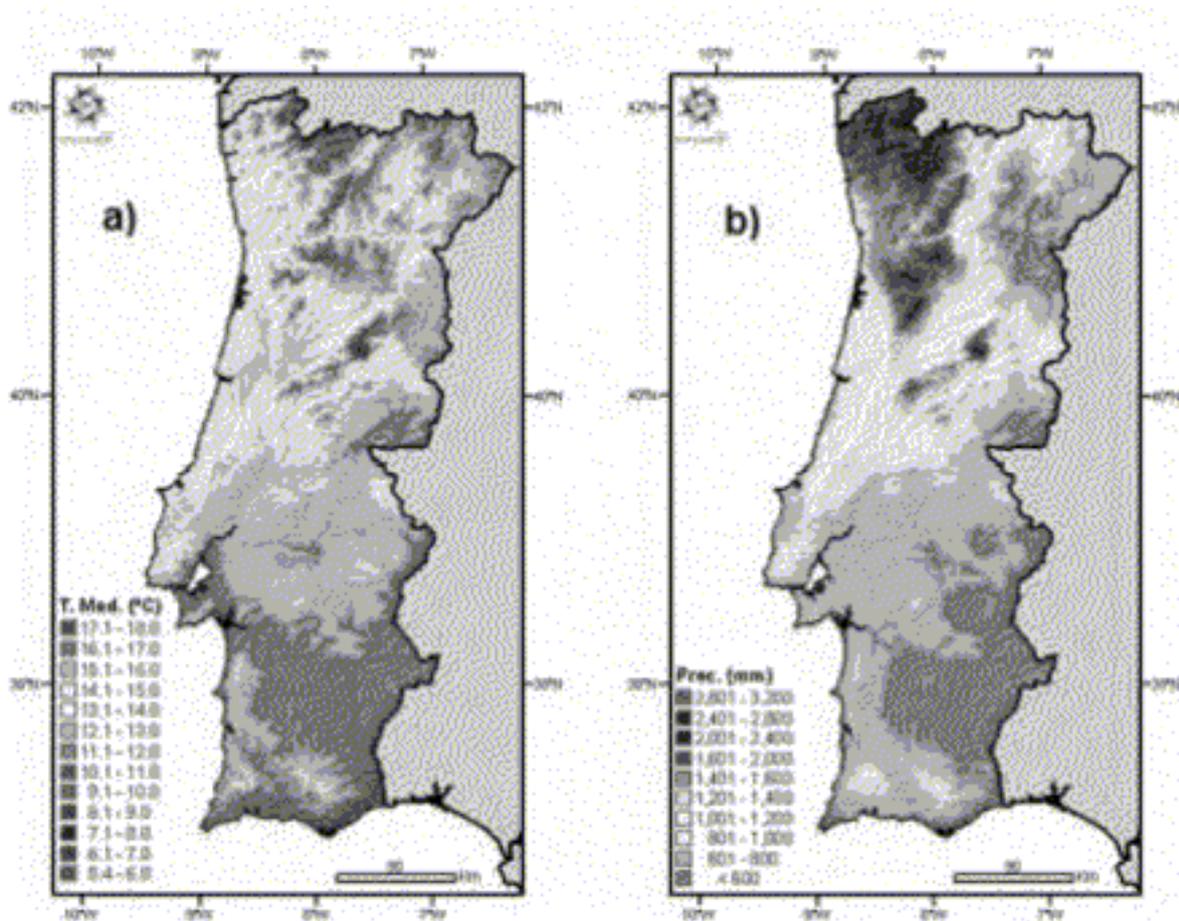
## 2 Country specific issues

### 2.1 Climate

Portugal is mainly characterized by a warm temperate, Mediterranean climate with a distinct wet season in winter. During winter, Portugal experiences a similar temperature pattern to the Spanish coastal towns, i.e. average daytime maximum of about 16 °C. Figure 4 resumes these characteristics (<http://www.ipma.pt>).

### 2.2 Active mining exploration in IPB

The southern part of the country shows excellent logistics for exploration and mining. There is a considerable amount of mineral deposits, as seen in Figure 3. Presently, active mining occur at the Neves Corvo mine, owned by Somincor-Lundin Mining ([www.lundinmining.com](http://www.lundinmining.com)), and at the Aljustrel mine, owned by Almina ([www.almina.pt](http://www.almina.pt)). Both mines produce copper ore concentrates from mined massive and stockwork sulphide ores. In the case of the Neves Corvo mine, zinc and lead concentrates are also produced. The ores are transported by train and by truck to the Setubal harbour located south of Lisbon and exported worldwide. Both mines have a strong contribution to regional and national economy.



**Figure 4.** a) Average annual temperature (°C) and b) Average annual precipitation (mm) (source <http://www.ipma.pt>).

### 3 CHPM2030 Goals in the portuguese IPB sector

#### 3.1 Properties to study (stratigraphic, lithological, structural, mineralogical, chemical)

To understand the rock-mechanical and geochemical properties of the IPB ore bodies special measurements were carried out in exploration drill hole cores, related with different mineralogical, geochemical and mechanical characteristics of the mineralization and related host rocks. Different scenarios were identified considering the presence of sedimentary and volcanic rocks of the IPB Volcano-Sedimentary Complex (VSC) and sedimentary rocks of the Phyllite-quartzite Group (PQG). Considering the IPB geology the following lithological units were considered:

- Mineralization: massive sulphides and stockwork (sulphide vein network);
- Upper VSC sediments - siliceous shales, grey shales, green shales, purple shales, cherts, jaspers and volcanogenic sediments;
- Lower VSC sediments – black pyritic shales, black cherts;
- VSC felsic volcanics (with and without hydrothermal alteration);
- VSC basic volcanics;
- PQG sediments – shales, silts and quartzites, forming the IPB basal siliciclastic basement.

Deep exploration drill holes located in the Neves Corvo region were evaluated, considering deep rock intersections, bellow 1 000 m depth (see drill hole distribution in Figure 2). In the Cotovio sector, located 5 km SE of the Neves Corvo mine, two drill holes were performed by Somincor, bellow 1500 m (see section in Carvalho et al., 2016). Considering the occurrence of these holes and deep seismic performed by LNEG (Inverno et al., 2015; Carvalho et al., 2016) a sampling program was prepared to the Cotovio area. Sulphide mineralization samples were also selected in the Neves Corvo mine.

Considering the presence of structural corridors in the Neves Corvo region, like the Neves thrust, related with Variscan deformation (Inverno et al., 2015), two scenarios were consider related with the rock samples: high deformation stages (e.g. shear zones) and less deformation areas.

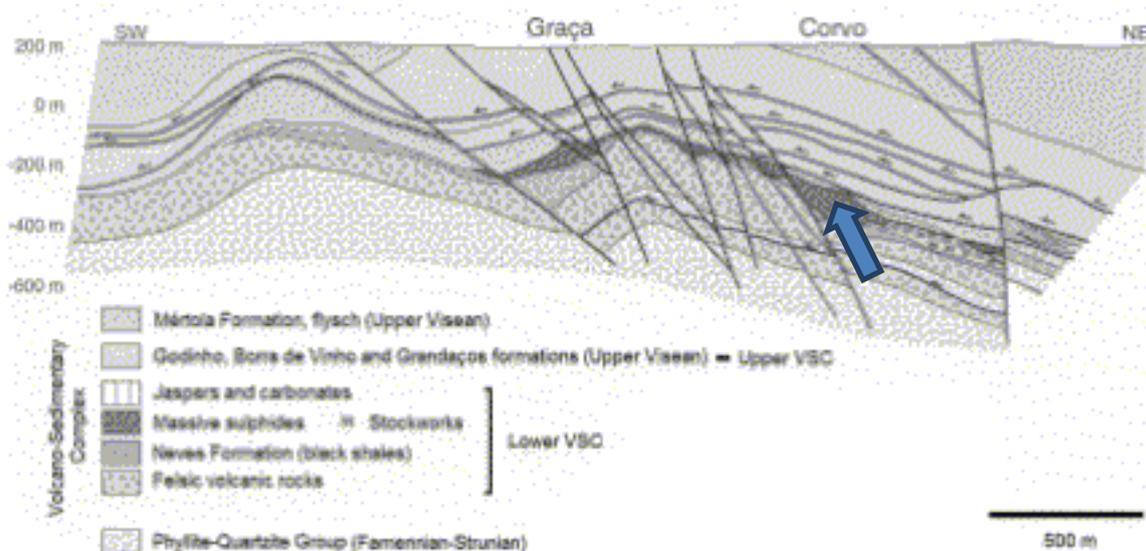
#### 3.2 Working progress considering project goals

LNEG archive samples were considered like massive ore, with high metal content (~7% Zn and >6% Cu ore grade). The collected sample was collected at the lower sector of the Corvo pyrite ore lens (Figure 5), at 610 m depth. This sample can be used as reference to the Neves Corvo study representing high metal grade massive sulphide ore (Figure 6). As non-mineralized example, a LNEG Archive drill-core sample was selected, related with exploration drill hole campaign, performed by the Redfern company in the Porto de Mel sector, located in the IPB north western sector (Sado Cenozoic basin, see Oliveira et al., 1998). These samples will provide preliminary data. The obtained results will be compared with historical data, present in the LNEG exploration database.

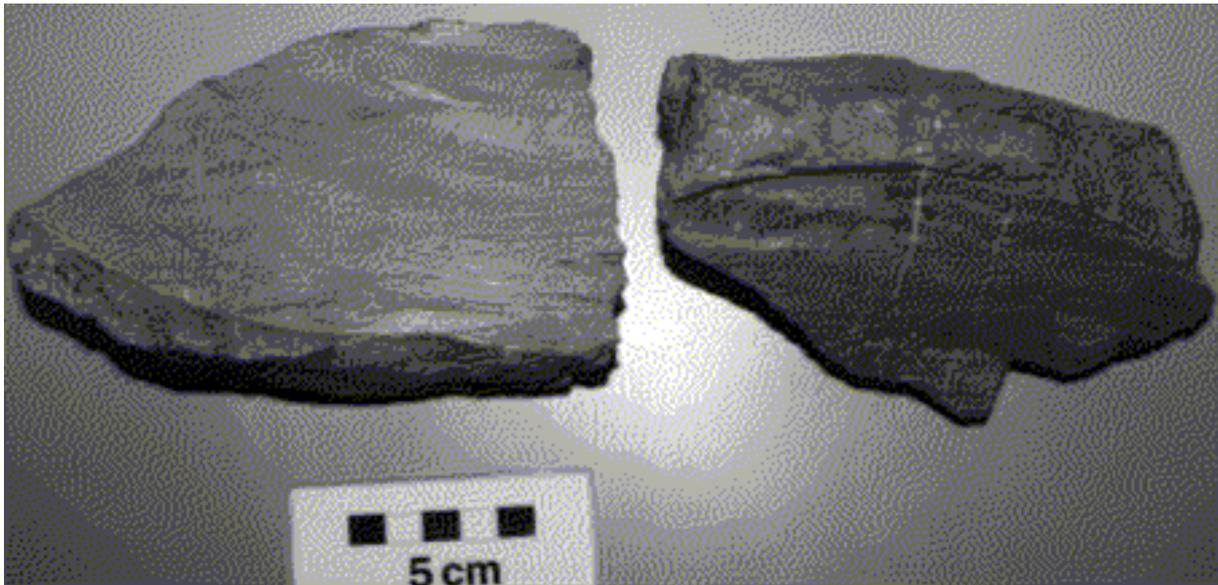
## 4 Previous research and available data

### 4.1 Structural settings inferred from geology and geophysics (incl. drilling)

The IPB is composed of two upper Paleozoic age major lithostratigraphic units, the Phyllite Quartzite Group (PQG), the Volcanic Sedimentary Complex (VSC), which is the focus of the present work (Schermerhorn 1971; Oliveira 1983, Oliveira et al., 2013). Above the VSC the Baixo Alentejo Flysch Group (BAFG) occurs. Associated with the VSC dozens of massive sulphide deposits occur related with felsic volcanic rocks and black shales of lower Carboniferous and upper Devonian ages (Oliveira et al., 2005; Pereira et al., 2008; Matos et al., 2011; Oliveira et al., 2013; Matos et al., 2014). Hydrothermal halos are present associated with the massive and stockwork ores. General syntheses on the IPB include those of Strauss et al. (1977); Routhier et al. (1980); IGME (1982); Barriga (1990); Sáez et al. (1996); Leistel et al. (1998); Carvalho et al. (1999); Junta de Andalucía (1999); Tornos et al., (2000); Tornos (2006); Oliveira et al. (2005, 2006, 2013); Relvas et al. (2006). Other general studies deal with stratigraphy (Oliveira 1990; Pereira et al 2007), volcanism (Munhá 1983; Mitjavila et al. 1997; Thiéblemont et al. 1998), structure and regional metamorphism (e.g., Munhá 1990; Silva et al. 1990; Quesada 1998) or the facies architecture of the volcano-sedimentary complex (Soriano and Martí 1999; Junta de Andalucía 1999; Rosa et al., 2008, 2016). The Baixo Alentejo Flysch Group well exposed in SW Iberia, represents the infill of a foreland basin, which was developed following a compressive Variscan tectonic inversion that occurred during the upper Visean and lasted until the upper Moscovian (Oliveira et al. 1979; Silva et al., 1990; Pereira et al., 2008). The sandy/shale turbidites that filled the foreland basin had their multiple sources in the SW border of the Ossa Morena Zone, in the IPB and in the Avalonia plate (Jorge et al. 2012).



**Figure 5.** Neves Corvo general geological section, adapted from Relvas et al., 2006. Location of the lower sector of the Corvo massive ore lens (blue arrow)



**Figure 6.** Neves Corvo massive sulphide ore, showing primary banded structures and rich layers of chalcopyrite and sphalerite. Sample collected at 610 m depth

The IPB regional structure is conditioned by a SW tectonic vergence. Globally the geological structures present an E-W direction in Spain and close to the Portuguese/Spanish border and a NW-SE direction in the western Portuguese IPB sector. Several complex antiforms are defined, forming VSC-PQG outcropping lineaments (see in the Portuguese sector the 1/200 000 SGP geological maps, Fls. 7 and 8, Oliveira et al., 1988 and 1992, Oliveira et al., 2013, Inverno et al., 2015). These structures are present in depth, under Flysch BAFG sediments and/or Cenozoic age sediments (e.g. Sado Basin, Oliveira et al., 1998). In the northern IPB regions allochthonous structures are dominant. In the southern IPB branch the complexity is lower. Detail geological mapping and information of exploration drill holes permit to define the geometry of the VSC-PQG antiforms. Gravity, magnetic and seismic surveys are useful tools to 3D modelling. As an example see the 3D models defined to the Rio Tinto (Martin-Izard, 2015) and SE Neves Corvo region (Inverno et al., 2015). The exploration goals of these programs is to define the constraints related with the presence of massive ore associated with the VSC volcanism and the presence of stockwork type of ore located both in VSC volcanic and sedimentary units and PQG sedimentary units. Variscan and late Variscan fault systems are also defined, in the first case correlated with dominant compressive faults and in the second case related with strike-slip faults.

#### 4.2 Geometry and composition of ore deposits

The IPB massive sulphides deposits are associated with volcano-sedimentary sequences present in sea floor environment. Genetic models are present in literature (e.g. Barriga et al., 1997; Leistel et al., 1998; Carvalho et al., 1999; Tornos, 2006; Relvas et al., 2006, Rosa et al., 2008, 2016) considering hydrothermal events formed by circulation of sea water in the host rock sequences and later discharge of mineralized fluids. Regional and hydrothermal alteration occur, the late represented by silica and chlorite in the inner zones and silica + sericite in the external zones. A significant number of deposits is directly associated with felsic volcanic rocks formed in the late Devonian (Matos et al., 2011) and early Carboniferous (Barrie et al., 2002; Tornos, 2006), see Neves Corvo section, Fig. 5. The deposits generally present a lenticular shape with up to 2 km of length and thickness usually < 150 m. The stockwork structures are commonly present in the root of the hydrothermal system. Variscan tectonics can change the original geometry by folding and faulting,

including thrust generation, promoting the existence of complex structures. The deposits are formed mainly by massive pyrite. Other minerals occur like chalcopyrite, sphalerite, galena and sulphosalts locally with economic importance. Present near mining exploration projects, like the Lundin Mining Neves Corvo DGEG Exploration Permit Area, are being developed and focused in the research of new metal rich massive and stockwork mineralizations.

### 4.3 Hydraulic properties, deep fluid flow

According with Batista (2003), water pumping tests performed in the Neves Corvo IPB area (See Figure 1) and surroundings, conducted by Bertand et al. (1982) in eight wells with maximum depth of 261 m and drill holes with depths ranging from 100 to 645 m, d concluded that drawdowns to the wells between 0.88 and 21.6 m and to the drill holes between 6 and 43.4 m. Transmissivities have values respectively of between  $9.1 \times 10^{-6}$  and  $1.1 \times 10^{-4}$  to the wells and between  $1.86$  and  $64.6 \times 10^{-6} \text{ m}^2/\text{s}$  to the drill holes.

In the Variscan Massif terrains (north and center of Portugal) the permeability is higher, reaching dozens of meters per second and is associated to fracturing zones. In these fracturing zones, decompression and terrain alteration allow a permeability that averagely ranges from 0.1 and  $2 \times 10^{-6} \text{ m/s}$ . At bigger depths, and away from the fracturing zones, permeability diminishes, and is lower than  $0.01 \times 10^{-6} \text{ m/s}$ .

Some conclusions could be taken from these hydrogeological data:

1. The possibility to find an important aquifer in this compact unit pile with low permeability and with low effective porosity is very low.
2. The deep fractures opened to water circulation are found in the top of the pyrite ore lenses, in the flysch greywackes from the base and not in the interior of the sulphide ore. These greywackes show more permeable crushing zones that, instead, can make groundwater circulation easier.

This last conclusion may be important, if these more permeable zones are near the sub-vertical faults that put the sulphide ore in contact with surface waters. Since the ductile shales are above these graywackes are much less permeable, making groundwater circulation towards the surface possible only in fracture zones. Zones with the contact between surface and mineralized ores are located in the Graça Hill and in the main meander of Ribeira de Oeiras, S of the Neves Corvo Mine.

Through monitoring and surface water control, Fernandez-Rubio y Asociados (1994), the hydrogeological system of Neves-Corvo identified three hydrogeological units:

- Upper Shallow System – This system is considered to be an aquifer or an aquitard, free to semi-confined, relatively heterogenous with permeability decreasing in depth , extends from surface to 100 to 200 meters depth.
- Intermediate system – Considered a semi-confined defined in the limit of the previous aquifer, until the top of the mineralization.
- Deep mining system – Confined aquifer composed by the mineralized deposits and overimposed rocks.

### 4.4 Fluid composition, brines, meteoric waters

No information available.

## 4.5 Thermal properties and heat flow

The Geothermal Resources Atlas of 2002 (Hurter and Haenel, 2002) has shown that heat flow density (HFD) values in the central Portuguese IPB are slightly higher than in the rest of the IPB area. This information is based on thermal properties that have been so far extensively studied in the IPB, using mostly mining data. Thermal conductivities, geothermal gradients and heat production values based on U, Th and K concentrations have been determined since 1982 by several research institutions and are processed and stored in LNEG, which instead makes them available to the general public using interactive internet tools (<http://geoportal.lneg.pt>), Atlas Geotérmico de Portugal Continental).

The HFD values for mainland Portugal vary from 40 mW/m<sup>2</sup> to 115 mW/m<sup>2</sup>, with an average value of about 75 mW/m<sup>2</sup>. HFD values for the CIZ (up north) of the Hesperic Massif ranging from 65 mW/m<sup>2</sup> to 80 mW/m<sup>2</sup>. In the northern part of the massif there is a HFD increase. In the SPZ, however, regional HFD values reach about 90 mW/m<sup>2</sup>, while in the Ossa Morena Zone (OMZ) these values decrease to about 60 mW/m<sup>2</sup>, which are similar to HFD values obtained for other European Hercynian regions. In the sedimentary basins, regional HFD values range from about 40 mW/m<sup>2</sup> to 90 mW/m<sup>2</sup>. Surface HFD in mining, water and geothermal wells is calculated multiplying the average geothermal gradient obtained in a well by the thermal conductivity of the geological formations crossed by the well.

A map of HFD Mainland Portugal was created with the information described before (Figure 7).



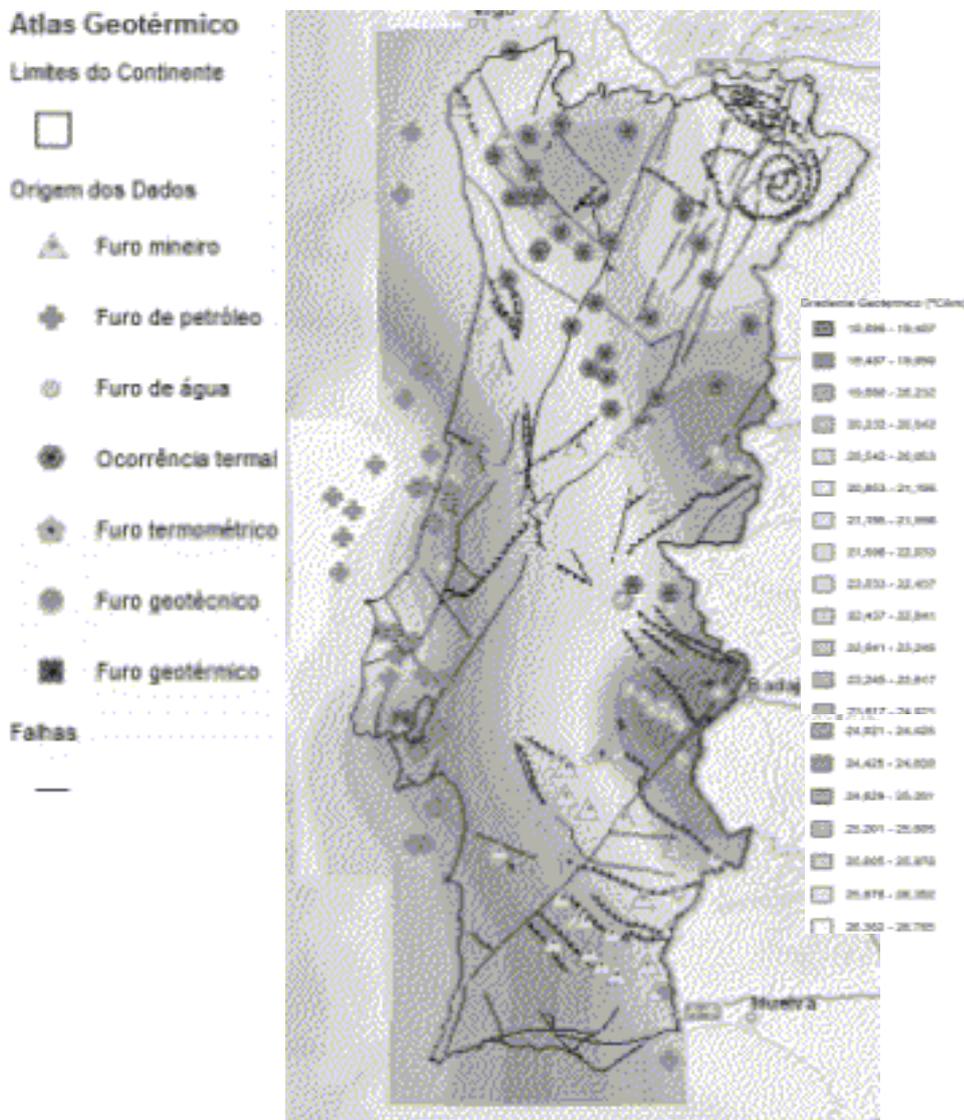
Figure 7. Heat flow map for mainland Portugal (<http://geoportal.lneg.pt>)

When determining HFD in these wells it is assumed that the formations crossed by the well are laterally homogeneous and isotropic, and that the thermal conductivity is independent of temperature. It is also considered that heat transfer is by conduction and stationary. The effects of heat production by radioactive decay of thorium, uranium and potassium are also considered. In these wells, HFD is calculated through the Fourier equation:

$$q = k (\text{grad } T) \tag{1}$$

where  $q$  ( $\text{W}/\text{m}^2$ ) is the HFD,  $k$  is the thermal conductivity ( $\text{W}/\text{mK}$ ),  $(\text{grad } T)$  is the vertical geothermal gradient ( $\text{K}/\text{m}$ ), usually represented in  $^\circ\text{C}/\text{km}$ . Most times the unit  $\text{mW}/\text{m}^2$  is used as a practical unit for HFD.

For this study all data considered reliable for heat flow density estimations had to satisfy several constraints concerning physical characteristics of the wells, number of temperature measurements in the well, precision of the temperature measurements, and borehole stability criteria (Ramalho and Correia, 2004).



**Figure 8.** Geothermal gradient for Mainland Portugal with the IPB sector (<http://geoportal.lneg.pt>)

Temperature data were collected from different sources. Selected wells were initially studied by Almeida (1992), Duque (1991), Ramalho (1997); some of them are wells in which temperature measurements were

carried out by Almeida (1992) and processed as described in detail in Ramalho and Correia (2004), creating national geothermal maps with zoom to the IPB (Figure 8). For those wells where thermal conductivity measurements were available (Duque, 1991; Almeida, 1993), the effective thermal conductivity was calculated using those values; otherwise, assumed thermal conductivities were assigned to the rocks, based on measured values obtained in other samples of the same rock type of nearby wells or, if the thermal conductivity of the formations is not known, average values mentioned in literature (for instance, in Cermak and Rybach, 1982) were used. In the wells where no lithology was available, assumed thermal conductivity was the same as considered in Fernandèz et al. (1995; 1998).

Thermal conductivities were measured in rock samples from boreholes in the IPB. As said before, estimations of heat flow density use the so called effective thermal conductivity. This was estimated using a ponderation of the thermal conductivity (laboratory or assumed) of each lithology crossed by the borehole with corresponding thicknesses. Effective thermal conductivity is estimated through the equation

$$k_{\text{effective}} = \frac{\sum_{i=1}^n \Delta Z_i}{\sum_{i=1}^n \frac{\Delta Z_i}{k_i}} \quad (2)$$

Where the index  $i$  corresponds to the different rocky materials crossed by the borehole,  $\Delta Z$  depth of measurements, and  $k_i$  is the thermal conductivity. A set of laboratory measurements of thermal conductivity in core samples from the IPB (Correia et al., 1982; Camelo, 1987a; Duque, 1991; Almeida, 1993) made that in most of the mining and water wells considered in this work was carried out through lithological logs. For each of the boreholes, this study consisted on the attribution of the average value of thermal conductivity in analogue samples whenever needed. Therefore, to estimate the thermal conductivity of each formation crossed by a borehole, two ways were used: (1) a value that was measured in laboratory, in a core sample from that precise borehole or (2) the average value of the thermal conductivities measured in core samples from analogue formations in other IPB boreholes. For those Portuguese geological formations without any laboratory measurement of thermal conductivity average values of thermal conductivity for similar rocks obtained containing physical properties of rocks (Cermak and Rybach, 1982).

Thermal conductivity determination in rock samples was made with a Showa Denko conductivimeter, model QTM-D2 and the measurements were made in rock samples from 12 boreholes, some of them reflected for heat flow density determinations (Correia et al., 1982; Camelo, 1987a; Duque, 1991; Almeida, 1993). Effective thermal conductivity attributed to each borehole was estimated through eq. (1).

The values of estimated average thermal conductivity though thermal conductivity measurements obtained in laboratory in rock samples from Mainland Portugal are represented in Table 1.

Table 2 shows thermal conductivity values of rocks with no laboratory determinations, but showing assumed values assigned from literature to estimate effective conductivity. These conductivities are therefore assumed as representative of the Portuguese geological formations, to which there are not laboratory thermal conductivities measurements. To those boreholes without lithological logs, assumed thermal conductivities used by Fernandèz et al. (1995) and later applied in Fernandèz et al. (1998), following identical criteria in the entire Iberian Peninsula.

Table 3 shows the list of borehole where thermal conductivity measurements were done on core samples where (1) effective and (2) assumed thermal conductivity was determined from one measurement in one single sample.

Lithology	Number of measured samples	Number of drill holes	Average value (W/mK)
Shales and greywackes	22	3	3.69
Shales	2	1	3.03
<b>Black shales (graphitic and pyritic)</b>	<b>1</b>	<b>1</b>	<b>4.16</b>
<b>Shales with Mn veins and disseminations</b>	<b>12</b>	<b>2</b>	<b>4.29</b>
Basic intrusive rock	7	1	3.31
<b>Purple (hematitic) and green shales and siliceous shales</b>	<b>4</b>	<b>1</b>	<b>5.41</b>
<b>Green shales</b>	<b>4</b>	<b>3</b>	<b>4.29</b>
Felsic aphyric volcanics	11	1	3.65
Silicified felsic volcanics	4	1	3.17
Chloritized felsic volcanics	1	1	3.29
Greywackes	6	1	3.48
Quartz dikes	1	1	3.07
Granite	1	1	3.40
Dolomite limestones	5	6	3.83
Mineralized dolomites	4	1	3.88
Limestones	3	1	3.42
Carbonate schists	2	1	3.56

**Table 1.** Average thermal conductivities estimated from laboratory measurements of core samples from boreholes OT1, AL2, FS25, FS26, SDV2 and S32. Average values correspond to the arithmetic average of values obtained in each borehole for the same formation

MATERIAL	THERMAL CONDUCTIVITY (W/mK)
Silts	2.38
Sandstones	2.30
Diabases	2.45
Talc and serpentinites	3.17
Clay	1.72
Sand	1.57
Argillaceous shales	2.59
Dolomitic shales	4.06

**Table 2.** Assumed average thermal conductivities of some rock materials in boreholes in Mainland Portugal (from values published in Cermak and Rybach (1982))

REF.	COORDINATES		CONDUTIVITY (W/mK) 1.EFFECTIVE 2.ASSUMED
	LONG.	LAT.	
S32	7°44'56"W	38°16'40"N	3.85 (1)
OT1	8°11'55"W	37°38'21"N	4.27 (1)
AL1	8°11'56"W	37°36'49"N	3.64 (1)
FS25	8°09'13"W	37°51'25"N	3.46 (1)
FS26	8°08'27"W	37°52'15"N	3.36 (1)

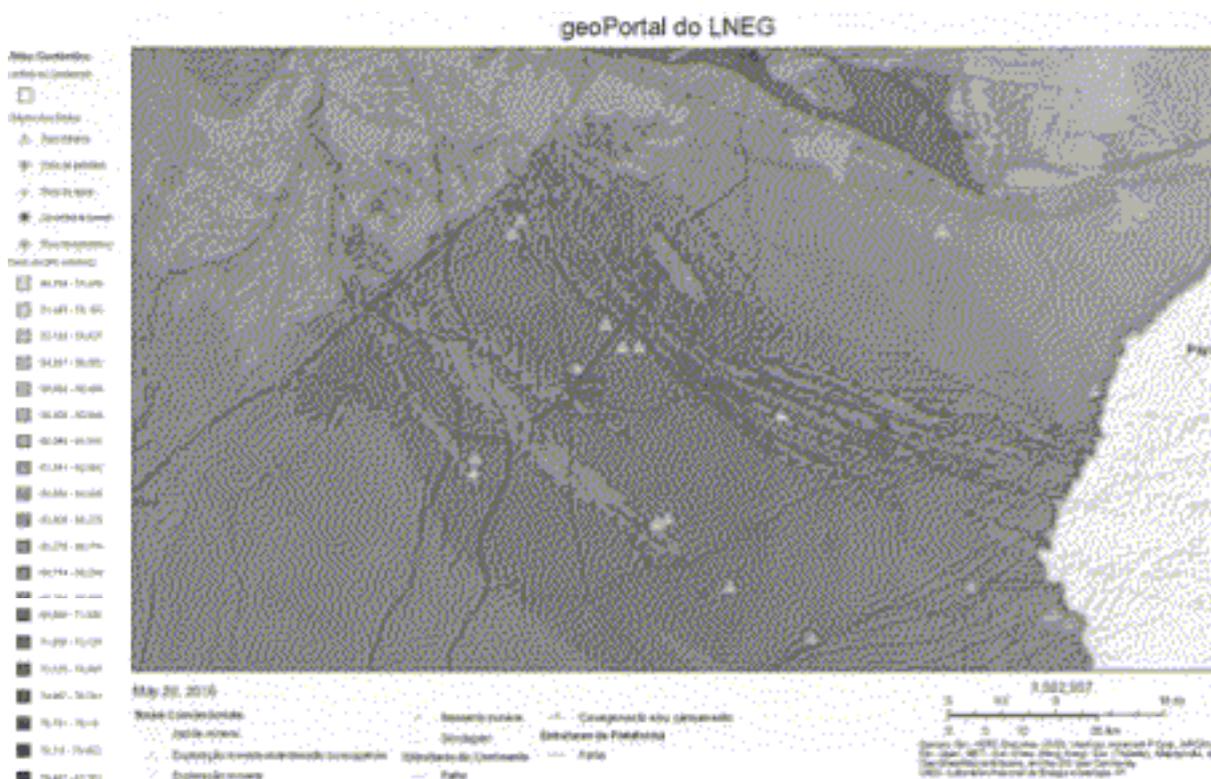
**Table 3.** Borehole list with thermal conductivity measurements made on core samples (Correia et al., 1982; Almeida, 1993) with (1) effective and (2) assumed thermal conductivity from one measurement on one single sample. Boreholes S4A and SD27 (Almeida, 1993), effective thermal conductivity is considered to be the same as for the core samples (see text for explanation)

However, some boreholes whose distribution of temperature in depth does not satisfy the previously mentioned criteria to estimate average geothermal gradient are not selected. This means that none of these boreholes shows a sufficiently straight score from which that gradient can be estimated. It's also noticeable that for boreholes where the lithological column is known but there are but there are no determinations in core samples, each lithological formation was assigned with an average thermal conductivity based in thermal conductivities measured in core samples from other boreholes (Correia et al., 1982; Camelo, 1987b; Duque, 1991; Almeida, 1993).

Heat Flow Density estimations ( $W/m^2$ ) for the IPB Portuguese sector is represented in Figure 9.

#### 4.6 Geophysical Exploration surveys in the IPB

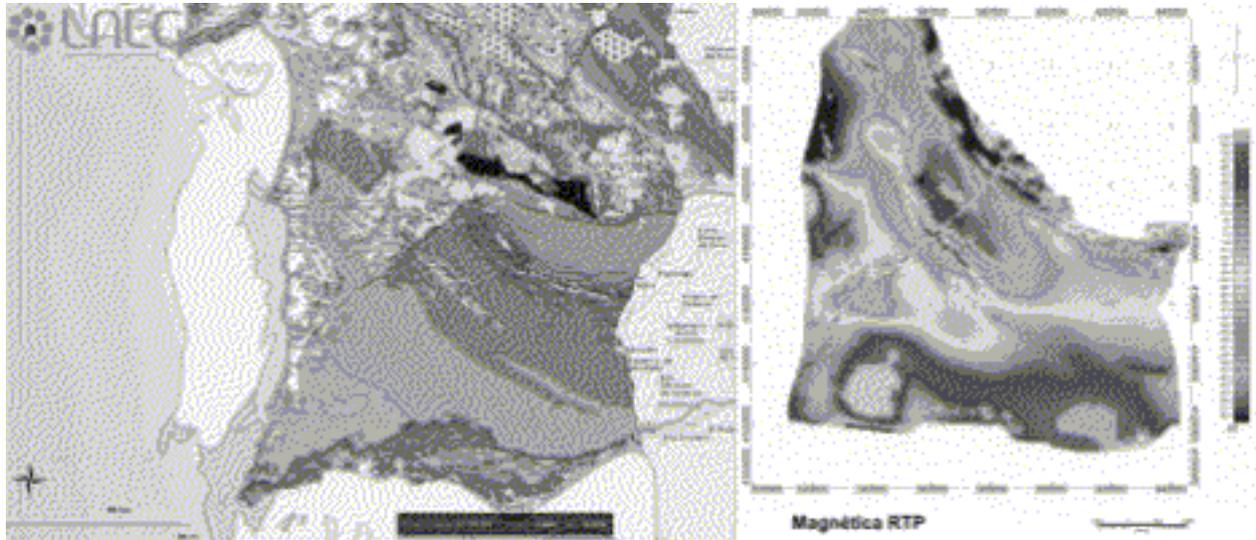
The application of geophysical techniques in massive sulphides deposits exploration has been a success in the Iberian Pyrite Belt province (IPB), both in Portugal and in Spain. Several hidden massive sulphide deposits associated to the IPB Volcano-Sedimentary Complex (VSC) were discovered in SW Iberia using integrated interpretation of geological and geophysical models, such as Neves Corvo (Albouy et al., 1981; Leca et al., 1983) and Lagoa Salgada (Oliveira et al., 1993; 1998a; 1998b) in Portugal, and Valverde (Castroviejo et al., 1996; Gable et al., 1998) and Las Cruces (Doyle, 1996) in Spain. In the IPB Portuguese sector, regional and systematic surveys were carried out by the governmental agencies Serviço de Fomento Mineiro (SFM)/Instituto Geológico e Mineiro (IGM), presently LNEG (Queiroz et al., 1990; Oliveira et al., 1993, 1998a, 1998b, Matos and Sousa, 2008). This public investment and other surveys promoted by exploration companies, permitted to develop large databases along time in particular methods like gravimetry, magnetometry (c.f. Figure 10), electrical and electromagnetics. This section of the report presents a brief description of the geophysical techniques applied in the IPB Portuguese sector, with emphasis on the regional gravity, magnetic and radiometric surveys.



**Figure 9.** Heat Flow Density estimations ( $\text{W/m}^2$ ) for the IPB Portuguese sector. Geology ad. from <http://geoportal.lneg.pt>

Geophysical methods have been widely used in the IPB since the early 1940's. As part of a national prospecting plan lead by the former SFM (Queiroz et al., 1990) and IGM (Oliveira et al., 1993), both Governmental Surveys dedicated to the mining industry, several campaigns were performed between the 1950's and 1990's. Multiple campaigns were carried out, encouraged by the SFM/IGM activity, the easy data access and the discovery of several massive sulphide deposits, including the giant Neves Corvo Cu-Zn-Sn world class rich deposit (Carvalho et al., 1999; Relvas et al., 2006; Matos and Sousa, 2008). The interest of

important international investors, like Anglo American (Minaport), Asarco, Atlantic Copper, Billiton, BP Minerals, Conasa, Elf Aquitaine, Ferragudo Mining, Lundin Mining (Somincor/AGC Minas de Portugal), Northern Lyon Oy, Redcorp, Redfern, Rio Tinto (Riofinex, Soc. Mineira Rio Artezia), Utah and the consortiums SPE/SEREM/EDMA and SMS/SEREM/SMMPPA, lead to a continuous investment in geophysical research, based in ground and airborne surveys (Matos et al., 2016).



**Figure 10.** (left) Geological map 1:1K (<http://geoportal.lneg.pt>) (right) Magnetic Total Magnetic Field Intensity map with reduction to pole, based on RTZ survey, ad. Represas et al. 2016

In some areas the technical support was provided by the SFM, IGM and LNEG teams (Matzke, 1971; Albouy et al., 1981; Leca et al., 1983; Castelo Branco, 1995; La Fuente, 1995; Carvalho et al., 1996; Castelo Branco, 1996; Palomero and Mora, 1996; Castelo Branco and Sá, 1997; Palomero, 1999; Mora, 2002; Faria, 2007; Matos et al., 2009a, 2009b; Araujo and Castelo Branco, 2010; Carvalho et al., 2011). National companies like the Emp. De Desenvolvimento Mineiro, Emp. Desenvolvimento Mineiro do Alentejo, Emp. Mineira Serra do Cercal, MAEPA, Portuglobal and Pirites Alentejanas invested also in different geophysical campaigns. A significant volume of exploration works were made by several junior mining companies, investing in the characterization of drill targets defined in the geological structures with high mining potential. Specialized consulting companies worked at IPB, improving data treatment and interpretation techniques – e.g. Adaro, Anglo American (Minaport), Bundesanstalt für Geowissenschaften und Rohstoffe, Condor Consulting, Compagnie Générale de Géophysique, Geoconsult, Geoterrex, Institut für Geophysik TU Clausthal, Int. Geophysical Technology, La Montagne SAP, Lea Cross Geophysics, Lab. Geophysique Appliqué et Structural, Univ. Nancy, Soc. Mineira Rio Artezia/Rio Tinto Zinc, Sanders Geophysics and Urguhart-Dvorak. The SFM, IGM and LNEG teams worked for various mining companies as geophysical consultants (gravity, magnetic, seismic and electric surveys), being examples the collaborations with MAEPA, Northern Lion Oy, Somincor and Soc. Mineira Rio Artezia.

The first geophysical method used in the Portuguese sector of the IPB was the electromagnetic Turam technique, with some initial essays in the early 1940's (Queiroz et al., 1990). The real geophysical prospecting activity only started in the early 1950's by the continuous work of the SFM teams, especially near the active main mining areas of Aljustrel and São Domingos, respectively operated by Mine d'Aljustrel (Leitão, 1998; Martins et al., 2003) and Mason and Barry (Matos et al., 2006) companies. The discovery in 1954 of the superficial part of the Aljustrel Moinho massive sulphide sub vertical orebody (Leitão, 1998),

named Carrasco, represents the first successful application of the Turam method. This positive result promoted the SFM regional campaigns dedicated to the exploration study of the areas were the VSC and Phyllite-Quartzite (PQ) (Givetian-Strunian age) formations outcrop (Pereira et al., 2008; Matos et al., 2014; Matos et al., 2016). The methodology consisted of dozens of NE-SW parallel Turam profiles, parallel to the VSC and PQ geologic structures. In the 1950's the magnetic method started to be used but the lack of signature of some orebodies opened way to other geophysical methods.

After the preliminary Turam and magnetic surveys, the gravimetric method became the main tool to detect new sulphide masses in the IPB. Until 1960's the role of the SFM was unique, based in detail ground surveys carried out over N-S, E-W grids with spacings of 200 m, 100 m and 50 m (Queiroz et al., 1990; Oliveira et al., 1993). The discovery of the Aljustrel Feitais orebody in 1964 (Leitão 1998; Martins et al., 2003) by Mines d'Aljustrel using gravity surveys showed the potential of this method. Later, the introduction of electrical methods improved the quality of the resistivity data, since they provided deeper and more reliable information than Turam. Underground gravity surveys were performed at the Lousal mine in the late 1960's (Matzke, 1971). The discovery of the Neves Corvo ores in 1977, as a direct result of the exploration work of mining companies, as well as previews of SFM exploration surveys (Carvalho, 1982; Leca et al., 1983; Carvalho et al., 1999; Oliveira et al., 2006; Matos et al., 2016), show the advantages of an integrated model interpretation, as it included the study and interpretation of geological structures based on the use of electrical resistivity and spontaneous potential simultaneously, followed by magnetics and gravimetric surveys. The extreme copper grades of the Neves Corvo deposit justified more investment in exploration, including deep structures (>500 m depth). Considerable efforts were developed in some areas like the Neves Corvo-Corte Gafo, a 600 km<sup>2</sup> polygon (Carvalho *et al.*, 1996), where Somincor developed a multidisciplinary program: gravity + magnetic surveys (9015 points distributed covering an area of 314.5 km<sup>2</sup>, with technical support of the SFM gravity team) and several profiles of transient electromagnetic (TEM, 215.5 km), magnetotelluric (27.0 km) and seismic reflection (24 km). Detail works were performed at Neves Corvo, João Serra and Corte Gafo areas, including down hole geophysical log: 2 000 m of resistivity + sonic surveys and 2 500 m of TEM surveys.

High logistic costs and the development of differential GPS topographic techniques promoted the change of ground gravity and magnetic surveys in 1990's from the regular grids to random grids with ~300 m spacing. The Rio Tinto Company was the first to apply this geometry in the region, after test programs developed in well-known areas like Águas Teñidas (Spain) (Castelo Branco, 1995; Braux et al., 1996; Castelo Branco and Sá, 1997). Rio Tinto and others companies like Minaport (Anglo American), also promoted, during that decade, the achievement of regional magnetic and radiometric airborne surveys (La Fuente, 1995; Castelo Branco, 1995; Castelo Branco and Sá, 1997; Torres and Carvalho, 1998). At a local scale, other geophysical methods are being used to characterize gravity and geological targets. Aiming at specific goals in well-defined targets, methods such as deep reflection seismic, electrical resistivity, induced polarization, TEM, VTEM, vertical electrical soundings and magneto-telluric have been applied. In massive sulphide mineralized structures down-hole surveys (e.g. Mise à La Masse, TEM) were essential to follow the mineralization trends, like in the Lagoa Salgada (Oliveira et al., 1993, 1998a) and Semblana (Araujo and Castelo Branco, 2010) sectors. Stockwork vein type mineralizations can also be identified using these methods, like the recent cases of the Serrinha induced polarization profiles (NW IPB sector, see Figure 1, Ramalho and Matos, 2009; Matos et al., 2009) and Chança, Montinho and Caveira massive sulphide orebodies detail exploration studies performed by Sociedade Mineira Rio Artezia (Mora, 2002) and Atlantic Copper (Palomero, 1999). At the Neves Corvo

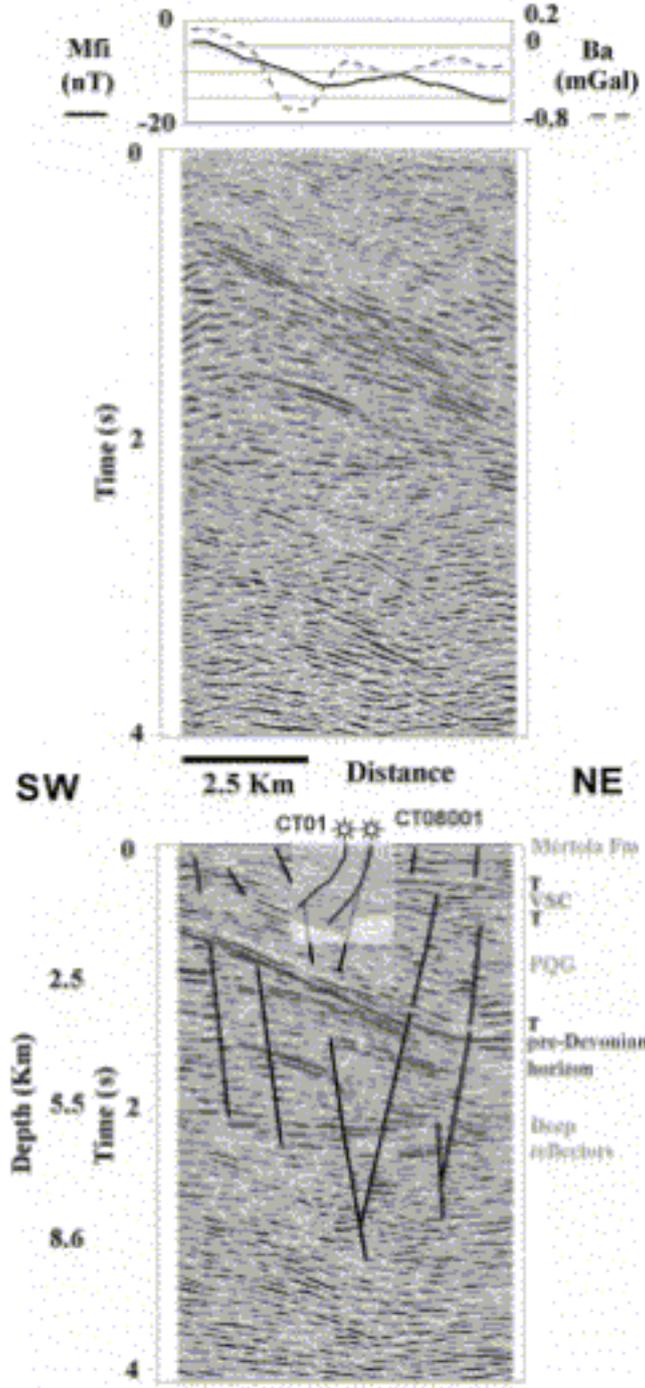
region, seismic profiles were used by Lundin/Somincor to define key tectonic structures (Araujo and Castelo Branco, 2010; Inverno et al., 2013, 2015; Matos et al., 2016).

The Neves Corvo deposit presents a gentle inclination to NE, with seven orebodies dispersed in a large complex antiform structure (Araujo and Castelo Branco, 2010; Oliveira et al., 2013). The correct understanding of the geometry of the study area implies a significant detail in the geological mapping based in surface surveys and/or drill holes logging (Matos et al., 2016). In areas with few drill-holes, the geophysical data can be essential to model construction. The geophysical and geological data integration using 3D model software is essential to define target zones in future drill campaigns. However, as potential field data modelling/inversion are an ill-posed problem and no unique solution exists, seismic reflection is often used to provide structural information (together with drill-hole and geological data), thus reducing the ambiguity of modelling/inversion. This strategy is being used with success by Lundin Mining in the Neves Corvo region, with 3D seismic reflection surveys acquired over existing massive sulphide ores (e.g. Lombador) and defining new targets, as the recent Semblana and Monte Branco discoveries (Araujo and Castelo Branco, 2010; Lundin Mining website, Feb. 2016, <http://www.lundinmining.com/>).

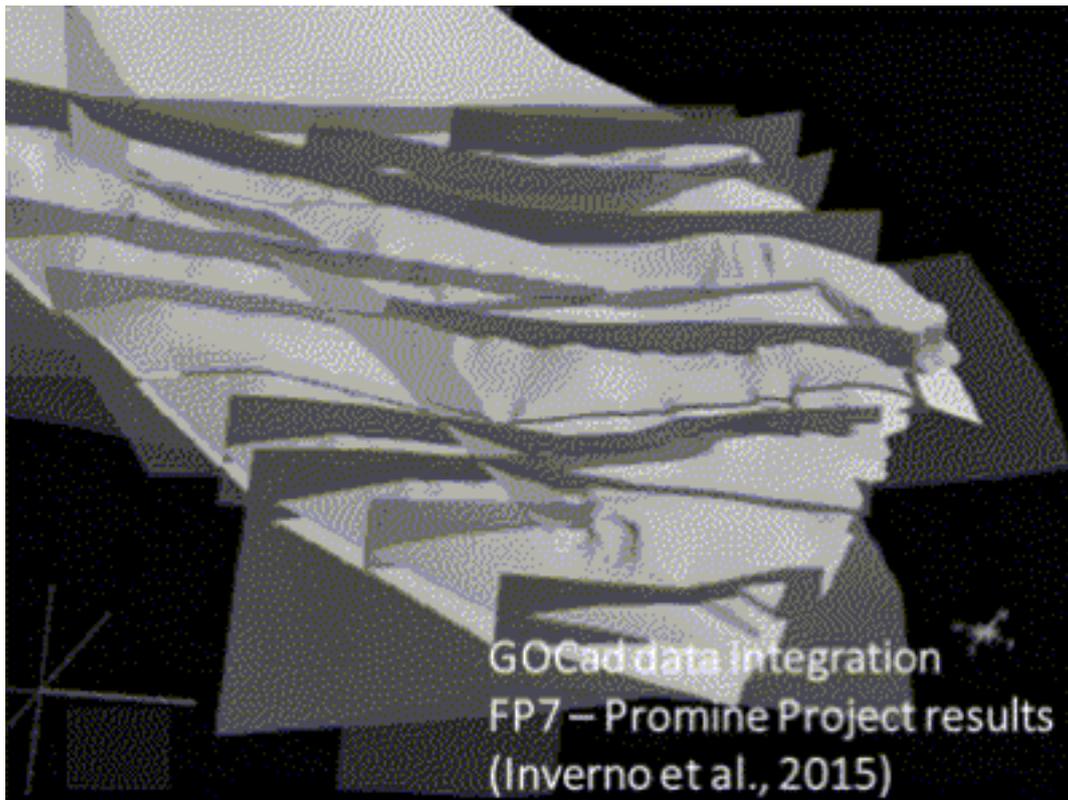
3D models based in geophysical, geological and drill-hole data are being defined for the IPB deposits of Neves Corvo (Inverno et al., 2013; Batista et al., 2014; Inverno et al., 2015), Caveira (Matos et al., 2015), Lagoa Salgada (Represas and Matos, 2012) and Rio Tinto (Martin-Izard et al., 2015). Data compilation and reprocessing of geophysical data in the regions is also being undertaken by private companies and governmental agency (LNEG) due to the development of new data processing techniques and computing advances.

Recently, 81 km of deep 2D seismic reflection data (up to 10 km) were acquired by LNEG/Prospectiuni between Neves Corvo and the Spanish border, to check the prolongation of the IPB volcanic axis to SE and its connection with the Spanish side of the IPB (Carvalho et al. 2016) (Figure 1). This dataset was interpreted in a 3D environment using gravimetric, radiometric, magnetic, drill-hole and surface geological data and it was possible to follow the volcanic axis from Neves Corvo till Spain and estimate its depths which are at places compatible with present day exploration (Figure 5, Figure 11 and Figure 12).

After 70 years of exploration work, a large area of the IPB is already covered with several geophysical methods. A large amount of acquired data is standardized and supervised by LNEG. Considering the IPB as an important base metals mineral province the mineralization targets are defined by massive/semi-massive sulphide ore lenses, stockwork veins and disseminated mineralizations with hydrothermal halos, present in VSC felsic and shale units (Carvalho, 1982; Matos et al., 2011; Matos et al., 2016).



**Figure 11.** Gravimetric and magnetic data a) plotted over CRS stack for seismic profile 1 without b) and with post-stack time migration with overlaid stratigraphic and structural interpretation c). The locations of drill-holes CT01 and CT08001 are shown (blue line) and a geological cross-section based on these two drill-holes and previously acquired seismic reflection data is overlaid the interpreted stacked section. Mfi: Magnetic field intensity (reduced to the pole); Ba: Bouguer anomaly. Black lines: faults; Yellow lines/T: thrust planes; VSC: Volcanic-Sedimentary Complex; PQG: Phyllite-Quartzite Group; Red line: pre-Devonian horizon; Orange lines: deep crustal reflectors. Figure ad. from Carvalho et al., 2016

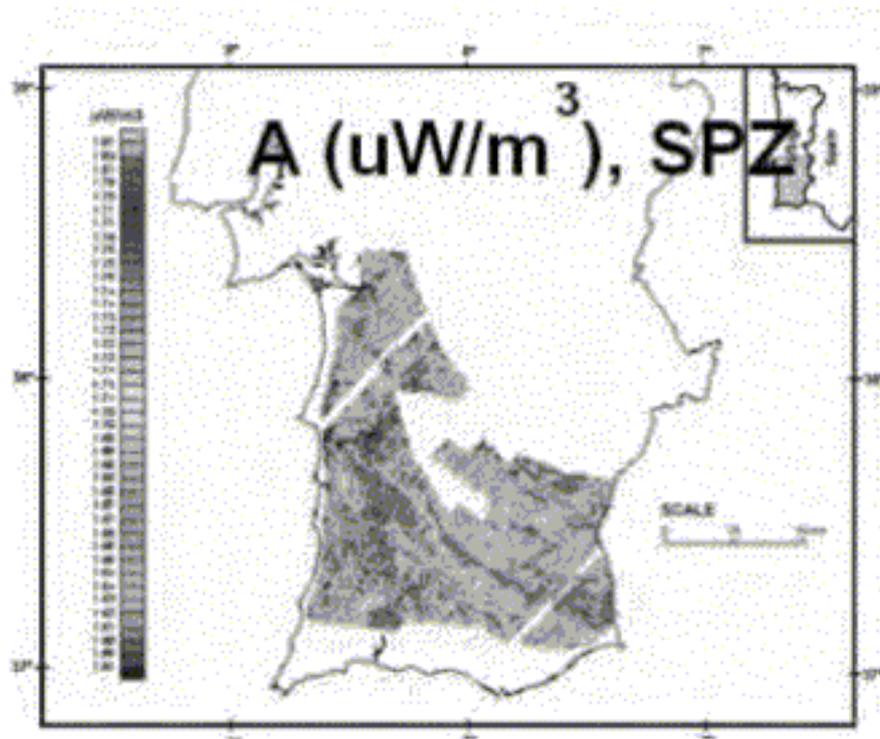


**Figure 12.** Example of late Variscan faults, represented by strike-slip faults that control basement block geometry, defined by horst and grabens. Some faults are mineralized, presenting copper veins, mined in the XIX century.

## 5 Identifying target sites for future CHPM

### 5.1 Extending existing models to greater depth, integrating data down to 7 km

Temperature in depth maps obtained with geothermal mapping together with thickness, transmissivity, and fluid chemical characteristics also in depth will have a significant importance in the entire process to evaluate areas with more accurate methods and additional resources. Therefore, temperatures at 1000, 2000 and 5000 m are estimated, following heat flow density estimations (from average thermal conductivity and geothermal gradient) and heat production values (A) (Haenel et al., 1980), based on spectrometric concentrations of U, Th and K, mostly from Rybach and Cermack (1982), Correia (1995) and aerospectrometric surveys for mining prospecting. (Figure 13) shows a map of A based on U, Th a K concentrations from an aerospectrometric survey conducted with mining prospecting purposes.



**Figure 13.** A based on U, Th a K concentrations from an aerospectrometric survey conducted in the SPZ, where IPB is located, with mining prospecting purposes (Torres et al., 2000)

In this case, the step model was used.

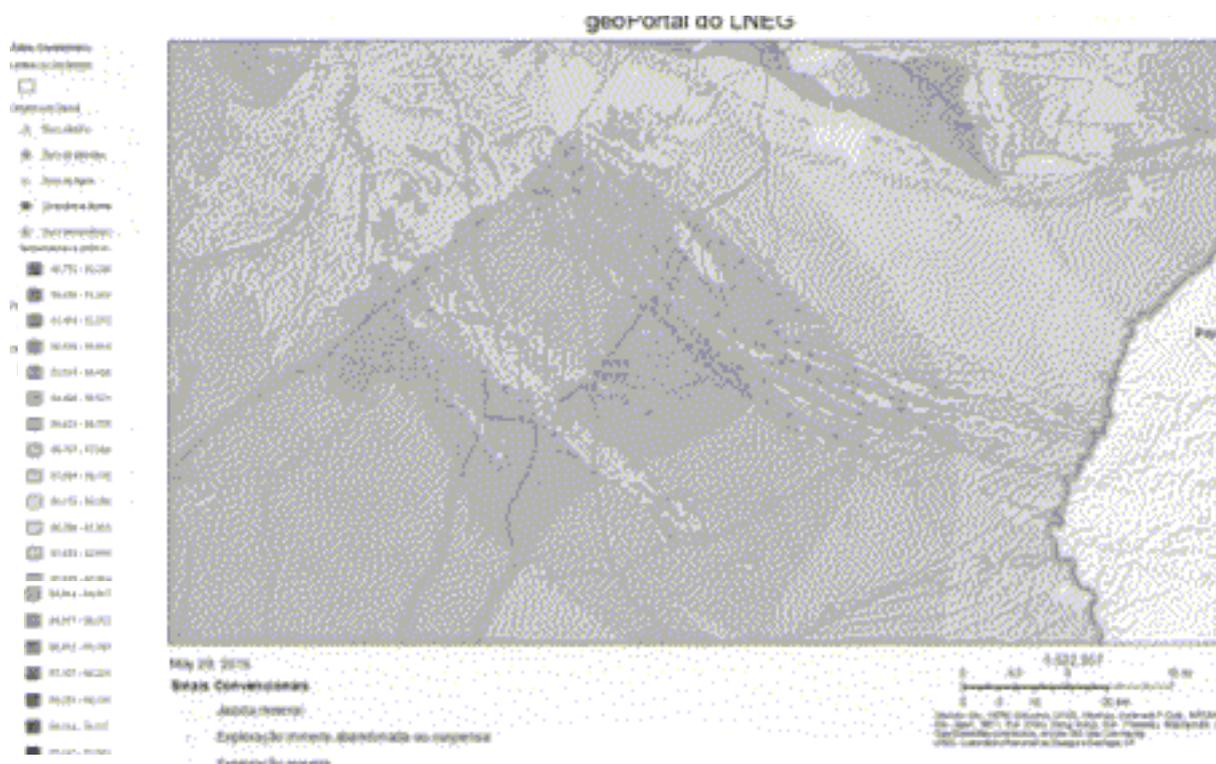
$$T(z) - T_0 = \frac{qz}{k} + \frac{Az^2}{2k} \quad (3)$$

where  $T(z)$  is the temperature at depth  $z$  ( $^{\circ}\text{C}$ ),  $T_0$  is the average surface temperature on Earth ( $^{\circ}\text{C}$ ),  $z$  is the depth (m),  $A$  is the heat production per unit of volume ( $\text{Wm}^{-1}\text{K}^{-1}$ ) and  $k$  is the thermal conductivity ( $\text{Wm}^{-1}\text{K}^{-1}$ )

Whenever possible, considered temperature was the measured temperature or interpolated between two measured temperatures, such as the case of onshore and offshore boreholes. In case of its inexistence, temperatures were extrapolated to bigger depths from shallower depths. The first was used only in several oil wells, after bottom bole temperatures correction for thermal disturbances caused by drilling (Haenel et al. 1988).

HFD from geothermometers was not used for the IPB area, although its values were considered at national level, since there was information enough about  $k$  and  $A$ . Generally, temperatures in depth are higher in the Lusitanian Basin and in the SPZ, where the IPB is located.

Temperatures at 1000 m depth for the IPB are represented in <http://www.geoportal.pt>, in the Atlas de Geotérmico de Portugal Continental group of layers, reaching about 40 °C in the IPB, estimated with the methods described previously. This value is confirmed by Nelson Pacheco (Lundin Mining oral communication, 2016) to the lower levels of the Neves Corvo Mine, about 900 m deep.



**Figure 14.** Temperature estimation (°C) at 2000 m deep in the IPB Portuguese sector. Geology ad. from <http://geoportal.lneg.pt>

Temperatures at 2000 m depth for the IPB are in Figure 14, and can reach about 63 °C in the IPB. Estimated temperature in the area for 5000 m deep, using the previously described methods for geothermal investigation is about 132 °C (Figure 15).

Existing temperature in depth models and structural models in IPB can be jointly interpreted with structural models suggested for the area, based on several types of geophysical data (e.g., magnetic, magnetotelluric).

## 5.2 Knowledge gaps and limitations

Within the framework of CHPM2030, there is some work to be done in this first task. Information on fluid composition, brines and meteoric waters is still missing as more representative samples from the Neves Corvo Mine can also be part of the project. Lundin Mining Company confirmed the technical support to the LNEG CHPM2030 project. This procedures will allow to the planned drill hole sampling, focused in deep rock intersections bellow 1000 m depth (e.g. Cotovio sector).

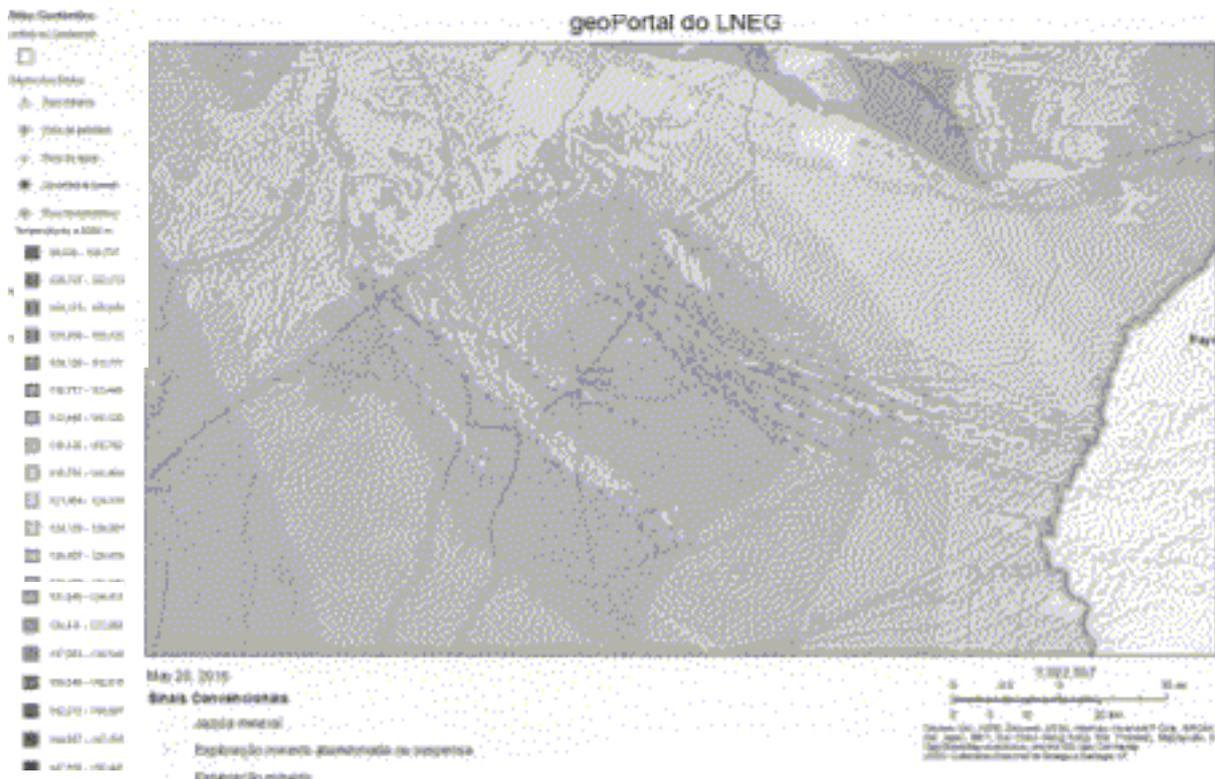


Figure 15. Temperature estimation (°C) at 5000 m deep in the IPB Portuguese sector. Geology ad. from <http://geoportal.lneg.pt>

## 6 Discussion and concluding remarks

Geothermal gradient, HFD estimations and consequently temperatures in depth obtained for the different depths, published along the years are considerably different from those presented in the Atlas of Geothermal Resources in the European Community, Austria and Switzerland” (Haenel and Staroste, 1988), resulting in the establishment of narrower criteria to select adequate thermometric wells to assure a good data set quality for the entire Iberian Peninsula, IPB included. The last edition of the “Geothermal Resources Atlas of Europe” (Hurter and Haenel, 2002), incorporates this dataset and added some thermometric boreholes drilled with specific geothermal purposes near the IPB.

According with Heat Flow Density Commission this approach is reliable and quality of data is improved as more information is acquired. The geothermal database followed the format described in Ramalho (1999) and follows as much as possible the standards defined by the International Heat Flow Commission (Jessop, 1990).

Table 4 shows the observed density in outcropping rocks and cores from several mining wells.

Unit	Rock type	Observed density	Density (ITGE data) <sup>a</sup>	Studied sectors (Portugal)
Mértola Flysch	Shales and greywackes	2.70-2.81	2.66-2.68	Taralhão <sup>1</sup>
Volcano-Sedimentary Complex	Siliceous shales	2.65-2.77	2.65	Rio de Moinhos <sup>1</sup>
	Green/purple shales	2.58-		Rio de Moinhos <sup>1</sup>
	Black shales	2.81		Rio de Moinhos <sup>1,2</sup>
	Jaspers and cherts	2.73-2.98	2.63-3.06	Rio de Moinhos <sup>1</sup>
	Basic volcanics	2.73-2.89	2.78-3.00	Lagoa Salgada <sup>1,2</sup>
	Acid volcanics	2.58-2.90	2.61-2.68	Lagoa Salgada <sup>1,2</sup>
Sulphide mineralization	Acid volcanics + hydrothermal alteration	2.63-2.96		Lagoa Salgada <sup>1,2</sup>
	Stockwork zones	2.88-3.,91		Lagoa Salgada, Rio de Moinhos <sup>1,2</sup>
	Semi-massive pyrite	2.25-3.54		Lagoa Salgada <sup>1,2</sup>
	Massive pyrite	4.29-5.03		Lagoa Salgada <sup>1,2</sup>
Phyllite-Quartzite Gr.	Shales and quartzites	2.58-2.67	2.56-2.65	Chaparral, Lameira <sup>1</sup>
	Dark grey shales	2.62-2.84		Chaparral, Lameira, Rio de Moinhos <sup>1</sup>
	Limestones	2.79		Rio de Moinhos <sup>1</sup>

**Table 4.** Observed density of outcropping rocks and cores from mining wells from 1 – IGM/SFM; 2 – Lagoa Salgada Consortium (Soc. Mineira Rio Artezia/EDM); 3 – AGC/Lundin Mining. \* – Disseminated magnetite/dike. Variations in depth related with rock porosity were not considered. A – ITGE data in García *et al.*, 1998 and Jiménez, 2013 (Matos *et al.*, 2016, in press).

## 6.1 How the Iberian Pyrite Belt Neves Corvo sector can positively contribute to the aims of CHPM2030

The Neves Corvo mine site includes > 300 Mt of sulphide ore, distributed in 7 ore lenses. The Neves, Corvo, Graça, Zambujal and Lombador deposits are being mined until 900 m depth by Somincor/Lundin Mining. A large exploration database, including deep drill holes (above 1 500 m deep) allow the definition of an accurate setting of the geological model. This data can be correlated with seismic profiles than can predict the tectonic structures until 10 km depth. All these data are essential to CHPM2030 objectives, considering the EGS thematic in an active mine site. The Neves Corvo samples study will be shared by LNEG and Miskolc teams.

After a reevaluation of the available information from Lundin Mining, extra material, comprising deeper and eventually more representative samples from the Neves Corvo mine will be studied.

## 7 Datasets pertinent to CHPM2030 held by LNEG

Datasets	Short description	Scale	Coverage	Access cost	Link
<b>Hydrogeology</b>					
Hydrogeological maps	Regional mapping, fl. 7 and 8.	1:200,000	South Portugal, Alentejo and Algarve regions	See web page	<a href="http://www.lneg.pt">http://www.lneg.pt</a>
<b>Geophysics and remote sensing</b>					
Gravity	Regional map, Bouguer 2.6 1/400,000 (available in the end of 2016)	1:400,000; 1:25,000; 1:5,000	South Portugal, Alentejo region	See web page	<a href="http://www.lneg.pt">http://www.lneg.pt</a>
Airborne magnetics	Regional map (available in the end of 2016)	1:400,000	South Portugal, Alentejo region	See web page	<a href="http://www.lneg.pt">http://www.lneg.pt</a>
Airborne radiometrics	Airborne survey data for the radioactive isotopes Th, U, and K, total count. Total count regional map (available in the end of 2016)	1:400,000	South Portugal, Alentejo and Algarve regions	See web page	<a href="http://www.lneg.pt">http://www.lneg.pt</a>
Land gravity	A database of over >300,000 gravity observations.	N.A.	South Portugal, Alentejo and Algarve regions	See web page	<a href="http://www.lneg.pt">http://www.lneg.pt</a>
Geophysical borehole logs	An archive of geophysical downhole log data.	N.A.	Various	See web page	<a href="http://www.lneg.pt">http://www.lneg.pt</a>

Datasets	Short description	Scale	Coverage	Access cost	Link
<b>Boreholes</b>					
Borehole database	A database of over one million records of boreholes, shafts and wells.	N.A.	South Portugal, Alentejo and Algarve regions	See web page and LNEG Geoportal	<a href="http://www.lneg.pt">http://www.lneg.pt</a> <a href="http://geoportal.lneg.pt/">http://geoportal.lneg.pt/</a>
<b>Geochemistry</b>					
Soil and stream sediments	Geochemical database and physical samples	N.A.	South Portugal, Alentejo and Algarve regions	See web page and LNEG Geoportal	<a href="http://www.lneg.pt">http://www.lneg.pt</a> <a href="http://geoportal.lneg.pt/">http://geoportal.lneg.pt/</a>

**Table 5.** Summary of datasets pertinent to CHPM2030 held by LNEG.

## 8 Acknowledgements

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## CHPM2030 DELIVERABLE D1.2 APPENDIX 1.2.3

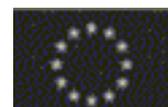
# REPORT ON DATA AVAILABILITY – ROMANIA

### *Summary:*

This document provides a review of the existing data which can substantiate further research that has, as a final objective, the preparation of a pilot aiming to use the potential of metal extraction together with geothermal water.

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## 1 Executive summary

In order to establish an enhanced geothermal system on a deep metal-bearing geological formation a study case perimeter was selected having some basic conditions fulfilled:

- Important geothermal resources are already exploited in Beiuș basin.
- This region has high heat flow values.
- The geothermal aquifer has a short recharging period of time, being supplied by water coming from the extensively karstified area of Bihor Mountains.
- Existence of magnesian skarns containing B, Cu (Mo, Zn-Pb), generated in the metasomatism contact aureola of a batholith with regional extension.
- This granodioritic-granitic batholith and its apophyses, which is the result of Late Cretaceous magmatism, determined the formation of several ore-deposits within North Apuseni Mountains, deposits that are included into Banatitic Magmatic Metallogenic Belt.
- It is possible that three of the most important mineral deposits, Pietroasa, Budureasa and Băița Bihor, to provide the metals for the envisaged Enhanced Geothermal System (EGS).
- Existence of a clear structural connection between the geothermal aquifer and the selected deep metal-bearing geological formation.

Within this deliverable the existing data were synthesized and can substantiate further research. The final objective is the preparation of a pilot which aims on extracting metals together with geothermal heat.

## 2 Introduction and outline of work

### 2.1 Goals

The paper aims to present and analyse relevant scientific research in the Bihor Mountains, being a part of Banatitic Magmatic Metallogenic Belt (BMMB) of Romania. These studies should be the base for further investigations that can contribute assessing the creation of an EGS – orebody system. The objective of this task is to summarize previously reported studies of the uppermost crust of the Earth, reflecting the current knowledge regarding geology, geothermal potential, prospecting, deep drilling, and geophysical surveys of a region that offers pre-conditions for the application of the CHPM concept. Knowledge gaps and limitations should be highlighted for the Bihor Mountains.

### 2.2 Country specific issues

Romania has metalliferous deposits that were exploited in the past, or which, for now, were only highlighted, waiting for a modality by which they can be exploited. Romania also has geothermal resources, insufficiently valorised.

CHPM2030 project is an excellent opportunity to investigate the possibility of realizing a combination of the two types of resources, in order to exploit them profitably. For this, a perimeter has been chosen, which, according to preliminary data that we have, offers *sine qua non* pre-conditions for further investigations of the possibility to achieve the objectives of the project.

The perimeter offers the following advantages:

- o Mineral resources well studied and documented,
- o Geothermal resources in operation, which have already assured the supply of heat and hot water for several districts of a town,
- o Accessibility in the region,
- o Available manpower.

This perimeter is considering the geothermal resources from Beiuş Basin, and, also, the existence of a pluton, which outcrops in the nearby areas, such as Pietroasa, and Budureasa. Perimeter is located in the North of the Apuseni Mountains and structural units concerned are the Beiuş Depression, and Bihor Mountains.

This report is mainly a compilation of the relevant data which can contribute in reaching a conclusion regarding the potential of extracting metals in combination with the exploitation of geothermal water.

There are several main elements that led to selection of this perimeter, namely:

- The existence, as a result of Late Cretaceous magmatism, of a granodioritic-granitic batholith that crops out only on restricted areas, among which Pietroasa and Budureasa are better documented, and is also associated to andesitic and rhyolitic minor intrusions. The intrusion of the banatites has resulted in contact processes that concerned the sedimentary deposits being traversed. At the contact of the banatites with the limestones, marbles and various types of calcic skarns have been formed, while at the contact with the detritic and pelitic rocks, hornfels, garnet skarns, etc. are met.
- From genetical point of view, the geochemical spectrum of banatitic mineralization in the Apuseni Mts is as follows: B, Cu (Mo, Zn-Pb).

- The existence of a geothermal anomaly, which is not as important as the one from the Pannonian Plain, but which is confirmed in Beiuş basin. Within Beiuş Basin, the geothermal water, with temperatures of 84°C, is extracted from depths of 2700 m.
- Regional structural cross sections indicate the extent of batolith under Beiuş basin, leading to the hypothesis that it could be a possible source of metal, for the exploitation plant of the *metals – geothermal water* complex.
- Gravimetric and magnetometric maps also indicate the existence of the batolith under the sedimentary basin of Beiuş.

## 3 Previous research and available data

### 3.1 Structural evolution, deep-seated faults and fracture zones, their alignment

In order to consider achieving of an EGS – ore body system, a region that meets to a greater extent several pre-conditions have been chosen. This is represented by Beiuș Depression, and Bihor Mountains situated in the North Apuseni Mountains.

#### 3.1.1 History of research

Since 1774 when Ignatz Edlen von Born makes the first mineralogical records, and then researches of I. E. Fichtel, I. Ruprecht, P. Partsch, Fr. Hingenau, L. Neugeboren etc, consist of petrographic and mineralogical descriptions of mineralisation deposits occasionally examined. In parallel, stratigraphy and paleontology notes start to appear, and in 1822 S.F. Beudant realises the first general geological map of the Apuseni Mountains.

A first embodiment is the valuable monograph on the geology of Transylvania, developed by F. Hauer and G. Stache 1863, which contain extensive descriptions of the Apuseni Mountains.

Geological researches of Bihor Mountains, mostly related to deposits of useful minerals have begun since the 19th mid-century. Baita Bihor area benefits from the research of K. Peters (from 1861 to 1862) and Fr. Pošepny (1873).

During 1889-1890 G. Primics realised the geological mapping of the central area of the Bihor Mountains, while M. Pálfy (1897-1899) realised the eastern part, and J. Szádeczky (1904-1907) was in charge with the northern area and Vlădeasa Massif. Since 1905 P. Rozloznsnik deciphers Biharia massive structure.

Since 1950 North Apuseni Mountains were the subject of detailed geological mapping. Thus, in Bihor Mountains mappings of crystalline basement were conducted by R. Dimitrescu, M. Borcoș, I. Hanomolo, E. Stoicovici, Aurica Trif, I. Mârza, C. Ionescu and H. Savu.

Sedimentary were clearly defined as follows: Permian was correlated by M. Bleahu, Triassic formations have been the subject of studies realised by D. Patrulius, M. Bleahu, S. Bordea, Josefina Bordea, Stefana Panin, Camelia Tomescu, D. Istocescu, Jurassic formations were studied by D. Patrulius and E. Popa and the Cretaceous formations by D. Patrulius, S. Bordea, Gh. Mantea and D. Istocescu. Neo-Cretaceous post tectonic basins formations have been the subject of studies conducted by Denisa Victoria Todirica - Mihailescu Lupu and the Neozoic were investigated especially by D. Istocescu.

Within Bihor Mountains, Codru nappe system was defined and specified by M. Bleahu and the Biharia nappe system by R. Dimitrescu and M. Bleahu.

Banatitic rocks from North Apuseni Mountains were mapped in detail by A. Ștefan and Gh. Istrate, and the phenomena of metamorphism and mineralization have been the subject of the research of G. Cioflică, V. Șerban, S. Stoici, C. Lazăr, M. Borcoș etc.

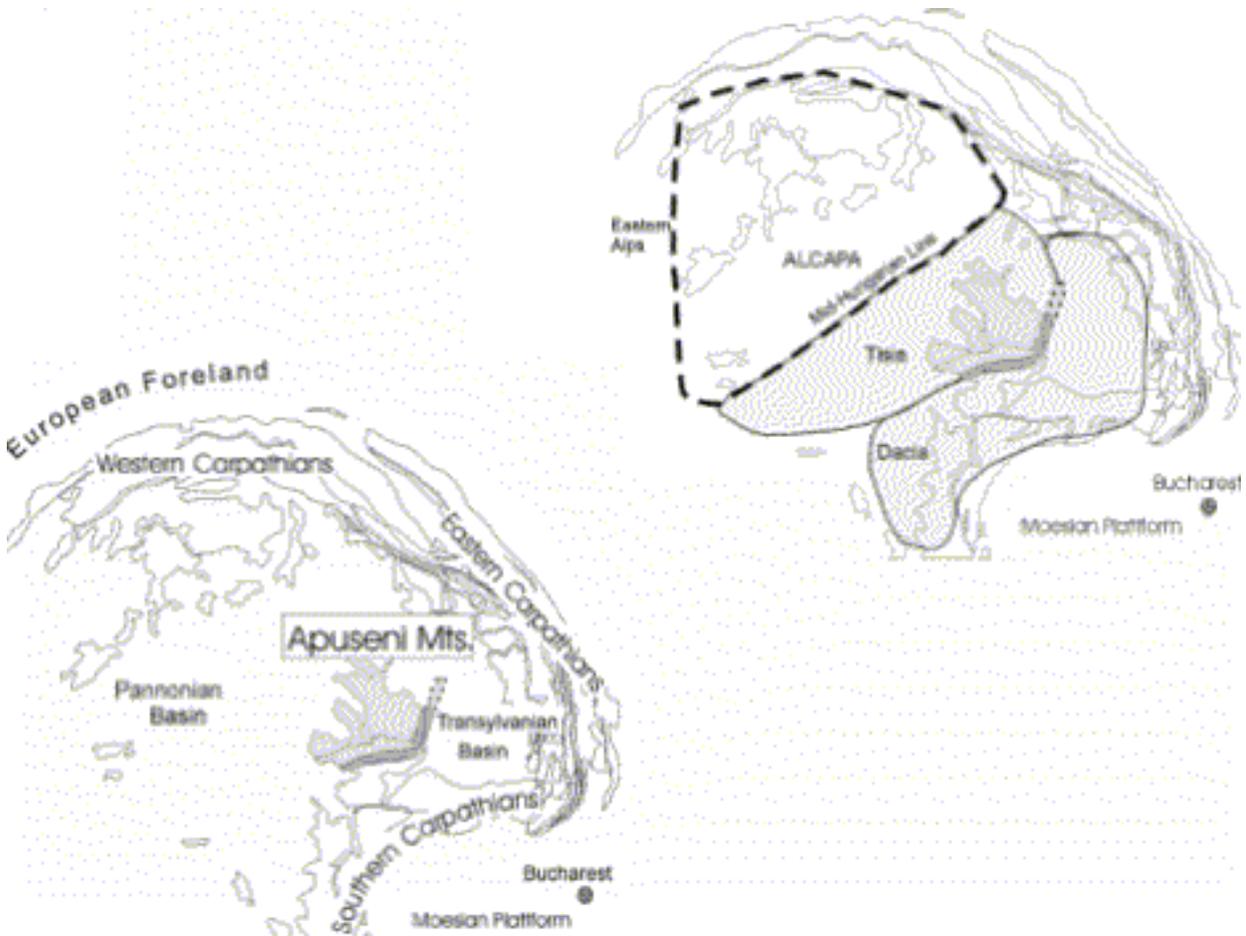
The research mentioned above, allowed the synthesis and development of cartographic representations that give a good overview of the structure and tectonic of the Apuseni Mountains and the geological map of the Apuseni Mountains scale 1: 200 000, was printed in the years 1967 to 1969. The map is accompanied by a text that containing summaries of stratigraphy, petrography and tectonic of the region. Apuseni Mountains, in a final assembly work is the guiding text of the Tectonic Map of the Carpatho-Balkan space, published in 1974 in Bratislava.

In 1976 the synthesis 'Geology of Apuseni Mountains' was published, having Ianovici V., Borcoş M., Bleahu M., Patrulius D., Lupu M., Dimitrescu R., Savu H., as authors.

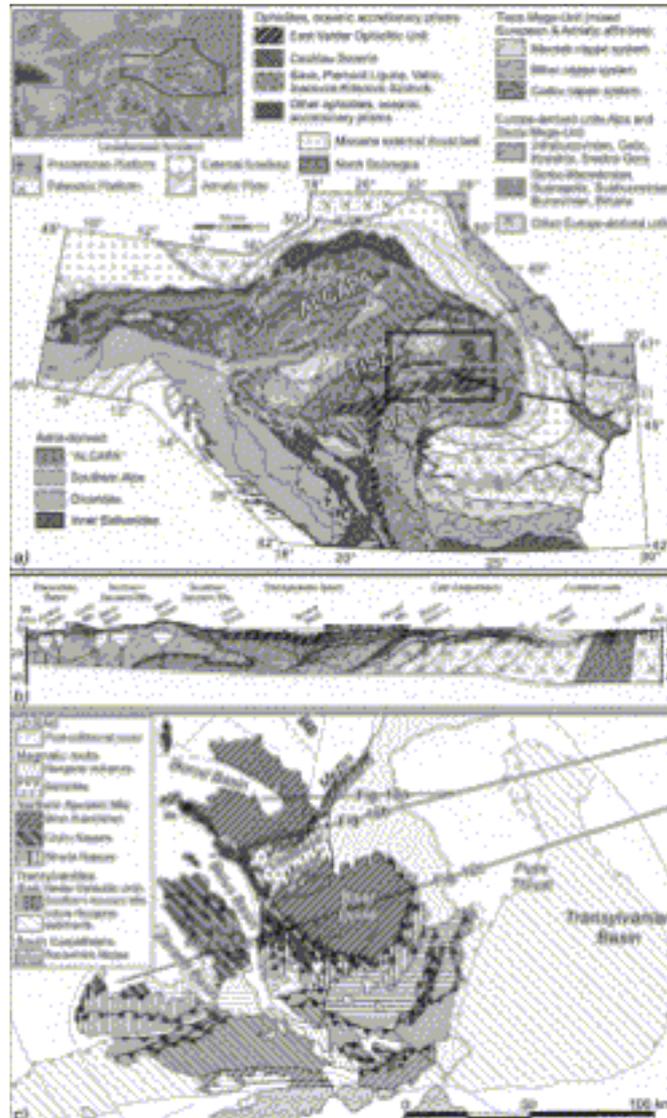
In 1985 the geological map of Pietroasa, scale 1: 50,000, elaborated by M. Bleahu et al. was printed by IGR.

### 3.1.2 Regional tectonic influenced the formation of North Apuseni Mountains

Apuseni Mountains have an isolated position within the Alpine-Carpathian-Dinaride orogen, amidst the Pannonian basin to the north and west, the Transylvanian basin to the east and the South Carpathians to the south. The Apuseni Mountains are located at the boundary between the continental Tisza and Dacia tectonic Mega-Units (e.g. Csontos and Vörös, 2004; Schmid et al., 2008). The continental Dacia Mega Unit is Europe-derived, whereas the Tisza Mega Unit shows mixed European and Adriatic sedimentary affinities (e.g. Csontos and Vörös, 2004; Haas and Péro, 2004; Iancu et al., 2005). Both Mega-Units comprise Variscan-metamorphosed basement with Neoproterozoic crustal components and Late Paleozoic to Mesozoic cover sediments (Pana et al., 2002; Balintoni et al., 2009; Balintoni et al., 2010). North Apuseni Mountains comprise the Bihor Unit, which outcrops on large surfaces and the Codru Nappe System both belonging to Tisza Mega Unit and Biharia Nappe System which belongs to Dacia tectonic Mega-Unit. Reiser et al. (2016) emphasizes an important aspect of the Apuseni Mountains: existence within these mountains of an exposed



**Figure 3.1** Geological setting of the Apuseni Mts (grey). The Moesian platform and the European foreland are forming the pre-Alpine continental basement. Dark grey (within the Apuseni Mts) shows the suture between the two microplates Tisia and Dacia. The dashed line is the prolongation of the suture in the Transylvanian basin, covered by Neogene sediments, Schuller (2004)



**Figure 3.2** Correlation between Mega-Units and structural units of the Apuseni Mts. Reproduced from Merten et al., 2011.

contact between the Tisza and Dacia Mega-Units (Săndulescu 1994; Haas and Péro 2004; Csontos and Vörös 2004; Schmid et al. 2008; Kounov and Schmid 2013). Biogeographic data (e.g. Vörös 1977, 1993) indicate a neighbouring position of the Tisza and Dacia Mega-Units along the European continental margin during the Triassic and Early Jurassic (*Figure 3.1 a*). The Apuseni Mts have been formed during Cretaceous times as a result of the convergence and collision of the two microplates Tisia and Dacia (*Figure 3.1 b*). The suture within the newly created Tisia-Dacia block crops out in the south and southeast of the Apuseni Mts. Its prolongation towards NE is covered by Neogene sediments of the Transylvanian basin. However, its existence is known from geophysical data.

From the Middle Jurassic, onwards, both units were separated from Europe. Palaeomagnetic data show a common apparent polar wander (APW) path for the European plate and the Tisza Mega-Unit up into the Cretaceous, 130 Ma ago (Hauterivian/ Barremian; Márton 2000). Between Campanian and mid-Miocene times, northward displacement and clockwise rotation by some 80°–90° affected both Tisza and Dacia Mega-Units (e.g. Pătrascu et al. 1990, 1994; Márton et al. 2007; Panaiotu and Panaiotu 2010).

**A brief chronology** of major geological events in North Apuseni Mountains, from oldest to youngest, includes:

1 - Formation of various basement tectonic units, made up of Early Proterozoic metamorphic rocks (mostly from high-grade metamorphic sequences) and associated granites (Late Cambrian ~502–490 Ma, Middle to Late Devonian ~372–364 Ma and Early Permian ~278–264 Ma), with a Permo-Mesozoic sedimentary and volcanic cover (e.g., Stan, 1987; Dallmeyer *et al.*, 1999, Pana *et al.*, 2002a).

2 - The delineation of system of nappes (Bihor, Codru, Highis-Drocea, Biharia, Baia de Aries), named the Inner Dacides (Sandulescu, 1984), which have been juxtaposed during Late Paleozoic (Variscan) orogenic activity (when they recorded three distinct tectonic phases at mid-crustal levels)

3 - Crustal shortening within Alpine tectonic activity during the Turonian

4 - Intra-Turonian ('Mediterranean') westward back-vergent thrusting, creating the retro-vergent side of the orogen in a series of four main nappe units: Mecsek, Bihor, Codru and Biharia (e.g., Săndulescu, 1984; Balintoni, 1994; Haas and Péro, 2004; Schmid *et al.*, 2008).

5 - Deposition of formations within Gosau-type basins during the Senonian.

6 - According to S. Merten *et al.* (2011), citing Bleahu *et al.*, 1981; Balintoni, 1994; Willingshofer *et al.*, 1999; Schuller, 2004, etc, the Apuseni Mountains and the neighbouring Transylvanian Basin experienced alternative deformation processes, as follows:

- o Late Cretaceous (late Turonian–early Campanian) extension. Gradual subsidence and deepening of sedimentary facies is recorded by the post-collisional covers of 'Gosau' type, associated with the contemporaneous formation of small grabens were mentioned.
- o Compression, recognized at the scale of the entire Romanian Carpathians, resumed during the late Senonian (late Campanian– Maastrichtian) 'Laramian' phase. Deformation generated structures which change strike from low-angle E-W, trending nappe contacts with top-N vergence in the Southern Apuseni Mountains to N-S high-angle reverse faults with large along-strike offset components at the eastern margin of the Apuseni Mountains (*Figures 3.3 b and c*).
- o The latest Cretaceous – earliest Palaeogene post-collisional sedimentation spans several sequences of mainly continental terrigenous sedimentation.

7 - Deformation was coeval with and followed by latest Cretaceous intrusive and extrusive (sub-) volcanic Banatitic magmatism. The magmatic rocks are mostly extrusive (sub-) volcanic in the southern part of the Apuseni Mountains (Seghedi, 2004) and mostly intrusive in the northern part, except for part of the Vlădeasa volcano plutonic complex (*Figure 3.3 c*).

- o Re-Os ages of Banatitic magmatic activity range between 88–81 Ma for the South Carpathians to 84–72 Ma for the Apuseni-Banat area (Zimmerman *et al.*, 2008).
- o For the Apuseni Mountains, K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages indicate latest Cretaceous–Eocene cooling of the Banatites (Bleahu *et al.*, 1981; Wiesinger *et al.*, 2005).
- o Based on  $^{40}\text{Ar}/^{39}\text{Ar}$  amphibole and biotite ages ranging between 89 Ma in the South Carpathians to 61 Ma in the Apuseni Mountains, Wiesinger *et al.* (2005) suggested three consecutive magmatic events: Turonian–Santonian, Campanian and Maastrichtian. The bulk of the Paleocene – Eocene ages are derived from older K-Ar measurements (Bleahu *et al.*, 1981) and represent cooling ages.

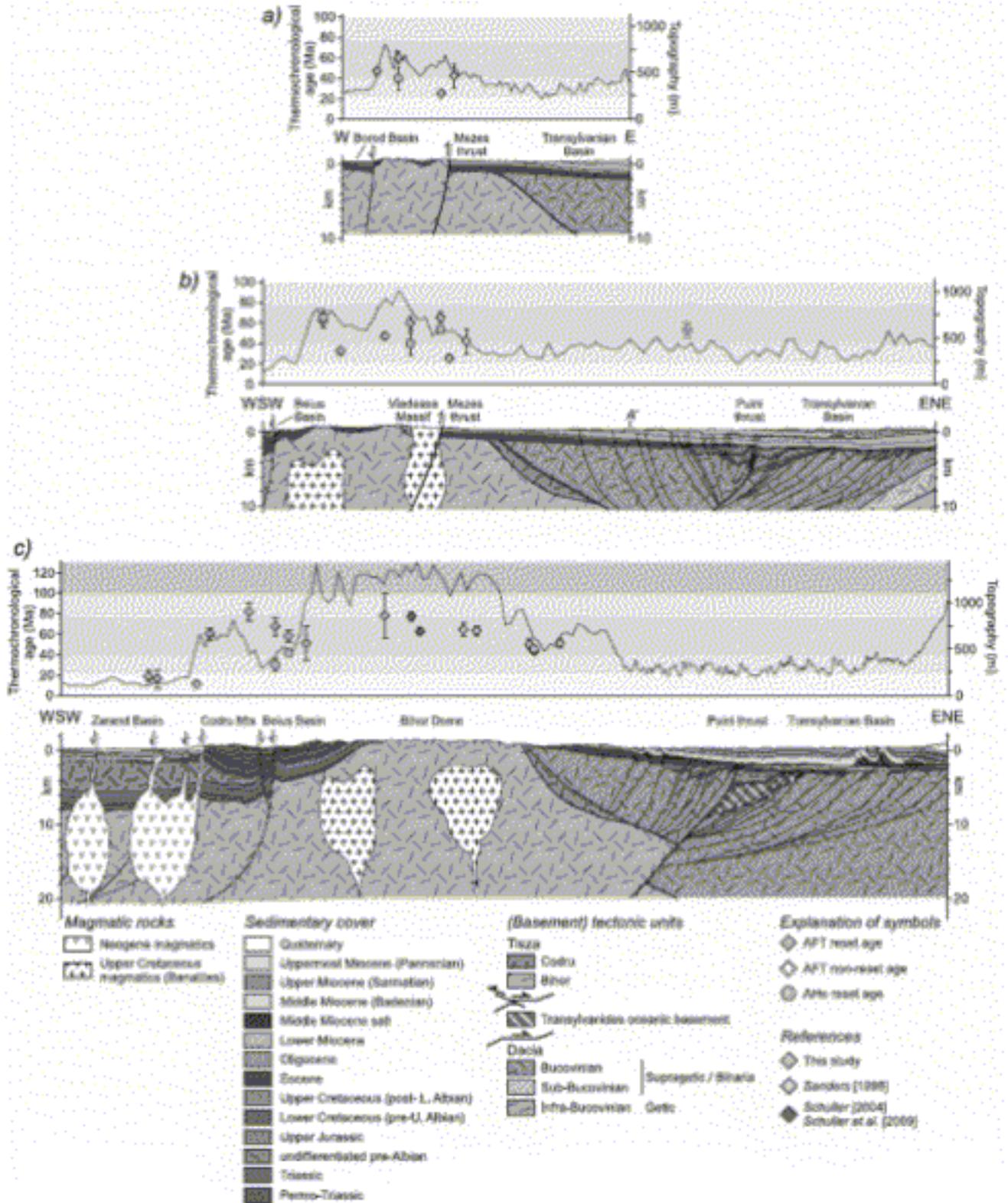
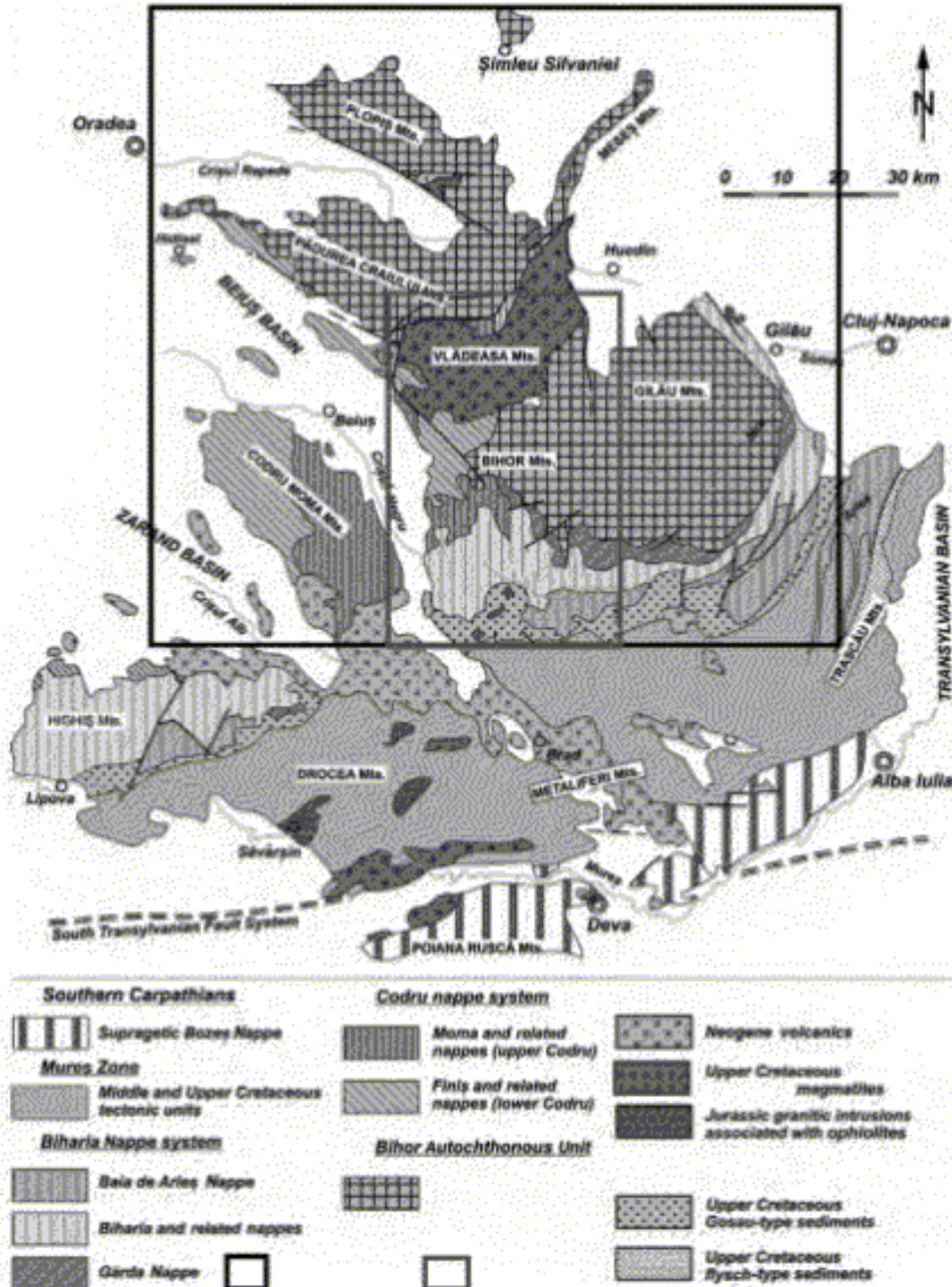


Figure 3.3 Cross-section illustrating deformation and magmatism processes in the Apuseni Mts (Marten et al, 2011)

### 3.2 Structural settings of North Apuseni Mountains

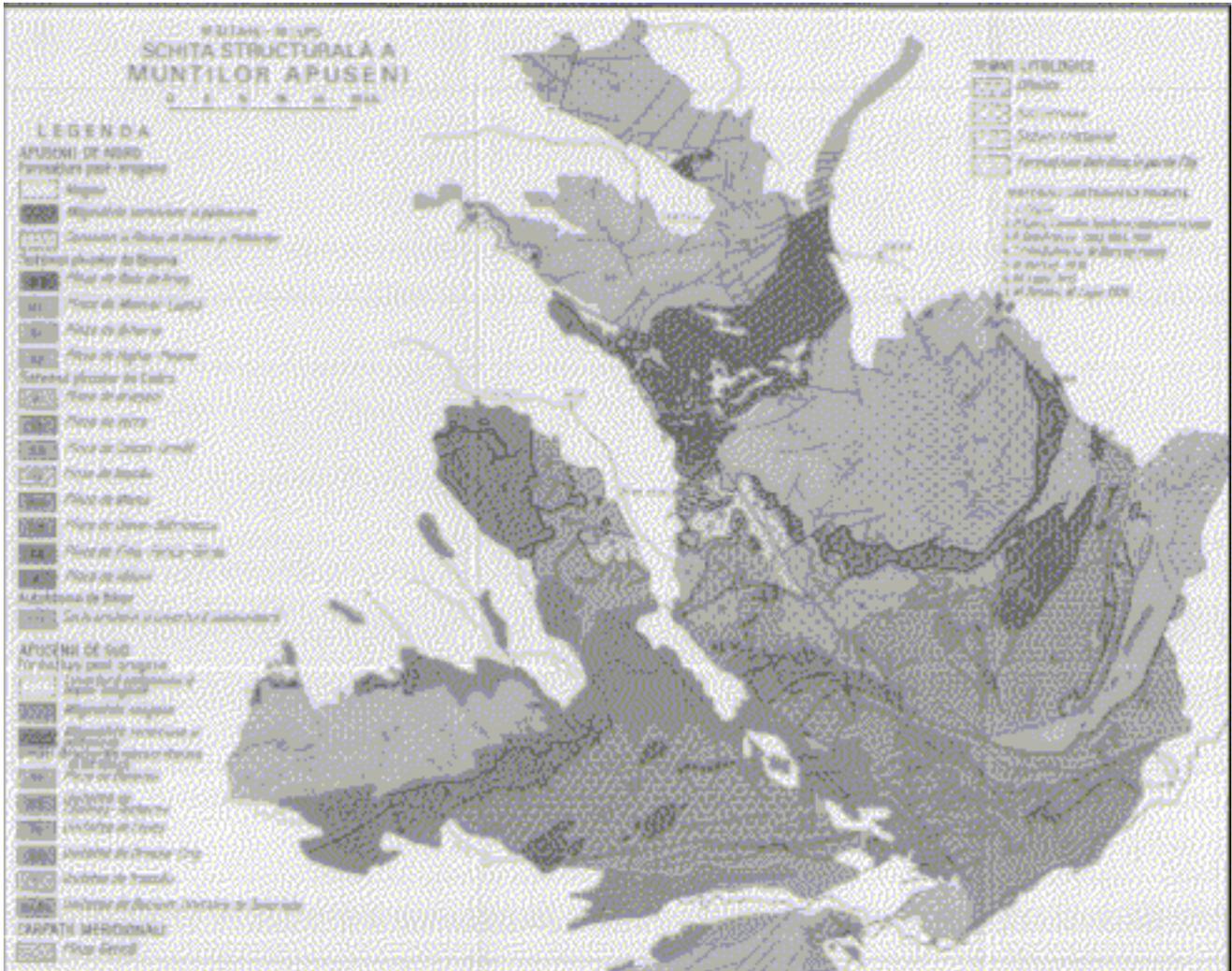
The Apuseni Mountains (*Figure 3.4*) in Romania take a central position in the Alpine – Balkan – Carpathian – Dinaride realm (Mitchell 1996; Janković 1997) between the Pannonian basin in the West and the Transylvanian basin in the East. From the morphologic point of view, the North Apuseni Mts (Northern



**Figure 3.4** Simplified Alpine structure of the Apuseni Mountains from Ionescu et al. (2009) compiled by C. Balica from papers by Ianovici et al. (1976), Bleahu et al. (1981), Săndulescu (1984), Kräutner (1996), and Balintoni & Puște (2002). Black square – North Apuseni Mts; blue square – Bihor Mts.

Apusenides or Internal Dacides) consist of Bihor Mountains together with Highiş, Codru, Pădurea Craiului, Gilău, Mezeş, and Plopiş Mts (see *Figure 3.4*). The architecture of the Apuseni Mts contains, as the structurally deepest unit, the “Bihor Autochthonous Unit” or the “Bihor Unit”. This unit has a regional extent and has a relative autochthonous position in respect to the higher nappe systems, covering a good part of the northern segment of the Apuseni Mts. The structurally higher units can be grouped, according to their origin and lithological content, in two nappe systems, thrust on top of the “Bihor Autochthonous Unit”:

- the deeper Codru Nappe system
- and the tectonically higher Biharia Nappe system.



**Figure 3.5** Tectonic map of Apuseni Mountains. Abbreviations for North Apuseni Mountains: B.A.- Baia de Arieş Nappe; M.L.- Muncel–Lupşa Nappe; Bi – Biharia Nappe; H.P. – Highiş-Poiana Nappe; A – Arieşeni Nappe; Ve – Vetre Nappe; C.U. – Coleşti-Următ Nappe; Va – Vaşcău Nappe; Mom – Moma Nappe; D.B. – Dieva-Bătrînescu Nappe; F.G. – Feniş-Ferice-Gîrda Nappe; V – Vălani Nappe; A.B.- Bihor Autochthonous

### 3.2.1 Study case perimeter

This paper focuses two main structural main units, which are relevant for our study purposes: Bihor Mountains and Beiuş Depression, which are part of North Apuseni Mts. Beside a general description of North Apuseni Mts emphasis of some specific features of these units is necessary (*Figure 3.6*).

### 3.2.1.1 Bihor Mountains

The Bihor Mountains consist of three distinct units, which are well defined both in their topography and their geological framework: Vlădeasa, Bihor and Biharia Mountains. All three have a pre-Alpine basement, consisting of crystalline schists and granitoids, generated in the pre-Baikalian, Baikalian, and Hercynian cycles and covered by a generally unmetamorphosed Permian molasse.

The basement is covered by Triassic to Lower Cretaceous carbonate and terrigenous sediments devoid of initial magmatism products. The Austrian orogeny generated the Northern Apusenides nappe structure consisting of three tectonic units.

- The Bihor Unit, built up by pre-Baikalian metamorphic rocks, and their Mesozoic cover;
- The Codru Nappe System, consisting of following nappes: Vălani Nappe, Finiş-Ferice-Gârda Nappe and Moma-Arieşeni Nappe, Dieva-Bătrânescu Nappe, Următ Nappe and Moma-Arieşeni Nappe, composed of Paleozoic and Mesozoic formations;
- The Upper Nappe System (The Biharia and Muncel Nappes), built up of deposits related to Baikalian and Hercynian tectogenetic cycles.

#### **Bihor Unit (Autochthonous)**

For the lowermost, Bihor Unit, the crystalline basement consists of the medium-grade Somes Series (micaschists, amphibolites, leptynites) and the retrogressive Arada Series (chlorite-sericite-albite schists, metarhyolites), both intruded by the Muntele Mare granitic massif. The ages of the metamorphism and of the intrusion are Paleozoic.

The sedimentary sequence of the Bihor Unit includes, (besides very scarce Permian rocks) Triassic, Jurassic and pre-Senonian Cretaceous formations. The following specific lithostratigraphic features must be underlined:

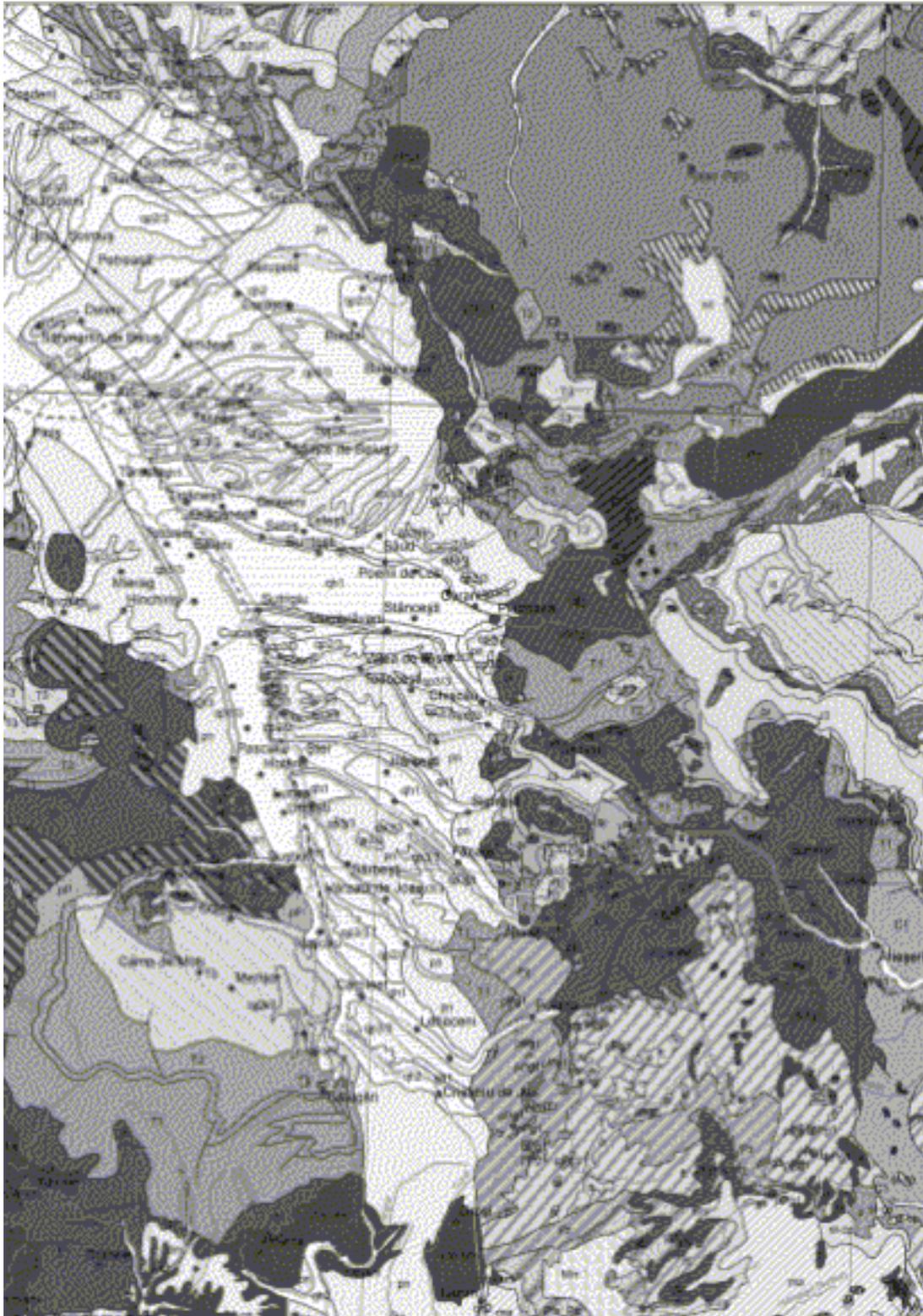
- development of a carbonate platform series from the Upper Werfenian to the base of the Carnian;
- absence of the major part of the Upper Triassic;
- Gresten paralic facies of the Lower Jurassic;
- marine sequence of the Middle Jurassic and of the base of the Upper Jurassic;
- development of a carbonatic platform in the Kimmeridgian and Tithonian;
- the uplifted and subaerially exposed Tithonian limestones were covered by residual bauxite deposits of Lower Cretaceous;
- calcareous neritic lithofacies of the Barremian and Aptian, passing into a marly sedimentation which continues in the Turonian.

The Bihor Unit corresponds to the Villány Unit in southern Hungary and to the Tatríde units in the Slovakian Carpathians, and is probably overthrust northwards onto the Tethysian Suture.

#### **Codru Nappe System**

A number of nappes are overthrust on the Bihor Unit (*Figure 3.5*).

The *Vălani Nappe* is the lowest unit, thrust over the Bihor Autochthonous, and consists of Permian to Lower Aptian sequences. The *Finiş-Ferice-Gârda Nappe*, has a metamorphic basement consisting of the Codru



**Figure 3.6** Study case perimeter map – edited in GIS by Gabriel Preda, after Geological map of Romania. Scale: 1:200,000. (Source: Geological and Geophysical Institute, authors: Bleahu, Savu, Borcoş for Brad Sheet and M.Lupu, Borcoş, Lupu, Bitoianu for Simleul Silvaniei Sheet) (*Legend on next page*)



Figure 3.6 (cont.): Legend of Study case perimeter

granitoids and migmatites, which are the oldest basic intrusions, pre-Hercynian iage (400 m. a.), according to Dallmeyer et al. (1994). As specific lithostratigraphic features, the following are to be mentioned:

- large development of Permian felsic ignimbritic volcanism;
- complete development of the Triassic sequence, with Carpathian Keuper and Kössen facies in the Late and latest Triassic;
- marine, marly-calcareous facies of the Lower Jurassic;
- development of a flysch-type sequence in the Tithonian-Neocomian.

*The Dieva-Bătrânescu Nappe* is characterized by:

- a complex magmatism in the Permian, with mafic rocks intercalated between two rhyolitic sequences;
- development of Reifling and Dachstein facies (until the Upper Norian);
- missing Jurassic rocks.

*The Următ Nappe* is developed similarly to the Finiş Nappe, in wildflysch type facies, with variations at the level of the Jurassic.

*The Moma-Arieşeni Nappe* overlies all the other units, including the Bihor Unit. The oldest formations of this nappe consist of the Lower Carboniferous Arieşeni Series (greenschists intruded by doleritic veins). The Upper Carboniferous and Permian molassic formations of reddish colour are well developed, including acidic eruptive products. The Middle and Upper Triassic formations, up to Rhaetian, occur in calcareous facies. The highest nappes of the Codru System display Triassic sequences in Hallstatt and Dachstein facies.

#### **Biharia Nappe System**

This group of nappes consists essentially of pre-Carboniferous metamorphic formations (Biharia Series: orthoamphibolites, chlorite-schists with albite porphyroblasts; Muncel Series: sericite schists, mylonitic granites, metarhyolites) overlain by the metaconglomeratic Upper Carboniferous Păiuşeni Series.

#### **Post-tectogenetic cover**

The described nappes, building up the Internal Dacides (Northern Apusenides), characterized by a Turonian main tectogenesis (similarly to the Slovak Central Carpathians or to the Eastern Alps), are post-erosionally overlain by the Senonian Gosau Formation. The reef facies of the Senonian consists of coralian limestones, while the volcanic-sedimentary formation includes alternating volcanic ashes, tuffs, tuffites, sandstones, micro-conglomerates, breccia and conglomerates with terrigenous-volcanic matrix (Mantea, 1985).

The post-tectonic subduction magmatism is represented by banatites.

#### **Neogene formations**

On the western rim of the Bihor Mountains, Pannonian s.s. (Malvensian) deposits, consisting of clays with coal, sand and gravel interbeds of the Beiuş Neogene basin infill are outcropping. In the close neighborhood of the mountains coarse deposits prevail, that are substituted gradually by pelitic facies towards the middle of the Beiuş Basin.

***Quaternary formations*** consist of sands, gravel, boulders, and, subordinately, clays. They occur in the terraces of rivers (Crişu Pietros) and along smaller streams.

#### **Late Cretaceous, Banatitic magmatism**

In the Bihor Mountains, an outstanding example of Late Cretaceous magmatism is the volcano-plutonic Vlădeasa Massif. Here a volcano-sedimentary formation is overlain by andesites, dacites and ignimbritic rhyolites; all crossed by minor quartz-dioritic and monzogranitic intrusions. The rhyolitic rocks are of different facies, ranging from massive to vitrophyres, as a function of the place where the rhyolitic magma solidification has occurred (i.e. under the Senonian sedimentary cover or subaerially). In the evolution of the

magmatic activity of this area there have been two outstanding events, namely the emplacement of the ignimbritic rhyolites formation and the set up of the intrusive bodies.

Southwards, a granodioritic-granitic batholith crops out and is also associated with andesitic and rhyolitic minor intrusions. The batholith body, which is of hypoabyssal origin, extends within Bihor Mountains, both at the surface and in the underground, up to the Galbena Fault. At the surface, in the Pietroasa – Aleului valley area, and further north, up to Budureasa, granodiorites largely outcrop. Associated with this banatitic intrusion, apophyses and bodies of andesitic or basaltic composition have been documented, especially in the upper reaches of Crișu Băița, along the Hoanca Moțului, Corlatu and Fleșcuța valleys, as well as in the Valea Seacă catchment area. The intrusion of the banatites has produced contact metamorphic phenomena affecting the sedimentary deposits traversed. At the contact of the banatites with limestones or marbles various types of calcic skarns have been formed, while at the contact with the terrigenous, granular and pelitic rocks, hornfels, garnet skarns, etc. resulted.

### 3.2.1.2 *Beiuș Basin*

The Beiuș Basin is a post-tectonic intramontane basin, infilled with Miocene, Pannonian, and Quaternary deposits overlying a heterogeneous basement of Mesozoic, Paleozoic and Proterozoic deposits of the Northern Apuseni Mountains. Around and inside the Beiuș Basin following tectonic units have been reported:

***The Bihor Unit*** is represented in the northern and north–eastern part of the basin by Upper Jurassic and Cretaceous formations; up to Albian carbonate platform deposits prevail, being substituted (toward the upper part of the Cretaceous, including the Lower Turonian) by shallow water, siliciclastic deposits.

***The Codru Nappe System*** - Bihor Unit is overlain by the Vălani Nappe, the lowest unit of the Codru Nappe System, occurring along the northern margin of the Beiuș Basin. Other tectonic units of the Codru Nappe System are the Vălani Nappe, the Finiș Nappe, and the Dieva Nappe.

The post-tectonic cover formed of Senonian formations in Gosau facies, mask the thrust contacts of the Codru Nappes, especially in Bihor Mts.

***The Neogene deposits*** are represented by Badenian, Sarmatian, Pannonian s.s. (Malvensian) and Pontian formations (Marinescu, Bordea et al, 1995). The Beiuș Basin represents an eastern gulf of the Pannonian Basin. The filling of this basin consists of Neogene deposits in Pannonian facies (Bordea et Mantea, 1999). The total thickness of these deposits does not exceed 1200 m.

***The Quaternary cover*** consists of widespread, alluvial deposits along the main streams and other genetic types of subaerial deposits.

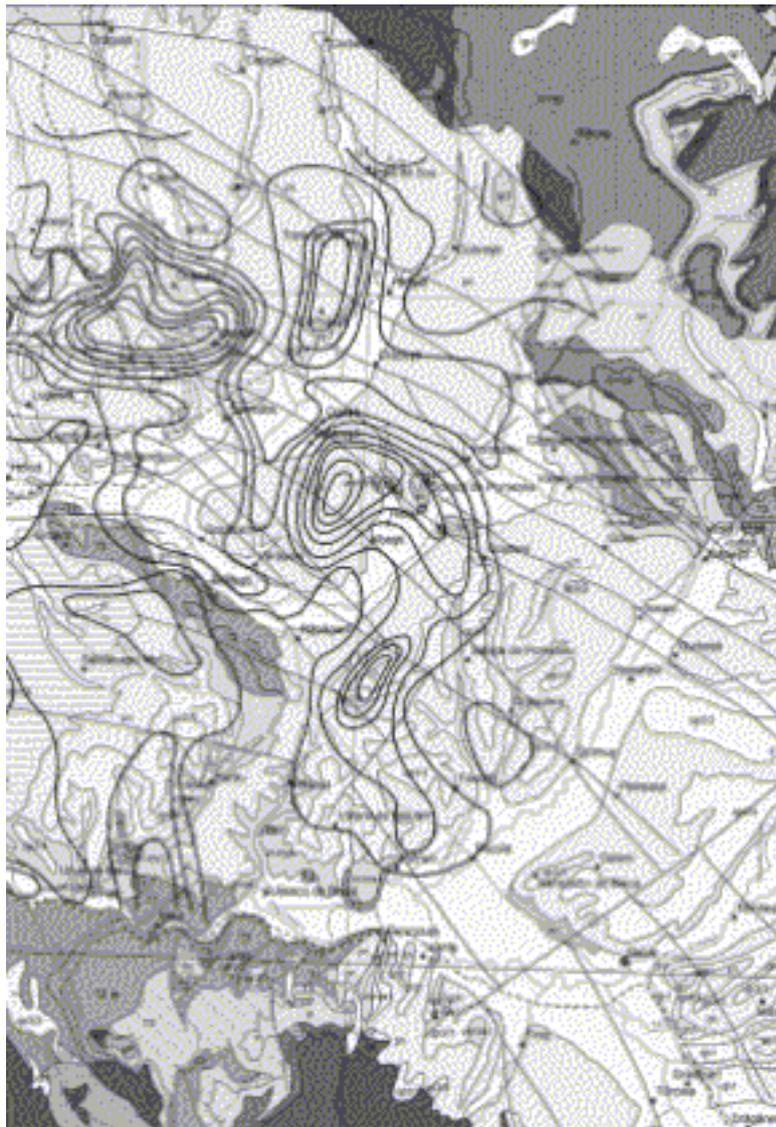
In the central–eastern part of the Beiuș Basin, east of the locality Pomezau, between Holod and Roșia valleys, banatitic intrusive rocks (Paleocene porphyric granodiorites) are cropping out. They form a 5 km long lineament, with a NW–SE trend, parallel with the Dobrești Fault (Bordea et Mantea, 1999).

### ***The tectonics of Beiuș Basin based on geological and geophysical data***

Bordea et Mantea (1999) identified a near-parallel pattern of steep, straight faults oriented along the Beiuș Basin. Some of these were intruded by banatite rocks, as in the case of the Galbena Fault, in the eastern margin of the basin. These deep, normal faults were generated in the upper crust by a tensional stress induced by thermal doming above a large banatite body and were infilled as a consequence of the vertical stress exerted by the rising of molten magma.

Aeromagnetic, surface magnetic, gravimetric and seismic (refraction methods) data were combined for obtaining an image of the deep structure of the Beiuș Basin (Dinu et al., 1991). Dinu et al (1991) presented an isobath map at the base of the Neogene fill of the Beiuș Basin. Base on this map Dinu et al concluded that the structure of the Beiuș Basin is of collapsed basin type, made of down-thrown blocks along steep-angle faults. Faulting caused topography with uplifted and dropped sectors trending NW-SE.

From the aeromagnetic anomalies two intrusive magnetic bodies have been identified (*Figure 3.7*). Aeromagnetic data show an anomalous zone with two maxima, of the same amplitude and morphology, situated in the center of the basin (Dinu et al., 1991). The anomalies are supposed to be the expression of two deep seated vaulted magmatic bodies. The top of one of these bodies is at 1.7 to 1.8 Km from surface (in the Lupoiaia zone) while the top of the second lies at 1.2-1.4 Km beneath the surface (halfway between Rotărești and Albești). The lateral extent of these anomalies was estimated to reach about 4 km at 4 km beneath the surface, suggesting the existence of a large magmatic body buried in the depth.



**Figure 3.7** Map of vertical gradient of magnetic anomaly (TZ) from Beiuș Basin

### 3.2.2 How Bihor Mountains can positively contribute to the aims of CHPM2030

- Extensive database of reports acquired especially during 1960–1995.
- Good understanding of the geological evolution of the region.
- Continuous digital geological mapping at 1:50,000 scale.
- The geological maps, scale 1: 200,000, are correlated to structural wells.
- The geological maps, scale 1: 200,000, are correlated to geophysical investigations of low resolution.

### 3.2.3 Limitations in our current understanding of Bihor Mountains

- The majority of the primary data that exists is related to the shallow sub-surface (<1,000 m, and often <200 m).
- There has also been no detailed deep geophysical investigation. As a consequence, this presents uncertainty in terms of extrapolating information and data at surface to any significant depth.

## 3.3 Geometry and composition of ore deposits

Many authors' analyses integrate Northern Apuseni Mountains Alpine magmatism within a broader context, defined by the term Banatitic Magmatic and Metallogenic Belt – BMMB –, which represents a series of discontinuous magmatic and metallogenic occurrences of Upper Cretaceous age, which are discordant in respect to Mid-Cretaceous nappe structures (Cioflica & Vlad, 1973; Ciobanu et al., 2002).

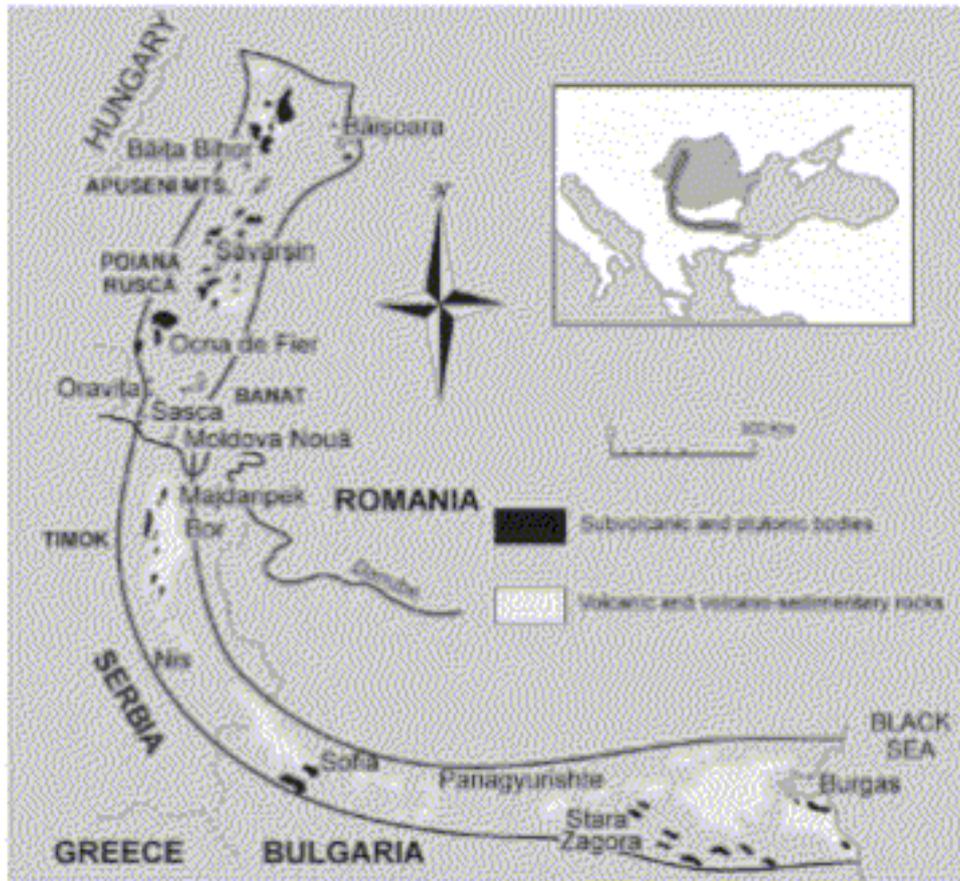
The subvolcanic /plutonic rocks belonging to the BMMB are known under the collective name of “banatites”, a term coined by Von Cotta (1864) who described a suite of cogenetic magmatic rocks occurring as either shallow intrusions or subvolcanic bodies, younger than Jurassic and Cretaceous sedimentary formations. Ever since this first description, the name “banatites” has reflected their locus typicus, that is, Banat and Timok region, covering parts of the south-western Romania and north-eastern Serbia. During the last few decades, the BMMB has drawn considerable interest in petrology, age, and structural-tectonic significance and in the contained skarn, porphyry-copper and hydrothermal ore deposits, with a vast amount of literature published to date (Ilinca, 2012).

In Europe the BMMB is exposed over approximately 900 km in length and around 30 to 70 km in width. It has a north-east to south-west trend over Apuseni Mts and Southern Carpathians, it aligns to a north - south direction over eastern Serbia (Timok and Ridanji-Krepoljin zones), and bends widely to the east, through the Srednogie area, reaching the shores of the Black Sea (*Figure 3.8*).

The occurrences of the BMMB in Romania are in Apuseni Mountains where banatites are found both as volcanics in Late Cretaceous Gosau-type basins (e.g., Vlădeasa, Cornițel-Borod, Gilău-Iara, Sălcium-Ocoliș, Vidra, Găina, Roșia) and as dyke swarms or major intrusions, cross-cutting these volcanics or any older formations or tectonic planes (e.g., Gilău, Budureasa, Pietroasa, Băișoara, Valea Seacă, Băița Bihor, Brusturi, Căzănești, Măgurea Vaței) – Ilinca, 2012.

The distribution area of banatitic magmatites in Northern Apuseni Mts is a complex geostructural assemblage represented by rocks emplaced previously to banatites, (metamorphic and/or sedimentary and igneous rocks), that are overlain by the Upper Cretaceous sedimentary cover consisting of carbonate and detrital rocks. The banatitic magmatites pierce or lie over these formations, generating magmatic contact phenomena or mineralisations, and are transgressively overlain by the Tertiary sedimentary rocks of the

Transylvanian Basin. The metallogenesis of Bihor Mountains is closely linked to the evolution of banatitic magmatism in the North Apuseni Mountains (Figure 3.9).



**Figure 3.8** Extension of the Banatitic Magmatic and Metallogenic Belt. Romania, Eastern Serbia and Bulgaria (with dark gray in the inset and with heavy outline in the map). Simplified after Cioflica and Vlad (1973)

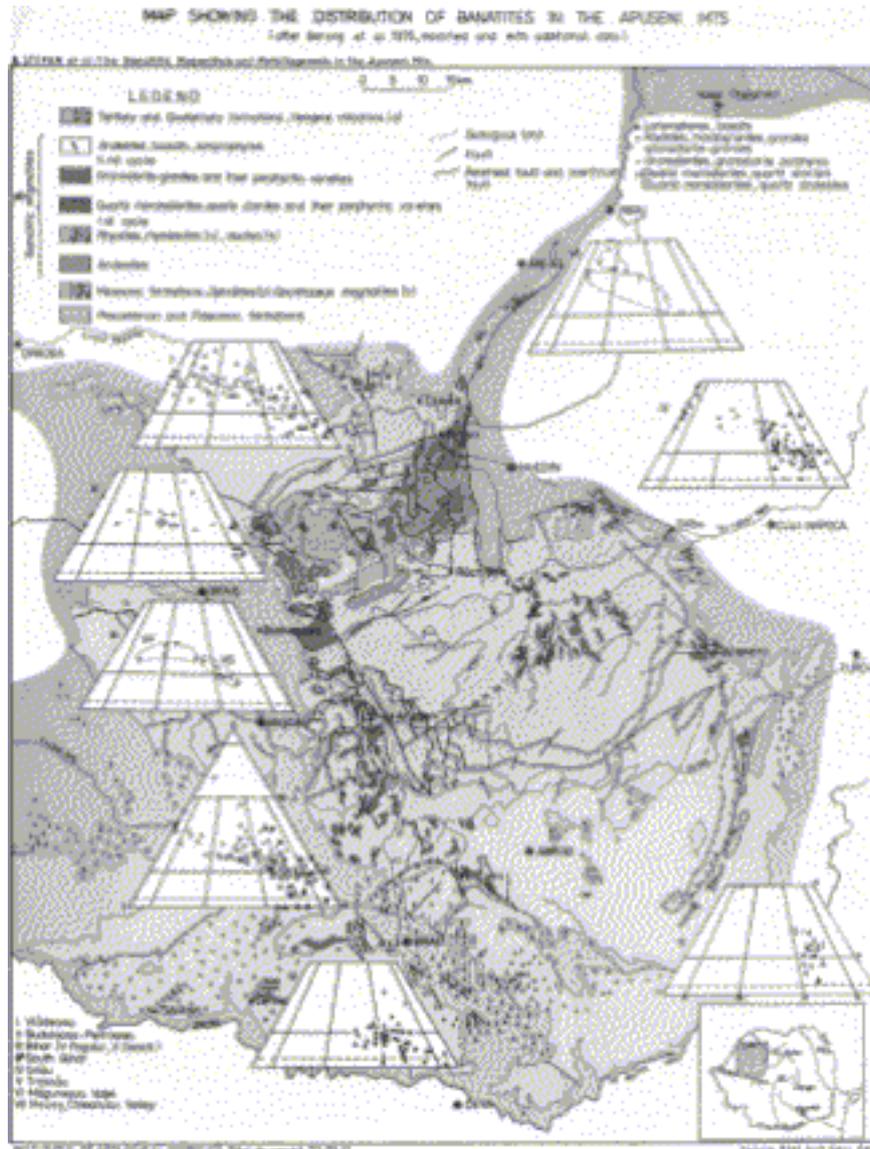
The data on evolution of banatitic magmatism and the metallogenesis of Northern Apuseni Mountains, were adapted from Ștefan et al, (1992), which synthetised the works conducted in the region before 1989 by: Mureșan, 1971; Lazăr et al., 1972; Istrate, Bratosin, 1976; Istrate, 1978; Ștefan, 1980; Udubașa et al., 1980; Istrate, Udubașa, 1981; Ștefan et al., 1985, 1986, 1988; Ștefan et al., 1989, unpublished report.

### 3.3.1 Evolution of banatitic magmatism of Bihor Mountains

The banatitic calcalkaline magmatism (Post-Lower Masstrichtian-Paleogene) which is widely developed in the Bihor Mountains, was emplaced within two important cycles unequally represented from one zone to another.

**The first cycle** is characterized by lava flows of quartziferous andesites (bearing pyroxenes and hornblende or only hornblende to which sometimes adds biotite) (Vlădeasa) sometimes accompanied by pyroclastic rocks (Vlădeasa); simultaneously superficial subvolcanic bodies have been emplaced (Vlădeasa, Bihor).

The typical development area of the first cycle volcanism – the Vlădeasa Mts – contains the greatest volume of rhyolites forming the volcano-plutonic massif of Vlădeasa (Giușcă et al., 1969). The rocks of the Vlădeasa main eruptive body cut and include andesites, dacites and two older rhyolite rock types producing contact breccias with them. Although the Vlădeasa rhyolites represent subvolcanic bodies, they exhibit ignimbrite features (Ștefan, 1980).



**Figure 3.9** Map showing the distribution of the banatites in the Apuseni Mts (Ştefan et al. 1992, modified after Borcoş, with additional data). The sites are: I-Vlădeasa; II-Budureasa-Pietroasa; III-Bihor (V. Fagului, V. Seacă); III'-South Bihor; IV-Gilău; V-Trascău; VI-Magureaua Vaței; VII – Mezeș, Chioarului Valley

The volcanic and the near-surface subvolcanic rocks belonging to the first cycle, rarely produce contact phenomena. However, andalusite hornfelses formed at the expense of some metamorphic rocks were reported in North Vlădeasa. In addition, all the xenoliths are nearly completely digested and transformed to hornfelses reaching the pyroxene facies.

The products of hydrometasomatic metamorphism are rather abundant in the rhyolites of Vlădeasa main body; epidote and sometimes zeolites are very well represented. Generally, the banatitic volcanic rocks and especially rhyolites are autometamorphically changed or are transformed by a late contribution of hydrothermal solutions; excepting pyrite, which is very rare, they are not accompanied by metalliferous minerals.

Within *the second main cycle* bodies of intrusive hypabyssal origin, or intrusive plutonic bodies have been emplaced (Proca, Proca, 1972; Cioflica et al., 1982). Late alkaline vein differentiation products of granodiorite-granitic magma were reported too. This stage of magmatic banatitic activity in the Bihor Mts ends with dykes of basic rocks (very abundant in Bihor).

Banatic magmatism of the second cycle begins with quartziferous diorites and their porphyritic varieties (porphyritic micro diorites, diorite porphyries - quartziferous andesites), which, in Bihor, cross the rhyolites of the first cycle (Jude, Ștefan, 1967). In the southern part of the Bihor Mts at Hălmăgel and Obârșă, quartziferous diorites are crossed by granodiorite-granites, and at Stânișoara, porphyritic rocks of diorites composition in the subvolcanic bodies are thermally changed into the contact aureole of a granodioritic-granitic body. At Băișoara, such rocks of diorite composition constitute the marginal facies of the rocks bodies of granodioritic composition.

In Pietroasa, Budureasa and Western Vlădeasa massif, quartz-dioritic rocks occur either as some independent bodies or at the periphery of granodiorite – granitic – monzodioritic rocks; in fact, they are included here as xenoliths. Porphyritic micro diorites are also met in the northern extremity of eastern Vlădeasa eruptive massif, north of Crișul Repede River.

Skarns often accompanied by magnetite concentration occur almost everywhere at the contact between dioritic and carbonate rocks, sometime base metal sulphides associate with the skarns (*Figure 3.9*). So, at Măgureaua Vaței skarns of a very rich paragenesis (gehlenite, spurrite, tilleyite, garnets, pyroxenes, wollastonite, and vesuvianite) are associated to  $Fe \pm Ba$  metasomatic mineralizations in the western extremity of quartz-monzodioritic body and sulphide veins in the eastern extremity on the magmatic body, where granodiorite-granites prevail. On Martin hill at Sârbi-Hălmăgel, in the aureole of dioritic body, which is crossed by granodiorites, iron oxides and sulphide mineralizations occur. Magnetite associated with banatic magmatites are also found at the spring of Arieșul Mic, Valea Seacă and Budureasa; at Valea Seacă and Budureasa, sulphide mineralizations overlie this kind of mineralizations.

Granodiorite-granites to which the main sulphide mineralizations are genetically connected constitute main mass of banatic bodies in the Apuseni Mts; although they crop out on small areas, their development in the depth was emphasized (in the Bihor Mts).

Around big bodies of granodiorite-granitic composition, phenomena of thermal metamorphism are reported. Their extension is around the pluton is 1500 m as in the Bihor Mts (Cioflică et al., 1974). Although products of thermal metamorphism are widely spread in the Bihor, excepting some intensely hornfelsed xenoliths (where sillimanite prevails) intensity of thermal metamorphism reached only the facies of hornblende hornfelses.

Under geologically favorable conditions, i.e. in the contact aureole of the granodiorite-granites plutons, Fe, B, Bi, Mo bearing skarns have been formed, locally overlapped by sulphide mineralizations, sometimes independently developed, such as the vein occurrences with Cu, Zn and Pb sulphides at Valea Seacă, Valea Mare-Budureasa etc.

The second cycle of banatic magmatism ends with alkaline differentiates rich in  $SiO_2$  and  $K_2O$ ; they form veins of aplites, micro granitic and/or micropegmatitic rhyolites, porphyritic micro granites etc. In the Bihor and Budureasa-Vlădeasa Mts such rocks form NNW-SSE trending dykes with extension varying between hundreds of meters to some (few) kilometers. Such rocks did not generate products of thermal metamorphism to be significant and are not accompanied by mineralizations (Istrate, Udubașa, 1981).

After the consolidation of the granodiorite-granitic magma, basaltic andesites, basalts and lamprophyres have been emplaced on deep fractures; they come from a different, deeper magmatic source. These basic rocks are nearly synchronous with the later differentiates of the granodiorite-granitic magma (as in the Gilău Mts) or they are much later emplaced simultaneously with the circulating hydrometasomatic solutions associated to granodiorite-granitic plutons, as in Bihor Mts. The lamprophyre dykes, typically developed in

the Bihor Mts have a similar trend, i.e. NNW-SSE, to that of differentiation products of the granodiorite-granitic magma (rich in SiO<sub>2</sub> and K<sub>2</sub>O); the former cut the alkaline differentiates.

### 3.3.2 Banatitic metallogenesis in Apuseni Mountains

Occurrences and ore deposits which are genetically associated to banatites in the Apuseni Mts belong to (Laramian) banatitic metallogenetic belt.

The Apuseni Mts banatitic metallogenesis is centred on the Bihor Mts zone, with a maximum complexity in the Băița Bihor ore deposit. An obvious horizontal zoning appears around this important ore deposit (*Figure 3.10*). The internal zone contains Co, Ni, Mo, Fe, Bi, Ag, Au mineralizations, the most typical being the Gruicul Dunii ore deposit, including the whole zone between the spring area of the Crișul Negru, Arieșul Mic and Arieșul Mare rivers. It follows a discontinuous zone with iron oxides (magnetite, hematite) and base metal sulphides; the typical ore deposit belonging to this zone is that at Brusturi (Dolii Hill). The external zone contains Pb-Zn and pyrite ores. All the zones may contain gold occurrences but they are typical of the external zone.

The regional zoning is however, incompletely known and the zones show uncertain boundaries towards east. Therefore, the metallogenesis cannot be ascribed to a single magmatic body but to several ones with simultaneous mineralizing activity. The most important is the Central Bihor pluton, in whose apical zone there are a lot of mineralized structures with skarns and subsequent polymetallic mineralizations. Periplutonic zoning of the Bihor Mts mineralizations was established both by means of metallic minerals associations and geochemical data (Lazăr et al., 1982; Cioflica et al., 1982). Northwards, the superficial pluton (Hochpluton) Budureasa-Pietroasa-Vlădeasa is accompanied by weaker mineralizations. East of the Apuseni Mts, a similar pluton, the Gilău-Băișoara zone, had a metallogenetic iron-polymetallic activity at the end of its evolution.

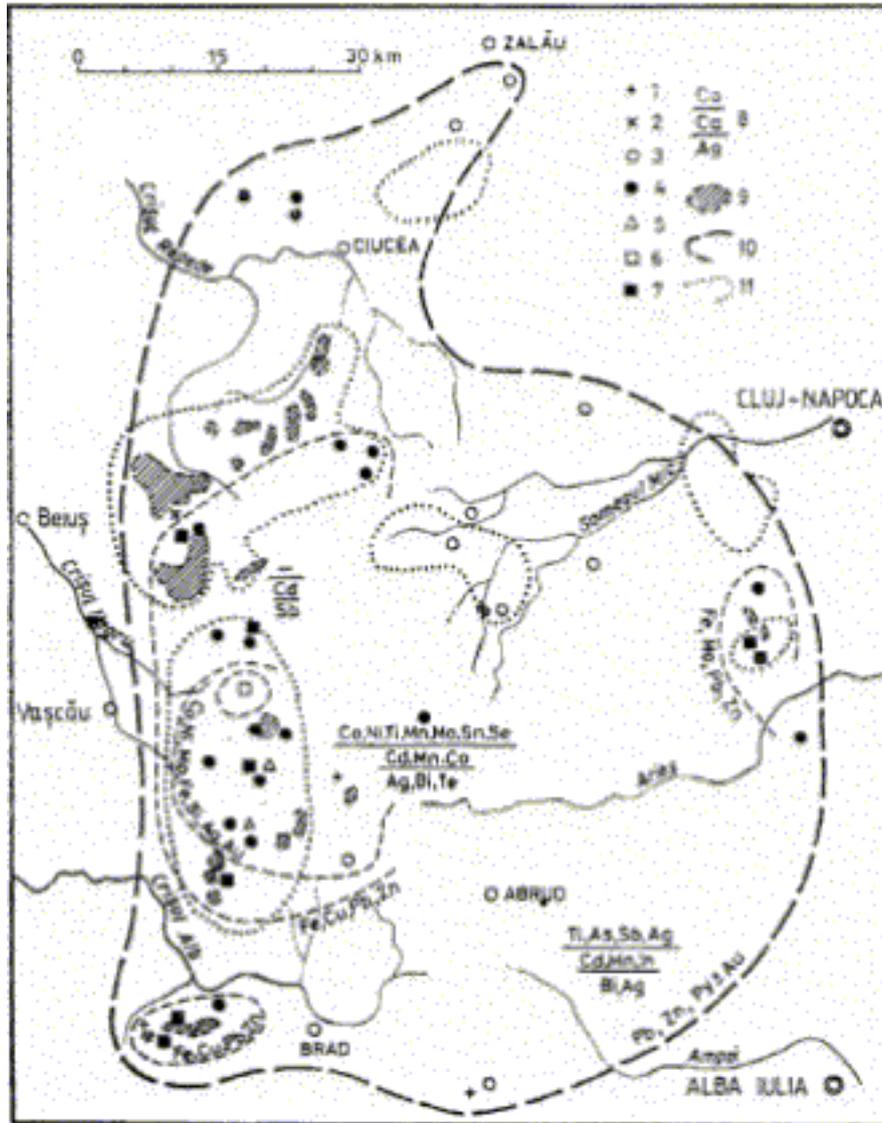
The most important types of mineralizations are the ones associated to skarns (especially B, Fe, Bi, Mo, W and Cu concentrations) and hydrothermal concentrations, in which impregnation and substitution processes played a subordinated part. Hydrothermal mineralizations are much more diversified in comparison with pyrometamorphic ones, which they often overlie.

Metallogenesis associated to banatites in the Apuseni Mts has distinct features in comparison with that from Banat. Firstly, in the Apuseni Mts skarns are not so developed; secondly magnetite mineralizations are only locally developed (Băișoara zone); thirdly the main metals in the ore deposits are more diversified than in Banat; their major geochemical spectrum includes Bi, Mo, Pb, Zn, Cu, B, Fe, W, Co, Ni, As etc. while in Banat, where according to the importance there is another series of metals: Cu, Fe, Bi, Zn, Pb, W, Mo, Co.

In the Apuseni Mts, representative bodies of skarns of very different forms and sizes are known in the Bihor-Budureasa, Gilău massifs and Măgureaua Vaței (*Figure 3.10*). Skarns generation was controlled both by the circulation ways occurred near the banatitic plutons and by the paleosome nature. The limestones and dolomites both from the crystalline series and Mesozoic deposits prove to be very favorable to the substitution processes.

Regarding the types of skarns which occur, we remark on one side, prevailing infiltration skarns in relation with the contact ones, on the other side, prevailing apocarbonatic skarns in relation with aposilicate ones; calcic skarns are more developed than magnesian ones.

Mineralizations of iron oxides occur in the Apuseni Mts, especially in Băișoara – Mașca -Cacova Ierii (Lazăr, Întorsureanu, 1982), at Măgureaua Vaței, Martin Hill (Hălmăgel), spring of Arieșul Mic end Valea Mare



**Figure 3.10** Regional distribution of the mineralization types in the Apuseni Mountains. Legends: 1, Baritine occurrences; 2, Brucite occurrences; 3, Pyrite occurrences with, or without gold; 4, polymetallic occurrences (Cu, Pb, Zn); 5, occurrences with Co, Ni, As, Bi, Ag ore; 6, Bi, Mo, W, B, Cu, Pb, Zn occurrences; 7, Fe with, or without Cu occurrences; 8, minor elements characteristic (downwards) in pyrite, spalerite, galena; 9, outcrop, areas with hollocrystalline, equigranular rocks; 10, zones contours; 11, geophysical anomalies. (Stefan et al. 1986).

(Budureasa). They associate spatially and maybe genetically either to some intrusive dioritic or monzodioritic bodies or to some basic envelopes of some granodioritic bodies. To granodiorite – granitic plutons (ex. Băița - Dedeș valley pluton, Bihor) are associated obviously polymetallic mineralizations, which consists mainly of sulphides and sulphosalts, more rarely sulphoarsenides and arsenides of Fe, Ni and Co.

Hydrothermal mineralizations are widely spread in the Bihor massif (Râul Mic, Brusturi-Luncșoara, Valea Vacii, Șipot brook, Valea Seacă etc.), as well as in Budureasa, Vlădeasa massifs, at Julești-Valea Fagului, in Plopiș Mts (at Bucea-Cornițel), in Gilău Mts (Valea Lita, Băișoara), on the Birtinului Valley and at Căzănești and Almașul Mic, in the Metaliferi Mts too.

The hydrothermal minerals are frequently spatially associated with skarn and high temperature minerals (such as magnetite, ludwigite, ilvaite, scheelite, molybdenite, bismuthite, pyrrhotite) and generally succeed

the skarn stage of post magmatic mineral formation. The hydrothermal ore minerals build up mainly veins and hydrometasomatic bodies; locally there are impregnation bodies, stock works, or simple nests.

The ore veins are related to breccias zones or along fractures and their trend (especially in the Bihor Mts) is mostly NNW-SSE, which is the same as the trend of the lamprophyres dykes closing the banatitic magmatic activity. The size of the ore veins is quite variable: hundreds of meters in length and some few meters in width. Their vertical extension varies from some tens of meters (Julești-Valea Fagului) to 100-200 m (Almașul Mic, Bucea, Cornițel) and, more rarely 300–500 m (Băița Bihorului, Brusturi-Luncșoara).

Some ore deposits have an obvious vertical zoning. A characteristic example is Brusturi-Luncșoara ore deposit, which was opened by means of mining works at about 350 m depth. At the upper levels, there is a lead-zinc mineralization, while at the lower levels; cupriferous character of the mineralization becomes more obvious. This modification of Cu/Pb+Zn ratio is accompanied by an increasing amount of skarn and iron oxides minerals.

Impregnation and/or substitution bodies can be sometimes lenticularly developed, being very long and flattened. They are often parallelly oriented with the regional system of fractures (SW-SE), rarely about E-W (ex. Bucea-Cornițel, acc. to Berbeleac et al., 1982).

Processes of metasomatic metamorphism which influenced both crystalline formations and Pre-Paleogene sedimentary rocks and banatites are very widely spread; therefore, their products are everywhere found. The aureola of hydrothermal metamorphism is much more extended than thermal and / or pyrometasomatic metamorphism, which it some time overlies.

The contact metamorphic aureola of the granodiorite-granitic pluton in the Bihor massif has the greatest extension; on the vertical scale, it reaches 2000 m or more (Lazăr et al., 1982). The alteration processes are described in numerous papers, e.g. (Gherasi, 1969; Cioflica et al., 1974, 1982; Giușcă et al., 1976; Ionescu, Berbeleac, 1971; Lazăr et al., 1982) and typical minerals of K-feldspar-, propylitic-, sericitic- and argillic alteration zones have been depicted; some alteration minerals occur in vugs, e.g. quartz, carbonates, feldspars, epidote, chlorite, clay minerals, zeolites, accompanying the ore minerals.

### 3.3.3 *Chemical composition and origin of banatites*

Stefan et al., 1992, realized a geochemical study of banatitic magmatites from Northern Apuseni Mts, based on both new analyses (chemical, emission and gamma-spectrometry, X-ray fluorescence, neutron-activation for REE) and published data; some isotope data analyses ( $^{87}\text{Sr}/^{86}\text{Sr}$  and K-Ar) were included.

The conclusions of this study are, as follows:

- The evolution of banatitic magmatism implies two cycles: a first cycle, marked by the emplacement or volcanics (andesites, dacites and rhyolites) and a second cycle, characterized by the emplacement of plutonic and hypabyssal rocks of dioritic, granodioritic and granitic composition, ending with their alkaline differentiates dykes. Basaltic andesites, basalts and lamprophyres dykes, of different origin, partly contemporaneous with the mentioned alkaline differentiates end the magmatic activity in the Northern Apuseni Mts.
- The major and minor contents and distribution, REE inclusively, compared to published data and graphically represented on diagrams, show the consanguinity of volcanics and plutonic and hypabyssal magmatites, better arguing the concept concerning the evolution of banatitic magmatism in the Northern Apuseni Mts.

- According to  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope data and other geochemical data graphically represented, one accounts for the genesis of calc-alkaline magmas by oceanic crust subduction, followed by complex evolution of melt, within several magmatic chambers, associated with assimilation and differentiation processes.
- The pointing out of two and respectively three zircon populations, which show different origins, agree with the petrogenetic concept according to which the calc-alkaline melt, generated by oceanic crust subduction, was contaminated with sialic matter during its ascension, the more obviously as the contact with the sialic crust had longer existed.

An exhaustive description of the banatitic rocks from Bihor Mts, is found in a study by Stoicovici and Selegean, 1970. Based on chemical composition, Niggli symbols, and QLM values, the authors realised Niggli's diagram for banatitic rocks, resulting the nature of magma generating the rocks from different locations of Bihor Mountains. It resulted that in Bihor Mountains, there is an important post orogenic magmatic activity, highlighted by outcropping of several intrusive bodies consisting of rock with generally neutral composition (Găina-Luncșoara), slightly acid or acidic (V. Seacă – Stânișoara) and acid composition (Pietroasa – Budureasa).

Along the principal direction of manifestation of banatitic magmatism of Bihor, which is SE-NW, there is a gradual increase in the acidity of the rock, so that, within Budureasa area, the most acidic term of banatites appears, whereas in the Găina-Luncșoara, the term most basic is in place.

The rocks that had been in contact with granodioritic magma and its apophyses, contaminating them, are made up of different series of crystalline schist rocks, of Permian sediments who were developed up to the springs of Galbena valley, and to Seaca valley. Best represented is the series of Mesozoic sedimentary rocks, of limestone composition and subordinate clay, Mesozoic rocks reaching their maximum development from V. Seacă until near the villages of Pietroasa and Budureasa.

These limestones with a regional development underwent a process of transformatin into marbles, and cracking, and these Triassic (Anisian) marbles represent the rocks in which geothermal aquifer is hosted.

The most intense magmatism is localized along a SE-NW direction, which is the direction of the main regional faults. But along this main direction, variations in the intensity of contact metamorphism of can be found. This contact metamorphism is manifested by a halo of about 100 m around intrusive bodies in the northwest region and by a halo of up to 1500 m the southeastern region.

Depending on the chemistry of the banatitic magma and depending on the specifics of surrounding rocks various types of deposits were formed, like those of molybdenum, boron, polymetallic and gold-bearing mineralized. Together they represent the important mineralised field of Bihor Mountains. These deposits are usually localized within the cupola of the intrusive body (Bihor-Molybdenum) in its flanks (Brusturi-Dobrin) or near the intrusive bodies that outcrop (Netiței-Pietroasa).

In 2015 Jacqueline Vander Auwera et al, realized an extensive analysis of the origin and composition of the Late Cretaceous igneous rocks of Romania (Apuseni Mountains and Banat). Based on new whole-rock major and trace elements as well as  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  isotopic data of a suite of samples collected in the Late Cretaceous volcanic and plutonic bodies of the Apuseni Mts (Romania) that belong to the Banatitic Magmatic and Metallogenic Belt. Major and minor concentrations from the main deposits are given below:

**Table 3.1** (next pages): Major and trace element concentrations in the Pietroasa, Budureasa, and Băița Bihor (Bihor Mts) whole-rock samples

Peri- meter	Băița Bihor	Pietroasa						Budureasa			
		Andesite	Dacite	Dacite	Dacite	Dacite	Trachy- dacite	Dacite	Trachy- andesite	Rhyolite	Trachy- andesite
SiO <sub>2</sub>	55.04	65.38	65.32	66.43	66.6	63.06	66.8	55.07	69.87	55.88	52.05
TiO <sub>2</sub>	1.08	0.6	0.49	0.62	0.6	0.92	0.62	1.16	0.42	1.29	1.47
Al <sub>2</sub> O <sub>3</sub>	15.33	15.09	14.93	15.39	14.98	15.93	15.31	18.61	13.97	19.15	18.16
Fe <sub>2</sub> O <sub>3</sub>	8.15	3.93	4.21	3.86	3.71	5.32	3.48	6.94	2.85	6.53	9.11
MnO	0.12	0.1	0.07	0.08	0.08	0.13	0.07	0.1	0.05	0.09	0.18
MgO	5.33	1.33	1.88	1.24	1.12	1.29	1.13	2.66	0.66	2.65	4
CaO	7.78	3.28	3.5	2.78	2.9	3.21	2.97	5.99	1.04	5.28	7.61
Na <sub>2</sub> O	1.03	3.66	3.29	3.84	3.69	4.46	3.79	4.08	3.16	4.09	3.27
K <sub>2</sub> O	3.19	3.79	3.52	4.02	3.85	3.62	3.82	2.32	5.73	2.91	1.8
P <sub>2</sub> O <sub>5</sub>	0.28	0.17	0.16	0.17	0.17	0.33	0.16	0.46	0.12	0.54	0.28
LOI	1.78	1.85	1.63	1.03	2	1.02	1.01	1.45	1.7	1.55	1.38
Total	99.11	99.18	98.99	99.47	99.7	99.29	99.16	98.84	99.56	99.97	99.32
<b>Minor elements</b>											
U	1.8	3.9	2.3	2.7	3	6.1	2.6	1.5	3.7	2	1.4
Th	7.2	14	12	15	14	18	13	11	16	7.5	6.5
Zr	130	207	130	208	213	287	218	211	185	1364	357
Hf	3.2	5.4	3.3	5.5	5.6	7.5	6.2	17	4.6	27	7.9
Nb	7.5	11	6.1	12	12	18	11	10	13	7.2	5.5
Ta	0.5	0.9	0.6	1	1	1.6	0.9	0.5	1.1	0.5	0.5
Ba	507	728	682	724	729	723	790	1514	647	2470	768
Rb	108	137	121	146	142	143	129	74	250	88	71
Sr	450	286	345	244	228	266	264	597	210	560	639
Cs	15.3	6.5	4.1	5.6	5.7	5.3	5.1	4.3	7.6	2.7	5.1
Ga	20	20	18	19	18	22	19	23	16	29	29
V	206	65	87	66	65	48	55	93	32	65	160
Cr	80	17	34	17	10	10	12	13	10	10	36
Co	22	7.7	10	7.7	10	11	9.7	12	7	15	22
Ni	16	8.2	9.2	4.8	6.1	5.2	5.2	6.3	4.4	6.7	12
Zn	88	55	37	50	64	66	55	64	39	94	99
Pb	8	35	17	26	34	27	29	16	23	23	10
La	25	35	26	33	37	38	36	27	35	30	17
Ce	50	66	47	67	71	79	73	56	65	57	40
Pr	6.6	8.2	5.5	7.7	8.6	9.9	8.8	6.8	7.3	7.7	5.2
Nd	25	28	19	28	32	38	31	26	23	28	19
Sm	5.7	5.3	3.9	5.3	6	8.3	5.8	5.4	4	5.8	4.6
Eu	1.5	1.4	0.8	1.3	1.4	1.9	1.5	2.2	0.8	2.2	1.9
Gd	5.1	4.9	3.3	5.3	5.7	7.8	5.3	4.8	3.8	5.4	4.1
Tb	0.77	0.77	0.47	0.78	0.9	1.26	0.79	0.71	0.57	0.67	0.64
Dy	4.5	4.5	3.1	4.9	5.5	7.4	4.9	4.3	3.5	4.4	4
Ho	0.9	0.91	0.65	1.04	1.12	1.6	0.98	0.91	0.75	0.9	0.83

Peri-meter	Băița Bihor	Pietroasa						Budureasa			
		Andesite	Dacite	Dacite	Dacite	Dacite	Trachy-dacite	Dacite	Trachy-andesite	Rhyolite	Trachy-andesite
Er	2.3	2.5	1.8	2.9	3	4.1	2.8	2.7	2.1	2.7	2.4
Tm	0.34	0.39	0.28	0.41	0.46	0.64	0.41	0.39	0.3	0.43	0.38
Yb	2.1	2.5	1.7	2.7	3.1	4.3	2.8	2.7	2	2.9	2.6
Lu	0.31	0.37	0.3	0.43	0.47	0.64	0.39	0.43	0.34	0.5	0.4
Y	26	28	20	32	32	45	30	26	24	28	22
Apatite T (°C)	837	911	901	923	921	962	920	903	919	940	794
Zircon T (°C)	622	730	690	739	741	752	744	692	752	922	711

Table 3.1 (cont.)

Sample	Rb (ppm)	Sr (ppm)	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr
R06	81	543	0.43	0.705066
R10	80	585	0.4	0.707469
R11	108	450	0.69	0.706317
R21	146	244	1.73	0.708449
R27	74	597	0.36	0.706750
R39	163	169	2.79	0.709487
R44	94	267	1.02	0.707916
R46	71	304	0.68	0.707504
R50	77	240	0.93	0.707672
R54	114	220	1.5	0.708273
R62	94	322	0.84	0.707910

Table 3.2 Whole-rock Rb–Sr isotopic data for the North Apuseni Mts (Auwera et al, 2015)

### 3.3.4 How Bihor Mountains can positively contribute to the aims of CHPM2030

- Mineralising fluids, saline mine waters and shallow ground waters are reasonably well characterised (e.g. by mineralogical studies, stable isotope, geochemical studies etc).
- Fluid circulation is reasonably well understood in the shallow subsurface.
- An ore-deposit, at Băița Bihor is in operation, and there is the possibility of new data acquisition depending on the requirements of the project.
- We could collect samples of mineralisation rocks from the mining galleries (about 300 m below surface).

### 3.3.5 Limitations in our current understanding of Bihor Mountains

- Much of the primary data that exists is related to the shallow sub-surface (<1,000 m, and often <200 m). Hence little is known about fluids existing at depths below 1,000 m, both in terms of chemistry and circulation.
- There is no possibility of having samples from deep wells.

## 3.4 Hydraulic properties, deep fluid flow

### 3.4.1 Lithology of karst in Bihor Mts

The analysis of the relationship between orebody and hydrogeology of the region defines the study perimeter, that includes Bihor Mountains and Beiuş basin. Within the geological constitution of Bihor Mountains, limestones and dolomites are prevailing, followed by sandstones, conglomerates and igneous rocks. Considering its extent, the variety and amplitude of the karstic landforms, the topography of the karstic type, ranks this specific region in the top position among all Romania's karstic territories (Orăşeanu, 2010).

The Bihor Mountains are characterised by broad surfaces of contact zones between karst and volcanic or plutonic rocks. Contact metamorphism is specific to these areas, as described in chapter 3.3. The importance of these contact zones between mineralized magmatic (metal generation units) and carbonatic rocks have to be emphasized; karst is the main transporting agent of the fluids to Beiuş Basin. There are three structural units which, together, are called Bihor Mountains, from which Crişu Negru, Someşu Cald and Arieşu Mare rivers originate.

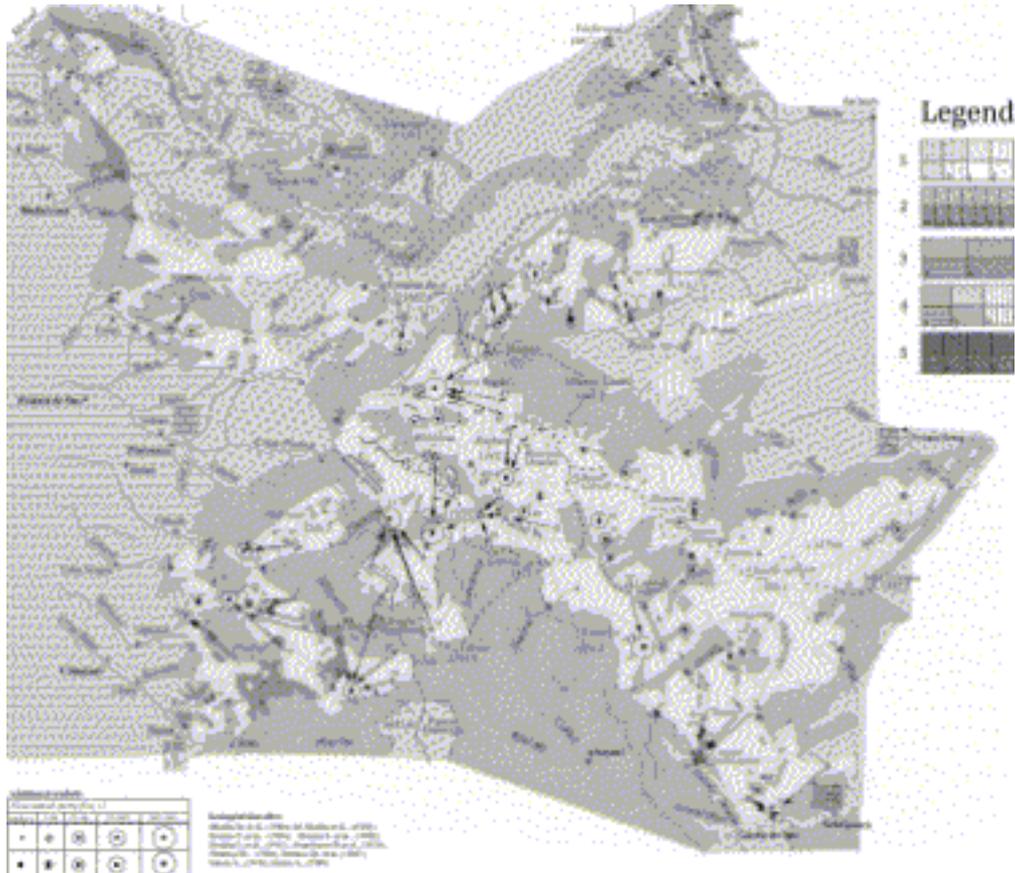
Vlădeasa massif consists mainly of intrusive and effusive formations, surrounded by sedimentary rocks. Among these, carbonate rocks are represented by: the karst area Meziad – Ferice – Valea Rea situated to the west and south-west, and the graben of Someşul Cald situated to the east and south-east.

The central compartment, Bihor Mountains, is widely developed, and is separated from Vlădeasa Mountains by Someşu Cald and Crişu Pietros river courses. To the South, Arieşu Mare and Crişu Băiţa streams delimit this compartment with respect to Biharia massif, made up of crystalline schists.

Bihor Mts display a wide variety of structural and lithological assemblages, but 5 types of deposits can be distinguished, as having distinct hydrological features. They are represented on the hydrological map and can be described as follows (*see Figure 3.11*):

1. Mesozoic carbonates series, (a- limestones, b- dolomites, c- undivided) and Paleozoic d- crystalline limestones and dolomites, highly fractured and karstified, characterized by very high effective infiltration and prevailing conduit porosity with intensive groundwater flow. They generate numerous karst systems with various size and dominant binary type. They host important water resources in large karst systems. Spring flows up to 550 l/s.
2. Paleozoic granites (a1), and rhyolites (a2) Mesozoic ophiolites (b) Laramian intrusive (c1) and volcanic magmatites (c2), and neogene volcanites (d) and metamorphites (e), with extensive fracture networks, and developed weathering zones, which provide a continuous and important supply of rivers flow and binary karst systems.
3. Prevalent molasse deposits (sandstones, conglomerates and less frequently argillaceous shales) with double porosity. The groundwater is mostly confined to the fissure and stratigraphic joints and less to intergranular pores. At large thickness, they act as an impervious barrier for karst water reservoirs and frequently form the bedrock and/or caprock for these. a- Permo–Mesozoic Molasse, b- Upper Cretaceous cover and Miocene transgressive deposits.
4. Pannonian deposits: marls, argillaceous shales, sands, gravels - (a), Pleistocene deposits - (b), and Holocene (c) deposits: sands, gravels, clays, hosting discontinuous water accumulations in more permeable terms.
5. Upper Cretaceous and Miocene marly and argillaceous deposits, devoid of groundwater flow, and flysch-like series, including rock-complexes of variable permeability (marls, argillaceous shales,

sandstones, limestones) hosting occasionally discontinuous aquifer accumulations. (a-Paleozoic; b- Upper Triassic – Early Jurassic; c-Titonian – Hauterivian; d-Upper Cretaceous – Miocene.



**Figure 3.11** Hydrogeological map of the Bihor Mountains karst areas (Orășeanu et al., 2010), according to the works of Bleahu et al., 1981, Bordea & Bordea, 1973, and to the sheets Avram Iancu (Dumitrescu et al., 1977), Poiana Horia (Bleahu et al., 1980), Pietroasa (Bleahu et al., 1985), Răchițele (Mantea et a., 1987) and Biharia (Bordea et al., 1988) of the geologic map of Romania, scale 1: 50,000. The legend details are included into the text of the report

### 3.4.2 Short hystorical review of the Bihor Mountains karst hydrology investigation

In the 1950-1970 period, the first fluorescein tracing experiments in Bihor Mountains have been performed by M. Serban et al., 1957, Viehmann, 1966, Rusu et al., 1970, the flow connections between Ocoale closed catchment area and the springs at Cotețul Dobreștilor, respectively the existence of the underground flows along the Padiș - Poiana Ponor - Cetățile Ponorului - Galbenei spring lineament being outlined as a result.

During 1976-1985 L. Valenas - alone or in cooperation, publishes in a series of papers the results of speleological investigations, which assumed a definite hydrologic character too, conducted in the karst of Bihor Vlădeasa Mountains and which have brought important contributions in this domain, as an outcome of the exploration of Groapa de la Barsa cave system (1977-1978), of Coiba Mică - Coiba Mare cave system (1978), of the cave in Pârâul Hodobanei (1982), of the karst at Casa de Piatră (1976), in the upper reaches of Someșu Cald (1978), Lumea Pierdută (1982) and in other areas.

The hydrogeologic investigations in Bihor Vlădeasa Mountains have been initiated in 1983 through the activities conducted by I. Orășeanu and Nicolle Orășeanu. During 1983-1985 they perform the first hydrogeologic mapping of the karst areas, as well as the groundwater reserves evaluation, and done some 30 new tracer experiments. The description of karst region afferent to our study perimeter area based on the

research described within the volume *Karst Hydrogeology of Romania*, having Iancu Orășeanu and Adrian Iurkiewicz as authors.

### 3.4.3 Orohydrography of the Bihor Mountains

Orohydrography of the Bihor Mountains is represented by Crișu Negru, Someșu Cald and Arieșu Mare catchment basins. The most important for our study is Crișu Negru catchment basin, because it is the river basin which connects Bihor Mountains to the eastern part of Beiuș Basin. The flow regime of both surface streams and groundwater in the karst area of the upper Crișu Băița catchment basin were dramatically influenced by the mining activities.

### 3.4.4 Karst systems

Karst systems in Bihor Vlădeasa Mountains are generally of binary type. They display a wide variety of dimensions, lithologic constitutions and dynamics that are mirrored by the physical, chemical and hydrogeological characteristics of the springs.

The karst springs are situated at different elevations, as a result of the pronounced dissection of the carbonate deposits and of the rugged topography. At the scale of the entire karst region a general base level cannot be outlined, each specific karst area having its own base level. The karst springs flow rates extend over a very wide range, with a 550 l/s maximum annual average value. So far, in Bihor Vlădeasa Mountains there have been conducted 59 tracer tests which resulted in outlining 75 underground flow paths.

The average elevation of the sinking points is 1084 m, while that of the outlets is 812 m, the distance between a sinking point and an outlet being 2098 m on the average, while tracers flowed at an average velocity of 65.5 m/hour (computed by considering the first tracer arrival). The longest distance between a sinking point and an outlet (4600 m) is that which separates the pothole in Hoanca Urzicarului from Păuleasa spring, while the maximum elevation drops (665 m) is that recorded between the underground stream sinking point in Muncelul cave (the cave in Dosul Broscoiului) and Blidaru spring in Sighiștel Valley.

### 3.4.5 Hydrogeology of karst areas

Based on tracers and hydrological monitoring studies and in correlation with lithology, and geological structure, each karst area was described and analysed by Iancu Orășeanu et al., (2010).

Within Bihor Mountains several distinct karst areas were generated by specific geological and tectonical conditions. Each of these karst areas has its own groundwater dynamics regime, and its own karstic systems.

Extracted from the Orășeanu's study, some main characteristics of these karst systems are, as follows:

Some of the springs collect their water from karst systems which display feeble inertia and which are concerned by intense karst processes, being hence highly conductive and subject to a poor capacity of storage. The rainfall input is filtered only to a small extent; heavy rainfall being immediately followed by significant flood pulses.

The average cumulated debit of karstic sources systematically monitored in X. 1984 – IX. 1985, was about 3 m<sup>3</sup>/s. The debit of 1 m<sup>3</sup>/s, representing an average cumulated debit of other springs in this mountain, must be considered too.

The memory effect of the catchment basin (Mangin, 1981a, 1981b, 1982, 1984) reflecting the groundwater reserves that sustain the runoff, is high (47 – 123 days) for basins extending on igneous rocks and/or

cristalline schists, and low (15 days) in case of basins extending prevalently on limestones, or Permo – Werfenian molasse deposits.

High values of memory effect parameter in case of igneous and cristalline rocks are due to the advanced development of the weathering layer, that acts as a storage reservoir which slowly delivers the rainfall derived water. An example is represented by Vlădeasa ignimbric rhyolites, that form an important reservoir, most of which being drained by the Drăgan river, and the Sebișel stream.

Besides the Bihor Mountains, that host important ore-bodies that can influence the water quality of the deep aquifer, we must consider Beiuș basin, where three wells for the exploitation of geothermal water are situated.

### 3.4.6 Geological and hydrogeological characteristics of Beiuș geothermal reservoir

In 1996, the well 3001 intercepted a geothermal reservoir at Beiuș. The 2576 m deep well shows a complex layer structure of the Beiuș basin. The reservoir is located in Middle Triassic limestones and dolomites, at 1887-2450 m depths. A high pumping flow rate and a water temperature of 84°C opened the perspective of extracting its thermal energy.

Transgex Company has the exploitation license for this perimeter. With state subventions, they realized the 2576 m deep geothermal well between 1995 and 1996. The following strata were intercepted:

- 0-988 m Neogen – closed with a 13 3/8-inch steel casing
- 988-1887 m Jurassic (carbonate rocks) – closed with an 9 5/8-inch steel casing
- 1887-2576 m Middle Triassic (fractured limestone and dolomites) –uncased borehole

It shows that the Beiuș geothermal reservoir, situated about 60 km south-east of Oradea, is not a local, isolated one, but of regional character.

- Well 3001 produces up to 55 l/s of hot water at 83°C, which is the well-head temperature (Transgex S.A., priv. communication).
- The second well, 3003, was drilled during 2004 and 2005, down to a depth of 2360 m (Triassic carbonatic reservoir). The well has a discharge of 65 l/s and a temperature of 73.4°C.
- Transgex S.A. drilled a reinjection well down to a depth of 2140 m, having as active layers dolomitic Triassic deposits intercepted in the interval 1285-2133 m. Pumping capacity is 180 m<sup>3</sup>/hour, and pressure of 5 bar.
- The geothermal water has a low mineralization (462 mg/l TDS), and 22.13 mg/l NCG, mainly CO<sub>2</sub> and 0.01 mg/l of H<sub>2</sub>S (ref. to table 3.3 for well 3001).

### 3.5 Fluid composition, brines, meteoric waters

Observations, measurements and analyses performed at the main springs of Bihor Mountains result in the following considerations:

- Temperature of the karst springs ranges between 5.4 and 10°C, directly related to the elevation of the supplying karst system. Some springs discharge higher temperature flows, as a result of deeper underground circulations along overthrust or fault planes.
- The pH of the discharged water is slightly alkaline, ranging between 7.15 and 7.86;
- Computed saturation indexes indicate that the water of most karst springs in Bihor Mountains is undersaturated in respect to both calcite and dolomite.
- Warm and cold springs at Valea Neagră and the spring Poarta lui Ioanel are supersaturated by calcite, the latter spring having large associated travertine deposits.

- Water of springs in the non-carbonated catchment areas of the binary karst systems is strongly undersaturated with respect to calcite and dolomite, inducing an intense dissolution of carbonate deposits. Typical in this respect are the waters of springs originating in igneous formations, with slightly acid pH value, which explains the intense development of the karst within the carbonate deposits.
- Waters of the karst systems are of calcium bicarbonate, calcium-magnesium bicarbonate and magnesium-calcium bicarbonate type, depending on the chemical composition of the traversed formations (limestones and/or dolomites), with TDS values ranging between 125–529.7 mg/l.

Laboratory	ICPT Campina		
	S.C.TRANSSEX		
Date of sample	6/14/1999		
pH/°C	7.1	Nitrate (NO <sub>3</sub> )	<1
Carbon dioxide (CO <sub>2</sub> )	163	Nitrite (NO <sub>2</sub> )	<0.1
Conductivity (μS/cm/°C)	500	Phosphate (PO <sub>4</sub> )	<.1
Silica (SiO <sub>2</sub> )	48	Sulphate (SO <sub>4</sub> )	70.4
Sodium (Na)	19	Alumina (Al)	0.1
Potassium (K)	4.4	Iron (Fe)	1.4
Magnesium (Mg)	20.7		
Calcium (Ca)	54.1		
Chloride (Cl)	6.89		

**Table 3.3** Chemical composition (mg/l) for well F-3001, Beiuș

### 3.5.1 *How Bihor Mountains can positively contribute to the aims of CHPM2030*

- There is a hydrologic database for the watersheds afferent to Bihor Mts and Beiuș Depression.
- The karst is relatively well described.
- The geothermal system is continuously monitored.
- We can have information regarding the quality of geothermal water.

### 3.5.2 *Limitations in our current understanding of Bihor Mountains*

There is not a groundwater model yet.

## 3.6 Thermal properties and heat flow

In 1985 the geothermal map of Romania, scale 1: 1,000,000, was prepared by the Institute of Geology and Geophysics. The authors, Veliciu S., Negut A., Vamvu V., synthetised of all the data acquired by that date. According to this map the geothermic flux ranges, for Romania, between 21 – 105 mW m<sup>-2</sup>. For the Beiuș basin the heat flow density ranges between 90 and 100 mW m<sup>-2</sup>, indicating an area with important geothermal potential.

The deep geological structure of the Romanian territory has been subjected to numerous studies carried out by means of various geophysical methods. Visarion et al (1978) published an article aiming to link the geothermal data to other geophysical evidence, in order to improve the knowledge on the structure and dynamics of the crust within the Romanian territory. For this purpose, a characteristic profile was selected along which most geological and geophysical features display their maximum variability. Apuseni Mts are included in this analysis. Overlapping the "International profile XI" recommended for the explosion seismology



**Figure 3.12** Extract from geothermal map of Romania (Institute of Geology and Geophysics, 1985). Only a fragment of the north – western part of the country was included, showing the situations for Apuseni Mts. The green lines = heat flow isolines ( $\text{mW m}^{-2}$ ); the red lines = geothermic isolines at 3000 m depth( $^{\circ}\text{C}$ )

investigation by KAPG and CBGA, the geotraverse under study crosses successively from south-east to north-west the following main tectonic units of the country: North Dobrogea, the Carpathian foredeep, the Bend of the Eastern Carpathians, the Transylvanian Depression, the northern part of the Apuseni Mountains and the eastern border of the Pannonian area.

In order to evaluate the thermal condition of the crust in the section of the geotraverse one has to start with surface heat flow data. According to the values reported by Veliciu et al., (1977), the surface heat flow ranges from 43–52  $\text{mW/m}^2$  in the North Dobrogea and the Carpathian fore-deep to 60–88  $\text{mW/m}^2$  in the inner part of the Eastern Carpathians and the Apuseni Mountains. The Transylvanian Depression is characterized by heat flow values of 55–75  $\text{mW/m}^2$  while the eastern border of the Pannonian Basin exhibits the highest surface heat flow exceeding 90  $\text{mW/m}^2$ .

In the western part of Romania, the thin granitic layer even if it has relatively rich radioactive content cannot entirely account for the high surface geothermal activity observed here. The considerably energy inflow from the upper mantle could have been a driving force in the geological evolution of the region as it is suggested by stronger subsidence of the Pannonian Basin in comparison with tectonic units from the east.

A zone of deep fractures established by seismic survey as well as an area of persistent shallow earthquakes of low magnitude has been contoured under the North Apuseni Mountains (Constantinescu et al., 1974).

An analysis of the heat flow of the main tectonic units in Romania, realised by Demetrescu and Maria Andreescu, in 1994 shows that the thermal regime of the lithosphere should be derived according, on the one hand, to the particular tectonic interactions the various tectonic units have been involved in and, on the other hand, to the investigated depth interval. A steady-state conduction model of the crustal temperature field based on the heat flow distribution and information on the structure is presented for the Romanian territory. The heat flow map is based on available heat flow data (167 heat flow values by the end of 1981), supplemented, in areas of poor coverage, with estimations from temperature and thermal gradient information from oil industry boreholes).

Most of the 167 heat flow values were obtained by temperature measurements down to 500–1000 m in thermally stabilized boreholes and conductivity measurements or estimations for the same depth interval (Demetrescu et al., 1991b). The heat flow contours are shown by broken lines in areas for which no (Southern Carpathians) or very poor (e.g. Apuseni Mountains, Western Transylvanian Basin) geothermal information is available.

### 3.6.1 *How Bihor Mountains can positively contribute to the aims of CHPM2030*

- The geothermal potential was evaluated based on a relatively low amount of data, but it is correlated with geophysical measurements.
- For the geothermal system in operation there is the possibility of experiments, depending on the requirements and needs of the project.

### 3.6.2 *Limitations in our current understanding of Bihor Mountains*

There is still significant uncertainty about the temperatures that might exist at the depth of an EGS system as most estimates and models are based on extrapolation of near surface historical data.

## 3.7 **Current metallogenetic models (2D- and 3D-)**

Within Bihor Mts there are three areas (Pietroasa, Budureasa and Băița Bihor) that meet some preconditions to be counted as possible pilot locations, such as:

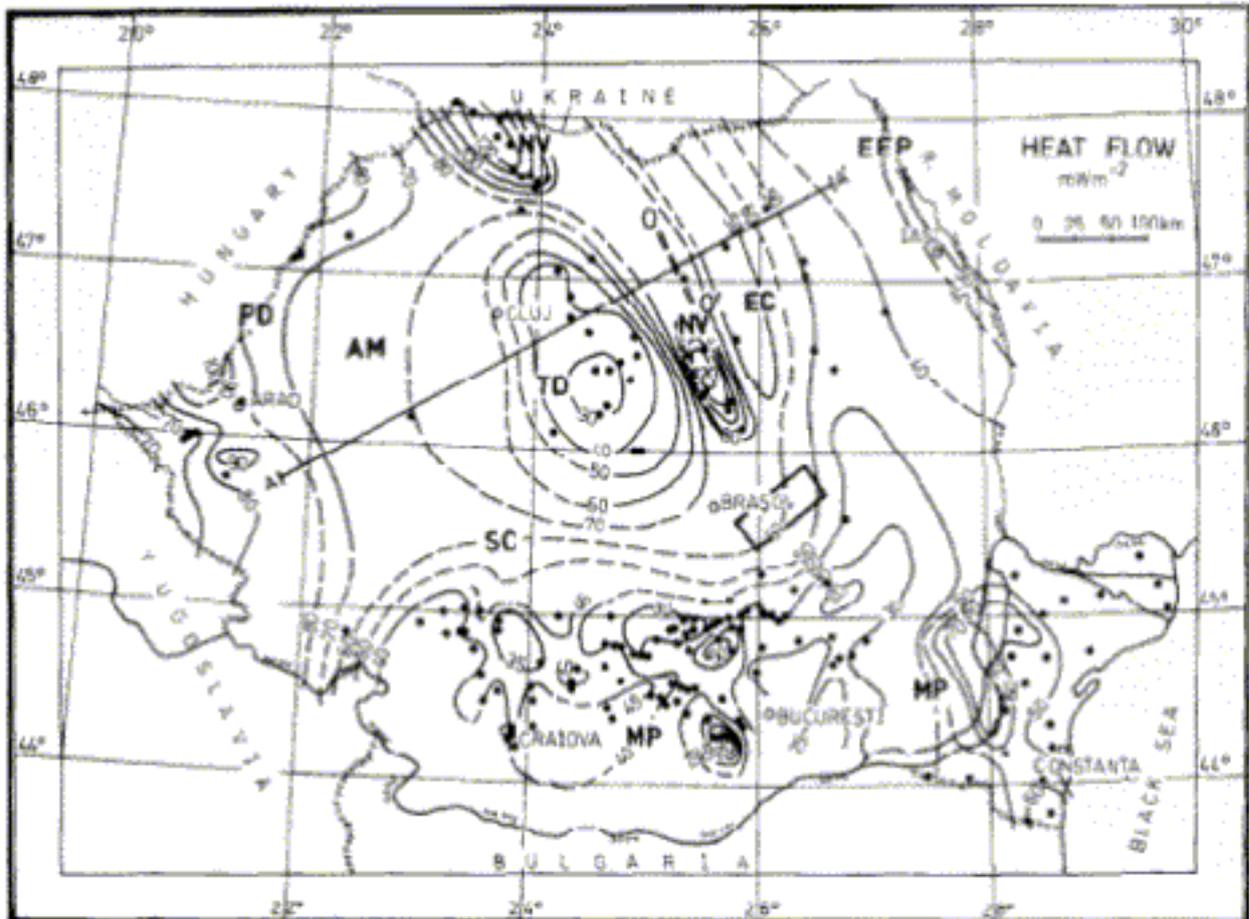
- the existence of mineralized zones in skarns, resulting from contact metamorphism in the aureoles of intrusive bodies;
- existence, in the Bihor Mountains, of carbonate deposits with regional expansion, which can be found in Beiuș Basin too, and which host the geothermal aquifer;
- intrusive bodies are situated in the proximity of Beiuș Basin, which is an area that has a high geothermal flow (greater than 90 W/m<sup>2</sup>), confirmed by extracting significant geothermal resources, which shows a temperature of 84°C at wellhead.

### 3.7.1 *Pietroasa and Budureasa sites*

Pietroasa and Budureasa represent large intrusive bodies, mainly granodioritic, associated to the huge pluton from Bihor Massif, Apuseni Mountains (Stoicovici and Sălăgean, 1970; Borcoș and Andrei, 1988 - in Borcoș and Vlad, 1994). They belong to the second stage of the Laramian magmatism (Ștefan *et al.*, 1988 and 1992). Several dacite, rhyolite and rhyodacite dykes, striking NW-SE, are crossing the two bodies. The final magmatic stage generated later several basic dykes (basalts, lamprophyres).

The intrusion of the Late Cretaceous granodioritic magma from Pietroasa (in the south) and Budureasa (in the north) into the surrounding sediments generated extended and complex contact aureoles. Permian siliciclastics and Mesozoic dolomites to limestones at the contact zone appear as hornfels, skarns, or more

general, as hydrated metasomatic rocks (Rafalet, 1963; Istrate & Udubaşa, 1981; Ionescu, 1987, 1996b, 1999; Ştefan et al., 1988; Marincea, 1993). Within the Anisian dolomitic and calcareous protoliths large brucite-bearing zones occur in the contact aureoles of the granodioritic intrusions. They form two main deposits: Pietroasa and Budureasa.



**Figure 3.13** Heat flow distribution on the Romanian territory; contours in  $\text{mW m}^{-2}$ . Dots represent surface heat flow data points (after Demetrescu et al, 1991). EC=East Carpathians; SC=Southern Carpathians; AM=Apsueni Mts; EEP=East European Platform; MP=Moesian Platform; PD=Pannonian Depression; TD=Transylvanian Depression; NV=Neogene volcanites; A-A'=possible direction of the cross-section of the Figure 3.15; O-O'=trench line; rectangle = epicentral area of intermediatedepth earthquakes (Demetrescu and Maria Andreescu, 1994)

The Pietroasa and Budureasa plutons were emplaced within a time range of 70-74 Ma (Bleahu et al., 1984). Late dacite and rhyodacite dykes, sometimes up to 15 km in length, crosscut the intrusions. According to Ionescu and Har (2001), despite the unitary appearance of the Bihor Mountains banatitic magmatism, the petrochemical studies reveal some differences between the Budureasa and Pietroasa igneous bodies. Generated in the same structural frame (continental arc granitoids), the Budureasa magmas preceded in time the more alkaline Pietroasa magmas. The petrochemical differences observed between the Budureasa and Pietroasa banatitic bodies are at variance with the presence of a single, deep situated, batholith with large apophyses (as the Budureasa and Pietroasa bodies were considered).

According to Corina Ionescu & Hoeck, (2010), the differences between the Pietroasa and the Budureasa intrusives are complex. The more  $\text{SiO}_2$ -poor composition would suggest an earlier crystallization of the

former than the latter within the overall evolution trend. This is not consistent with the relative enrichment of Fe, Mg, Ti and the depletion of Al in the Pietroasa rocks. This requires, compared with the overall trend, additional processes. Possibly granodioritic to quartz monzodioritic magmas may have assimilated Al-poor but Fe, Mg and Ti-rich minerals, i.e. amphiboles or clinopyroxenes, which altered the composition in the appropriate way. This assumption is also supported by the presence of numerous basic xenoliths in the granitoids from Pietroasa. Similar xenoliths are observed elsewhere in the Apuseni banatites but in a lower amount, as for example in the Budureasa intrusion.

### 3.7.1.1 *Brucite deposits*

Between 1982 and 1990 the brucite deposits from Budureasa and Pietroasa were investigated by surface pits, drillings and underground galleries. The brucite-bearing zones were sampled at 1 m spacing resulting in an enormous wealth of analytical, mainly chemical data (Ionescu, 1999).

A schematic and idealized view of the contact of granodiorites with the Anisian dolomites shows a structure with four zones, ranging from granodiorites to pure dolomites (Ionescu & Hoeck, 2005):

1. Granodiorites are holocrystalline hypidiomorphic, sometimes porphyritic, with large feldspar phenocrysts. Various magmatic, metamorphic and sedimentary xenoliths are common at the periphery of the intrusion.
2. Mg skarns, forming the innermost zone of the contact aureole, consist mainly of forsterite, garnet (andradite) and clinopyroxene (diopside, hedenbergite). Periclase and spinel occur as well. A wealth of hydrated minerals mainly serpentine minerals, phlogopite, talc, chlorite, epidote–zoisite, apatite, tremolite–actinolite and subordinately hydrogarnet, vesuvianite, chondrodite, clinohumite, hydrotalcite, brucite, hydromagnesite and pyrophyllite were also formed. Younger veins with quartz, magnesite, sepiolite, calcite, pyrite, pyrrhotite, sphalerite, chalcocopyrite, galenobismutite, and galena are common. The skarn thickness around the granodioritic body is relatively small, ranging from 0.5 up to maximum 7 m. The first occurrence of hydrogarnet and magnesioferrite in Romania was described from the Budureasa area by Ghergari & Ionescu (2000).
3. Brucite-bearing zones occur only at some distances (0.5 to 7 m) from the contact. The irregular, sometimes lens-shaped brucite-bearing zones range from several metres up to tens of metres in width and from tens to several hundreds of metres in length, respectively. The thickness of the brucite-bearing zone can significantly vary within the short distance. The variation of brucite content across the contact aureole around the granodioritic intrusion is highly inhomogeneous, ranging from brucite-rich, with up to 40 wt% brucite to brucite-poor domains, with less than 5 wt% brucite. The average content of brucite is around 10.5 wt% in the Budureasa area and 7.5 wt% in the Pietroasa area, respectively (Ionescu, 1999).
4. Recrystallized Anisian dolomite, without or with only very low Si and Al content, follows the brucite-rich zones. Brucite forms small lamellae of 20×20×2 μm up to 80×50×6 μm (length, width, thickness). Large individual lamellae, over 1 mm in length are only exceptionally found. Brucite lamellae group in clusters of various shapes and sizes (in average from 0.05 to 1.3 mm). Fillings of small veinlets or isolated lamellae are rare.

The studies carried out on the mineralogy, petrology and genesis of the brucite deposits reveal a model of heating and cooling sequence under conditions of very low  $X_{CO_2}$  during the contact metamorphism (Ionescu & Hoeck, 2005). The pressure estimates for the heating and cooling paths can be based on field relations.

The stratigraphic column of sediments covering granodiorites at the time of the intrusion ranges from 2.5 to 4 km (Bleahu et al., 1985), approximately equals to 0.1–0.2 GPa pressure for the contact metamorphism.

The brucite-bearing assemblages were described by Ionescu & Hoeck (2005) in the model system CaO–MgO–SiO<sub>2</sub>–H<sub>2</sub>O–CO<sub>2</sub>, with calcite–dolomite–periclase–brucite–forsterite–antigorite–(+magnesite–tremolite–quartz) as main mineral phases. The stability fields for the main dolomite-bearing assemblages in the Budureasa and Pietroasa brucite deposits show that the stability field of brucite is restricted to the very low XCO<sub>2</sub> (< 0.05) over a wide range of temperatures, up to approximately 610°C.

According to the reaction (1) Brucite = Periclase + H<sub>2</sub>O the upper stability limit of brucite at 0.1 GPa pressure, is at 600–610°C. Lower temperatures, below 400°C, can be estimated from the reaction 20 Brucite + Antigorite = 34 Forsterite + 51 H<sub>2</sub>O. The reaction Dolomite + H<sub>2</sub>O = Brucite + Chalcocite + CO<sub>2</sub> can take place over a wide range of temperatures.

Based on field observations and theoretical considerations it is concluded that brucite formed by three main processes: a) a prograde reaction, which generated periclase in the close vicinity of the intrusion, followed by a retrograde reaction forming brucite in the presence of a vapour phase; b) directly from dolomite at lower temperatures and c) by decomposition of forsterite.

### 3.7.1.2 Borate deposit

In the middle basin of the Aleului Valley (Bihar Mountains), at its confluence with the Sebisel Valley, at the Gruilui Hill, an important endogene borate deposit, including ludwigite and szaibelyite, pointing to the kotoite presence, was identified. The mineralized site is situated at about 4 km NE of the locality of Pietroasa (Bihar District). The occurrence, investigated by mine workings, had also been pointed out (Stoicovici, Stoici, 1969; Stoici, 1974). In 1992 this deposit constitutes the study object of a thorough mineralogical study, realised by S. Marincea.

The ore deposit is hosted in a zone with magnesian hornfels (*sensu* Turner, Verhoogen, 1960), at the contact of the Pietroasa banatitic pluton with Anisian dolomite limestones of the Ferice Nappe (see Bordea, 1973, for details).

The data analysed by Marincea, (1992) consisting of mineralogical and physico-chemical study of szaibelyite and associated minerals in the Gruilui Hill occurrence, correlated with general geological aspects led as to the following conclusions:

- The formation of the borates from the contact aureole of the Pietroasa granitoid body is the result of an infiltration metasomatic process. This process explains the frequency of the occurrence of ludwigite disseminations in other parts of the contact aureole of the body (Rafalet, 1963). In case of the Gruilui Hill occurrence the significant boron-fluorine supply implies large metasomatic processes compatible only with an intense diffusion metasomatism.
- The hypothesis of a diffusion metasomatism implies the tectonic control of the boron minerals disposition in case of the Gruilui Hill occurrence. This hypothesis, also supported by Stoicovici and Stoici (1969), is based on the location of the mineralized zone nearby a Major fault of the Galbenii fracture system (with a NW-SE disposition): Tirău-Măgura Guraniilor Fault, at its intersection with a network of conjugated fractures.
- The presence of minerals with potential fluorine contents (clinochumite can contain up to 4 per cent F according to Aleksandrov, 1982) makes plausible the hypothesis of the boron transport as fluoro-boric compounds with alkaline solutions as an age. (Barsukov, Egorov, 1957). The interaction with

the dolomitic background makes possible the decrease of the alkalinity of such solutions, necessary for borate precipitation.

- Iron seems to be the primary precipitant of boron, as indicated by ludwigite formation before the pure magnesian borates. The iron deficit in the system would make possible the synchronous crystallization of such borate (that is of suanite or fluoborite) as well as the later crystallization of kotoite (Barsukov, Egorov, 1957).
- Boron-(fluorine) metasomatic supply is unique, influencing the preservation of the pure magnesian character of the primary borates, imprinted by the paleosome origin. The character of these borates, highly susceptible to the acceptance into the network of cations like  $Mn^+$ ,  $Sn^{4+}$ ,  $Ti^{4+}$ , induces the extreme magnesian character of the Gruicul Hill szaibelyite, for which the secondary genesis has been admitted.
- The constancy of the magnesian contents in calcites occurring in areas with hornfels affected or unaffected by the boron metasomatism (see point 2) leads to the conclusion of the extension of this metasomatism in zones where the limited development of the silicate minerals made possible the formation of an "excess" of magnesium available in the carbonate phases. The reverse correlation between the abundance of the silicates and the abundance of the boron minerals implies the active role of the lithologic control in the location of the Gruicul Hill mineralization.

### 3.7.2 Băița Bihor site

As the majority of Romanian skarn areas, the skarns at Baita Bihor are developed in the contact aureole of an important body of "banatites" (a major granite- granodiorite intrusion of Late Cretaceous - Paleogene age). The banatites at Baita Bihor belong to an extended pluton (the Southern Bihor batholith) and were ascribed by Stefan et al. (1988) to the second cycle of the Iaramian magmatism in the Apuseni Mountains (Danian-Ypresian in age). Calcic and magnesian skarns largely develop within the contact aureole. They have as protolite Mesozoic sedimentary formations belonging to some structural units individualised as the Codru Nappes System (the Vetre, Urmat and Vălani Units) and the Bihor Autochthon (the Bihor Unit): Bordea, Bordea (1973).

As a peculiarity, the magnesian skarns at Baita Bihor materialise metasomatic columns described as bodies by Stoici (1974) or by Cioftica et al. (1977). They are preferentially hosted by some areas of dolomitic marbles or magnesian hornfels resulting from the thermal metamorphism of the dolostones in the Vetre Unit (the Frăsinel dolosparite, of Carnian – Norian age) and in the Vălani Unit (the Obârșia Izbuț Formation, of Anisian - Carnian age). Magnesian skarn bodies were described by Stoici (1974) at. Baia Rosie, Bolfu - Tony, Hoanca Motului, Antoniu, Sturzu and Martha.

From the mineralogical point of view, the magnesian skarn assemblages consist of forsterite, spinel, clinohumite, humite, chondrodite, diopside, phlogopite, tremolite, dolomite, calcite, with superposed talc, serpentines, and brucite. They show strong disequilibria with scarce or no paragenetical intergrown phases. Mineralizations of iron oxides, magnesian borates, base-metal sulphides and Bi-sulphosalts were recognised to overlap on the magnesian skarn areas (Cioftica, Vlad, 1968; Stoici, 1974; Cioftica et al. 1977).

According to Stoici, (1983), at Băița Bihor there are the following are types of deposits: metasomatic bodies, columns, veins, impregnations, lenticular sheet lenses and layers.

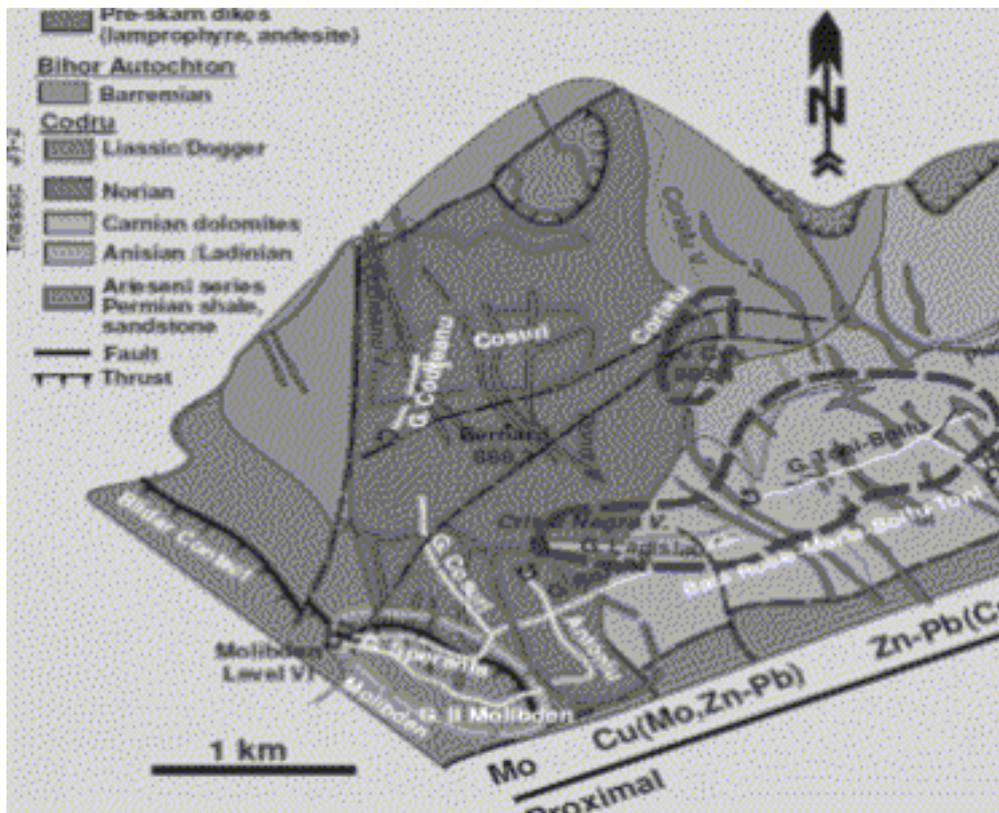
Metasomatic bodies are localized along fractures with a regional alignment that coincide with the contact between a carbonated rock and intrusive body. A classic example is the contact Blidar, along which there have mineralized skarns, with a thickness of 5 to tens of meters, which are opened by mining works over a length of 600 m and a height difference of 500m.

Columns are widespread in the Baita Bihor. They are situated at the intersection of two fault systems (Baia Roşie, Sturzu, Antoniu) at the incidence place of a dyke with a fault system (Bolfu - Tony, Hoanca Moţului), or in tectonic zones between two eruptive veins (Gustav, Reichenstein). Veins are less widespread, and impregnations are widespread, but with an insignificant economic importance.

Polymetallic sulphide and Iron mineralization from Băii Valley have form of lenticular layers, consistent with blastodetritic complex schists. The lenses are the result of residual aluminum and iron accumulations (Sighisel Valley, Valea Seaca).

The contact-metamorphic zone at Băiţa Bihor is developed over a wide area (many square kilometers) owing to the influence of an unexposed intrusive body, the Bihor batholith. The batholith consists mainly of granodiorite and granite porphyry with subordinate quartz monzodiorite and diorite (Stoici 1983, Ştefan *et al.* 1988). A whole-rock Rb–Sr isochron age of  $70 \pm 5$  Ma has been reported for granodioritic rocks of the Bihor batholiths (Pavelescu *et al.* 1985). This is some 10 Ma younger than a K–Ar age of 81 Ma reported for similar rocks in satellite bodies by Bordea *et al.* (1988), but older than other K–Ar ages (in the range 50–61 Ma) mentioned by the same authors (Bordea *et al.* 1988). The intrusion may be consequently assigned to the most important magmatic event in the region, the “banatitic” one, of Upper Cretaceous – Paleocene age.

The influence of calcium and magnesium metasomatism, and these lithologic-petrographic and tectonic factors, led to the formation of important masses of skarns. Depending on the rock that generated the suite of neoformation minerals, skarns are of several types: calcic, magnesian, calcic – magnesian and microdiopsidic.



**Figure 3.14** Sketch representing Baita Bihor Cu (Mo, Zn-Pb) skarn location (Ciobanu *et al.* 2002). Deeper parts of Antoniu have grades of 1-2 g/t Au in bornite ore, also rich in Ag, and Bi. 2 Mt of Gold are target for the present exploitation.

**Calcic skarns**, having wollastonite, garnets (grossular and andradite), vesuvianite and calcite, and as secondary minerals: diopside, hedenbergite, zeolites, fluorine, quartz, apatite, bustamite, are connected to industrial ore of Mo, Bi, W, with important content of Cu, Pb, Zn, Au, Ag.

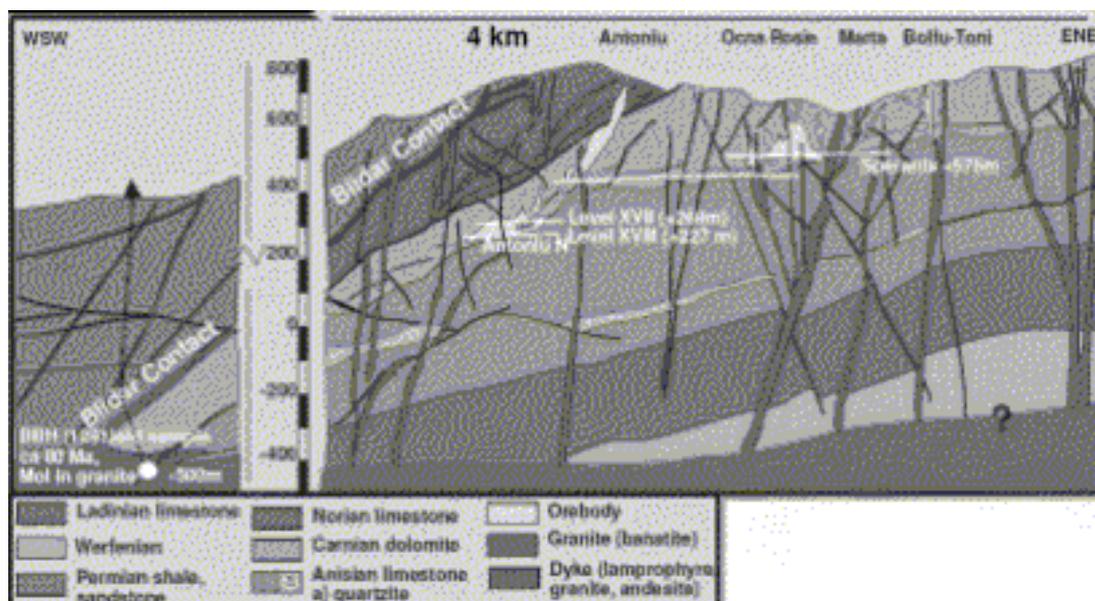
**Calcic – magnesian skarns** are formed mainly by diopside and calcite, which contain a suite of minerals, from oxides and sulphides class, which were exploited since the last century.

**Microdiopside skarns** are characteristic for the veins situated within Băița Molybden ore-body.

**Magnesian skarns** are described below (see Marincea, 2001):

Extensive boron metasomatism affected the rocks in the contact-metamorphic zone and is locally manifested in magnesian skarns developed at the expense of sequences of dolostone of Anisian – Carnian or Carnian – Norian age (Bordea *et al.* 1988). Such skarns are commonly boron-bearing and occur in well-expressed metasomatic columns or “skarn bodies” (*i.e.*, those at Baia Roșie, Antoniu, Hoanca Moțului and Bolfu–Tony). The skarn bodies, now mostly removed by intensive mining for base-metal sulfides, extended downward to more than 400 m below the surface; only small exposures may now be observed at the surface. A geological sketch of the Băița Bihor area is given in *Figure 3.14*. Stoici (1974, 1983) gave additional details concerning the geology and mining operations in the area, as well as extensive cartographic descriptions.

Magnesian borates (*i.e.*, kotoite, suanite, ludwigite, fluoborite, szaibelyite) are found in the outer zones of the metasomatic columns, whose inner zones generally consist of diopside-bearing skarns. The boron-bearing skarn is always located at the very contact of the dolomite marble. The abundance of kotoite is remarkable; for this reason, Watanabe (1939) gave the name “kotoite marble” to this rock. In fact, the internal zoning of the boron-bearing skarn is more complex, including an external zone with suanite and an internal one with kotoite (Marincea 1998). Szaibelyite is widely distributed and occurs in all the boron-bearing skarns. Its modal abundance (up to 30% of the rock volume) is highest in the outer zones of the boron-bearing skarn bodies, where the mineral extensively replaces suanite (Marincea, 2001).



**Figure 3.15** Cross-section representing Baita Bihor Cu (Mo, Zn-Pb) skarn location (Ciobanu *et al.* 2002). The intersection of the Antoniu and Blidar faults is considered the main control for this trend (mine geologist O.

Kiss)

Ciobanu et al. (2002) described the link between bismuth tellurides and gold within deposits in the Banatitic Magmatic and Metallogenic Belt, describing the situation from Băița Bihor. We extract some data from this article.

In 2015 a short presentation of the Băița Bihor mine is posted on the internet by VAST Resources PCL, which has the exploitation license. It states the following:

- Mine hosts; copper, silver, zinc, lead, tungsten, gold, molybdenum, bismuth and antimony;
- Depth potential below the deepest Level 18 has only been drill tested for about 90 m – it is not yet certain how deep the skarn mineralisation will persist before being cut off by an underlying granite intrusion – see below
- The branching skarn geometry suggests the mine is currently in the shallow upper levels of the system and the deep roots could persist for at least several hundred metres – an old Russian hole in the 1970s indicated +350m from base of mine to granite.
- Orebody is zoned vertically with Au-Ag caps and Pb-Zn being richer at upper levels.
- Copper grades increase with depth from ~0.8% Cu near surface to >2% Cu below Level 18, with spectacular Ag and Au grades (200–2,000 g/t and 1–4 g/t respectively) associated with copper on thin veined contacts with the host dolomite.
- Antonio 2 pipe lies approximately 300m north of Antonio 1, both have good access from drives (galleries) down to Level 18 at Antonio 1 and Level 15 at Antonio 2.
- Postulated that the Antonio 1 and 2 pipes may merge at depth forming a substantially larger orebody representing a priority drilling target.
- VAST Resources has rights to mine polymetallic minerals (Cu, Pb, Zn, Ag, Au), molybdenum, bismuth, wolfram, boron, and wollastonite on exploitation licence LE 999/1999 until 2019, renewable thereafter in 5 year periods.

### *3.7.3 How Bihor Mountains can positively contribute to the aims of CHPM2030*

- A large amount of data (e.g. geochronology, fluid composition, mineralogy, geochemistry, etc.) has been generated from ore deposit research in Bihor Mountains.
- A good understanding is developing of how magmatism, fluids and large-scale structures have interacted to produce economic mineralisation. This data and knowledge has implications for engineered geothermal systems.

### *3.7.4 Limitations in our current understanding of Bihor Mountains*

- There is significant uncertainty about the form and scale of mineralisation below 1,000 m.
- The distribution of data coverage is generally skewed towards areas where economic mineralisation has been exploited or commercial mineral exploration has occurred.

## 4 Identifying target sites for future CHPM

### 4.1 Extending existing models to greater depth, integrating data down to 7 km

More information can be added in order to decipher the relation between the two structural units Bihor Mts and Beiuş Basin, and to indicate to what extent alpine magmatism that is described within Bihor Mts can influence the sedimentary basin, from where geothermal water is extracted.

#### 4.1.1 *Magnetic and gravity contributions to the deciphering of banatitic structures*

The extensive petrophysical studies carried out by Andrei et al. (1989) have shown the main contrasts of both magnetisation intensity and volumetric density which command the way of reflection of the banatitic structures in the gravity and magnetic images. Moreover, these studies have allowed to identify the presence and to establish the importance of other sources of gravity and magnetic anomalies with similar features to those caused by banatitic magmatites.

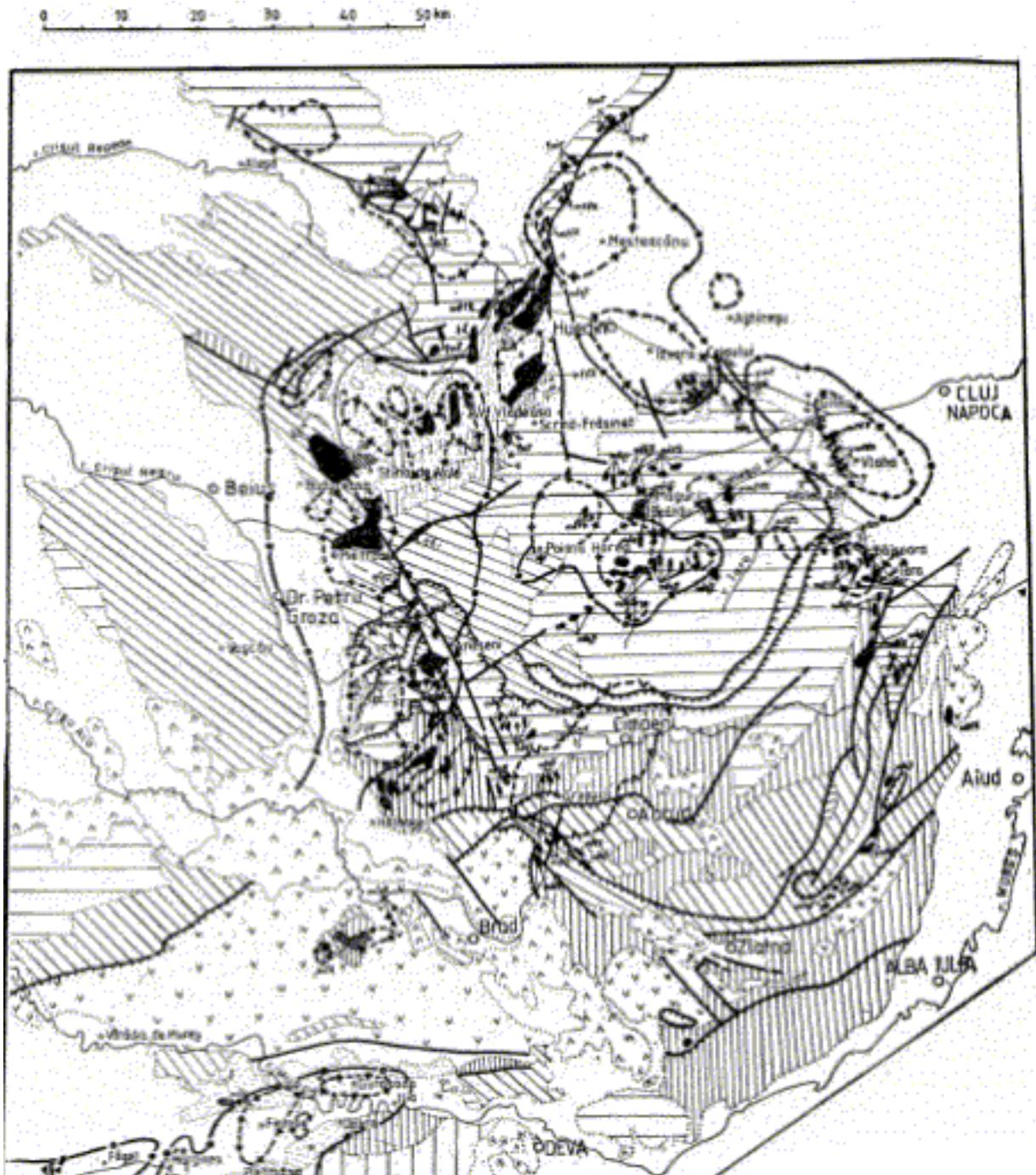
The banatitic magmatites cause in most cases positive contrasts in magnetisation, with the exception where host formations are Moesozoic ophiolites or crystalline series including important masses of metabasitic rocks. Thus, the banatitic magmatites, in the absence of hydrothermal alterations in argillaceous facies, have usually values- of magnetic susceptibility of over 1000–1500 cgs units.

Only the main mass of the rhyolites from Vlădeasa show magnetic susceptibility values lower than 100-200 cgs units. The magnetic susceptibility of intermediate-basic banatites (diorites, monzodiorites, gabbros, etc.) is, as an average, almost double in comparison with that of the acid ones (granodiorite, granite, monzogranite) especially because of the higher content of ferromagnetic accessory minerals (magnetite, titanomagnetite, ilmenite).

In most cases the intensity of natural magnetic magnetization is subordinate to the induced magnetization, especially in the case of acidic banatites. At the magnetization excess caused by the banatitic magmatites, there are added, with varying importance, those of the thermal metamorphic aureole either izochemical or allochemical. In this respect, the most outstanding example was pointed out in the upper part of Bihor - Vlădeasa pluton in v. Leuca — v. Băiţa area where the Permian deposits of the Arieseni unit have acquired a high magnetization because of the muschetovization of the hematitic pigment of rocks under the influence of izochemical thermal metamorphism on an aureole of around 1600 m. The skarns with magnetite show large values of magnetic susceptibility in direct connection with the amount of this mineral. The hydrothermal alterations in argillaceous facies diminish down to cancellation of the magnetic properties of banatites and associated formations depending on the intensity of these processes.

The acid banatitic intrusive rocks show density deficits of 0.10–0.15 g/cm<sup>3</sup> in comparison with crystalline basement formations, ophiolitic basalts, Permian deposits and several levels of the Triassic. Compared to the Jurassic and Cretaceous formations, their density deficits are small (sometimes very small), while in comparison with the granitoids of internal and middle Dacides, as well as with Werfenian deposits in Seiss facies, the acid banatites do not create any density contrast. The intermediate-basic banatitic intrusive-bodies usually generate density excesses against the host formations with the exception of metabasic terms of several crystalline series. The quartz diorites and quartz monzodiorites have a density similar to that of the mainly metaterrigenous crystalline formations. The hornfelsification processes that influenced the host rocks cause a minor modification of density while the pyrometamorphic metamorphism brings about an important increase of the density. The hydrothermal alteration in argillaceous facies of the banatitic rocks causes a density decrease if no significant pyritisation occurs.

This short picture of the petrophysical contrast reveals that the acid banatitic intrusions cause usually normal magnetic anomalies, combined frequently with gravity minima especially over areas with crystalline formations. The intermediate basic banatitic intrusions bring about steeper magnetic anomalies that may be doubled by gravity maxima. The magnetic anomalies always add the effect of the thermal metamorphism aureole to that of the banatitic intrusion itself. In case of very deep hydrothermal alterations in argillaceous facies, the banatitic structures may not disturb the geomagnetic field. In such situations like Masca-Baişoara and Florimunda - Varad, the magnetic anomalies are caused only by the magnetite  $\pm$  pyrrhotite skarn cover of the respective bodies.



**Figure 4.1** Distribution of depth banatitic structures deduced from aeromagnetic and gravity data (Andrei et al., 1989) - see the legend on the next page

## GEOLOGICAL SKETCH MAP OF THE DISTRIBUTION OF DEPTH BANATITIC STRUCTURE OF ROMANIA DEDUCED FROM AEROMAGNETIC AND GRAVITY DATA

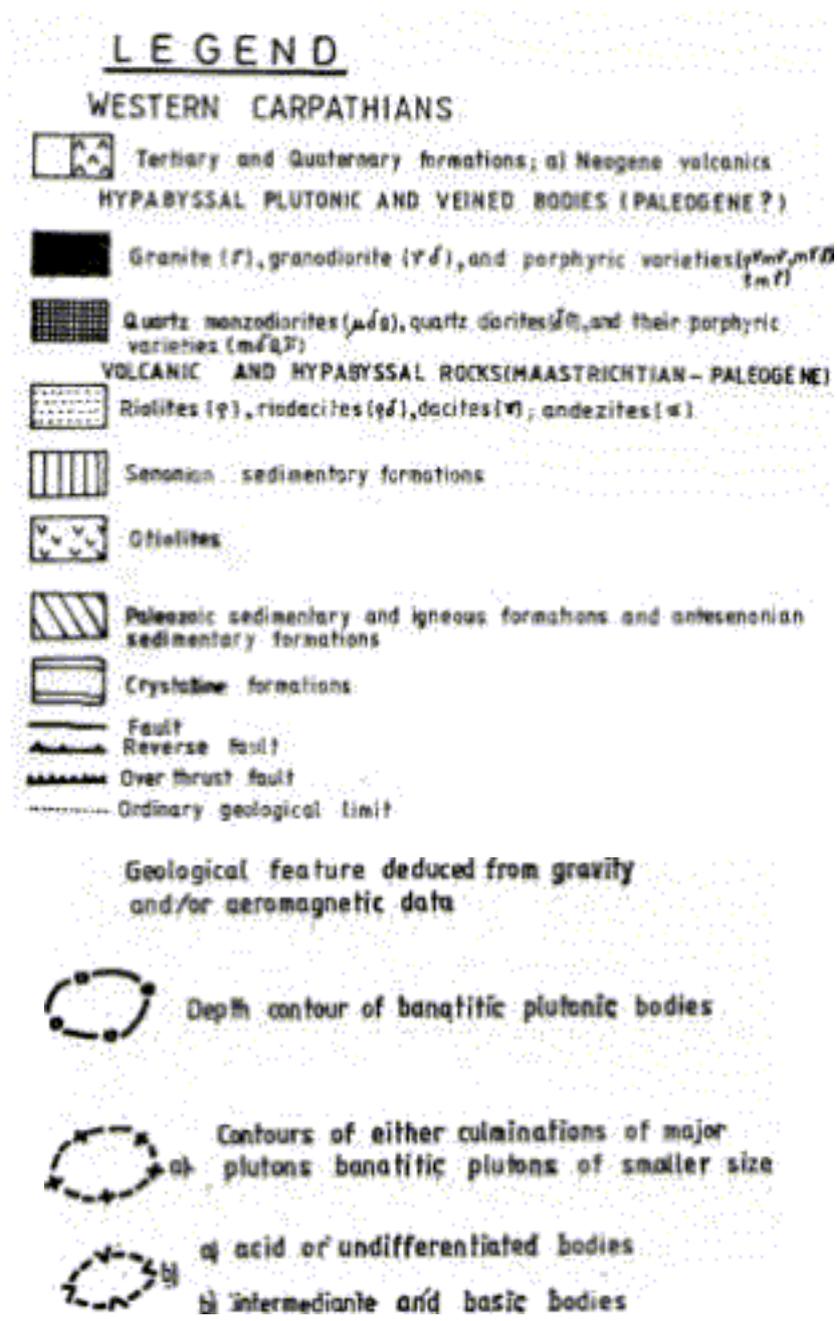
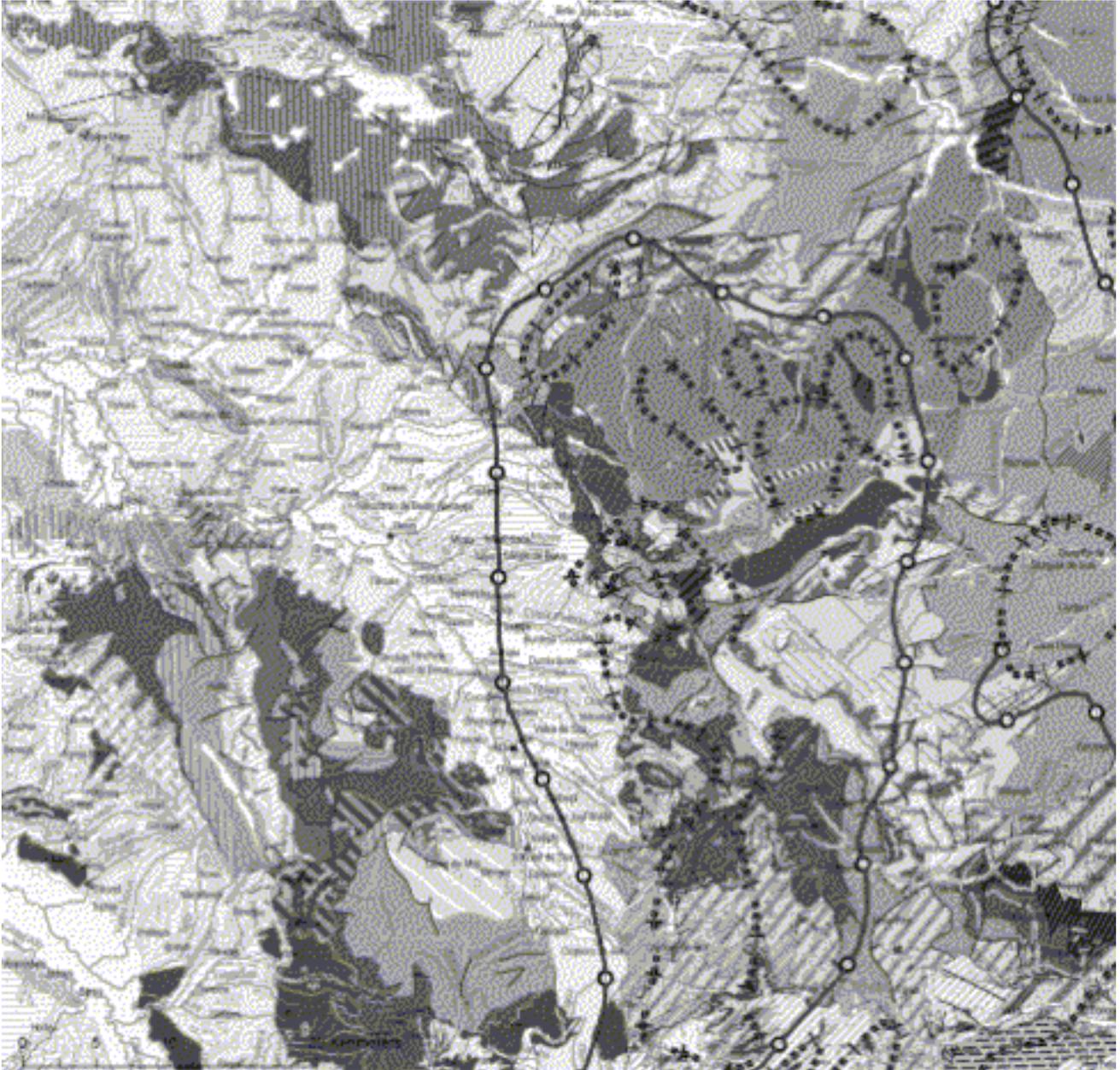


Figure 4.1 continued

By applying the interpretation criteria described above, the map of banatitic structures from Romania as inferred from aeromagnetic and gravity structures was elaborated by Andrei et al, (1989). Most of the structures pointed out are of intrusive type, but sometimes (Vladeasa, Mureș Through and Rusca Montana basin) the perturbing bodies comprise masses of volcanics and/or epiclastic formations.

Figure 4.1 qualitatively presents the depth and culmination contours of plutonic bodies and also of several main hypabyssal intrusions. The geophysical map was projected on the study case perimeter map. The result

is shown in Figure 4.2. From this map, the extension of hypabyssal plutonic body can be seen, within both Bihor Mountains, and the Beiuş basin.



**Figure 4.2** Geophysical data projected on the study case perimeter map. Legend for geophysical features: 1. depth contour of the Bihor banatitic plutonic body=O----O; 2. contour of culmination of banatitic plutons of smaller size; +- - - + 2a – acid or undifferentiated bodies; 2b-intermediate or basic bodies. > - - >

#### 4.1.2 Geological contributions to the deciphering of banatitic structures

A team from the Geological and Geophysical Institute of Romania coordinated the elaboration of general profiles accross Romania, that synthetise all geophysical and geological knowledge gathered from reports. The team was coordonated by Ştefănescu and, for the Bihor Mountains the following data were integrated:

- aeromagnetic, gravimetric and seismic data from: Fl. Ionescu, M. Niculin, L. Popescu – Brădet, V. Teodorescu, E. Spînoche;
- geologic data from: M. Ştefăneacu, Şt. Panin, S. Bordea, I. Balintoni and P. Polonic;

For this study we present a fragment of one of these profiles, 1-A (Ștefănescu et al.), which is a cross-section between Codru Moma Mts – Beiuș Basin – Bihor Mts, (Figure 4.3). The profile crosses from south west to north east the central part of the study case perimeter. The section indicates a succession of nappes that overlie the intrusive plutonic body. According to this cross-section, over Bihor Autochthonous, Vălani Nappe is extended and, in its turn, is covered by Finiș Nappe. Above them Arieșeni Nappe overlies to the south, or Dieva Nappe overlies to the north. According to this cross-section one can observe that all these nappes are to be found in both the eastern part of Bihor Mountains and the western part of Beiuș basin.

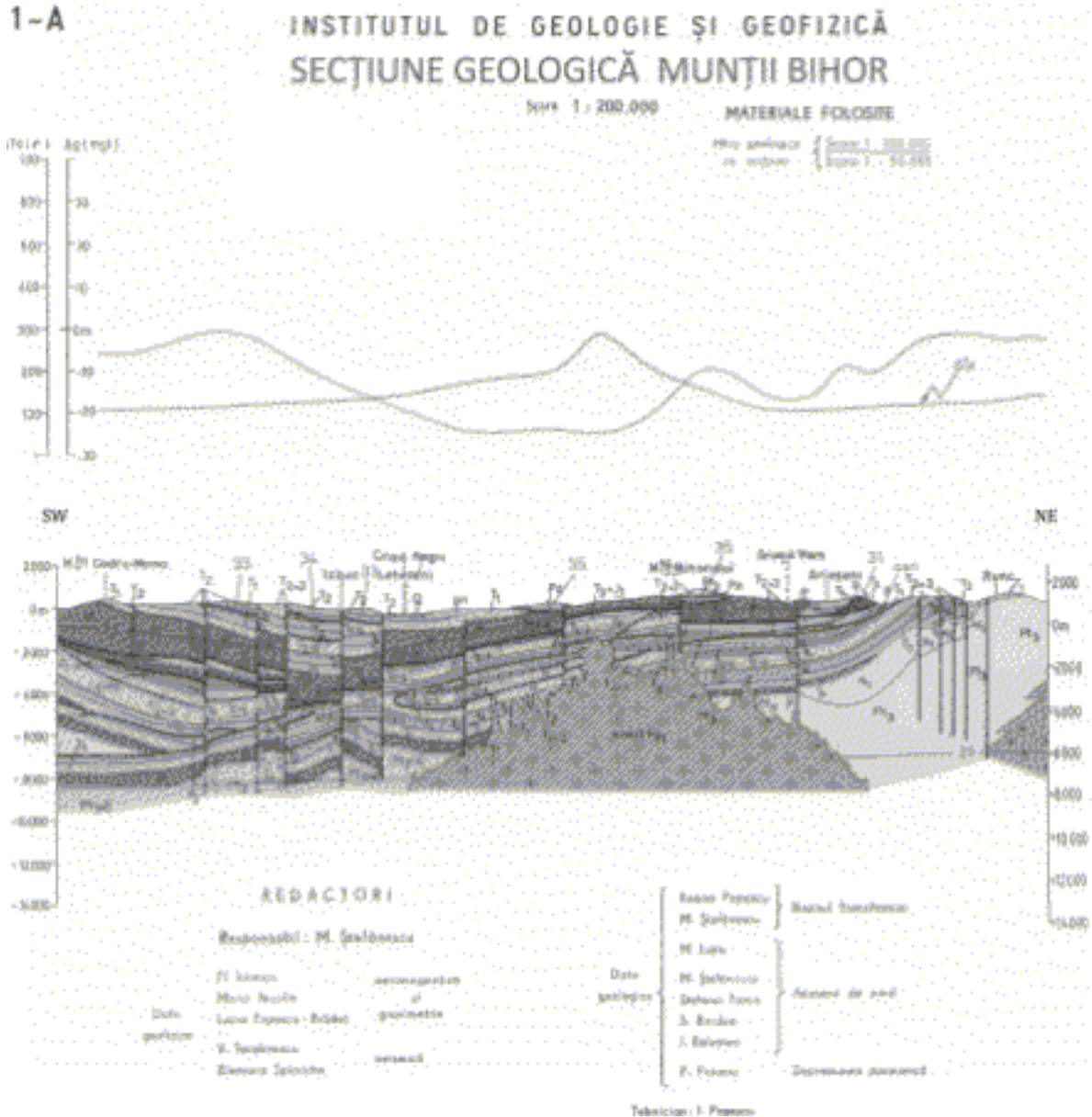


Figure 4.3 Cross-section between Codru Moma Mts – Beiuș Basin – Bihor Mts extracted from the profile 1-A (Ștefănescu et al.). See legends on next page

#### 4.1.3 How Bihor Mountains can positively contribute to the aims of CHPM2030

- The IGR holds a large amount of information about the geological, geophysical and geochemical properties of the Romania.
- Data coverage for the Bihor Mts is at a scale 1: 50,000 for geology and 1: 200,000 for geophysics.

- IGR has modern mineralogical laboratories that can bring an input to the new data analyses depending on the project requirements.



## 4.2 Limitations in our current understanding of Bihar Mountains

- The majority of the data sets only relate to the shallow sub-surface (0–1,000 m).
- Some datasets are incomplete.
- Some datasets are based on old data that are hosted on paper.

## 5 Concluding remarks

This review of the Bihor Mts has shown their potential for the CHPM project, i.e., extracting metals together with geothermal waters from larger depth. Here, we summarize data supporting this idea.

### 5.1 Geological data

Within the Bihor Mountains, a granodioritic-granitic **batholithic body**, which is of hypoabissal origin, extends, both at the surface and in the underground up to the Galbena fault. At the surface, within the Pietroasa - Aleului valley area, and further north, up to Budureasa, granodiorites crop out. Associated with this banatitic intrusion, apophyses and bodies of andesitic or basaltic composition have been documented, especially in the upper reaches of Crișu Băița along the valleys Hoanca Moțului, Corlatu and Fleșcuța, as well as in the Valea Seacă catchment area. The intrusion of the banatites has resulted in contact processes that affected the sedimentary deposits being traversed. At the contact of the banatites with the limestones, marbles and various types of calcidic skarns have been formed, while at the contact with the detritic and pelitic rocks are met, e.g., hornfels and garnet skarns.

Owing to the Bihor pluton, the Bihor Mts are integrated within the Banatitic Magmatic and Metallogenic Belt, which represents a series of discontinuous magmatic and metallogenic occurrences of Upper Cretaceous age, and being discordant in respect to Mid-Cretaceous nappe structures. The most important occurrences are Pietroasa, Budureasa and Băița Bihor, where the magmatic bodies intruded Permian-Mesozoic sequences and produced contact-metamorphic aureoles. As a consequence brucite and borates were reported for skarns from Pietroasa and Budureasa, and Cu (Mo, Zn-Pb), Au and Ag were exploited in Băița Bihor.

### 5.2 Geophysical and structural data

The maps from *Figures 4.1, 4.2, and 3.13* corroborated with magnetometric and gravimetric field measurements indicate that the Bihor batolith and its apophyses have regional extention. These intrusions essentially changed the whole previous geological assemblage. A fault system, mainly oriented from north-west to south east affected the Permo-Mesozoic deposits from above.

The Codru Nappes System is common to both, Bihor Mountains and Beius basin, overlying the Bihor unit. Moreover, a succession of several overlapping nappes, each containing Middle and Upper Triassic carbonate deposits are shown in *Figure 4.3*. It results in that the sequences of Middle and Upper Triassic carbonate deposits can be intercepted two or even three times at different depths.

These Middle and Upper Triassic deposits are concurrently:

1. magnesium skarn areas, which resulted from thermal metamorphic processes, providing metals;
2. permeable strata, through which metal rich fluids are transported at long distances, from Bihor Mts to Beiuș Basin;
3. geothermal aquifers where hot water is extracted.

### 5.3 Hydrogeology

Being an intense karstified region, the Bihor Mountains are characterised by a very high rate of circulation of fluids, generating aquifers with large discharge, and with short periods of time for recharging (in case of intensive exploitation).

Both at the surface and at depth, there are extensive contact areas between the magmatic body and the carbonated deposits, facilitating the mobility of waters and their enrichment and diversification in chemical components.

The Beius well 3001 intercepted a productive geothermal layer, represented by the Anisian – Ladinian of Ferice Nappe, at 2700m depth. According to the section in Figure 4.3, another geothermally productive sequence of Middle – Upper Triassic deposits may be intercepted at even larger depths.

## 5.4 Metallogenesis

In our study we include three sites, Pietroasa, Budureasa, and Băița Bihor. They have similarities but also differences. It is still unclear, which of these sites delivers metals to the aquifer.

At both Pietroasa - Budureasa and Baita Bihor metamorphosed dolomitic layers (dolomitic marbles) are present, framed by calcic marbles, and similar to those that mainly host karst geothermal aquifers from Beius.

Such sequences are represented by anisian dolomites from Pietroasa and Budureasa, belonging to the Ferice Nappe, which contain mineralisations of boron, brucite and, at Budureasa, skarns with magnetite. The sequences are also represented by Carnian – Norian 'Băița dolomites and marbles'. They belong to the Vetre Unit or to the Vălani Unit and host magnesian skarns with boron Molybden and a suite of minerals, mainly oxides and sulphides.

Metallogenesis conditions determine and even facilitate the mobility of elements in hydrothermal fluids. This process needs to be deciphered for the skarn deposits from Pietroasa, Budureasa and Băița Bihor, as well as for boron and magnesian minerals dissolved in aqueous solutions.

## 5.5 Geothermal data

Visarion (1978), and later Demetrescu (1994) demonstrated that regional geothermal conditions are strongly influenced by the tectonic and magmatic activity around.

In the Beiuș basin, situated in the proximity of the Pannonian basin where maximum values of heat flow for Romania of  $> 100 \text{ mW m}^{-2}$  are observed, heat flow density is estimated value to  $> 90 \text{ mW m}^{-2}$ . According to Visarion, the thin granitic layer in the western part of Romania cannot entirely account for the high surface geothermal activity observed here, even though it is rich radioactive elements. A considerable inflow of heat from the upper mantle could have been one of the driving forces in the geological evolution of the region. This is also suggested by stronger subsidence of the Pannonian Basin in comparison with tectonic units from the east. Demetrescu has estimated temperature at 20 km depth beneath the Beiuș basin to c.  $500^{\circ}\text{C}$ .

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## CHPM2030 DELIVERABLE D 1.2 APPENDIX 1.2.4

### REPORT ON DATA AVAILABILITY: SWEDEN

*Summary:*

This report aims to provide a brief overview of three major ore districts in Sweden, including description of the geological setting, and on-going efforts in geophysics in seeing deeper and increasing resolution for detecting mineralised zones at depth, as well as attempting to estimate their low to mid enthalpy geothermal potential.

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## 1 Executive summary

There are four major ore districts in Sweden. These are Bergslagen, the Skellefte field, Northern Norrbotten and the Caledonides. The latter one is not assessed in this report. A number of mineralisations are hosted by rocks of the Palaeoproterozoic Karelian Greenstone group, but the tectonic setting of the majority of occurrences in the Precambrian is a Sveco-Karelian (c. 1.9 - 1.8 Ga) magmatic arc; most of these are early-tectonic, but late- to post-tectonic mineralisations occur as well. A number of mineralisations were formed in relation to the Sveconorwegian (c. 1.0 Ga) and Caledonian (c. 0.4 Ga) continent-continent collisions, respectively. In addition, greisens-style vein mineralisations in some felsic plutonic rocks (at both c. 1.7 and 1.45 Ga) of anorogenic or unclear relation to tectonic processes and Fe mineralisations in Jurassic sandstones occur.

Since their formation large volumes of the bedrock in Sweden have been subjected to intense tectonic deformation and subsequent erosion, and rocks, including mineralisations, and structures originally formed at some depth in the crust are locally accessible for study at or close to the present surface. Examples of such mineralisations are structurally controlled iron oxide-copper-gold (IOCG), skarn, porphyry and, possibly, some rare earth element (REE). In contrast, several mineralisations in Sweden that presently are being mined at and evaluated to some depths were originally formed at or close to the Earth's surface, and genetical data from these may have limited relevance to the present task.

For most of the bedrock in Sweden, the last metamorphic event with regional ductile deformation occurred at c. 1.8 Ga. Between 1.8 and 1.7 Ga the temperature of the bedrock presently exposed was such low that brittle deformation has taken place. Locally, rocks were affected by ductile deformation in relation to later events such as the Blekinge-Bornholm (Danopolonian; 1.5–1.4 Ga), Sveconorwegian and Caledonian orogenies. Outside these orogens and local shear zones, the bedrock of Sweden has mainly reacted as far-field brittle response to tectonic events since c. 1.7 Ga.

The Geological Survey of Sweden has a long standing tradition in geological mapping of the country, especially with the support from airborne geophysics which is motivated by the low degree of bedrock exposures. Early geophysical investigations at crustal scales or even deeper were mainly done by other research groups for understanding deep geology and the tectonic evolution of Fennoscandia and its surroundings. The European Geotraverse (Fennolora), the BABEL project, test profiles in the Skellefte field and in Norrbotten are all examples of such research projects.

Electrical conductivity studies at crustal and upper mantle scales reported a highly conductive belt in the Skellefte district, extending laterally more than 150 km and having total conductance of more than 1000 Siemens. This is interpreted as shallow graphitic shales embedded in otherwise resistive crust.

During the last decade reflection seismic investigations were introduced in some pilot studies of larger extent in Sweden for prospecting after minerals and ores in the Earth's uppermost crust. The seismic survey, competing with other geophysical exploration methods was judged as economically more justified. The Kristineberg area in the western Skellefte district was chosen as well suited for these studies. The chosen area was in addition well documented by earlier investigations, including boreholes drilled to greater depths than 1000 m. High resolution reflection seismic data provided detailed images of an ore body of volcanogenic massive sulphides and associated structures. It's habit had not been as detailed, and visible in

previous studies. The seismic experiments have also shown that considerable efforts need to be undertaken in geologically complex areas to properly acquire data, i.e., preferably as 3D- instead of 2D surveys.

Boreholes of several kilometres in depth are fairly rare in Sweden. The deepest boreholes reaching a depth of 6779 m and of 6529 m are located in the Siljan ring structure in central Sweden. One of these two holes is still accessible down to about 5500 m. The third deepest borehole was drilled in southernmost Sweden, close to the city of Lund and reached a depth of 3702 m. This borehole penetrates a thick sedimentary succession of Mesozoic strata before entering the crystalline basement at 1946 m depth. A large number of deep boreholes are performed by the Swedish Nuclear Fuel and Waste Management Company (SKB) in their study and research fields. The deepest hole of 1700 m depth is located in south-eastern Sweden. Recently, a deep borehole reaching a depth of 2496 m has been drilled in the Scandes within the project Collisional Orogeny in the Scandinavian Caledonides (COSC). A very large number of boreholes, some of these still accessible, are located in the ore bearing districts of Sweden, mainly in Bergslagen, Skellefte and Northern Norrbotten. Few of these holes are reaching depths greater > 1000 m. Over 8000 holes were drilled to > 100 m in depth. SGU is hosting an archive where about 33000 of these boreholes are documented and more than 3000 km of drill cores are stored (see even tables A.1, A.2 in the appendix).

Our understanding of deep seated fluids in the crystalline bedrock is still rudimentary. In recent years, extensive studies of hydraulic properties of the basement in Sweden have mainly been done by SKB. The hydraulic conductivity decreases with depth with a high degree of variability. Investigations in boreholes indicate that hydraulic conductivity below 650 m depth varies between  $10^{-7}$  and  $10^{-12}$  m/s. Data on the composition of fluids indicate that brines (> 5 % TDS/l) occur far inland at several 1000 meters depth. Their residence time was estimated to the order of some hundreds of millions years by the analysis of He-isotopes. In coastal areas down to about 1000 m depth meteoric waters (about 1.5 Ma in age) account for about 80 % of the total fluid content. Below that depth brines represent 60 – 80 % of the fluid volume. The corrected geothermal heat flow ranges between 30 and 70 mW/m<sup>2</sup> with the lowest values in the northern part of Sweden. Data on heat production show obvious differences between rock types related to their content in radioactive elements.

The generally low geothermal gradient of less than 20 °C/km in the crystalline basement of the Fennoscandian Shield in Sweden should allow for low- to mid-enthalpy geothermal systems as part of a possible CHPM unit.

## 2 Introduction and outline of work

### 2.1 Country specific issues

Available data on the bedrock geology of Sweden (fig. 1) derive mainly from observations at the Earth's surface. The overall low degree of bedrock exposure (on average < 10 % due to Quaternary till and sediment cover) in the country means that most bedrock maps are based on results from geophysical investigations. At best, the maps should therefore be considered as probable two-dimensional (2D) models of possible rock configuration and structures. Locally, e.g., in some coastal areas, higher degrees of exposure of the bedrock allow for more accurate models.

From certain sites in Sweden, underground bedrock data are also available. Examples are mines, areas with infrastructure projects (mainly cities), deep drilling projects and site-investigations for nuclear waste material (fig. 1).

Large volumes of the bedrock in Sweden have been subject to intense tectonic deformation and subsequent erosion, and rocks, including mineralisations, and structures originally formed at considerable depths in the crust are locally accessible for study at or close to the present surface. Examples of such mineralisations are structurally controlled iron oxide-copper-gold (IOCG), skarn, porphyry and, possibly, some rare earth element (REE). In contrast, several mineralisations in Sweden that presently are being mined at and evaluated to some depths (e.g., Garpenberg and Zinkgruvan) were however originally formed at or close to the Earth's surface, and genetical data from these have limited relevance to the present task.

### 2.2 Goals

This report aims on providing an inventory of three major ore districts in Sweden, namely, Bergslagen in central Sweden, and further north the Skellefte district, and Northern Norrbotten. Where possible, based on geophysical data and borehole records, the work includes subsurface information aiming on the occurrence, composition and location of potential deep ore bodies in the Fennoscandian Shield area. We also shed some light on spatial variations in crustal heat production, heat flow and temperature and discuss to which extent these parameters may be affected by convection related to groundwater flow. The big challenge is to predict fracture geometry and permeability at depth in the crystalline bedrock by combining geological and physical techniques. Though sub-surface information in mining areas in Sweden has increased during the last years, the work will be more conceptual as large data gaps still exist and much of the information is based on few data points of regional character.

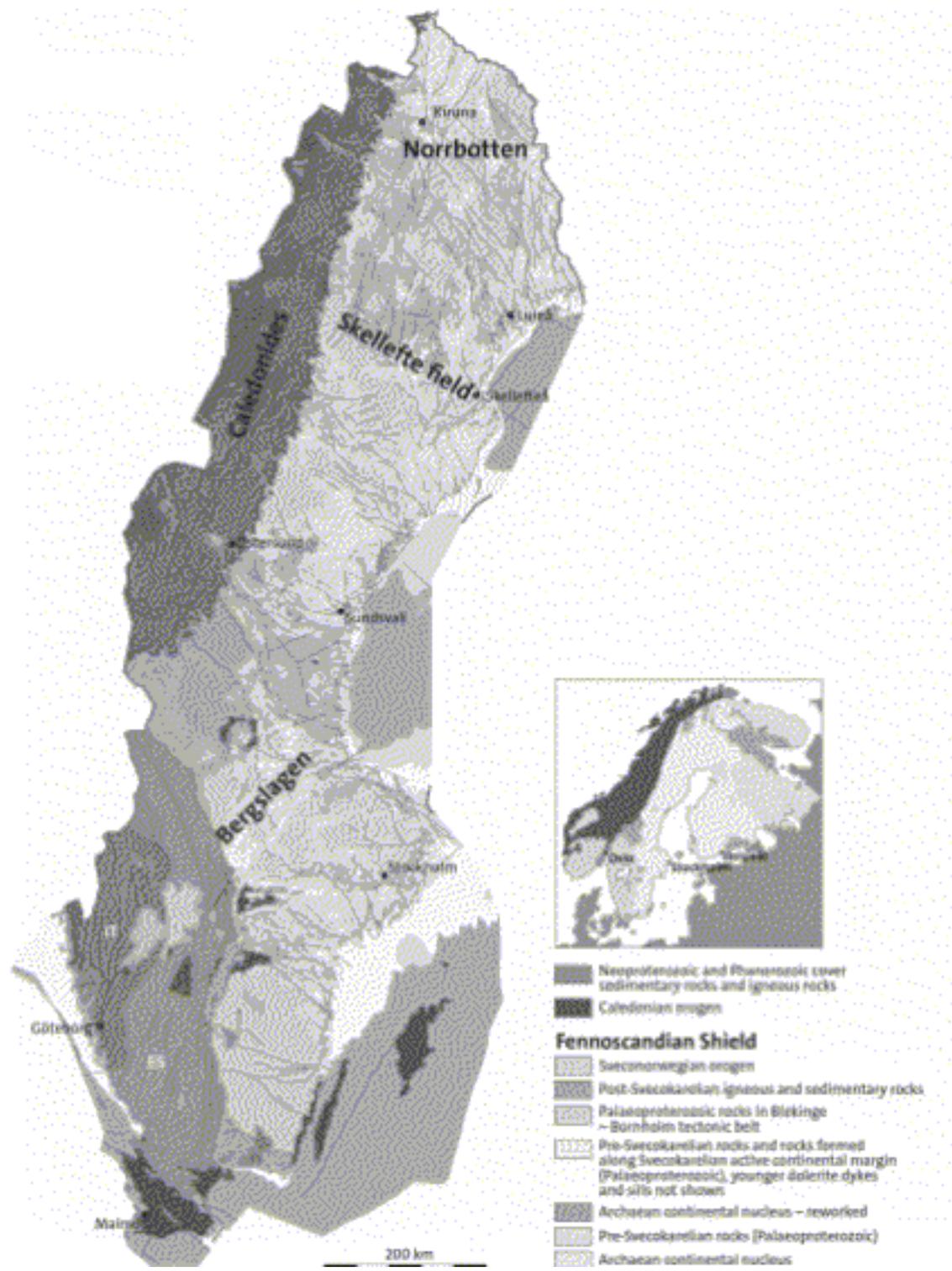


Figure 1. a) Bedrock geology of Sweden (SGU data). Insert shows the geographical and tectonic setting of Fennoscandia

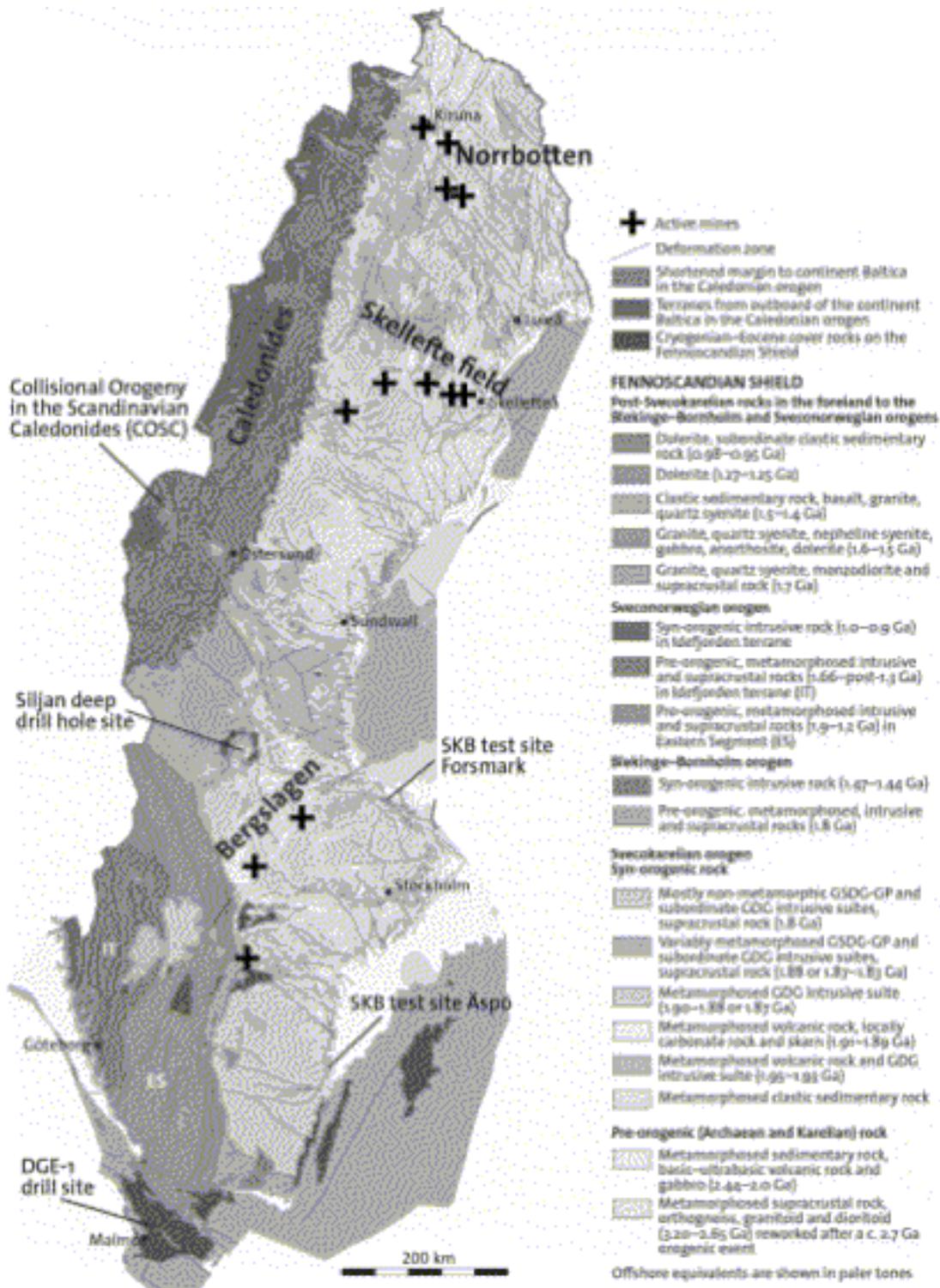


Figure 1. b) The map of (a), where major ore districts, potential sites for nuclear waste disposal (SKB test site) and sites of deep drill holes (COSC, Siljan, DGE-1) are noted. Presently active mines are marked by +

## 3 Previous research and available data

### 3.1 Structural settings inferred from geology and geophysics (incl. drilling)

General overviews of the tectonic setting, geology and mineralisations of the major ore districts in Sweden (fig. 1) are presented in Bergman et al. (2001) and Martinsson et al. (2016) for Northern Norrbotten, Kathol and Weihed (2005) for the Skellefte district, Stephens et al. (2009) for Bergslagen, and Grenne et al. (1999) and Corfu et al. (2014) for the Caledonides. A review on geodynamics and ore formation in the Fennoscandian shield is presented in Weihed et al. (2005). A comprehensive description of the of Fennoscandian deposits is given in an edited work by Eilu (2012). The most recent overviews on Swedish metallogeny are the excursion guide books to the SGA meeting in 2013 (12<sup>th</sup> Biennial SGA meeting, excursion guide books SWE1-7). The SGA excursion guide books include an up to date general description of the geological and tectonic evolution of Sweden. Regarding Northern Norrbotten deposits there is also the paper by Martinsson et al. (2016). The above mentioned works all contain references to specific deposits and their type.

The Geological Survey of Sweden has a long standing tradition in geological mapping of the country, especially with the support from airborne geophysics, which is necessary due to the low degree of bedrock exposures. Since the early 1960's airborne surveys were performed covering almost entire Sweden, except for the range of the Scandes. These surveys have acquired data on the Earth magnetic field, gamma radiation and the VLF electromagnetic field. In addition to these surveys the gravity field of the Earth was measured using ground based techniques (see appendix, figs. A.1, A.2, A.3, and A.4).

In Norrbotten, a number of base metal (e.g., the Viscaria Cu deposit), skarn iron and banded iron formations are hosted by the Karelian Greenstone group, but the tectonic setting of the vast majority of mineralisations in the Precambrian of Sweden is a Svecokarelian (c. 1.9-1.8 Ga) magmatic arc; most are early-tectonic but late- to post-tectonic mineralisations occur as well. A number of mineralisations were formed in relation to the Sveconorwegian (c. 1.0 Ga) and Caledonian (c. 0.4 Ga) continent-continent collisions, respectively. In addition, greisens-style vein mineralisations in some felsic plutonic rocks (at both c. 1.7 and 1.45 Ga) of anorogenic or unclear relation to tectonic processes and Jurassic sandstone-hosted Fe mineralisations occur.

Early geophysical investigations at crustal scales or even deeper were mainly done for understanding deep geology and the tectonic evolution of Fennoscandia and its surroundings. To name here some of these projects, including seismic refraction experiments, like, e.g., the European Geotraverse (Fennolora) (Guggisberg et al. 1991; Lund and Heikkinen 1987), the BABEL project (BABEL working group 1990), a test profile in the Skellefte field of 100 km in length (Elming and Thunehed 1991), and another one in Norrbotten close to Luleå, being about 30 km long (cf. Juhlin et al. 2002). But, already in the 1950's Båth and Tryggvason (1962) conducted seismic experiments around Kiruna, using the blastings of the mine as seismic source to study upper crustal structures connected to the ore body. In the following decades only some few seismic reflection experiments aiming on exploring ores and minerals, were done in Scandinavia.

Electrical conductivity can tell us something about structures, but the method can also indicate processes in the crust and mantle. This parameter was studied at larger scales by, e.g., Jones et al. (1983) and Rasmussen et al. (1987). As a result of magnetotelluric investigations within the Fennolora project, Rasmussen et al. (1987) reported a crustal zone of higher electrical conductivity, extending laterally more than 150 km, centered on the Skellefte district (SD) and having at least thickness of 15 km. New magnetotelluric data were

acquired on a larger scale in north-west Fennoscandia by Cherevatova et al. (2014, 2015a, b) and Korja et al. (2008). These studies confirmed the highly conductive belt in the Skellefte district (total conductance > 1000 Siemens) which is interpreted as shallow graphitic shales embedded in the otherwise resistive crust. Along the Caledonian Thrust Front in the Caledonides highly conductive alum shales have been identified between the resistive Proterozoic basement and the overlying nappes, marking the ramp of overthrusting.

For a long time applying reflection seismic surveys for prospecting after minerals and ores in the Earth's uppermost crust, was looked upon as economically unjustified. Potential and electrical resistivity methods were seen as being more powerful and cost efficient in exploring for ore deposits. Since the experiments of Båth and Tryggvason (1952) it took some decades, until reflection seismics was used in Sweden to any larger extend for proving its feasibility in exploring ore deposits: Tryggvason et al. (2006) and Rodriguez-Tablante et al. (2007) studied the Kristineberg area in the western Skellefte district while Malehmir et al. (2006) extended these investigations further to the East. This part of the SD is well documented by boreholes reaching depths greater than 1000 m, high resolution potential field data, i.e., magnetic and gravity, as well as by petrophysical data. The investigations in the Kristineberg area were followed up by employing magnetotellurics (MT) on one of the seismic lines allowing for the joint interpretation of velocity and electrical resistivity data (Hübert et al. 2009). Malehmir (2007) has summarized the outcome of this pilot study: A strong N dipping reflection in conjunction with higher electrical conductivity is interpreted as the structural basement for the rocks of the Skellefte group (for a map see fig. 2). Postorogenic granitoids were modeled down to various depths between one and five km (fig.3). Among others, e.g., Garcia Juanatey (2012), Bauer et al. (2014) and Tavakoli et al. (2012a, 2012b, 2016a, 2016b) further studied the subsurface of the central Skellefte district, in order to delineate the structures related to volcanogenic massive sulphide deposits and to model lithological contacts down to various depths, of some hundreds to some thousands of meters.

In Bergslagen, the areas around Dannemora, Grängesberg and Garpenberg mines were targeted for the reflection seismic experiments with the purpose to screen the sub-surface for potential zones of higher mineralization (Malehmir et al. 2011, Place et al. 2014, and Ahmadi et al. 2013). Recently, the Geological Survey of Sweden conducted temperature measurements in prospection boreholes in these mining areas (unpublished data).

In Northern Norrbotten, around the Kiruna iron ore mine, Båth and Tryggvason (1962), Juhohunti et al. (2014), and Holmgren (2013) have reported from seismic reflection experiments, having the objective of imaging bedrock contacts and the geometry of structures at depth. These studies were accomplished by reprocessing of VLF airborne data (Abtahi et al. 2016) and by magnetotellurics (Bastani et al. 2016a, 2016b). The resistivity models show low resistivity zones at various depths and locations almost over the entire study area, which may be related to occurrences of graphite or sulfide mineralizations in the uppermost crust.

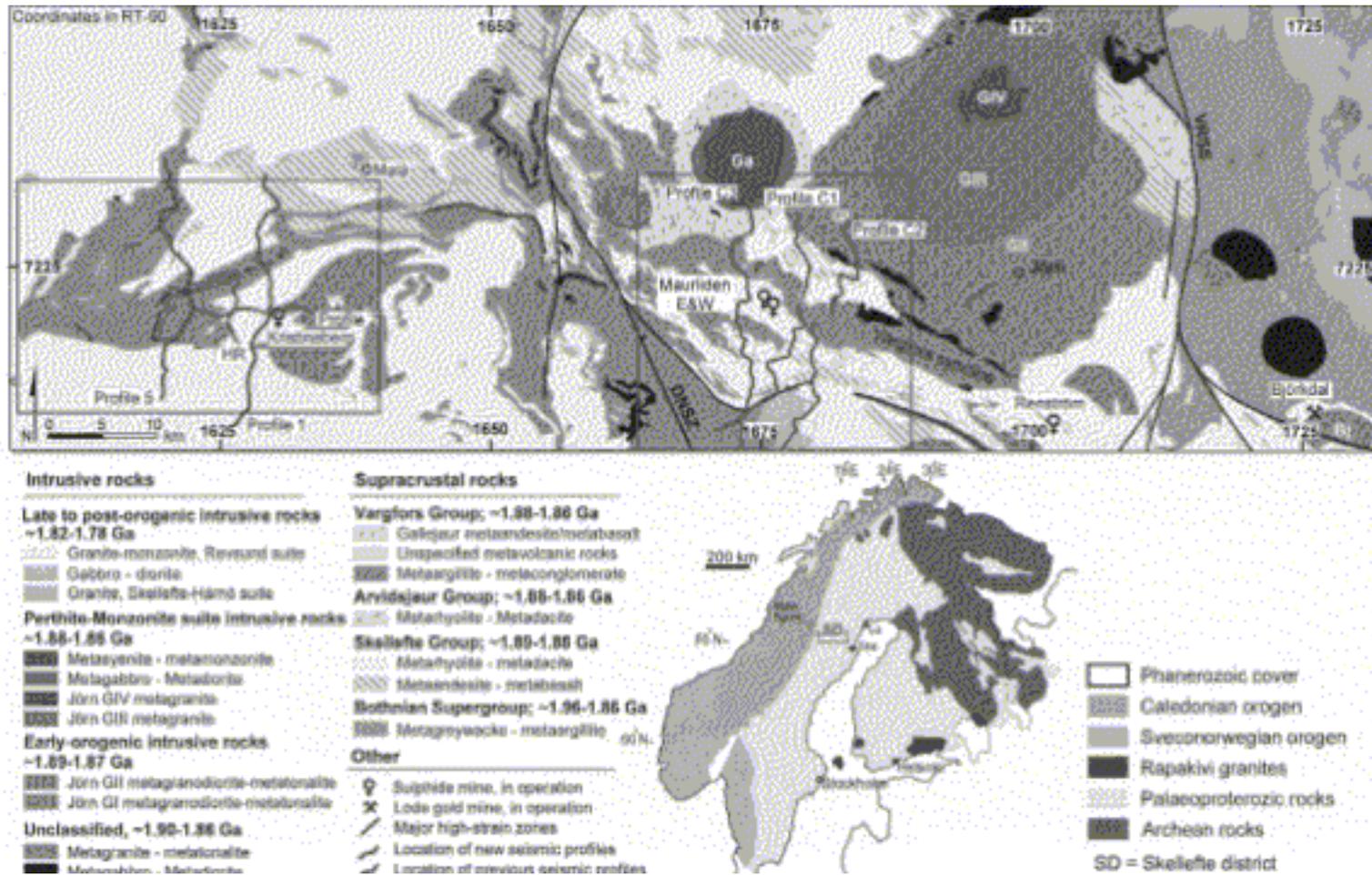
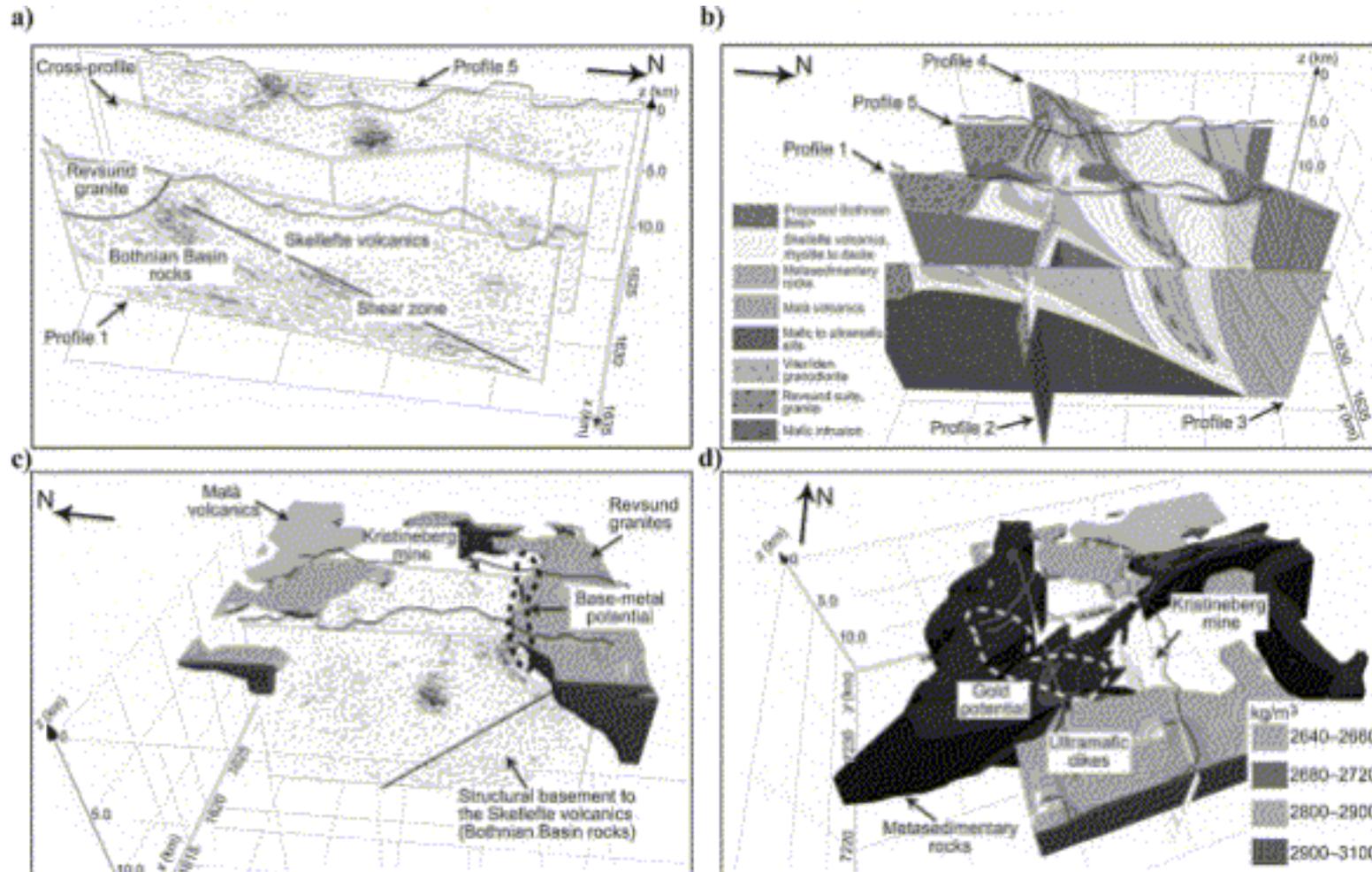


Figure 2. Geological map of the Skellefte district (SD), where, e.g., reflection seismic investigations of the upper crust were done (Dehgannejad et al. 2012a) within the GEORANGE3D and the VINNOVA4D projects



**Figure 3.** 3D views and geological models around the Kristineberg mine in the Skellefte district down to larger depth (Malehmir et al. 2009b). A combination of seismic reflection data (a) and geological cross sections (b), and final models (c, d) where all geological and geophysical information available was combined for targeting new prospecting areas

The interpretation of structural settings of individual mineralisations or districts is normally based on combinations of surface data, core-drilling, geophysical data and 3D- and 4D-modelling. For deeper structures and mineralisations, geophysical data are often the only available means for 3D evaluation unless drilling has been performed. Examples of 3D- (and 4D-) modelling that relate to Swedish bedrock conditions are Bauer (2013), Bauer et al. (2009, 2010, 2011, 2012, 2014), Malehmir et al. (2009), Carranza and Sadeghi (2010), Kampmann (2015), Skyttä et al. (2009, 2012, 2013), Wareing (2011) and Weihed (2014) (see even fig. 3).

Data on deep drilling projects in Sweden were presented by Erlström and Sivhed (2003), Lorenz (2010) and Gee et al. (2010). Predictions of structures at depth (c. 500 m) were to some extent evaluated by the Swedish Nuclear Fuel and Waste Management Company (SKB) at the test sites in Forsmark (Stephens et al. 2007) and Äspö (Wahlgren et al. 2008).

### 3.2 Geometry and composition of ore deposits

The prospects and deposits that are mentioned by name in the following text are shown in figure 4 and listed in Table 1. Most pre- and early-orogenic Svecokarelian metal deposits in Sweden were originally formed as volcanogenic or sedimentary, stratabound (Fe oxide and base metal skarn) or stratiform (Fe oxide and base metal) mineralisations at or close to the palaeosurface (see references in section 2.1). Their present shape, position and orientation are, however, mainly controlled by subsequent polyphase tectonic deformation. In general, they have been affected by two phases of folding and ductile shearing and by brittle faulting.

In contrast, the present shape of the Tallberg Cu-Mo-Au porphyry deposit in the Skellefte district is controlled by its host rocks, the isotropic to weakly deformed early-orogenic Jörn intrusive complex (Weihed et al. 1987, Weihed 2001). A weakly porphyry-style mineralised and slightly deformed quartz monzodiorite in the footwall of the Aitik Cu-Au-Ag deposit in Norrbotten has also an early-orogenic Svecokarelian age (Bergman et al. 2001; Wanhainen 2005).

In both Bergslagen and the Skellefte district, early-orogenic mafic intrusive rocks locally carry subeconomic Ni-mineralisations (Weihed et al. 2005). The rocks are variably deformed to almost undeformed.

Many late- to post-orogenic Svecokarelian and younger mineralisations are epigenetic formations in and related to deformation zones. Such mineralisations, e.g., Nautanen c. 1.8 Ga IOCG (Bergman et al. 2001; Martinsson et al. 2016); Björkdal c. 1.8 Ga orogenic Au (Weihed et al. 2005) and Harnäs c. 1.0 Ga orogenic Au (Alm et al. 2003), are largely vein-hosted, and the orientation and shape of the veins are controlled by the orientation of the deformation zone and their tectonic emplacement in time.

Outside obvious deformation zones, late-orogenic orthomagmatic mineralisations and skarn and porphyry mineralisations as well as post- to anorogenic greisen veins occur. Associated with the c. 1.8 Ga phase of mafic igneous activity in the Transscandinavian Igneous Belt (e.g., Högdahl et al. 2004), some orthomagmatic Ni-Cu mineralisations occur (e.g., Bjärnberg et al. 2015). The late-orogenic Yxsjöberg W-Cu-F skarn deposit was described by Ohlsson (1979a) and Romer and Öhlander (1994) and the late-orogenic porphyry-style, Mo-bearing Pingstabergr granite was described by Billström et al. (1988).



Name	District	Type	Tonnage	Grade(s)	Status	Deepest level	Reference(s)
Aitik	Norrbotten	Porphyry + IOCG	>1300 Mt	Cu 0.25 %, Au 0.14 g/t, Ag 2 g/t	Active mine	Open pit, 450 m	12th SGA Excursion Guidebook SWE5
Bastnäs	Bergslagen	Orogenic?	4.5 kt	Ce ? %	Closed mine	120 m	Geijer 1921
Björkdal	Skellefte	Orogenic gold	50 Mt	Au 1.7 g/t	Active mine	350 m?	12th SGA Excursion Guidebook SWE2
Garpenberg	Bergslagen	Skarn	160 Mt	Zn 4.6 %, Pb 2 %, Au 0.3 g/t, Ag 130 g/t	Active mine	1250 m	Rodney Allen pers. com. 2014; SGU
Grängesberg	Bergslagen	Orthomagmatic-hydrothermal	>156 Mt	Fe 60 %, P 0.81 %	Closed mine	650 m	12th SGA Excursion Guidebook SWE4
Harnäs		Orogenic gold	60 kt	Au 2 g/t	Closed mine	n.d.	Alm et al. 2003
Kiruna	Norrbotten	Orthomagmatic-hydrothermal	>2000 Mt	Fe 60-68 %, P 0.04-0.32 %	Active mine	1540 m	12th SGA Excursion Guidebook SWE5
Laisvall	Caledonides	Sediment-hosted	110 Mt	Zn 0.3 %, Pb 3.8 %, Ag 11 g/t	Closed mine	<200 m	SGU; Eilu 2012
Malmberget	Norrbotten	Orthomagmatic-hydrothermal	930 Mt	Fe 51 %, P 0.5 %	Active mine	1385 m	Eilu 2012
Nautanen	Norrbotten	IOCG	16 Mt	Cu 1.5 %, Au 0.7 g/t, Ag 5.5 g/t, Mo 64 g/t	Closed mine and prospect	180 m	<a href="http://www.boliden.com">www.boliden.com</a>
Norra Kärr		Orthomagmatic	58 Mt	REE-oxides 0.59 %, ZrO <sub>2</sub> 1.7 %	Prospect		12th SGA Excursion Guidebook SWE3
Pingstaberget	Bergslagen	Porphyry	n.d.	Mo <<0.3 %	Prospect		Ohlsson 1979b
Stekenjokk-Levi	Caledonides	VHMS	26 Mt	Cu 1.35 %, Zn 2.93 %, Pb 0.31 %, Au 0.27 g/t, Ag 48 g/t	Closed mine	Circa 500 m	Stephens 1986
Tallberg	Skellefte	Porphyry	44 Mt	Cu 0.27 %	Prospect		Weihed et al. 1987
Viscaria	Norrbotten	VMS	64 Mt	Cu 1.05 %	Closed mine and prospect	Circa 650 m	<a href="http://avalonminerals.com.au/">avalonminerals.com.au/</a>
Yxsjöberg	Bergslagen	Skarn	5 Mt	Cu 0.4 %, WO <sub>3</sub> 0.4 %, CaF <sub>2</sub> <5 %	Closed mine	300 m	SGU; Magnusson 1970; Tegengren 1924
Zinkgruvan Cu	Bergslagen	Skarn?	9 Mt	Cu 3 %, Zn 0.4 %, Ag 30 g/t	Active mine	1125 m	SGU
Zinkgruvan Zn	Bergslagen	SEDEX	74 Mt	Zn 9 %, Pb 3.5 %, Ag 75 g/t	Active mine	1125 m	SGU

**Table 1.** Listing of prospects, deposits and mines mentioned in text. Tonnage includes known or estimated production, reserves and resources. Grades are approximate. N.d.: No data available

Along the so-called REE line in Bergslagen, REE mineralisations associated with sulphide-bearing and skarn-altered banded iron formations and limestone-/skarn-hosted Fe-oxide ores occur; the most prominent example is Bastnäs (Andersson 2004; Jonsson and Högdahl 2013). The age of the REE-mineralising event is

debatable, but a preliminary interpretation of geophysical data from the ongoing EuRare-project suggests that it may be late-orogenic Svecokarelian.

Associated with the c. 1.7 Ga phase of felsic igneous activity in the Transscandinavian Igneous Belt (Högdahl et al. 2004), some greisen-type veins occur, but are of no economic value (e.g., Ahl et al. 1999).

A REE-Zr bearing c. 1.5 Ga alkaline nepheline syenite complex at Norra Kärr in southern Sweden, east of and close to lake Vättern, (see map, fig. 4) is described in the 12th biennial SGA meeting, excursion guidebook SWE3.

In Dalsland and Värmland, in southwestern Sweden, some post-tectonic Sveconorwegian (c. 1.0-0.9 Ga) either mainly Cu- or Pb-bearing quartz veins occur. A description of the mineralised veins is given by Johansson (1985). In this region, sediment-hosted Cu-mineralisations also occur. They are most likely epigenetic in relation to their host rocks, which formed between c. 1.3 and 1.1 Ga.

The autochthonous Ediacaran (c. 590-570 Ma) to Lower Cambrian sandstones at the present eastern erosional front of the Scandinavian Caledonian Mountains host several Pb-Zn deposits, one world class example is the deposit at Laisvall (Saintilan et al. 2015). The mineralisations are epigenetic and formed during the Middle Ordovician in response to early far-field Caledonian deformational events (Saintilan et al. 2015). Allochthonous Ediacaran sedimentary rocks in the Caledonian nappes locally contain Ni-bearing serpentinites, some of which are or recently have been evaluated for exploitation (see [www.nickelmountain.se](http://www.nickelmountain.se)). The uppermost Caledonian nappes (Köli) are exotic terranes with local mineralisation such as the Ordovician Stekenjokk-Levi Zn-Cu(-Pb) volcanogenic massive sulphide deposit (Stephens 1986).

### 3.3 Structural evolution, deep-seated faults and fracture zones, their alignment

The majority of the bedrock and mineralisations in Sweden were formed at c. 1.9 to 1.8 Ga during the Svecokarelian orogeny. The last Svecokarelian metamorphic event with regional ductile deformation occurred at c. 1.8 Ga, and sometime between 1.8 and 1.7 Ga the temperature of the bedrock that presently is exposed was low enough for brittle deformation to occur (e.g., Stephens 2010). Locally, mainly in the south-easternmost and south-western parts of the country, rocks have been affected by ductile deformation in relation to later events such as the Blekinge-Bornholm (Danopolonian; 1.5 - 1.4 Ga), Sveconorwegian (1.1 - 0.9 Ga) and Caledonian (c. 0.4 Ga) orogenies (see e.g., the 12<sup>th</sup> SGA meeting excursion guide books for a general description of the tectonic evolution in Sweden). Thus, outside these orogens and in local shear zones, the bedrock of Sweden has mainly reacted as far-field brittle responses to tectonic events since c. 1.7 Ga.

Dating of minerals in fractures at the test sites for nuclear waste disposal at Forsmark (e.g., Stephens 2010) and Äspö (Drake et al. 2007) gives variably reliable ages of between about 1.6 and 0.28 Ga for their emplacement. These age intervals may be correlated to the intrusion of Rapakivi rocks and the Danopolonian, the Sveconorwegian, the Caledonian and the Hercynian (or Variscan) orogenies, respectively.

The Phanerozoic evolution in Skåne in southernmost Sweden, in terms of sedimentation, dyke intrusions, basaltic volcanism and structures was discussed by Sivhed et al. (1999). Effects of the Caledonian, Hercynian (Variscan) and Alpine orogenies were identified by these authors in this area.

### 3.4 Hydraulic properties, deep fluid flow

Several kilometres deep boreholes are rare in Sweden. Consequently, data from deep parts of the crust are available only from a few sites (fig. 5). The following boreholes or groups of boreholes have been selected as relevant for presentation in this study (see even table 2):

- The deepest boreholes are located in the county of Dalarna where drillings have been done at Gravberg and Stenberg down to a total depth of 6779 m and 6529 m, respectively. The objective was to find mantle derived hydrocarbons (Gold 1992). At present, the Gravberg hole is accessible down to about 5500 m, while the Stenberg hole to unknown reasons is dropped at c. 2500 m (Balling, priv. comm.).
- The third deepest borehole is located close to the city of Lund in southern Sweden. Two boreholes were drilled to a total depth of 3701.8 m and 1927 m. The objective was to investigate prerequisites for heat extraction. Both holes penetrate a thick sedimentary succession on top of the basement. The shallower borehole reached only the top of the crystalline basement while the deep one penetrated crystalline rocks from 1946 m to the total depth of 3701,8 m.
- A larger number of boreholes are located at the study and research sites of the Swedish Nuclear Fuel and Waste Management Company (SKB). In addition, a number of boreholes are located at the SKB research site at Äspö and a few other sites, too. The deepest borehole is located at Laxemar with a total depth of 1700 m.
- A borehole reaching a depth of 2496 m has been drilled in the Collisional Orogeny in the Scandinavian Caledonides (COSC) project in the Scandes, close to the village of Åre (e.g., Gee et al. 2010, Lorenz et al. 2015). The objective is focused on investigating the structure and composition of the Scandes, deep fluid flow, temperature at depth and reconstructing palaeoclimate.
- A large number of boreholes are located in the ore bearing districts of Sweden. Usually, the depth of these holes is not exceeding 1000 m, about 100 holes have reached depths larger than 500 m, and more than 8000 holes were drilled deeper than 100 m in depth. SGU hosts a database on boreholes drilled in Sweden where about 33000 drillings are documented and ca 3000 km of drill cores are archived. Only recently, about 200 km of drill cores from the Skellefte field and from Northern Norrbotten, as well as ca. 33 km of cores from Bergslagen were photographed and scanned by IR techniques. Prospecting companies, after having finished the investigations in their respective claims are obliged to report about their activities. Information provided varies considerably between companies. Boreholes related to on-going mining activities normally are not reported to the SGU databases (see table A.1 in the appendix).

The deepest bore holes so far drilled in Sweden, Gravberg and Stenberg are located in the Siljan ring, an impact structure about 377 Ma old (Devonian age). No data on hydraulic properties and flow measurements of these boreholes have been found in the literature. But, changes in the temperature gradient at depth (fig. 6) give some indications of fractures in the bedrock where increased flow of water and transporting of heat may occur (Balling 2013).

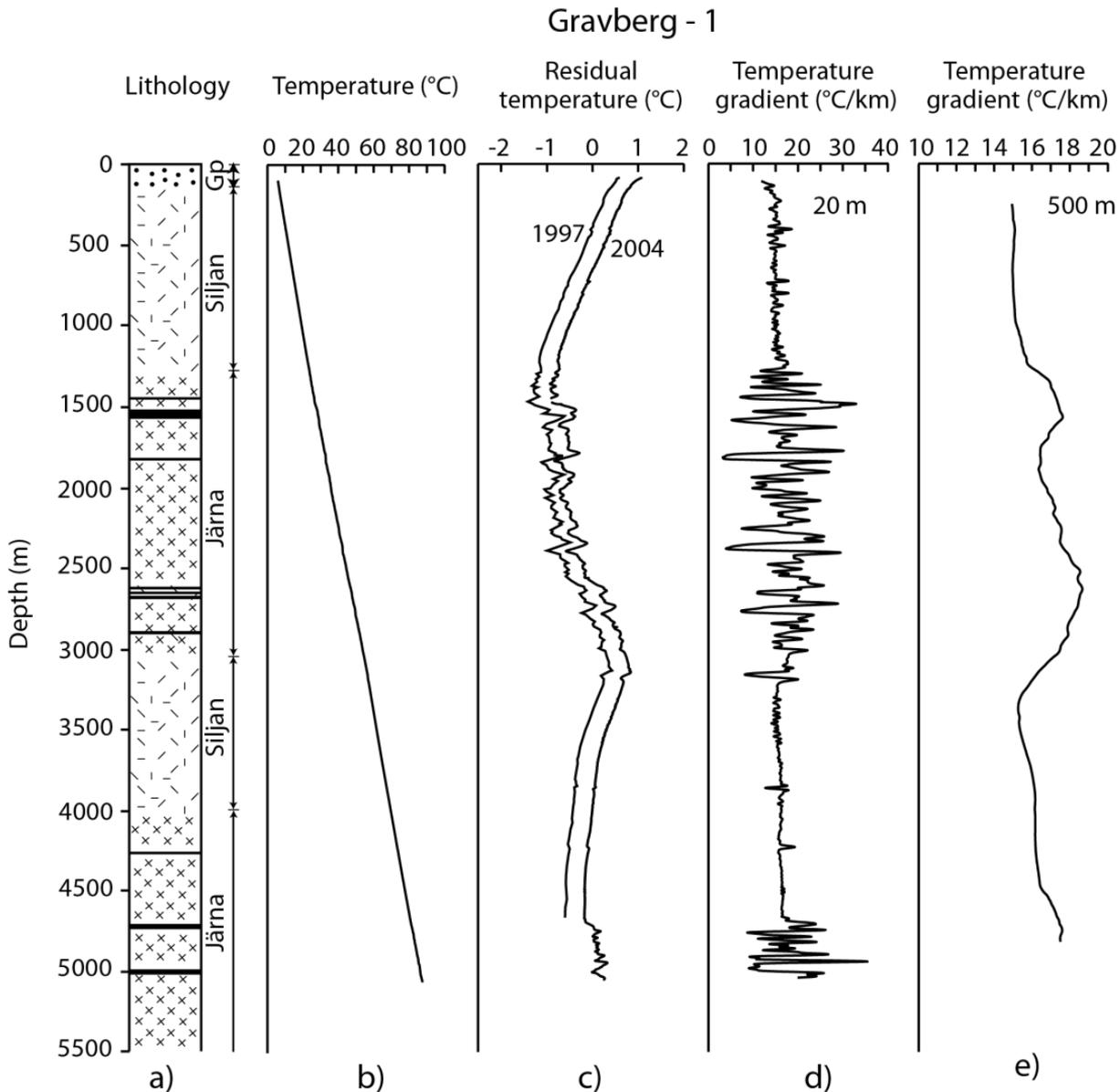


Name of borehole or site	North, Sweref99TM	East, Sweref99TM	Depth (m)	Single (S) Group (G)	Objective of drilling	Hydraulic properties	Thermal properties	Fluids
Gravberg	6778640	499550	6779	S	Hydrocarbons	X	X	X
Stenberg	6769480	494240	6529	S	Hydrocarbons	-	-	-
Lund	6172560	388230	3702	S	Heat extraction	X	X	X
COSC	7031850	410260	2496	S	Research	X	X	X
Laxemar (SKB)	6365800	696500	1700	S	Research site	X	X	X
Laxemar (SKB)	6365800	696500	<1000	G	Research site	X	X	X
Äspö (SKB)	6699000	676800	<1000	G	Research site	X	X	X
Stripa (SKB)	6366000	601000	<1000	G	Research site	X	X	X
Forsmark (SKB)	6618700	505400	<1000	G	Study site	X	X	X
Finnsjön (SKB)	6692400	660000	<1000	G	Study site	X	X	X
Kråkemåla (SKB)	6370600	599000	<1000	G	Study site	X	X	X
Sternö (SKB)	6221900	490200	<1000	G	Study site	X	X	X
Fjällveden (SKB)	6535400	612000	<1000	G	Study site	X	X	X
Gideå (SKB)	7045600	698700	<1000	G	Study site	X	X	X
Kamlunge (SKB)	7342600	855900	<1000	G	Study site	X	X	X
Svartboberget (SKB)	6807200	531000	<1000	G	Study site	X	X	X
Björkö	6577771	645519	900	S	Reserch (SGU)	-	X	-
Blötberget	6664148	503967	730	S	Reserch (SGU)	-	X	-
Dannemora	6679258	659056	700	S	Reserch (SGU)	-	X	-
Floholm	6729264	523059	852	S	Reserch (SGU)	-	X	-
Garpenberg	6691586	570801	923	S	Reserch (SGU)	-	X	-
Kokträsk	7249682	678532	961	S	Reserch (SGU)	-	X	-
Kristineberg	7219078	664659	1401	S	Reserch (SGU)	-	X	-
Långban	6636326	459263	701	S	Reserch (SGU)	-	X	-
Långträsk	7200667	750541	1421	S	Reserch (SGU)	-	X	-
Stollberg	6675012	515577	951	S	Reserch (SGU)	-	X	-
Zinkgruvan	6517785	504815	1349	S	Reserch (SGU)	-	X	-
Ore bearing areas			Various	G	Prospecting	X*	X*	X*

**Table 2.** Boreholes in Sweden with relevant data. X indicates availability of data. X\* indicates available data of various quality and quantity within this group of boreholes

The borehole close to the city of Lund in southern Sweden is located in an area with sedimentary bedrock. The crystalline basement is encountered at 1946 m. Hydraulic conductivity, storage coefficient and water flow were measured (Rosberg 2006, 2010). Hydraulic conductivity in the sedimentary bedrock at various sections from 1427 to 1853 m was estimated from drawdown data and recovery data with obvious differences depending on the methods. Hydraulic conductivity estimated from drawdown data varied

between  $1.1 \cdot 10^{-6}$  m/s and  $1.2 \cdot 10^{-5}$  m/s whereas estimations from recovery tests provided values between  $4.9 \cdot 10^{-7}$  and  $7.2 \cdot 10^{-6}$  m/s.

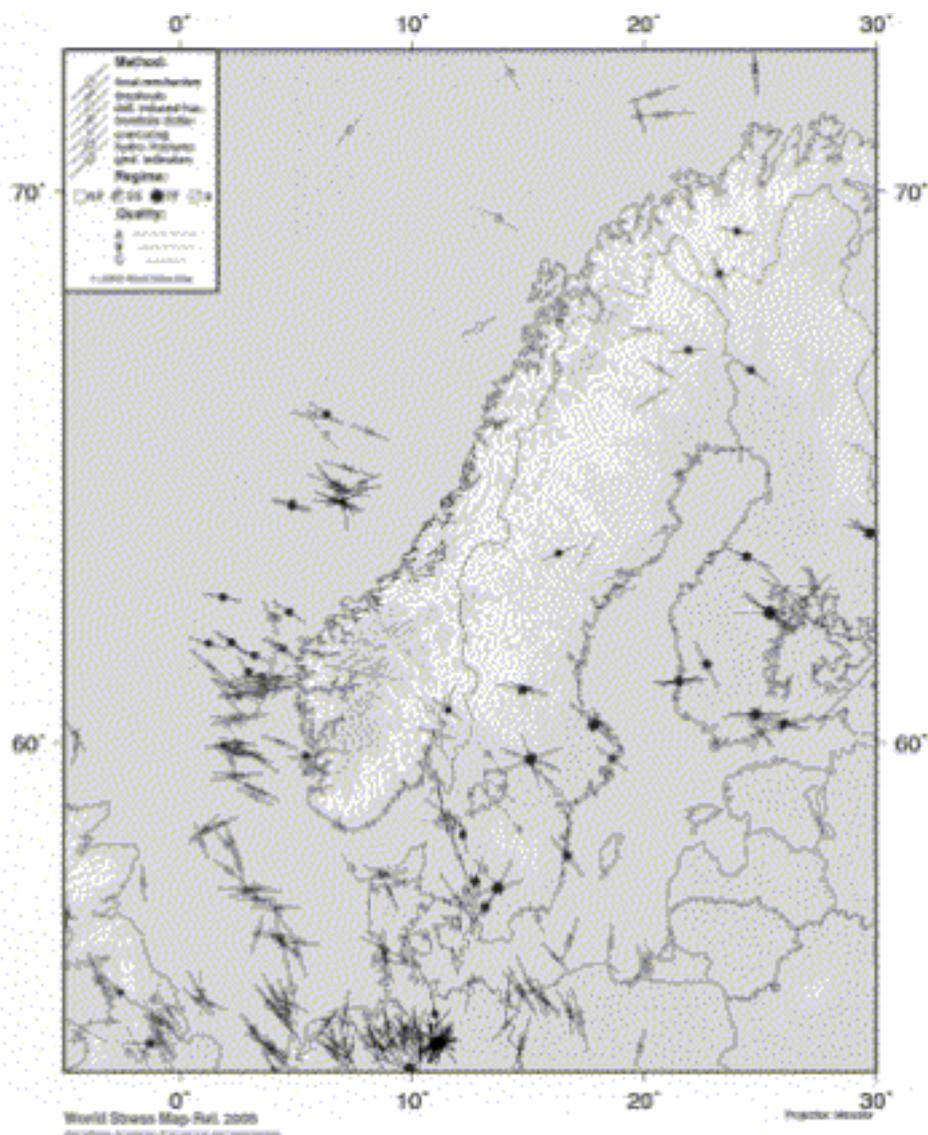


**Figure 6.** The Gravberg hole in the Siljan ring of central Sweden (cf. with fig. 1b). a) Lithology with two types of granites; b) Measured temperature at depth; c) Residual temperature, the difference between measured – and constant gradient temperature (data measured in 1997 and 2004, with an artificial offset of 0.5°C introduced); d, e) temperature gradients as running mean values of depth intervals of 20 and 500 m. Gradient data of section d) are implying the presence of fractures in the bedrock (Balling 2013)

Available data on hydraulic properties from other deep boreholes are mostly related to studies carried out by SKB. These investigations of SKB were concentrated at the study sites of Forsmark and Laxemar (SKB 2008; 2009) and even done at the Äspö Hard Rock Laboratory (SKB 2006a). In addition, the study sites at Finnsjön, Kråkemåla, Sternö, Fjällveden, Gideå, Kamlunge and Svartboberget (Ahlbohm 1995; Laurent 1982) as well as the Stripa research site (Carlsson 1986) provide a lot of data of interest. The investigations at the

SKB sites were generally very extensive, though the depths of boreholes usually do not exceed 1000 m below surface. The deepest borehole (KLX02), however, at Laxemar was drilled down to a depth of 1700 m. Hydraulic tests in these holes provide data on transmissivity at different depth intervals (SKB 2001). Hydraulic conductivity below 650 m depth varies between  $10^{-7}$  and  $10^{-12}$  m/s (Réhn et al. 2008).

The underground part of the Äspö Hardrock Laboratory in southern Sweden consists of a main tunnel, accessible by vehicle from the surface reaching almost 500 m depth below ground level, and additionally, of some short blind tunnels at various depths. The laboratory has been used by SKB for extensive tests and research for the development of a repository of nuclear waste. Finally, it was decided to locate the waste deposit at Forsmark in central Sweden.



**Figure 7.** Orientation of the maximum horizontal compressive stress in Scandinavia (Heidbach et al. 2008)

Data from the COSC borehole were evaluated, e.g., by Hedin (2015). An overview of the investigations is provided by Lorenz et al. (2015). The borehole did not penetrate the bottom of the thrust zone. It was drilled by using the Swedish National Scientific Drilling Infrastructure, *Riksriggen*, that has a maximum capacity in

drilling length of 2 500 m. The rig and the equipment around is primarily available for scientific work, but can also be used in commercial projects. Country wide hydraulic properties of the bedrock down to about 200 m depth below the ground surface can be calculated by using data from the Swedish Well Archives (Pousette 1988). At present, data from more than 600 000 wells are included in archive. Based on these well data the calculated hydraulic conductivity is found to have a spatial variability with obvious differences between regions (Berggren 1998). However, extrapolation of hydraulic properties of the upper part of the bedrock down to several kilometres depth would most likely provide results with unacceptable uncertainty. Close to the ground surface the average hydraulic conductivity of the crystalline bedrock is estimated to  $10^{-5}$  m/s and at 100 m depth the hydraulic conductivity is assessed to be about  $10^{-8}$  m/s.

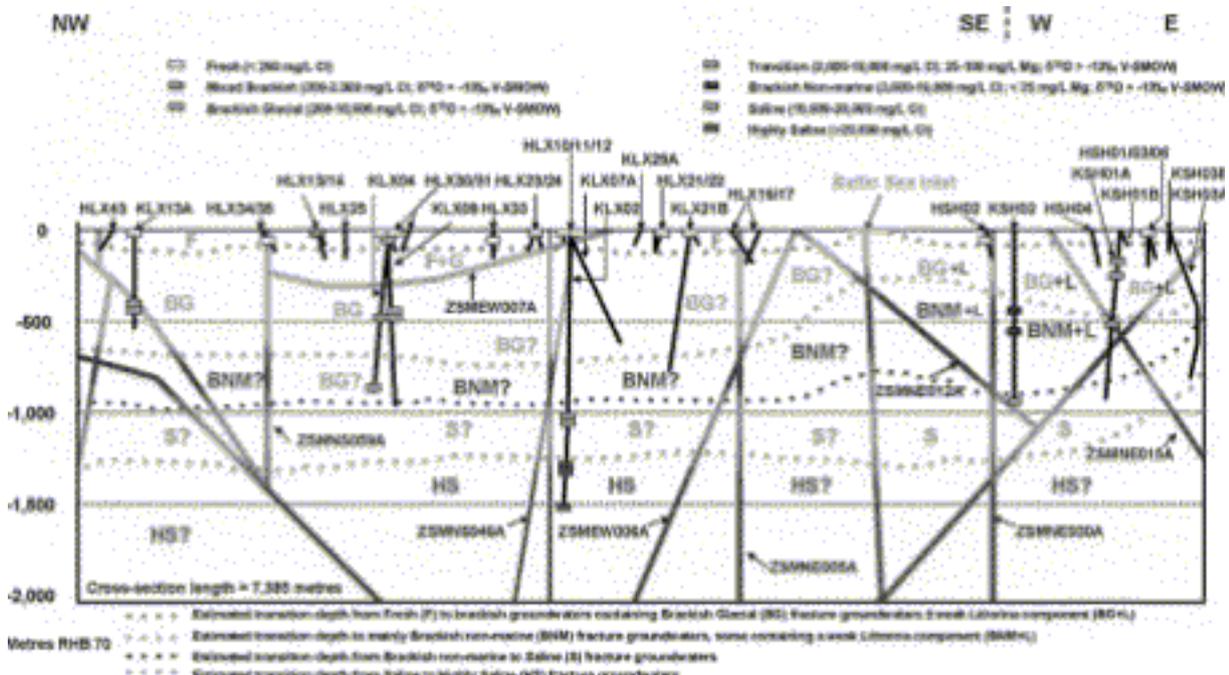
The occurrence of fractures in the bedrock is related to the stress field (fig. 7). The magnitude and the orientation of the components in the stress field govern the size and the directions of the fractures. It should be emphasized that the hydraulic properties of the bedrock depend on a number of properties of the fractures (spacing, porosity, direction, dispersivity, and aperture).

### 3.5 Fluid composition, brines, meteoric waters

Many stratabound and stratiform mineralisations in Sweden are spatially and, in many cases, genetically related to local, semi-regional and region scale hydrothermal alteration zones (e.g., Frietsch 1982; Lagerblad and Gorbatshev 1985; Trägårdh 1988; Ripa 1994; Frietsch et al. 1997; Kathol and Weihed 2005). In general, the hydrothermal systems were based on seawater (variably mixed with magmatic fluids) and led to Na-enrichment at deeper and K-Mg-Si enrichments at shallower levels in surrounding volcanic strata. In the same processes, base metals, Mn and Fe were leached from the volcanics and deposited as oxides and sulphides at the palaeo-seafloor, in favourable horizons or at contacts between strata.

Data on fluids, brines and meteoric waters from deep boreholes are fairly uncommon. Most of the investigations have been made by SKB down to a few 100 m depth. The borehole KLX02 at the Laxemar site was extensively investigated including analysis of chemical properties of the fluid (SKB, 2001; 2006b). The Cl-isotope composition of the brine from 1000 m depth indicates a residence time of approximately 1.5 Ma (Louvart et al. 1999). The fluid composition in the borehole at Gravberg indicates that the brine (> 50 000 mg/l) occurs at 6000 m depth, corresponding to about 5700 m below sea level (Juhlin and Sandstedt 1989; Juhlin, et al. 1998), with a maximum salinity of 150 000 mg/l at the deepest level. By analyzing He-isotopes, the brine's residence time at depth was estimated to some hundreds of millions of years (Juhlin et al. 1981). Close to the coastal area of Sweden brines occur at about 1300 m below sea level, which is indicated by data from the borehole KLX02 (SKB 2001). Salinity at the deepest level of this borehole was 75 000 mg/l. According to this study, no brines were found at any other borehole in the crystalline basement in Sweden. However, in the sedimentary bedrock brine was found in a number of boreholes.

The chemical composition of the fluid has been extensively analysed in the borehole at KLX02 borehole at Laxemar. Meteoric water accounts for about 80 percent of the water down to about 1000 m depth. At deeper levels, below 1000 m, the brine accounts for 60 – 80 % of the total content (Laaksoharju 1995). The salinity of the formation fluid in the Laxemar area is visualised in a cross section down to 2000 m depth (fig. 8). At deeper levels in the cross section the salinity values are largely supported by the data from the KLX02 borehole.



**Figure 8.** Approximately NW-SE/W-E cross-section through the Laxemar-Simpevarp area (SKB 2009). Shown are: a) the location of boreholes and sections which have undergone hydro-geochemical sampling, b) the main fracture groundwater types (colour coded) which characterise the site, and c) the chloride distribution with depth along the major deformation zones. Dotted lines in different colours represent the approximate depths of penetration of the various fracture groundwater types along hydraulically active deformation zones

Data from the borehole close to Lund with a depth down to 3 701.8 m provide no detailed information about the chemical composition of the fluid (Rosberg 2006; Marsic and Grundfelt 2013). The total dissolved solids (TDS) at the deepest part of borehole were higher than 20 % (200 000 mg/l). However, this borehole was largely located in sedimentary rocks with the crystalline bedrock found below 1946 m depth.

In the crystalline bedrock brines were only proved in the boreholes at Gravberg and Laxemar. The brine in the borehole close to Lund is hosted in sedimentary bedrock. This indicates that brine occurs inland at very deep levels of several 1000 meters, while in coastal areas brines occur at levels closer to the Earth’s surface (Juhlin, et al. 1998). In comparison, in the deepest borehole in Finland having 2500 m in depth, brines were found close to the bottom of the hole (Kukkonen 2007; Nyssönen et al. 2014).

Countrywide data on groundwater chemistry derive mainly from private wells (Aastrup et al. 1995). The data reflect the chemistry of the bedrock down to a depth of about 100 m below ground level. Extrapolating these relatively shallow data to deeper levels of several kilometres depth needs to be investigated.

### 3.6 Thermal properties and heat flow

Country wide estimations of the temperature at 500 and 1000 m depth have been presented by Hurter and Haenel (2002). The pattern reflects differences in the temperature gradient and heat production at depth (fig. 9), but even climatic effects.

Temperature measurements in the deep borehole at Gravberg have given a gradient of 15–18°C/km with a temperature of 87.5°C at a depth of 5050 m (Balling 2013). Thermal conductivity was estimated to about 3 W/m K corresponding to values of the corrected geothermal heat flow ranging from 66 mW/m<sup>2</sup> at ground level to 46 mW/m<sup>2</sup> at 5000 m depth. Radiogenic heat production in the upper 4700 m of the borehole is estimated to range from 3.3 to 5.2 μW/m<sup>3</sup>, while below 4700 m heat production was estimated to reach 2.3 μW/m<sup>3</sup>.

The deep borehole close to Lund yields a much greater temperature gradient than elsewhere in Sweden, reaching values between 16 and 27°C/km. Maximum temperature was measured to 85.1°C at a depth of 3 666 m (Alm and Bjelm 2006).

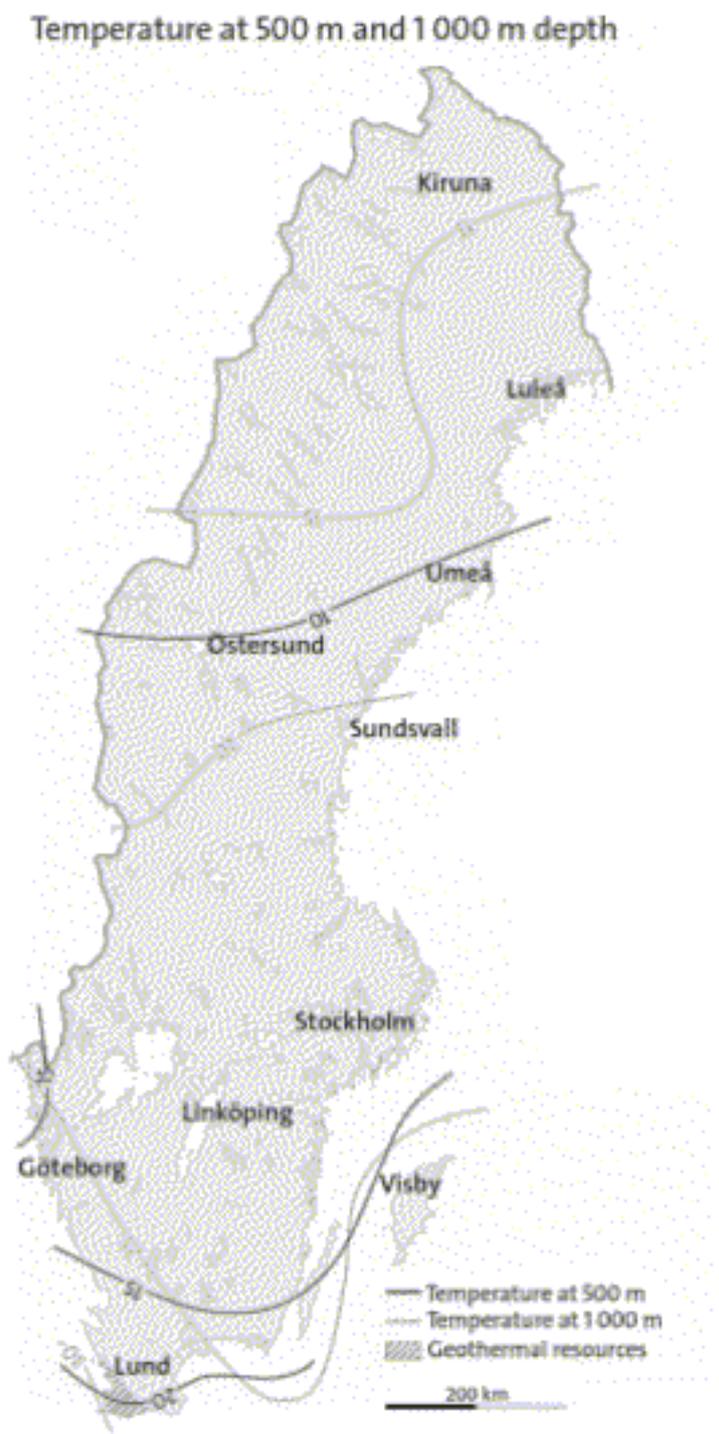
Measurements of temperature and thermal properties in boreholes outside the ore districts were made by SKB at the study sites of Forsmark and Laxemar (Sundberg et al. 2009). The deepest borehole is located at Laxemar (1 700 m). The depth of the other boreholes at the two sites does not exceed 1 000 m. The corrected surface heat flow at Forsmark and Laxemar was estimated to be 61 and 56 mW/m<sup>2</sup> respectively. The temperature gradient at both sites was about 15°C/km. Heat production for different granites in the Laxemar area ranged from 2.07 to 4.45 μW/ m<sup>3</sup>.

Temperature measurementst in the COSC borehole show a geothermal gradient close to 20°C/km with the bottom hole temperature reaching about 55°C (Lorenz et al. 2015). Heat generation varies considerably downhole. Further measurements of thermal and hydraulic properties are planned.

Measurements of temperature and thermal properties were made in 17 boreholes in the ore districts of Aitik and Skellefte (Parasnis 1975). The vertical depth of these holes is ranging between 365 and 780 m and corrected heat flow was estimated to 50 mW/m<sup>2</sup> for Aitik and to 49 mW/m<sup>2</sup> for the Skellefte area.

In eight boreholes in the iron ore district of Malmberget and Kiruna, with depth ranging from 287 to 1 100 m below ground level the corrected heat flow was estimated to 51 mW/m<sup>2</sup> (Parasnis 1981).

Heat production of outcrops all over Sweden was estimated using airborne as well as ground based radiometric measurements provided from the databases of the Geological Survey of Sweden (Schwarz et al. 2010). The map derived from airborne data only connected to known outcrops (fig. 10) shows obvious differences between bedrock types. The extrapolation of data to deeper levels was not yet tested. The differences in heat production reflect differences in radioactivity of the bedrock.



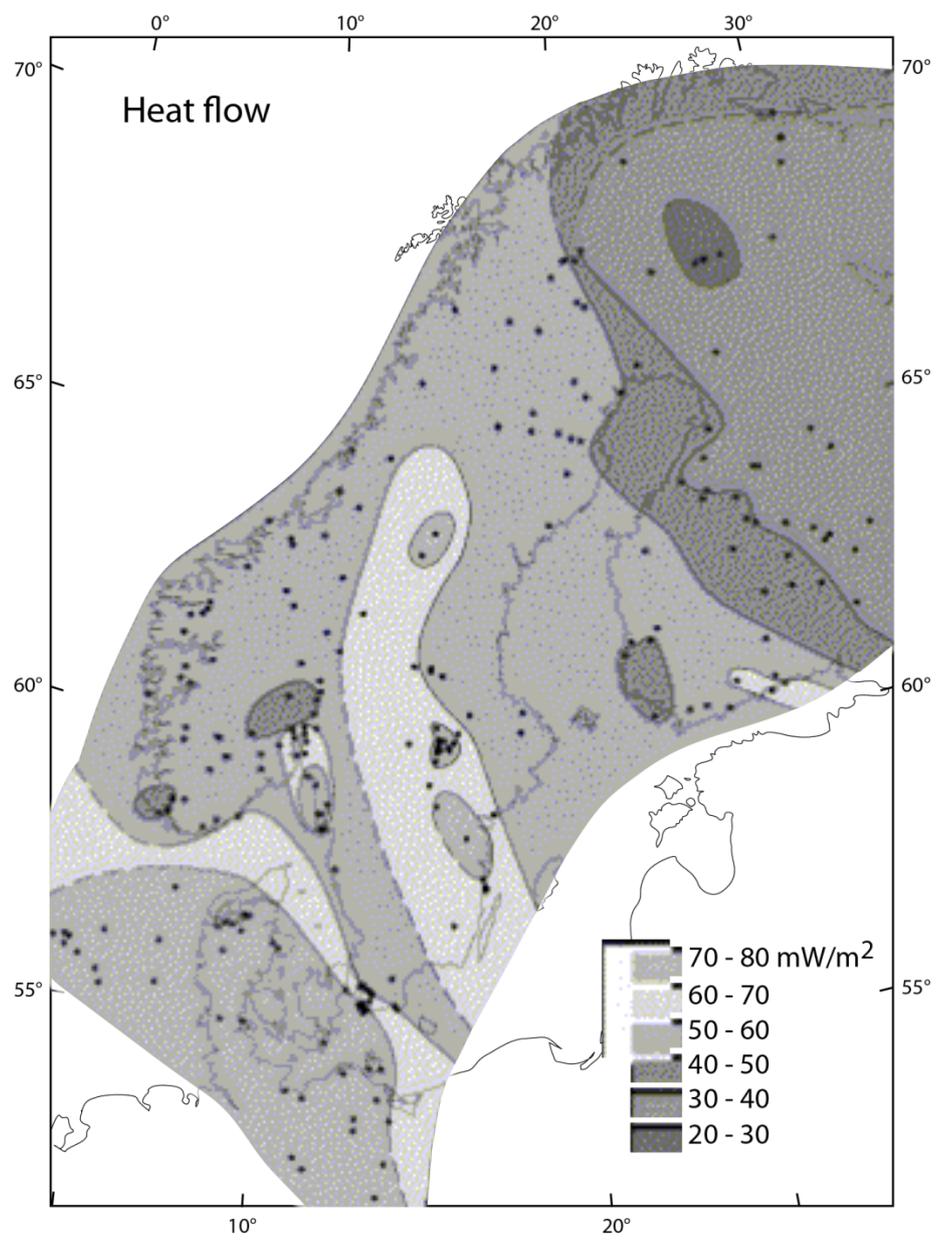
**Figure 9.** Temperature of the uppermost crust in Sweden, at 500 m and 1000 m depth (Hurter and Haenel 2002)

Within a research project at the Geological Survey of Sweden sub-surface temperature and geothermal heat flow in Sweden is re-investigated, in an attempt to up-grade older data (e.g., Eliasson et al. 1991). Heat flow is estimated from the temperature gradient measured in existing deep prospecting boreholes and thermal

conductivity measured on drill cores of these holes. The data are used to improve the earlier estimations of the geothermal heat flow in Sweden (Hurtig et al. 1992; Balling 2013), fig. 11.



**Figure 10.** Heat production calculated from airborne radiometric data from outcrops all over Sweden (except of the mountain areas), in  $\mu\text{W}/\text{m}^3$  (Schwarz et al. 2010)



**Figure 11.** Map with corrected surface heat flow in Fennoscandia (Balling 2013), based on measurements at more than 250 sites (marked by dot)

### 3.7 Current metallogenic models (2D- and 3D-)

Most metal deposits in Sweden were originally formed as volcanic-hosted, largely synvolcanic or slightly epigenetic, stratabound or stratiform mineralisations at or close to the palaeosurface (e.g., Bergman et al. 2001; Kathol and Weihed 2005; Stephens et al. 2009). Their present shapes, positions and orientations are mainly controlled by subsequent tectonic deformation. Apart from dominantly stratigraphically underlying hydrothermal alteration zones (see section 2.5) their style of formation has little or no bearing on present day deep-seated processes. Some of these deposits are or have been mined at or evaluated to considerable depths (> 1000 m). Major examples are the sulphide mineralisations in the mines at Zinkgruvan and Garpenberg in Bergslagen (cf. with tab. 1).

The depth and style of formation for the apatite-bearing iron ores is a matter of debate (see e.g., Bergman et al. 2001; Martinsson et al. 2016). The mineralisations are in part hosted by volcanic and in part by subvolcanic rocks and thus epigenetic. The actual depth of the mineralising process is however unclear. The responsible fluids were at least in part orthomagmatic (magmatic hydrothermal), which suggests some depth in the crust. Deposits of this kind may thus represent fossil analogues to deep-seated hydrothermal activity in present day corresponding settings. The more prominent Swedish examples are Kiruna and Malmberget in Norrbotten and Grängesberg in Bergslagen.

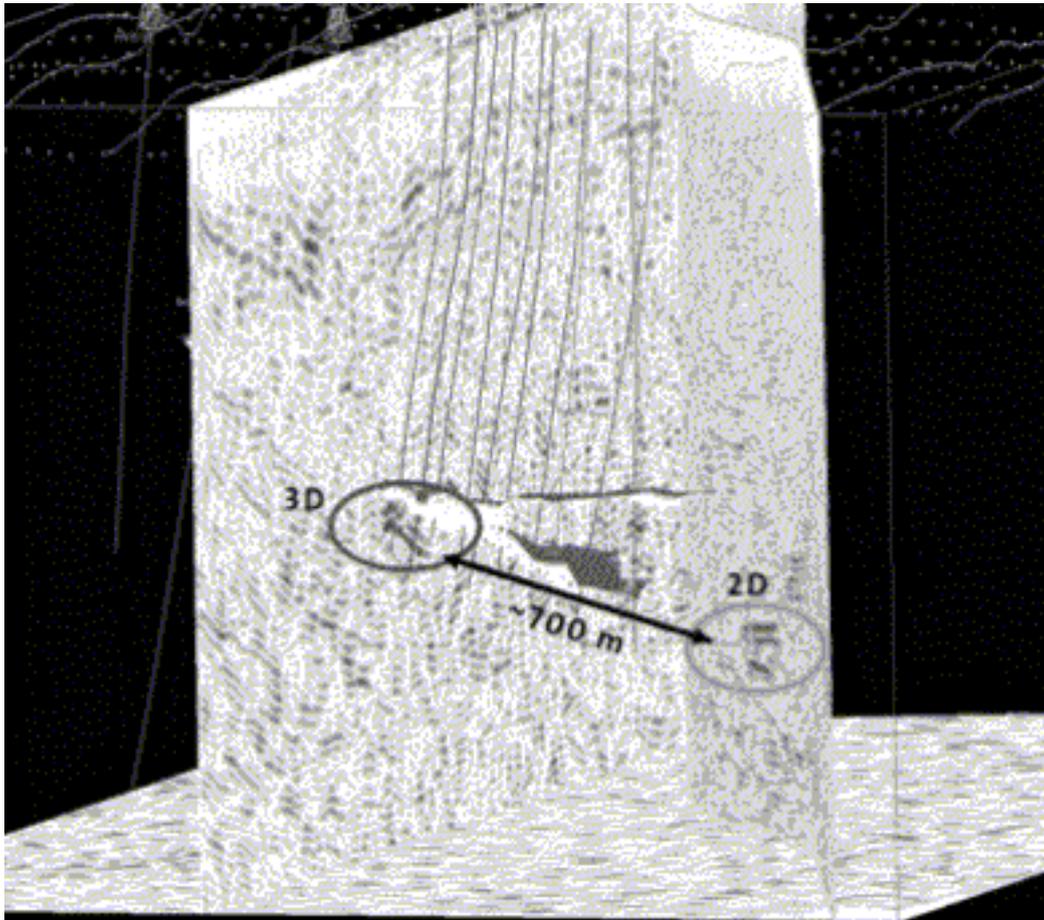
Some Svecokarelian late- to post-tectonic and younger mineralisations formed through and in relation to metamorphic processes. Thus, these mineralised systems also represent fossil, variously deep-seated analogues to what may be occurring in corresponding present day tectonic settings, and thorough and detailed descriptions of them may have relevance to the present task. The most promising Swedish examples in this respect are those mentioned in section 2.2.

## 4 Identifying target sites for future CHPM

### 4.1 Extending existing models to greater depth, integrating data down to 7 km

In recent years, ore prospecting campaigns in Sweden have not only increased by number but even by their depth of investigation. Efforts are undertaken looking deeper into the sub-surface and enhancing resolution for detecting mineralised zones, ore bodies and imaging faults, fracture zones and lithological contrasts. This is not only based on using traditional potential field methods, like gravity and magnetic methods, but also applying deep electromagnetic-, e.g., magnetotelluric (MT) and reflection seismic methods. Because of an often suitable contrast in electrical resistivity between the host rock and the mineralised zone, MT and especially AMT measurements, make it possible to identify such zones, though depth resolution may not be satisfying. Reflection seismics, instead, can provide high-resolution images of the underground and sufficient depth of investigation. Several studies where high resolution seismics was used for mineral exploration and site characterization were published, e.g., Juhlin and Palm (1999), Malehmir et al. (2006, 2007, 2009a, b, 2011), Tryggvason et al. (2006), Schmelzbach et al. (2007). The limiting factor in applying high resolution reflection seismic waves, and, in a powerful combination, also electromagnetics (AMT) to screen the sub-surface is the economy of such investigations.

In the addressed mining areas of Sweden, especially in the Skellefte district combined reflection seismic and electromagnetic investigations were performed, e.g. within two larger projects, namely GEORANGE3D (e.g., Malehmir et al. 2009a, b; Hübert et al. 2009) and VINNOVA4D (e.g., Dehghannejad et al. 2012a, b; Bauer et al. 2011). The technical parameters for the acquisition of reflection seismic data were adopted to explore structures at even greater depths, though not being exploitable with present day techniques. High resolution reflection seismic profiles provided detailed images of an ore body and structures around (Dehghannejad et al. 2010), not being visible in that detail in earlier data collected by Tryggvason et al. (2006). The latter work resolved structures down to a depth of 12 kilometres and was complemented by electrical resistivity studies (García Juanatey 2012). Malehmir et al. (2010) give an example of 2D and 3D interpretation of reflection seismic data, where reflections owing to a massive sulfite deposit at about 1200 m depth are interpreted with a laterally misfit of about 700 m (fig. 12). These examples show that considerable efforts need to be undertaken in geologically complex areas to properly acquire data, i.e., preferably having 3D- instead of 2D seismic surveys – though again limited by economical issues. It should be noted that in 2010 the Skellefte district was suggested being the location for a deep drilling project. The borehole should provide the possibility to constrain the established models for the ore district (Weihed 2010) by penetrating the upper crust down to at least 2500 m. This pre-proposal was a part of the then Swedish Deep Drilling Program (SDDP, Lorentz et al. 2010).



**Figure 12.** The location of seismic reflectors owing to a massive sulphite deposit at about 1200 m depth, and its position in the 2D- and 3D interpretation (Malehmir et al. 2010): A warning example, demonstrating the need for proper data coverage and processing to avoid misinterpretations

## 4.2 Knowledge gaps and limitations

This project, CHPM2030, requires the prediction of structures and lithologies in complex environments at depth down to 7 km. Predicting fracture geometry and permeability at depth in the crystalline bedrock is a crucial point as well and highly challenging. With the present knowledge and data availability this task is not easily to fulfill. For pilot areas within CHPM2030, further intensive multi-disciplinary studies must be considered, e.g., three-dimensional electromagnetic and seismic surveys, as well as better predictions of temperature, heat flow and permeability at depth. The 3D integration of geological and geophysical results will then better allow for planning and conducting of exploration and possibly later-on production drillings.

## 5 Concluding remarks

Mineral deposits in Sweden that may have bearing on the present task are those that originally formed at some depth in the crust as they may represent fossil analogues to ongoing processes. Examples of such mineralisations are Tallberg, Aitik, Nautanen, Yxsjöberg, Pingstaberg, Bastnäs, Harnäs and Laisvall. The apatite-bearing iron deposits of Kiruna-type may also be relevant. The generally low geothermal gradient being less than 20 °C/km in the crystalline basement of the Fennoscandian Shield in Sweden (Eliasson et al. 1991) will allow for low- to mid-enthalpy geothermal systems as part of a possible CHPM unit.

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## 8 Appendix

Figure A.1. Map of the anomalous total magnetic field over Sweden derived from airborne magnetic measurements (SGU 2016). Typical distance between flight lines is 200 m, measuring altitude either, 30 or 60 m, with data points along flight pass every 17 m.

Figure A.2. Coverage of Sweden by airborne very low frequency (VLF) measurements (SGU 2016). Areas in colour where electrical resistivity of the uppermost surface could be obtained while data of areas in grey represent older data not being methodologically applicable for deriving resistivity.

Figure A.3. Map of Sweden with areas where airborne measurements of natural gamma radiation were done (SGU 2016). Shown here is the concentration of uranium ( $^{238}\text{U}$  in ppm) in the uppermost soil and bedrock of the Earth. The other two isotope elements observed are potassium and thorium making it possible, e.g., to identify bedrock units close to the surface and calculate their heat production rate.

Figure A.4. Gravity anomaly map (Bouguer anomaly in mGal) of Sweden (SGU 2016) based on the SGU database with contributions from third parties. Measuring sites account to about 183000, with gridding of data done for areas of 500 x 500 m<sup>2</sup>.

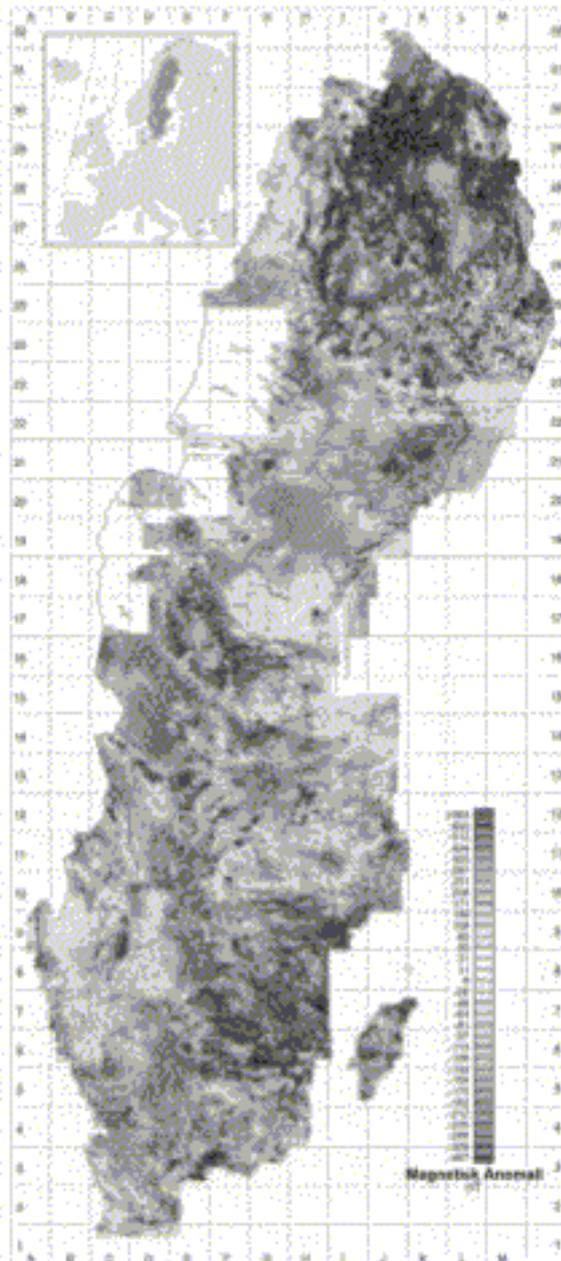
Table A.1. Summary of databases held by SGU and relevant for the CHPM2030 project.

Table A.2. Summary of data in web map services (WMS) – as from the Map Viewer, held by SGU and relevant for CHPM2030. In accordance with INSPIRE access is free of charge.

Airborne geophysics

# MAGNETIC ANOMALY MAP

February 2015



The map shows measured variations in the magnetic total field after subtraction of the geomagnetic reference field (DGRF 1965.0). The map is based on measurements carried out 1960–2014.

The magnetic properties of the Earth's crust is mainly determined by the content of the mineral magnetite in various rock types. The concentration may vary from nearly zero up to 10% or more in for instance gabbros and up to almost 100% in iron ores.

The magnetic field has been measured and registered in systematic and detailed airborne surveys. Measured data are corrected and stored in digital form in databases and may for instance be visualized as maps.

The distribution of various rock types at surface and depth is reflected by the anomaly pattern in the map. The extension of rock types, strike and dip direction can be determined using geophysical interpretation techniques. Faults and their relative movements can be seen as dislocations in the magnetic pattern.

**Survey Parameters:**

- Nominal altitude: 30 or 60 m
- Nominal line spacing: 200–800 m over land areas, 400–1 000 m over sea areas, and 2 000 m over the northern Caledonides
- Altimeter: radar
- Navigation: GPS
- Flight direction: N–S or E–W
- Reference field: DGRF 1965.0
- Relative accuracy:
 

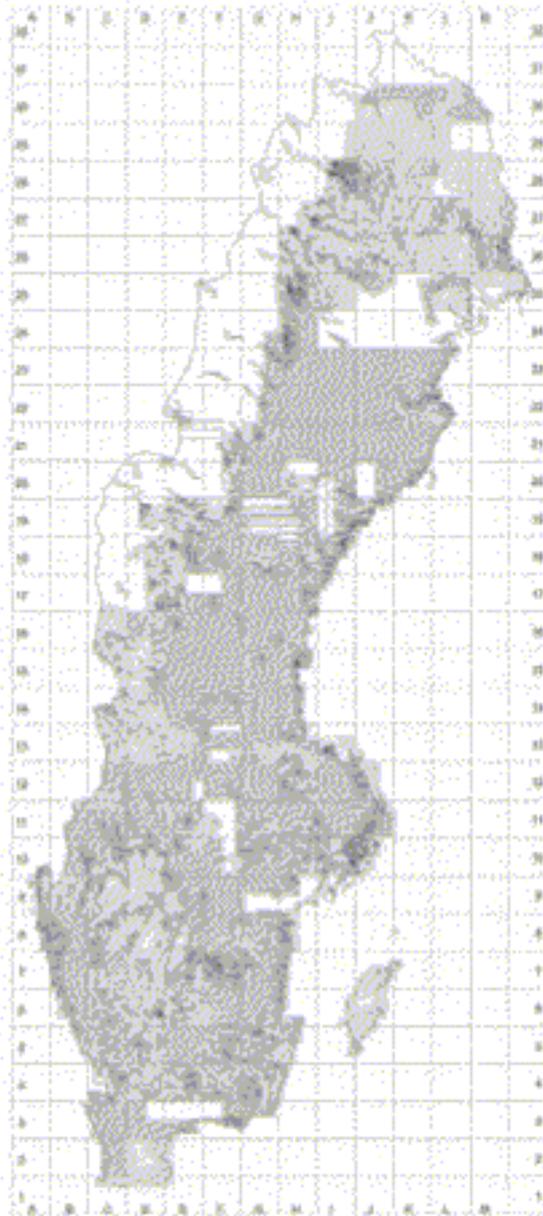
1960–1967	10–15 nT
1968–1981	5 nT
1982–1994	2 nT
1995–2006	<1 nT
2007–	<0,3 nT

Figure A1.

Airborne geophysics

# RESISTIVITY

February 2015



Grey colour shows areas with older VLF-data from where there is no possibility to calculate the resistivity of the ground. Before 1995, measurements were made from only one transmitter and these data are dependent on the direction to the transmitter.

The electrical resistivity of the ground is derived from airborne electromagnetic (VLF) measurement. The radiotransmitters used operate in the frequency band 10–30 kHz (Very Low Frequency, VLF). The low-frequency radio waves penetrate deep into both water and the ground.

The Geological Survey of Sweden (SGU) uses these low frequency radio waves to gather information about the subsurface. The method is based on the fact that the radio waves change character depending on the electrical properties of the ground. The receiver is mounted in an aircraft and has an antenna system that measures the signal in three orthogonal directions from two VLF transmitters.

The surveys are carried out along straight lines with 200 m separation. Survey height is today 60 m and point distance 16 m.

The collected data are then transformed to electrical resistivity, i.e. inability to conduct electric current.

The map shown is based on measurements until 2014. The resistivity data are used i.e. for localising waterbearing fracture zones and deformation zones in the bedrock, graphite and sulphide bearing horizons and clay occurrences. On the resistivity map it is also possible to distinguish highly resistive bedrock units from more conductive ones. In areas with large soil depth, the resistivity map also reflects variations in the quaternary layers.

SGU uses VLF data together with other information in the mapping of the soil and bedrock and in the mapping of available water supplies in Sweden. Other examples of usage are mineral prospecting and environmental applications.

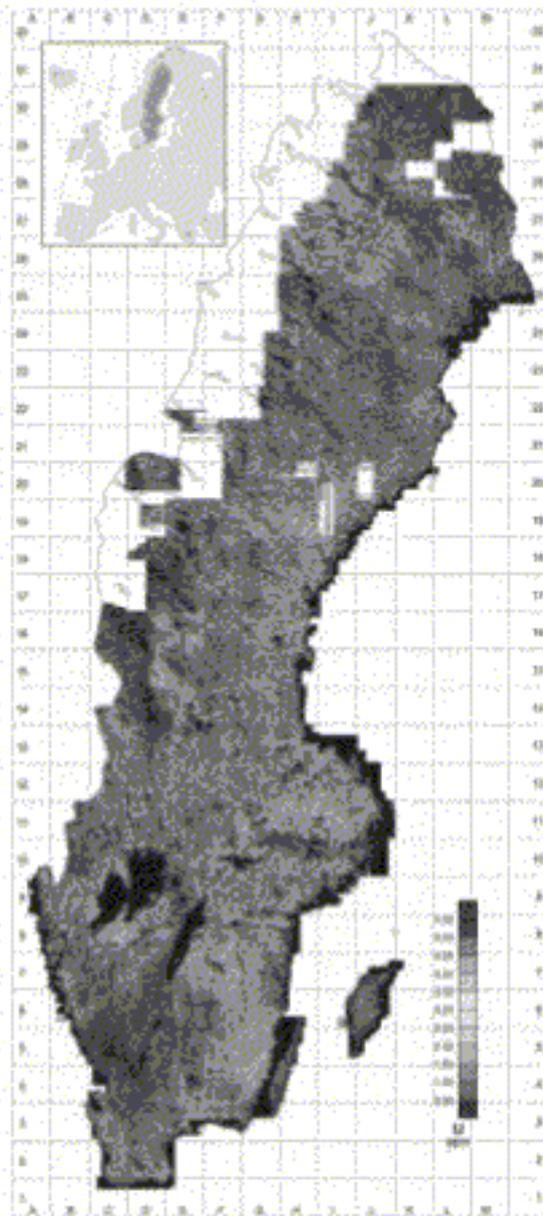
Today it is possible to obtain information about the resistivity of the ground from approximately one third of the country.

Figure A.2.

Airborne geophysics

## RADIOMETRIC MAP (U)

February 2015



The map shows the distribution of uranium in the uppermost part of the bedrock and soil. The uranium concentration is given in ppm (parts per million) eU, where eU indicates that radiometric equilibrium was presupposed in the decay chain of uranium when calculating the concentration.

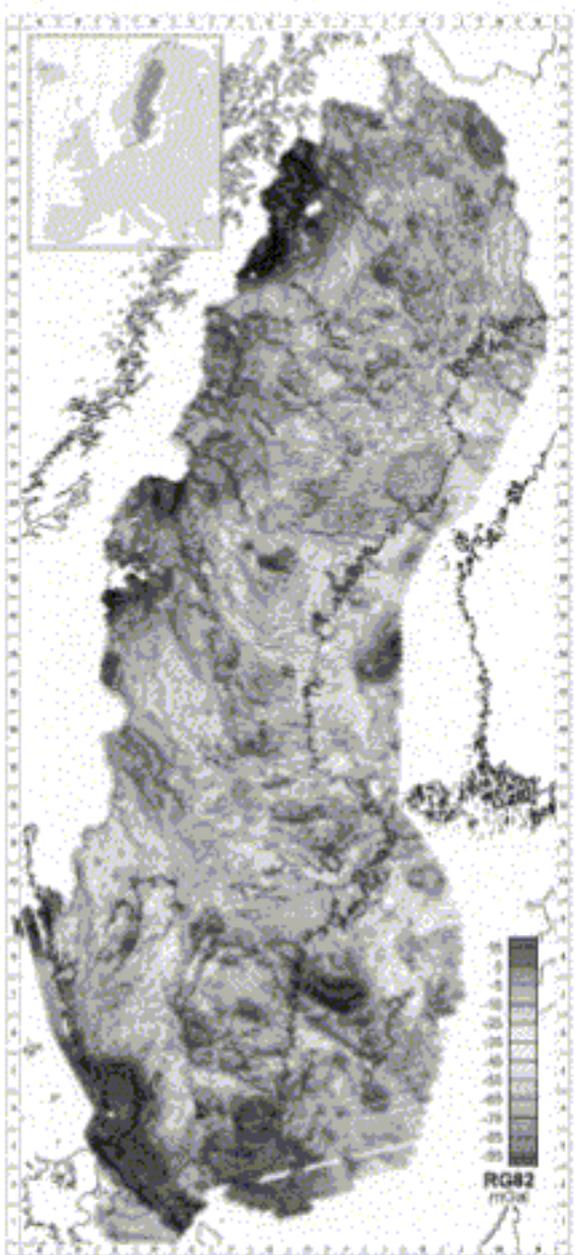
SGU has performed airborne gamma-ray surveys of the natural gamma-ray emitters in the ground since the late 1960's. These measurements allow for the amounts of naturally occurring radioactive isotopes – potassium, uranium and thorium – to be calculated. The map is based on measurements until 2014.

The spectrometer has been calibrated by measuring its response over concrete plates with known concentrations of the radionuclides above. This is routinely performed at the SGU calibration facility in Borlänge. Spectral-fitting is then performed to calculate the nuclide concentration. The effect of absorption in the air has been determined through experiments using wood as absorbing material. The calibration has been verified by comparing measurements on the ground with airborne surveys over the same area. There are however some uncertainties in the result, since variations in air humidity to some amount affect the deduction of all three nuclides. Radon in the air between the ground and the aircraft introduces additional uncertainties. There is also an electronic noise in the instruments and an ionizing radiation from the measuring platform. By measuring the background level over large water areas it is possible to reduce these effects in processed data.

Figure A.3.

# GRAVITY MAP OF SWEDEN

February 2014



**Bouguer anomaly RG82**  
 The map is based on gravity measurements available from the Geological Survey of Sweden's (SGU) database. The measurements have been carried out by SGU, Swedish National Land Survey, Swedish Nuclear Fuel and Waste Management Co (SKB), OPAB, Uppsala University, Luleå University of Technology, Stockholm University, Royal Institute of Technology, Finnish Geodetic Institute (FGI), LKAB, Boliden AB and Zinkgruvan Mining AB.

- Number of regional measurement sites: approx. 183 000
- Grid: 500 x 500 m
- Illumination: D= 15° and I= 85°
- Database: sw1312



Measurement sites.

Figure A.4.

<b>Datasets</b>	<b>Short description</b>	<b>Scale</b>	<b>Coverage</b>	<b>Access cost</b>	<b>Link</b>
Source/Contact	kundservice@sgu.se				
Access cost	<a href="http://www.sgu.se/produkter/kundtjanst/avgifter-for-sgus-material/">http://www.sgu.se/produkter/kundtjanst/avgifter-for-sgus-material/</a> (in Swedish). Remark: Data covered by INSPIRE or for scientific research are free of charge.				
<b>Bedrock, Mineral Resources</b>					
Dating, isotope analysis			See web		
Drill cores					
Bedrock, observations					
Drill cores	Drill core archive		c. 18000 cores, c. 3000000 m		
Drill cores, hyperspectral scanning, IR data	Drill core archive		233 000 m (Sept 2016)		
<b>Quaternary geology</b>					
Quaternary deposits		different scales			
Sedimentary thickness					
<b>Hydrogeology</b>					
Groundwater					
Wells					
<b>Geochemistry</b>					
Biogeochemistry					
Soil geochemistry					
<b>Geophysics</b>					
Gravity	Land, sea based and airborne point data, grid 500 x 500 m <sup>2</sup>		c. 186000 measuring sites	See web-page	
Magnetic Field	Airborne total magnetic field data, Profile density mostly 200 m, data points every 18 m.			Grid data 200 by 200 m, 200 by 40 m, or less.	
Gamma radiation	Airborne survey data for the radioactive isotopes U, K and Th.			Grid resolution as above.	
ElectromagneticField	Airborne Very Low Frequency (VLF) data. Slingram data partly available.			Grid data 200 by 18 meters.	
Petrophysics	Density and magnetic properties of rocks. Content of U, K, Th..		c. 75000 samples. 5900 outcrop data.		

Table A.1.

Datasets	Short description	Scale	Cove- rage	Access cost	Link
Source/Contact	<i>Web map services (datasets):</i> <a href="http://www.sgu.se/en/products/data/data-in-web-map-services-wms/">http://www.sgu.se/en/products/data/data-in-web-map-services-wms/</a> <i>Maps:</i> <a href="http://apps.sgu.se/kartgenerator/maporder_en.html">http://apps.sgu.se/kartgenerator/maporder_en.html</a> ; <a href="http://www.sgu.se/en/products/maps/map-viewer/">http://www.sgu.se/en/products/maps/map-viewer/</a>				
Access cost	<i>These datasets are covered by INSPIRE and free of charge.</i>				
<b><i>Bedrock, ores and minerals</i></b>					
Bedrock		1:1 M		See above	See above
Drill cores					
Ores and mineralizations					
Mineral resources					
Mineral permits					
Mineral deposits of national interest					
<b><i>Groundwater, wells and groundwater monitoring</i></b>					
Wells					
Groundwater		1:1 M	Sweden		
Environmental monitoring					
Springs					
<b><i>Geophysics</i></b>					
Geophysical ground measurements, prospecting areas					
Airborne geophysics, magnetic field	Airborne survey data showing variation in the total magnetic field.				
Airborne geophysics, gamma radiation uranium, potassium, thorium	Airborne survey data for the radioactive isotopes U, K and Th.	Resolution information on website			

Datasets	Short description	Scale	Cove- rage	Access cost	Link
Geophysical ground measurements, gravity	Airborne survey data showing variation in the magnetic field.	Resolution information on website			
<b>Geochemistry</b>					
Biogeochemistry, copper					
Ground geochemistry, copper					
<b>Quaternary deposits</b>					
Ground stability properties				free	
Ground permeability				free	
Quaternary deposits	At scales from 1:25000 to 1:1 M*			free	
Landslides and gullies				free	

**Footnote:** \* Other scales available (e.g., 1:200000; 1:250000; 1:750000).

Table A.2.



CHPM2030 DELIVERABLE D1.2 APPENDIX 1.2.5

REPORT ON DATA COLLECTION  
BY THE EFG LINKED THIRD PARTIES

(EUROPEAN DATA INTEGRATION AND EVALUATION)

*Authors:*

Vanja Bisevac, Isabel Fernandez (*European Federation of Geologists*)

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**Table 1. Data Overview:** Please note that some of the LTPs reported also on metal enrichments which do not satisfy the CHPM2030 criteria. See text for further explanations. y – yes; n - no

**Table 2.** List of Belgian deep wells crossing the 100°C isotherm depths. Balmatt-2 is not incorporated since the drilling is still in progress. The wells of both St-Ghislain and Havalange have partially been closed. \* Temperature extrapolated from 105°C at 2155 m to the depth of 2195 m

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**Figure 1.** Distribution of the drillholes in Slovenia

## 1 Executive summary

The information reported here has been obtained by reviewing information from 24 European Countries reporting by the European Federation of Geologists, EFG, Linked Third Parties, LTPs. EFG LTPs collected publicly available data at national level on deep drilling programs, geophysical and geochemical explorations and any kind of geo-scientific data related to the potential deep metal enrichments. The task provides a “European outlook” on data availability in order to identify data gaps. In this survey we used the term “metal enrichment” considering the geological formations in which the metal content is at least five times higher than the average in the given formation type. This term also includes the “real ore bodies” which have economic value on their own. The LTPs were asked to consider the following metals: Cu, Zn, Pb, Fe, As, Sb, Ag, Au, Co, Cr, Ni, U, Sn, W and Mo, but were also invited to report on any other metal enrichment they find important and relevant in their countries.

The 19 countries out of 23 which participated in this survey reported that drillholes with temperatures exceeding 100°C exists in their country (Table 1). The number of such drillholes varies from 1 (Ireland) to 2809 (Germany) (Table 1). The data are publicly available for drillholes in Belgium, Greece, Netherlands, Poland and Portugal, while only partly available in Austria, Hungary, Ireland, Serbia, Slovenia, Spain, Sweden and UK. Unfortunately, the drillholes data are not publicly available in Croatia, Germany and Switzerland. The Czech Republic, Finland and Luxembourg did not report the existence of the drillholes with temperatures exceeding 100°C and are not considered in further discussion.

Among them, eight countries mentioned the identification of metal enrichment (Austria, Belgium, Cyprus, Hungary, Poland, Serbia, Slovak Republic and UK, while five of those (Belgium, Hungary, Poland, Serbia and Slovak Republic) provided more detailed insight into these metal enrichments providing some data on geographical, geological, geochemical and geophysical data. These countries could be of further interest of the CHPM2030 interest. Since the data of the project’s interest only partly publicly available or not available at all, further cooperation with National experts and possible contact to organizations in charge/owning the data will be necessary to obtain all relevant information.

## 2 Introduction and the scope of the survey

Since the objective of CHPM2030 WP1 is to prepare the conceptual framework for a novel enhanced geothermal system (EGS) for the production of energy and the extraction of metals from ore deposits located at great depths, first step was to synthesize our knowledge on deep metal enrichments that could be converted into an “orebody EGS”, and to investigate the characteristics of these bodies. We aimed to discover and examine the geological, tectonic, geochemical, and petrologic factors that define the boundary conditions of such novel EGS both in terms of energy and potential for metal recovery.

The information reported here has been obtained by reviewing past investigations in Europe that have resulted in public access geological and geothermal datasets. In addition to these data, associated publications and studies have been also reviewed. EFG Linked Third Parties collected publicly available data at national level on deep drilling programs, geophysical and geochemical explorations and any kind of geo-scientific data related to the potential deep metal enrichments. They also collected data on the national geothermal potential. The task provides a “European outlook” on data availability in order to identify data gaps. A horizontal task is to connect two insofar unconnected communities: mining and geothermal earth science professionals for a common goal on EU and national levels. In the third year of the project implementation, within WP6 – Roadmapping and Preparation for Pilots, the EFG Linked Third Parties will assess the geological data on suitable ore-bearing formations and geothermal projects, which were collected in this Survey, in relation with the potential application of the CHPM technology.

### 3 European outlook

As we want to apply an EGS system, in the data collection we were looking for the depths where the temperature is above 100°C. The LTPs were asked to use the average geothermal gradient in their country and during the data collection to consider only drillholes which reached at least this depth. If such drillholes are available, LTPs were asked to provide the number of the drillholes, availability of the data, to specify the metal enrichment in such drillholes if identified.

For each metal enrichment they were asked to provide additional and specific information, if available, such as:

- a) Geographical data of metal enrichment (metal, locality, coordinates)
- b) The depth in meters where the metal bearing formation was reached
- c) The extent of the metal enrichment known in the sense of width, length and height
- d) To specify many drillholes identified the given metal enrichment
- e) The geological data from the metal enrichment regarding stratigraphy, lithology and structure
- f) The geochemical data - rock chemistry and fluid chemistry
- g) The geophysical data - Normal resistivity logs, Fluid resistivity logs, Spontaneous-potential logs, Acoustic logs and Gamma logs together with information on any other surface or airborne geophysical surveys which provide additional data related to the metal enrichment.

Additionally, LTPs were asked to provide the list of references for the data they specified together with any other remark they considered important for this data collection.

#### 3.1 Survey data overview

The Table 1 shows the data overview collected during the survey with some basic information on data on drilling programs and detected metal enrichment.

Note that some of the LTPs reported also on metal enrichments which do not satisfy the CHPM2030 criteria.

Country	DATA ON DRILLING PROGRAMMES			METAL ENRICHMENT(S)		
	Drillholes with temperatures exceeding 100°C reported (y/n)	Number of such drillholes	Data from drillholes publicly available (y/n)	Identified (y/n)	Reported (y/n)	Elements reported
Austria	y	ca. 100	y, partly	y	n	Ni
Belgium	y	4	y	y	y	Cu, Pb, Zn, U, Th
Croatia	y	ca. 1000	n	n	n	-
Czech Republic	n	-	-	-	-	-
Cyprus	n	-	-	y	n	Cu
Finland	n	-	-	-	-	-
Germany	y	2809	n	-	-	-
Greece	y	5	y	n	n	-
Hungary	y	100	y, partly	y	y	Cu, Zn, Pb,
Ireland	y	1	y, partly	n	n	-
Italy	y	694	y	n	n	-
Luxembourg	n	-	-	-	-	-
Netherlands	y	>800	y	n	n	-
Poland	y	a few dozens	y	y	y	Cu, Ag, Au, Pt-Pd, Se, Pb, Zn, Mo, V, Ni, Co, W, Bi, Ag, Te, Ni
Portugal	y	min 18	y	n	n	-
Serbia	y	min 3	y, partly	y	y	Cu, Au
Slovak Republic	y	3	y	y	y	Fe, Cu, Mo, Bi, Pb, Zn, Au, Ag, Te, Sb, Hg, and As
Slovenia	y	41	y, partly	n	n	-
Spain	y	33	y, partly	n	n	-
Sweden	y	3	y, partly	n	n	-
Switzerland	y	2	n	n	n	-
Ukraine	n	-	-	-	-	-
UK	y	27	y, partly	y	y	Sn, W, Cu, Li, Rb, Cs

**Table 1.** Data collection overview

### 3.2 Availability of the data and number of the drill holes per country

The 19 countries out of 23 which participated in this survey reported that drillholes with temperatures exceeding 100°C exists in their country (Table 1). The number of such drillholes varies from 1 (Ireland) to 2809 (Germany) (Table 1). The data are publicly available for drillholes in Belgium, Greece, Netherlands, Poland and Portugal, while only partly available in Austria, Hungary, Ireland, Serbia, Slovenia, Spain, Sweden and UK. Unfortunately, the drillholes data are not publicly available in Croatia, Germany and Switzerland.

Please find below the detailed overview per country (listed alphabetically) from the 19 countries which reported existence of drillholes with temperatures exceeding 100°C. Countries which provided additional data which could be of the project interest are also mentioned in this section. The Czech Republic, Finland and Luxembourg did not report the existence of the drillholes with temperatures exceeding 100°C and are not considered in further discussion, if not stated otherwise.

#### 3.2.1 AUSTRIA

According to the available data, Austria could have a large geothermal potential throughout its' deep (alkali) metal enrichment zones. The Geological Survey of Austria reported that around 100 drilling programmes reached the +100°C isotherm of which some with known Ni-enriched reservoir(s) (P.C. Gregor Goetzl, 2016).

Nevertheless, most of the data requested is not or only partly publicly available since most of the hydro chemical datasets related to deep aquifers are obtained by the hydrocarbon industry. Interesting to note is an ongoing research on scaling and erosion at thermal wells in Austria with focus on geochemical components in deep reservoirs. More information on this could be obtained from the contact if project consortium decides it is necessary.

#### 3.2.2 BELGIUM

Judging from the data received Belgium could be of CHPM2030 interest. 5 wells reached the 100°C isotherm depth, in the Table 2 information about 4 wells is presented: Balmatt-1, Havelange, St-Ghislain and Turnhout. The 5 well is Balmatt-2, not incorporated since the drilling is still in progress.

The Balmatt-1 and Balmatt-2 wells were drilled for hydrothermal energy exploration (VITO).

Both Havelange and St-Ghislain wells have been sealed at certain depth some time ago. Nevertheless, reopening of the Havelange well is being considered at the moment. According to geothermal maps and several temperature logs in deep wells, a temperature of +90°C is found at 2000 m depths in the northeast of the Campine Basin.

Wells	location	Depth (m)	temp gradient (°C/Km)	Temp (°C)	Stratigraphy
Balmatt-1	Mol	3600	35.5	138	Lower-Carboniferous
168W314	Havelange	5648	18.6	115	Mississippian, upper Dev.
150E387	St-Ghislain	5403	30.5	175	Mississippian, upper Dev.
29E144*	Turnhout	2195	47.8	115*	Lower-Carboniferous

**Table 2.** List of Belgian deep wells crossing the 100°C isotherm depths

### 3.2.3 CROATIA

Geothermal gradient in Croatia varies significantly between the Dinarides (av. 18°C/km) and the Pannonian basin (av. 49°C/km). Around 1000 boreholes have a depth greater than 2000 m in Croatia, but an exact number has not been provided. Those wells, lying in the Pannonian Basin, should reach around 100°C. However, some of these past drilled wells have been sealed off (P.C. Borovic S., 2016). Data on deep metal enrichments may exist but are not listed in databases, not examined or have not been made publicly available.

In Croatia, mostly in period from the 1950s until 1990s, thousands of boreholes were drilled in the scope of hydrocarbon prospection, mostly in the Pannonian part of Croatia and northern Adriatic by a public petroleum company INA. INA was later partially privatized and data became unavailable. Nevertheless, some years ago the Ministry of Economy took charge of this data, which are now in the ownership of the Ministry. All data is physically placed at HGI-CGS (Croatian Geological Survey). Data availability will be regulated by a special regulation issued by the same Ministry. However, the Ministry did not issue the regulation so the data is until now unavailable and, even if data were fully accessible, it is in a form of scanned reports from 1950s onwards. Only manual scanning and analyzing is possible on this data since no further digitalization and creation of comprehensive database has been performed, which means a very time-consuming activity. Moreover, data about metal enrichment zones would be extremely rare in the reports (P.C. Borovic S., 2016).

### 3.2.4 GERMANY

The 2809 drillholes which reached the depths where the temperature exceeds 100°C has been identified in Germany, although there is not publicly available date for those drillholes, as reported. At the moment, Germany should be considered as potential interest of the CHPM2030, although different approach should be used to obtain desired data.

### 3.2.5 GREECE

The 5 drillholes which reached the depths where the temperature exceeds 100°C were identified in Greece, but no metal enrichment has been identified. Despite that fact, additional data related to drillholes were provided and listed below.

Drillhole 1: WGS84 coordinates: E24.448737 N36.735608 - The drillhole has a 1163 m total depth and the temperature reached 308°C.

*Stratigraphy:* The topmost horizons of the stratigraphy are tuffs reaching a depth of 107 m followed by an 8 meter thick green lahar. The succession continuous with altered calcite tuffs. Another interbedded green lahar horizon appears in a depth of 470 m and the series continues with altered tuffs associated with anhydrite, calcite and pyrite. A 707 m bellow surface, a 50 meter characteristic horizon of Neogene limestone is present and then follows the stratigraphically lowermost part which is the metamorphic crystalline basement.

Drillhole 2: WGS84 coordinates: E24.487253 N36.704649 - The total drillhole depth is 1101 m and the higher measured temperature was 310°C.

*Stratigraphy:* The drillhole initially penetrates alluvial deposits and then in a depth of 100 m reaches a green lahar volcanic rock. 60 m bellow, there are alternations of silicified and kaolinitic tuffs. In a depth of 260 m, a series of low-grade schists appears to form the basement in the area, whereas, the deeper part appears to be layered by sericite chlorite schists with quartz.

Drillhole 3: WGS84 coordinates: E24.50093 N36.710754 - The drillhole is 1017 m deep and the temperature of the surrounding rocks exceeded 250°C.

*Stratigraphy:* A relatively thin layer of green lahar is underlain by 100 m of altered volcanic rocks. The succession continuous with Neogene sediments. The 172 m below the surface is the contact with the low-grade metamorphic basement.

Drillhole 4: WGS84 coordinates: E27.172702 N36.581755 - The total borehole depth is 1800 m and the temperature exceeds 350°C.

*Stratigraphy:* The borehole penetrates series of volcanic rocks comprising basaltic andesite, andesite, dacite to trachydacite and rhyolites, associated with different phases of past volcanic eruptions.

Drillhole 5: WGS84 coordinates: E24.622379 N40.956164 - The drillhole has a depth of 1377 m and the rock temperature reaches 122°C.

*Stratigraphy:* The 250 m of mainly deltaic sediments are followed by 300 m of impermeable marly-argillaceous Pliocene sediments. The succession continuous with a transitional sedimentary zone of calcarenites and oolitic limestones. In a depth of 690 m, a basal conglomerate and breccia appears. A lower amphibolitic series and schists with marble intercalations forms the lowermost lithologies.

### 3.2.6 HUNGARY

Around 100 drillholes, which reached the depths where the temperature exceeds 100°C, were identified in Hungary. For more than 10 of them the data, which could be useful for the future actions of the project, are publicly available via database of National Office of Mining and Geology, in concession database of Oil researches. Unfortunately, no metal enrichment important for the scope of projects was identified below the depths where the temperature exceeds 100°C. Nevertheless, the other metal enrichments were reported (see 3.3. for detail explanation).

### 3.2.7 IRELAND

One drillhole which reached the depths where the temperature exceeds 100°C was identified in Ireland. It was drilled in 1965 for hydrocarbon exploration with no mineral enrichment noted. The data from the drillhole is only partly publicly available. Additionally, there is regional geophysical data (magnetics, radiometrics and EM) for approximately one third of the country available on [www.tellus.ie](http://www.tellus.ie)

### 3.2.8 ITALY

Exact 694 drillholes, which reached the depths where the temperature exceeds 100°C, were identified in Italy managed by the Ministry of Economic Development in the frame of "Geothermal Resources National Inventory". The inventory comprise data for 948 geothermal wells (the first one was drilled in 1900 and the last one being drilled yet). At the moment the 268 are free for consultation. Among all the geothermal wells included in the inventory, 694 of them can be distinguished as those with  $T > 100^{\circ}\text{C}$ . Unfortunately, none of the geothermal wells provide any metal enrichment information.

### 3.2.9 LUXEMBOURG

According to the information obtained from the Service Géologique du Luxembourg, no drillholes which reached the depths where the temperature exceeds 100°C exists neither metal enrichment

were identified below the depths where the temperature exceeds 100°C. The deepest well has a depth of +700 m with a bottom temperature of 25°C.

Schintgen (2015) expects temperatures of +90°C to around 120°C at depths of respectively 3.5 km to 5 km based on 2D models. Quartzite-rich Lochkovian deposits, near the western Eifel region in Luxembourg, could prospectively enable combined geothermal heat production and power generation.

### 3.2.10 NETHERLANDS

More than 800 drillholes, mostly drilled for the purposes of oil/gas industry, which reached the depths where the temperature exceeds 100°C has been identified in Netherlands. There are data publicly available for each drillhole ([www.nlog.nl](http://www.nlog.nl)). No metal enrichment has been identified below the depths where the temperature exceeds 100°C. Most of the data about the subsurface is freely available via various web portals with regards to subsurface models, drillhole descriptions and geothermal potential like [www.thermogis.nl](http://www.thermogis.nl), [www.nlog.nl](http://www.nlog.nl) and [www.dinoloket.nl](http://www.dinoloket.nl).

### 3.2.11 POLAND

A few dozen of drillholes which reached the depths where the temperature exceeds 100°C were identified in Poland with publicly available data and metal enrichment identified (see 3.3. for detail explanation).

### 3.2.12 PORTUGAL

The 8 drillholes in Continental Portugal and at least 10 geothermal wells in Azores were reported which reached the depths where the temperature exceeds 100°C. The data are publicly available for 8 drillholes. The metal enrichment below the depths where the temperature exceeds 100°C was not identified.

### 3.2.13 SERBIA

The 3 drillholes which reached the depths where the temperature exceeds 100°C were identified in Serbia. A few more (5) are close to this temperature, and will be probably reached if drilling go deeper. For 4 of these drillholes the data are publicly available and metal enrichment identified (see 3.3. for detail explanation).

### 3.2.14 SLOVAK REPUBLIK

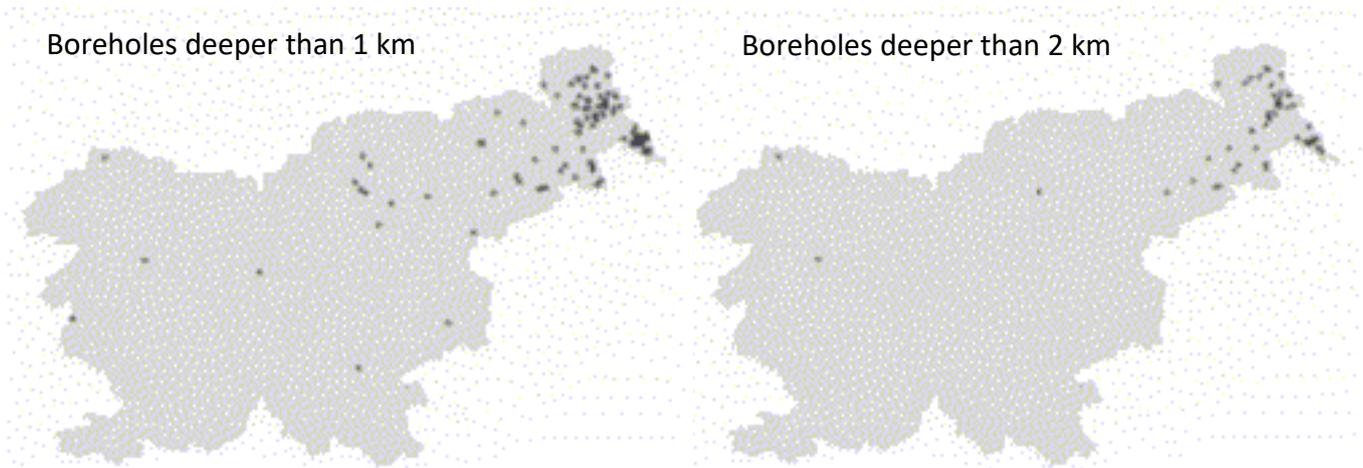
Total of 3 drillholes which reached the depths where the temperature exceeds 100°C together with metal enrichment identified below the depths where the temperature exceeds 100°C were identified in Slovak Republic. Data for all 3 drillholes are publicly available (see 3.3. for detail explanation).

### 3.2.15 SLOVENIA

Total of 41 drillholes reached the depths where the temperature exceeds 100°C exists in Slovenia (+additional 24 drillholes where 100°C would be reached certainly if measured) All drillholes in Slovenia in which temperature exceeds 100°C belongs to exploration oil & gas drillholes, drilled in Tertiary sediments and its basement in the eastern part of Pannonian basin.

Most of data from these drillholes are not public available, but many data were published in the scope of EU funded projects T-JAM and TRANSENERGY. The data is available on internet: [akvamarin.geozs.si/t-jam\\_boreholes/](http://akvamarin.geozs.si/t-jam_boreholes/) and [www.arcgis.com/home/webmap/viewer.html?webmap=f82fe0f737174219a354f4209ea7448a&extent=12.1518,45.3238,20.2487,49.1158](http://www.arcgis.com/home/webmap/viewer.html?webmap=f82fe0f737174219a354f4209ea7448a&extent=12.1518,45.3238,20.2487,49.1158).

There is currently neither one drillhole in Slovenia where metal enrichment would be found and which exceeds 100°C. The problem is that large part of Slovenian territory is not investigated deeper than 500 m yet as is seen from the figures below.



**Figure 1.** Distribution of the drillholes in Slovenia

### 3.2.16 SPAIN

The 33 drillholes which reached the depths where the temperature exceeds 100°C were identified in Spain. For 8 of them the data are publicly available. The metal enrichment below the depths where the temperature exceeds 100°C were not identified.

### 3.2.17 SWEDEN

As an active partner of the CHPM2030 project and coordinator of taskforce 1.2 in WP1 the Geological Survey of Sweden will deliver a full report on the Swedish CHPM potential in taskforce 1.2.4. Information given here is thus very briefly. Sweden has 3 deep cores crossing the 100°C isotherm (Räby (Skania) 3702 m, Gravberg (Siljan) 6957 m and Stenberg (Siljan) 6529 m). Unfortunately, no deep metal enrichment zones have been identified. Data of these drillholes are partially public available.

### 3.2.18 SWITZERLAND

The two drillholes which reached the depths where the temperature exceeds 100°C were identified in Switzerland with no mineral enrichment identified. Unfortunately,, both projects (Basel and St Gall) are abandoned and the data from these drillholes are not publicly available at this moment.

### 3.2.19 UNITED KINGDOM

The UK and British Geological Survey is an active partner of the CHPM2030 project and will analyze several samples. A full report on the potential of the UK is most likely published during the next project years.

At least 27 offshore North Sea hydrocarbon fields where temperatures exceed 100°C have been drilled with multiple wells per field, and some with 10s of wells. Data is partly available. Since these are hydrocarbon wells, older ones have more openly available information, but newer well may still be under restricted access. Geochemical data points out that some sulphide minerals are present (reducing circumstance of hydrocarbons). Nevertheless, no economic metallic mineralization is noted or expected.

Deep onshore wells exist, e.g. Rosemanowes site with a 2180, 2350 and 2800 km deep well) but bottom hole temperatures do not reach the CHPM restrictions. Above mentioned cores were part of a Hot Dry Rock (HDR) geothermal project from the 1970s to the 1990s in southwest England (see HDR-references). One well is still available for bottom hole testing. The HDR potential of southwest England originates from several granite batholiths and intrusions (e.g. Cam Brea granite and Cammenellis granite).

The Cornubian orefield, or other orebodies in SW England (Cornwall, Devon & part of Somerset), are related to high heat productivity and stress history of these granite batholiths. The whole region is enriched with a variety of metals, the primary ones of which occur in zones around bodies of granite. Typically initial (higher temperature) mineralization consisted of Sn, W ( $\pm$  others). This was followed by later (i.e. lower temperature) precipitation of Cu ( $\pm$  others), and finally at even lower temperatures Zn, Pb ( $\pm$  others). Locally, enrichment is generally concentrated within 500m of the contact between granite and surrounding sediments. Such ore deposits are mined until depths up to 790m (South Crofty deep mine) and consist almost certain at depths reaching 100°C (BGR). Since the metals are mineralized in fractures of thermally metamorphosed Devonian mudstones, no estimation of the real size of this ore body at such depths is available.

Borehole measurements, geophysical logs and geophysical airborne data (TELLUS-project, 2013) can be consulted at GSB or in several HDR reports. Underground observations in South Crofty deep mine (790m) by Bromley and Thomas (1988), summarized in Smedley et al. (1989), suggested the presence of intermediate salinity circulating water in crosscourse fractures and veins, distinct from high salinity waters trapped in cavities along the lodes. ongoing alteration phenomena associated with the circulation of warm saline water (up to 45°C) is observed. Here the brine consists of iron oxy-hydroxides and calcium silicate (Thomas and Milodowski, 1988). Hydrogeochemical analysis of the shallow groundwater's of the Cammenellis granite prove the presence of trace alkali metals Li, Rb and Cs (Smedley 1989) but no mention is made of the exact quantity of these alkali metals. Even so, the granite batholith may have caused some alkali metal enrichments, true ore deposits caused by hydrothermal fluid flow linked with these granites are of a bigger importance for CHPM.

### 3.3 Identification of the metal enrichment

Eight countries mentioned the identification of metal enrichment: Austria, Belgium, Cyprus, Hungary, Poland, Serbia, Slovak Republic and UK, while five of them (Belgium, Hungary, Poland, Serbia and Slovak Republic) provided more detailed insight into these metal enrichments providing some data on geographical, geological, geochemical and geophysical data. See further text for more details, countries listed alphabetically).

#### 3.3.1 AUSTRIA

Although Austria possesses a large number of wells crossing the 100°C isotherm little data on deep metal enrichment zones is publicly available, apart from the occurrence of interesting amounts of Ni in some deep aquifers. No details were provided on those aquifers.

#### 3.3.2 BELGIUM

The two metal enrichment zones, with a hypothetical occurrence around depths reaching 100°C or more, are expected in some areas:

1. The U and Th enriched Chokier and Souvré Formations occur in the Campine Basin, Liege Basin and Mons Basin. Only the most north-eastern part of the Campine Basin has modelled Chokier

and Souvré depths reaching up to 5000 m, thus crossing the +100°C isotherm. The U and Th enrichments have been measured during logging and reached respectively 18 and 17 ppm. Both formations consist of shales deposits of Viséan-Serpukhovian age. The thickness of the combined formations increases towards 100 m thick in this north-eastern Campine area. Nevertheless, it should be noted that thick underlying Under-Carboniferous carbonate aquifers are a target for deep geothermal energy, geological storage of natural gas and CO<sub>2</sub> and the Chokier and Souvré Formation are a possible target for unconventional extraction of shale gas.

2. A mineralized fault systems comprising Cu-Pb-Zn sulphide type hydrothermal deposits with minor Au and Ag in central to NW Belgium. The enrichments have been identified in several drillholes going up to 400 m depth (St-Pieters-Kapelle wells). Low-angle and high-angle faults have been tracked by aeromagnetic prospection and faults dip towards the northeast. The existing steep dipping mineralized faults are thought to cross the 100°C isotherm. Pyrite veinlets and quartz mineralized veins have at measured depths maximum 0.25, 0.25 and 1.6 wt% of Cu, Pb and Zn in the cored low-angle faults. The degree of ore mineralization might increase at greater depths.

More information about the two metal enrichments on stratigraphy, lithology, structure and geochemical data could be provide if it is required by CHPM2030.

### 3.3.3 CYPRUS

Although, no drillholes which reached the depths where the temperature exceeds 100°C exists neither any metal enrichment were identified below the depths where the temperature exceeds 100°C on Cyprus, some general information on metal enrichment were collected.

Regarding Cu and associated Ag and Au, the massive sulphide deposits (Cyprus type) are very well known how they are formed. They are located between the upper and lower pillow lava horizons and all on or near the surface deposits have been explored and extensively exploited since antiquity. In fact, the mining wastes of the past are currently exploited with the recovery of Cu from wastes with concentration of Cu as low as 0.1% by using hydrometallurgy. In addition to this, in-situ leaching is also carried out in ore deposits with concentration of Cu as low as 0.05%.

Please note that the Cyprus Crustal Study Project run in 1984 and Geological Survey Department (GSD) was involved. Its' framework included deep borehole drilling in different places in Europe. In Cyprus, five deep boreholes were drilled at the Ophiolite near Palaichori, Mitsero, Ayio Epiphanio and Klirou (two boreholes) with 2263 m, 701 m, 689 m, 485 m and 226 m depth respectively. Finally, a large number of parameters were measured like Resistivity and Temperature.

### 3.3.4 HUNGARY

The Cu, Zn, Pb with a few Ag and Au polymetallic metal enrichment in shallow hydrothermal dykes: 160–400 m, skarn type polymetallic ores in 600–1100 m depth (Recsk, Hungary; 47°55'48.9"N 20°04'55.5"E). The estimated width and length of the body is more than 500 m while height is about 200–600 m with separated dykes. This metal enrichment was identified by more than 100 drillholes.

Geological data:

Triassic limestone over burned by Eocene andesitic subvolcanic material. The documentation is in manuscript in National Archive of Mining, Geology and Geophysics in Budapest.

a) Stratigraphy - Shallow ore deposit: Eocene andesitic dykes, skarn deposits: Triassic limestones, silicified

b) Lithology - Andesitic dykes and silicified limestones

c) Structure - Complicate, as a subvolcanic body

Geochemical data:

It was measured, published in nationwide and international periodics. The last summary is in a manuscript made by Hungarian Geological Institute (Scharek 2004).

Geophysical data:

Drillhole geophysics during the geological investigation. Data are in National Archive of Mining, Geology and Geophysics, Budapest. Normal resistivity logs as well as Spontaneous-potential and Gamma logs are available for all drill holes. Additional data related to the possible metal enrichment are in Helsinki, Finland.

### 3.3.5 POLAND

In a few drillholes in SW Poland (Foresudetic Monocline): Cu-Ag mineralization, 100°C at the depth ca. 2500-3000 m, drillholes depth 2430–3860 m, geothermal degree 28-33 m/1°C, e.g. drillholes: Mozów (2537 m), Wilcze (2432 m), Paproć (2609 m), Kaleje (3136 m), Żerków (3548 m), Florentyna (3865 m) the metal enrichment has been identified below the depths where the temperature exceeds 100°C.

#### **METAL ENRICHMENT 1:**

Copper-silver ore of the stratiform type, a dozen occurrences in the Foresudetic Monocline, from western border of Poland to SE part of Wielkopolskie voivodeship on the different depths 900–3700 m at lower Zechstein Kupferschiefer ore series. All occurrences are divided on two group, first to the depth 2000 m and second on the depth below 2000 m. The extent of the metal enrichment is known as follows:

First group of the occurrences - up to depth 2000 m:

1. KULÓW - prognostic area 132 km<sup>2</sup>, depth 1500-2000 m in 8 wells
2. LUBOSZYCE - prognostic area 91 km<sup>2</sup>, depth 17460-1550m in 7 wells
3. ŚCINAWA WEST - prognostic area 16 km<sup>2</sup>, depth 1200-1368 in 4 wells
4. ŚCINAWA NE - perspective area 25 km<sup>2</sup>, depth 1338 at 1 well
5. BORZĘCIN - perspective area 9 km<sup>2</sup>, depth 1496m in 1 well
6. MIRKÓW - perspective area 35 km<sup>2</sup>, depth 1176 m in 1 well
7. ŚLUBÓW - perspective area 25 km<sup>2</sup>, depth 1384m in 1 well
8. ŻARKÓW - perspective area 9km<sup>2</sup>, depth 1359 m in 1 well
9. CZEKLIN - hypothetical area 31 km<sup>2</sup>, depth 1733m, 1 well
10. HENRYKOWICE – hypothetical area 17 km<sup>2</sup>, depth 1466-1602,5m 4 wells
11. JANOWO - hypothetical area 50km<sup>2</sup>, depth 1712,7m in 1well
12. MILICZ - hypothetical area 15 km<sup>2</sup>, depth 1646,6m in 1 well
13. SULMIERZYCE - hypothetical area 261 km<sup>2</sup>, depth 1580,2-1909,1m in 4 wells
14. WARTOWICE WEST - prognostic area 6 km<sup>2</sup>, depth 941,3-1463,0 m in 4 wells

Second group of occurrences below depth 2000 m:

1. MOZÓW - depth 2176-2537m in 4 wells
2. WILCZE - depth 2431,9 1 well
3. PAPROĆ - depth 2609m 1 well
4. KALEJE - depth 3136m 1 well
5. ŻERKÓW - depth 3548,5m 1 well

## 6. FLORENTYNA - depth 3865, 5m 1 well

The size of the body: Width - E.g. ŚCINAWA WEST 2-3 km; Length - E.g. ŚCINAWA WEST 4-10 km;  
Height - First group of occurrences up to the depth 2000 m:

- KULÓW - av. 1,41 m with av. 2,98% Cu and 96 ppm Ag,
- LUBOSZYCE - av. 1,66 m with av. 1,76% Cu and 57 ppm Ag,
- SCINAWA WEST - av. 3,4 m with av. 1,47 % Cu and 54 ppm Ag,
- ŚCINAWA NE - av. 2,0 m with av. 0,93%Cu and 88 ppm Ag,
- BORZECIN - av. 0,51 m with av. 4,91% Cu,
- MIRKÓW - av. 1,17 m with 1,56% Cu,
- ŚLUBÓW - av. 0,2 m with av. 10,73% Cu and 164 ppm Ag,
- ŻARKÓW - av. 1,13 m with av. 3,07 % Cu,
- CZEKLIN - av. 0,23 m with av. 10,54% Cu
- HENRYKOWICE - av. 1,18 m with av. 2,14% Cu and 19 ppm Ag,
- JANOWO - av. 0,9 m with av. 2,28% Cu,
- MILICZ - av. 1,86 m with av. 0,98% Cu,
- SULMIERZYCE - av. 1,60 m with av. 3,52% Cu
- WARTOWICE WEST - 1,9-4,3 m with 0,88-1,5% Cu and 20-160ppm Ag

Second group of occurrences below depth 2000 m:

1. MOZÓW - 0,6-5,25 m with 2,6-4,8% Cu and 11-116 ppm Ag,
2. WILCZE - 0,55 m with 7,75% Cu and 417 ppm Ag,
3. PAPROĆ - 0,1 m with 21,48% Cu and 421 ppm Ag,
4. KALEJE - 1,0 m with 7,07% Cu,
5. ŻERKÓW - 2,8 m with 1,38% Cu and 22 ppm Ag,
6. FLORENTYNA - 1,0 m with 2,99% Cu and 33 ppm Ag.

\*Remark: More than 500 wells in all Poland, where Zechstein Kupferschiefer ore series occurring, e.g. from the Foresudetic Monocline and western border of Poland to SE part of Wielkopolskie voivodeship, but also Łeba Uplift in Pomorskie voivodeship (N Poland).

Geological data:

Geological data are recorded from middle 1950-ties to present time as a result of huge prospecting program for Cu-Ag ores which have been realized by Polish Geological Survey-Polish Geological Institute, KGHM Polish Copper SA, MiedziCopper Ltd., and oil&gas wells too.

- a) Stratigraphy - Uppermost part of the Rotliegendes and bottom of the Zechstein
- b) Lithology - Sandstones, black shale, dolomites and limestones
- c) Structure - Beds and rarely lenses in the southern part of the Foresudetic Monocline

Geochemical data:

Since 1960-ties geochemical data from drillholes and underground works are collected by the KGHM Polish Copper SA and its subsidiary KGHM Cuprum Ltd., also by Polish Geological Survey-Polish Geological Institute.

- a) Rock chemistry - Au, Pt-Pd, Se, Pb, Zn, Mo, V, Ni, Co

Geophysical data:

Regional seismic, gravimetric and magnetic works drillhole as geophysical methods; Seismic profiles and seismic or micro seismic works.

### **METAL ENRICHMENT 2:**

The Cu-Mo-W ore of the porphyry and skarn type near Myszków in Upper Silesia.

Geological data:

Metal bearing formation in porphyry, granites and different metacontact rocks of Paleozoic and Proterozoic age have been discovered by the drillhole on the depth 170–1300 m in the middle of 1970-ties. The main occurrence and ore body is Nowa Wieś Zarecka-Myszków-Mrzygłód. Perspective area are: Mysłów – 11 km<sup>2</sup>, Żarki-Kotowice – 20 km<sup>2</sup>, Zawiercie – 1,2 km<sup>2</sup>, Pilica – 12 km<sup>2</sup>, and Dolina Bękowska – 11 km<sup>2</sup>. These areas were established by the cut-off 0,02% Cu, 0,001% Mo and W, while metal enrichment were identified in approximately dozen drillholes.

- a) Stratigraphy - Mainly Paleozoic rocks, Proterozoic too
- b) Lithology - Porphyry, granitoids, diabase, skarn
- c) Structure - Ore body, anomalies-occurrences are located near contact zone of two huge tectonic blocks - Małopolski and Górnośląski. Ores forms are stockwork, veinlets, and impregnation.

Geochemical data:

Since 1960-ties geochemical data from drillholes and underground works are collected by the KGHM Polish Copper SA and its subsidiary KGHM Cuprum Ltd., also by Polish Geological Survey-Polish Geological Institute.

- a) Rock chemistry - Cu, Mo, W, Au, Bi, Ag, Te

Geophysical data:

Mainly seismic, gravimetry, magnetic profiles, drillholes geophysics

### **METAL ENRICHMENT 3:**

Uranium, Peribaltic Syncline, between Piaski on the Wiśłana Spit to the north (Baltic Coast) and Frombork and Pasłęk on a land near Baltic Coast to the south east. The approximate depth in meters where the metal bearing formation was reached is about 800 m at Wisłana Spit (Ptaszkowo, Krynica Morska), but near Frombork and Pasłęk the depth is 1000–1200 m. Size of the body is: Width - At Wiśłana Spit 10 km, up to 75 km between Frombork – Pasłęk; Length - up to 75 km between Pasłęk-Malbork; Height - Av. 3.4 m with av. 0.34% U. The 23 wells out, of them 13 are located on Wiśłana Spit and 10 wells on the land, identified the given metal enrichment.

Geological data:

Data from investigation works carried on in the late 1970-ties - geophysics and wells. The main sources of these information are:

- Perspective resources of raw material in Poland at the end of 2009, Chapter: Uranium, Editors S. Wołkowicz, T. Smakowski and S. Speczik (only in Polish version), PGI 2011 Warsaw
- Miecznik J.B., Strzelecki R., Wołkowicz S., 2011 – Uranium in Poland – history of the prospecting and prospects to discovery (only in Polish version). Przegląd Geologiczny (Geological Review), vol. 59, no. 10., pp. 688-697.

1. Stratigraphy - Buntersandstone (lower or early Triassic)

2. Lithology - Sandstone, conglomerate
3. Structure - Beds

Geochemical data:

- a) Rock chemistry - V, Mo, Pb, Se

#### **METAL ENRICHMENT 4:**

Uranium, Rajsk (Bielsk Podlaski county, Podlaskie Voivodeship, NE Poland) where metal bearing formation was reached from 400 m in the NE part up to 1200 m in the S and W part. The estimated size of the body where metal enrichment has been identified is ca. 16 km<sup>2</sup>, av. 250 ppm U. The 62 wells, out of them 30 wells at Rajsk area identified the given metal enrichment.

Geological data:

- a) Stratigraphy - Lower Ordovician
- b) Lithology - Dictyonema shale
- c) Structure - Bed

Geochemical data:

- a) Rock chemistry - V 1100–2000 g/t, Mo up to 500 g/t

#### **METAL ENRICHMENT 5:**

The Fe-Ti with V ores at mafic and ultramafic rocks massif, Krzemianka and Udryń deposits, Suwalki area, NE Poland at depth of 850–2700 m. The estimated size of this body is ca. 1340 million t of ore, av. content 28% Fe, 7% TiO<sub>2</sub> and 0.3% V<sub>2</sub>O<sub>5</sub>. The mineral enrichment has been identified in over 100 drillholes.

Geological data

The Suwalki Massif has been recognized during 1970-ties. Due to lack of effective technologies of beneficiations of titanomagnetite ore and environmental problems on the surface, investigation program was stopped in 1980-ties.

- a) Stratigraphy – Proterozoic
- b) Lithology - anorthosite, norite
- c) Structure - stockwerk, lenses and beds

Geochemical data:

- a) Rock chemistry - Ni, Co, Cu, Au

### **3.3.6 SERBIA**

Two metal enrichments were identified below the depths where the temperature exceeds 100°C.

#### **METAL ENRICHMENT 1:**

Borska reka - Bor, Metals: Cu, Au. Coordinates: X= 4883100 – 4884300 Y= 7587300 – 7588200 Z = 346 m – 465 m. The depth in meters where the metal bearing formation was reached: (-10 m) – (-1005 m). The extent of metal enrichment is not known. Size of the body: Width - maximum: 650 m (level -455 m), NE-SW; Length - maximum: 1450 m (level -455 m), NW-S; Height - open; >1000 m; the length of mineralization, along the dip, has not been completely defined. The 63 drillholes including 21 drillhole deeper than 1000m identified the given metal enrichment.

### Geological data:

These rocks (i.e. the Timok andesites; I phase of volcanic activity) occur in the eastern parts of the Timok Magmatic Complex (TMC), where overlie Cenomanian and Turonian sediments. Timok andesites are covered by Senonian sediments (Oštrej sediments and Bor clastites) and the Metovnica epiclastite.

- a) Stratigraphy - Copper mineralization (metal enrichment) is situated in hydrothermally altered andesites (predominantly amphibole andesite and high potassium trachyandesites) and their pyroclasts. According to high precision U/Pb,  $^{40}\text{Ar}/^{39}\text{Ar}$  age (von Quadt et al., 2002; Clark & Ullrich, 2004), the Timok andesites ranged from  $89.0 \pm 0.6$  to  $84.26 \pm 0.67$  Ma (Upper Turonian to Upper Santonian).
- b) Lithology - According to their lithological, volcanological and petrographic characteristics, the andesites are distinguished into the following facies: lava flows (coherent and autoclastic), shallow intrusions – lava domes, dykes and sills and various volcanoclastic rocks. Volcanic activity was predominantly subterrestrial in an earlier volcanic phase and subarial to submarine in later volcanic phase (Drovenik, 1959; Đorđević & Banješević, 1997; Banješević M., 2006, 2010). Small intercalations of marbles and skarns and mineralized dykes of quartzdiorite porphyries are present, too. Copper mineralization has been deposited in intensive hydrothermally altered andesite and their pyroclastites (Jelenković et al., 2016). Products of K-alteration prevails. In the ore mineralization zone dominant are: silicification, pyritization, argillization and sulphatization.
- c) Structure - Structural setting of the mineralized area is complex. Prevails longitudinal fault structures of NW-SE directions (parallel to regional structure in the Timok magmatic complex), transverse (NE-SW) structures and, less represented diagonal E-W faults. According to their dimensions, one can differentiate regional and local structures and as related to ore mineralization, structures are of pre-ore, intra-mineralization and post-ore type. The most dominant fault structure is Bor fault. It represents lower boundary of mineralized area. Volcanic structures are difficult to recognize today, since, due to multi-stage volcanic activity and post-volcanic tectonic movements, they have been destroyed.

### Geochemical data

Major element variations of all magmatic bodies within the Timok Magmatic Complex follow typical differentiation trends that are generally consistent with phenocryst assemblages (Kolb M. et al., 2013). Concentrations of MgO,  $\text{Fe}_2\text{O}_3$  total,  $\text{TiO}_2$ , and CaO decrease with increasing  $\text{SiO}_2$ , whereas  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  concentrations increase or remain constant. Concentrations of  $\text{Al}_2\text{O}_3$  and  $\text{P}_2\text{O}_5$  first remain constant with increasing  $\text{SiO}_2$ , then decrease at  $\text{SiO}_2 > 55$  wt%.  $\text{K}_2\text{O}$  increases slightly with increasing  $\text{SiO}_2$ , up to 60 wt%  $\text{SiO}_2$ .

- a) Rock chemistry - Unaltered hornblende-biotite-pyroxene andesites as phenocrysts contain andesine (40–52, mean 45% an), hornblende, subordinated biotite or augite, or both. Silica is mostly 54–60%,  $\text{Na}_2\text{O} > \text{K}_2\text{O}$ , lime is in general equal to the sum of alkalies, the rocks correspond to calc-alkaline magma (Karamata et al., 2002).

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### **METAL ENRICHMENT 2:**

Čukari Peki - Bor; Metals: Cu, Au, Locality: Serbia, Brestovac Coordinates: X= 4875000 – 4877000 Y= 7590000 – 7593000 Z = 300 m – 400 m, approximately 375 m amsl. 44° 01' 30" N and longitude 22° 08' 00" E. Mineralization occurs at depths between 400 m below surface to greater than 2000 m (0 m – > -1500 m). The extent of the metal enrichment is not known, but estimated: Width ca. 1000 m, N-S; Length - ca. 1500 m, W-S; Height – open >1500 m; the length of mineralization, along the dip, has not been completely defined. The top of the LZ mineralization occurs at depths below surface ranging from approximately 1400 meters in the west to 750 meters in the east. More than 50 drillholes identified the given metal enrichment.

### Geological data

In summary, the geology of the Brestovac-Metovnica mineralized area includes first phase andesites, volcanoclastics and sediments typical of the eastern block, a small area of second-phase pyroxene-bearing basaltic andesite typical of the western block, and unconformably overlying Miocene sediments in the centre of the area of exploration (<http://www.reservoirminerals.com/>).

- a) Stratigraphy - Metal enrichment is situated in hydrothermally altered andesites of I phase (predominantly amphibole andesite and high potassium trachyandesites) and their pyroclasts. These rocks (i.e. the Timok andesites, or I volcanic phase) occur in the eastern parts of the Timok Magmatic Complex (TMC), where they overlie Cenomanian and Turonian sediments. Timok andesites are covered by Senonian sediments (Oštrej sediments and Bor clastites) and the Metovnica epiclastite. According to high precision U/Pb,  $^{40}\text{Ar}/^{39}\text{Ar}$  age (von Quadt et al., 2002; Clark & Ullrich, 2004), the Timok andesites ranged from  $89.0 \pm 0.6$  to  $84.26 \pm 0.67$  Ma (Upper Turonian to Upper Santonian).
- b) Lithology - According to their lithological, volcanological and petrographic characteristics, the andesites are distinguished into the following facies: lava flows (coherent and autoclastic), shallow intrusions – lava domes, dykes and sills and various volcanoclastic rocks. Volcanic activity was predominantly sub terrestrial in an earlier volcanic phase and subaerial to submarine in later volcanic phase (Banješević M., 2006, 2010). Small intercalations of marbles and skarns and mineralized dykes of quartzdiorite porphyries are present, too. The host rocks to all the mineralization styles consist of various hornblende and hornblende-biotite andesites, andesite breccias, hydrothermal breccia, and relatively rare diorite porphyry.
- c) Structure - A regionally significant NNW-striking fault cutting through the Brestovac river valley is probably the largest fault in the mineralized area. This fault marks the boundary, between the first phase andesitic volcanism in the eastern block and the second phase volcanism in the western block and could represent a major basement suture. There is also at least one subordinate fault trend which varies in strike from E-W to NE-SW. These faults also have both apparent sinistral and dextral slip senses.

#### Geochemical data

Unaltered hornblende-biotite-pyroxene andesites as phenocrysts contain andesine (40-52, mean 45% an), hornblende, subordinated biotite or augite, or both. Silica is mostly 54-60%,  $\text{Na}_2\text{O} > \text{K}_2\text{O}$ , lime is in general equal to the sum of alkalis, the rocks correspond to calc-alkaline magma (Karamata et al., 2002).

a) Rock chemistry: Major element variations of all magmatic bodies within the Timok Magmatic Complex follow typical differentiation trends that are generally consistent with phenocryst assemblages (Kolb M. et al., 2013). Concentrations of MgO,  $\text{Fe}_2\text{O}_3$  total,  $\text{TiO}_2$ , and CaO decrease with increasing  $\text{SiO}_2$ , whereas  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  concentrations increase or remain constant. Concentrations of  $\text{Al}_2\text{O}_3$  and  $\text{P}_2\text{O}_5$  first remain constant with increasing  $\text{SiO}_2$ , then decrease at  $\text{SiO}_2 > 55$  wt%.  $\text{K}_2\text{O}$  increases slightly with increasing  $\text{SiO}_2$ , up to 60 wt%  $\text{SiO}_2$ . Incompatible element concentrations (e.g., Th, La) generally do not correlate with  $\text{SiO}_2$  in the TMC. Enrichment in light REE (LREE) and relatively flat heavy REE (HREE) patterns are general features of the dataset for the TMC. Large ion lithophile elements (LILE) such as U, Th, and Pb are enriched.

Geophysical data - Induced polarization, DC resistivity, SP and other geoelectrical surveys

#### 3.3.7 SLOVAK REPUBLIC

Two metal enrichment were identified below the depths where the temperature exceeds  $100^\circ\text{C}$  in Slovak Republic.

**METAL ENRICHMENT 1:**

Geographical data - As enrichment in geothermal waters in the Durkov geothermal structure in eastern Slovakia. The structure lies in between the Slanské Mountains and the Slovenske Rudohorie Mountains (Franko et al. 1995; Vranovská et al., 2015).

The depth in meters where the metal bearing formation was reached:

- (1) GTD-1: Q = 56 l.s-1,  $T_{\text{btm}} = 144^{\circ}\text{C}$ ,  $T_{\text{wh}} = 125^{\circ}\text{C}$ , TDS = 30 000 mg.l-1, h = 3210 m.b.t.;
- (2) GTD-2: Q = 50 l.s-1,  $T_{\text{btm}} = 154^{\circ}\text{C}$ ,  $T_{\text{wh}} = 129^{\circ}\text{C}$ , TDS = 31 000 mg.l-1, h = 3151 m.b.t.;
- (3) GTD-3: Q = 65 l.s-1,  $T_{\text{btm}} = 131^{\circ}\text{C}$ ,  $T_{\text{wh}} = 123^{\circ}\text{C}$ , TDS = 31 000 mg.l-1, h = 2252 m.b.t.

Estimated size of this body - 33.6 km<sup>2</sup> where the formation reaches 2000 m of thickness

Detailed dimensions of the deep geothermal reservoir in the Durkov area are accessible true reports which are available in a manuscript form and are in Slovak language, and can be accessed through the website of Digital archive of the State geological institute of Dionýz Štúr, or personally at our address in Bratislava (see Slovak references in the reference list). Here given is only an estimate where the Durkov structure aquifer dolomites are as thick as 2000 m. Note that the depth and thickness increases towards the east. More information of the dimension of the whole structure (and not only the 2000 m area) might be found in Vranovská et al., 2015 & Hók et al. 2001. The geothermal reservoir is located in Mesozoic carbonates (Middle and Upper Triassic) and also in basal clastics of the Carpathian.

Geological data:

- a) Stratigraphy -Middle and Upper Triassic dolomites (up to 2000 m thick) covered by Neogene sediments, andesites and vulcanoclastics.
- b) Lithology - Secondary As-enrichment in a Triassic sedimentary dolomite deposit in the reservoir brine. (Vranovská et al., 2015).
- c) Structure - The geothermal structure is a part of the Kosice Basin in Eastern Slovakia (Vranovská et al., 2015). The Kosice Basin is delimited by the volcanic Slaánské Mountains, which have a strong impact on the genesis of geothermal waters and are the principal source of trace elements.

Geochemical data:

Infiltration of meteoric water and dissolution of evaporates, especially halite, in the overlying Neogene formation (b) reaction of the highly mineralized water with Hg–As–Sb type of mineralization, related to the Neogene volcanism, and, (c) accumulation of As-rich geothermal water in Triassic carbonates with an additional input of CO<sub>2</sub> (Vranovská et al., 2015).

a) Rock chemistry - dolomite

b) Fluid chemistry - Na-Cl type of geothermal water, trace elements: As, Fe, Mn, Cd, Cr, Cu, Li, Pb, Sr, Zn, F, I, Br. Only As has high concentrations in the Durkov structure. (Table 1, Vranovská et al., 2015).

Geophysical data:

All data of the cores is publicly accessible in manuscripts archived at the State Geological Institute of Dionýz Štúr in Bratislava (webpage: [www.geology.sk](http://www.geology.sk)). Data are accessible online after registration, or hand-printed personally in the archive.

\*Remark - GeoMaps of subsurface geothermal reservoirs are available in “Geothermal and mineral water sources” (Fendek et al., 2002)

## METAL ENRICHMENT 2:

Note that this metal bearing zone is drilled but not at temperatures of > 100°C. At the bottom of the complex however, temperatures are expected to be close to 100°C in some zone's. Situated in the Eastern Carpathian metalogenetic region. One drillhole identified the metal enrichment.

Geological data:

- a) Stratigraphy - Neogene Volcanoclastic and andesitic deposits
- b) Lithology- andesitic, volcanoclastic

Geochemical data - Epigenetic mineralization is characterized by Fe, Cu, Mo, Bi, Pb, Zn, Au, Ag, Te, Sb, Hg, and As (Vranovska, 2015)

a) Rock chemistry - Cu–Pb–Zn–Mo association are most common (Mello et al. 2005)

## 4 Conclusions

Data collected from the 23 European countries revealed the potential of some countries for CHPM2030 EGS application providing the European overview on data availability. The 19 countries out of 23 which participated in this survey reported that drillholes with temperatures exceeding 100°C exists in their country (Table 1). The number of such drillholes varies from 1 (Ireland) to 2809 (Germany).

Among them, eight countries mentioned the identification of metal enrichment (Austria, Belgium, Cyprus, Hungary, Poland, Serbia, Slovak Republic and UK, while five of those (Belgium, Hungary, Poland, Serbia and Slovak Republic) provided more detailed insight into these metal enrichments providing some data on geographical, geological, geochemical and geophysical data (see text for more information). These countries could be of further interest of the CHPM2030 interest. Since the data of the project's interest only partly publicly available or not available at all, further cooperation with National experts and possible contact to Organizations in charge/owning the data will be necessary to obtain all relevant information.

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## 7 Appendix 2. Template for data collection by the EFG Linked third Parties in the frame of Task 1.2.5 - European data integration and evaluation CHPM2030, Work-package 1 - Methodology framework definition

### 7.1 Background

The objective of CHPM2030 WP1 is to prepare the conceptual framework for a novel EGS for the production of energy and the extraction of metals from ore deposits located at great depths. First we need to synthesise our knowledge on deep metal enrichments that could be converted into an “orebody EGS”, and to investigate the characteristics of these bodies. We aim to discover and examine the geological, tectonic, geochemical, and petrologic factors that define the boundary conditions of such novel EGS both in terms of energy and potential for metal recovery.

The information will be obtained by reviewing past investigations in Europe that have resulted in public access geological and geothermal datasets. In addition to these data, associated publications and studies will also be reviewed. EFG Linked Third Parties will collect publicly available data at national level on deep drilling programmes, geophysical and geochemical explorations and any kind of geo-scientific data related to the potential deep metal enrichments. They will also collect data on the national geothermal potential. The task provides a “European outlook” on data availability in order to identify data gaps. A horizontal task is to connect two insofar unconnected communities: mining and geothermal earth science professionals for a common goal on EU and national levels.

In the third year of the project implementation, within WP6 - Roadmapping and Preparation for Pilots, the EFG Linked Third Parties will assess the geological data on suitable ore-bearing formations and geothermal projects, which were collected in WP1, in relation with the potential application of the CHPM technology.

In this template we use the term “metal enrichment”. For this term, please consider the geological formations in which the metal content is at least five times higher than the average in the given formation type. This term also includes the “real ore bodies” which have economic value on their own.

Please consider the following metals: Cu, Zn, Pb, Fe, As, Sb, Ag, Au, Co, Cr, Ni, U, Sn, W, Mo

On the last page of the data collection template please provide a list of references which were used for filling the form. For the references in your national language, please provide an English translation.

## 7.2 Data on drilling programmes

As we want to apply an EGS system, in the data collection we are looking for the depths where the *temperature is above 100°C*. Please take the average geothermal gradient in your country and during the data collection consider only drillholes which reached at least this depth. It can be different in the different areas of Europe, depending on the geothermal characteristics.

1. Are there any drillholes in your country which reached the depths where the temperature exceeds 100°C?
2. If yes, please indicate the number of these drillholes:
3. Are the data from these drillholes publicly available:
  - a. yes, for each drillhole
  - b. yes, for a part of them
  - c. no publicly available data
4. If yes, please indicate the number of drillholes where there are publicly available data:
5. Is there any metal enrichment in your country identified below the depths where the temperature exceeds 100°C?
  - a. yes
  - b. no
6. If yes, please indicate the number of the identified metal enrichments:

## 7.3 Data on deep metal enrichments

Below you can take multiplied questions, (Metal enrichment 1, 2, 3...) according to the number of identified metal enrichments. Please answer the questions separately for each metal enrichment which has been identified in your country.

Metal enrichment 1:

1. Geographical data of metal enrichment (locality, coordinates) :
2. Please indicate the depth in meters where the metal bearing formation was reached:
3. Is the extent of the metal enrichment known?
  - a. yes
  - b. no
4. If yes, please indicate the estimated size of this body:
  - a. width:
  - b. length:
  - c. height:

5. How many drillholes identified the given metal enrichment:
6. Geological data from the metal enrichment (please provide a few lines summary and the most important publications/links which are relevant):
  - a. Stratigraphy
  - b. Lithology
  - c. Structure
7. Geochemical data (please provide a few lines summary and the most important publications/links which are relevant):
  - a. rock chemistry, trace elements
  - b. fluid chemistry, trace elements
8. Geophysical data (please provide a few lines summary and the most important publications/links which are relevant):
  - a. Normal resistivity logs
  - b. Fluid resistivity logs
  - c. Spontaneous-potential logs
  - d. Acoustic logs
  - e. Gamma logs
  - f. Other
9. Are there any surface or airborne geophysical surveys which provide additional data related to the metal enrichment?
  - a. yes
  - b. no
10. If yes, please specify these geophysical methods:

Metal enrichment 2:

Metal enrichment 3:

#### 7.4 Personal data

1. Your name:
2. Your organisation:
3. Your country:

Thank you for your cooperation!