McGill Fieldschool
Massif Central, France

May 2018

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1 Introduction

The geosciences are a highly interdisciplinary field, using the full diversity of physical and chemical characteristics of natural materials to understand the Earth. In this Massif Central field school we aim to show you this diversity in geoscience approaches, tools and techniques, from mapping, to structural geology, to geochemistry, to geophysics, petrology, volcanology, hydrology, economic geology, and soil science. The field school uses a holistic approach where the various aspects of the geosciences are not treated consecutively, but observed and interpreted together, with one strengthening the other; Geochemical analyses can confirm or guide mapping, whereas mapping can explain geochemical anomalies.

The Massif Central provides a unique field area where a full diversity of geological phenomena can be observed in a relatively compact area. It is also one of the classical geological field areas, where some of the key theories on mountain building, ore formation and metamorphism were developed. The basement exposes the mid-crustal levels of the Variscan orogen, dominated by metamorphic and intrusive rocks, and with abundant ore deposits. These are covered by young, mostly mafic, volcanics.

The field school will be run from a base camp in the village of Lavoûte-Chilhac, with individual field areas distributed around the village. By working from a base camp for the duration of the field school, you have the opportunity to investigate your assigned area in great detail, and from different angles. A first visit to an outcrop rarely leads to a full understanding (even for seasoned geological mappers), and you now have the time to revisit outcrops as your understanding of the area matures. You can follow up on ideas and hypotheses, and test whether geochemical results are consistent with surface geology, and vice versa. To further facilitate this, you will be given flexibility in scheduling the various field components, so that you can set your own priorities.

The field school consists of 3 main components:
1) Geological surface mapping;
2) Regional geochemical survey;
3) Ore exploration soil survey

Mapping of surface exposures and transects is a key component, and allows for developing an understanding of a major orogenic belt from local observations. With the dominant lithologies being metamorphic and intrusive, and most contacts being tectonic, you will have to carefully map out lithological boundaries and use structural measurements to help you. The regional geochemical survey provides geochemical maps for elements including Cr, Ba, Co, Cu, As, Pb, Sb, F, pH, and EC centred on the same area where you conduct surface geological mapping. It provides information on rock compositions, and shows how these impact sediment and river water compositions, and picks up ore deposits and pollution. In the detailed exploration soil survey, you use grid geochemical sampling + geophysical measurements (self-potential) to delineate a mineralization that does not crop out on the surface. The aim of this component is to get famil-

iar with the techniques used in exploration, and the "diffusion" of an ore deposit into its environment. The two geochemical parts include a lab component, where water, soil and sediment samples are prepared and analyzed. A small field lab will be available for this purpose consisting of a mini-benchtop XRF instrument and spectrophotometer. The main idea behind this field lab is to provide geochemical data on-site, so you can use these data in your field planning and interpretations.

Geography and geology overview

The field area is centred on the town of Langeac in the central part of the Massif Central, south of the Limagne graben, and covers approximately 600 km². The Margeride plateau borders the area in the south, and the region is crosscut by the Allier river. The range in altitude within the field area is limited, and varies from about 400 to 1000 m. The area is dominated by farmland, with small villages, as well as forest on steeper slopes. Road access is generally very good. Basement exposure is highly variable, and ranges from 5 to 50 %, averaging about 15-20 %. The best outcrops are found in river valleys and in road cuts.
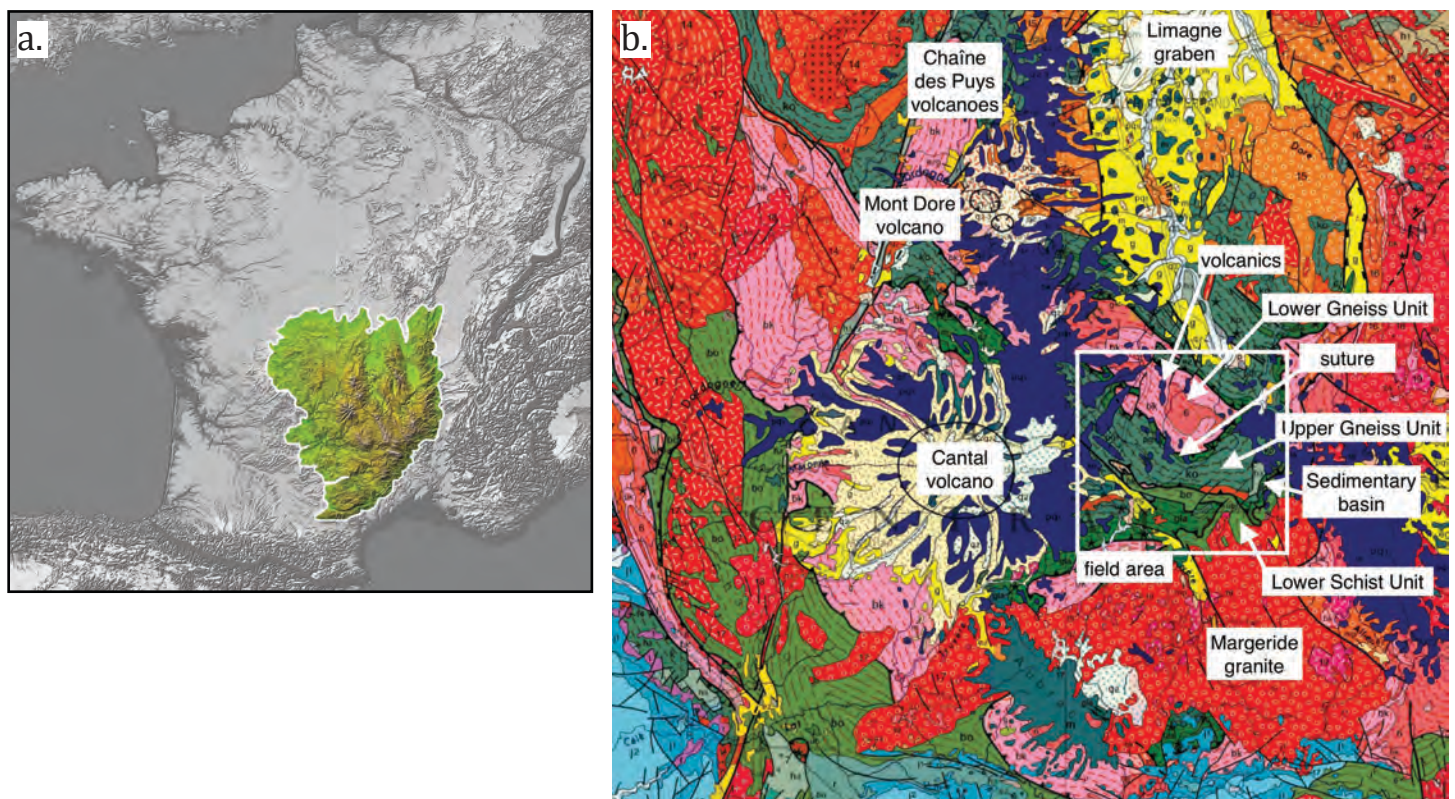

Figure 1. a) Topographic relief map of France showing the location of the Massif Central. Note that this is the topographic Massif Central, whereas the geological definition is narrower (see Fig. 2) Image from wikipedia.org. b) Overview geological map of the central part of the Massif Central with location of the field area and important geological landmarks.

The French Massif Central is part of the Variscan belt and represents the orogen in which Europe was put together. The area was an ocean at ~450 Ma, with deep-sea sedimentation, followed by an accretionary prism sequence as Gondwana started moving north and subduction was initiated. The continental suture was established at ~380 Ma, at which time a mountain belt rivaling the Alps had been constructed. Thermal equilibration initiated extensive granite plutonism, with associated Sn-W-Mo ore deposits. Crustal delamination subsequently led to orogenic collapse and formation of abundant, but small, strike-slip basins. These high-elevation basins (evidence for glacier activity) were largely filled with peat in the Stephanian. Delamination also sent a heat pulse through the crust, which cooked this peat to anthracite and liberated

metamorphic fluids, which formed major Sb ore deposits, with subordinate Ag and Cu. During the waning stages of this hydrothermal activity, fluid flow through the basins formed barite-fluorite deposits with associated Pb-Zn ores. The area was subsequently eroded down to a peneplain sectioning mid-crustal levels of the orogen, and remained in this state for all of the Mesozoic. During the opening of the Atlantic, the area was subjected to extensional tectonics with development of the Limagne graben. At the same time, possibly even initiating the extension, a plume established itself and produced abundant, mostly mafic, magmatism as well as uplift of the Massif Central and the development of its current topography.
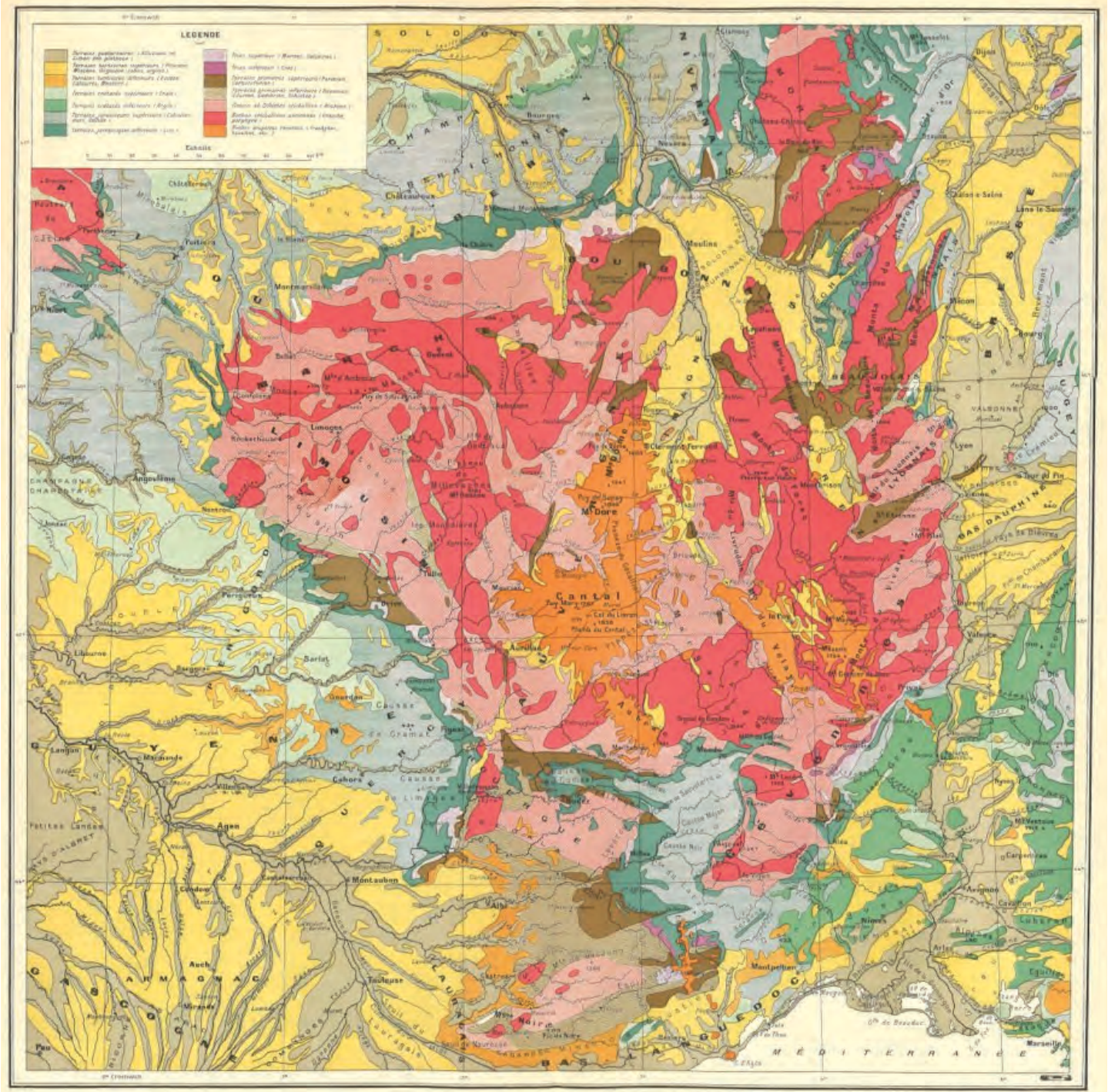

Figure 2. Overview geological map of the Massif Central (1930s vintage). Light pink shows metamorphic basement, dark pink intrusive rocks (mainly granite plutons), and Carboniferous basins are shown in brown. The other colours denote post-Variscan units, including recent volcanics in orange.

The abundance of ore deposits made the area a thriving center for mining, with evidence for underground mining going back to Roman times. Initially, mining focused on silver and gold, but large-scale mining exploited the Sb-deposits of the Brioude-Massiac Sb-As province and fluorite and barite in the Langeac belt. Coal mining of several of the small Stephanien basins also took place. In recent years, most of the adits, shafts and collapsed mine workings have been sealed, but you will still find evidence of past mining in the field, mainly as waste dumps.

Climate and hydrology

The climate in the Langeac area is considered to be mild, generally warm and temperate. In the Köppen-Geiger climate system, the area is classified as Cfb (maritime temperate climates). The area receives approximately 630 mm of rain annually, most of it in the spring and autumn. Snow makes up a significant proportion of precipitation in the winter months. The average annual temperature is 10.5°C and ranges from 2.5°C in January to 19.5°C in August. The main river in the area is the Allier river, which flows north and eventually into the Loire river and the Atlantic. Smaller streams and rivers are very abundant and generally flow into the Allier.

2   A brief geological history of Europe

The construction of Europe as a coherent continent commenced in the Precambrian, about 660 Ma. At that time Europe consisted of a number of micro-continents and Northern and Eastern Europe were part of the Baltica and Russian cratons respectively. Most of Western Europe is therefore geologically "young", especially compared to Canada, and where old rocks are found, for example, the 2 Ga gneisses of Brittany in France, they appear not to be basement but slivers of cratons sheared off in rifting events, in this case from Gondwana.

Cadomian orogeny

The first mountain building event that involved many parts of what is now Europe is the Cadomian orogeny, which took place between approximately 660 Ma and 550 Ma. This orogeny was an Andean style, accretion of microcontinents and volcanic arcs onto the Gondwana craton, and plate reconstructions (e.g. Fig. 3) show that it formed a continuous 2000 kilometre long mountain chain.
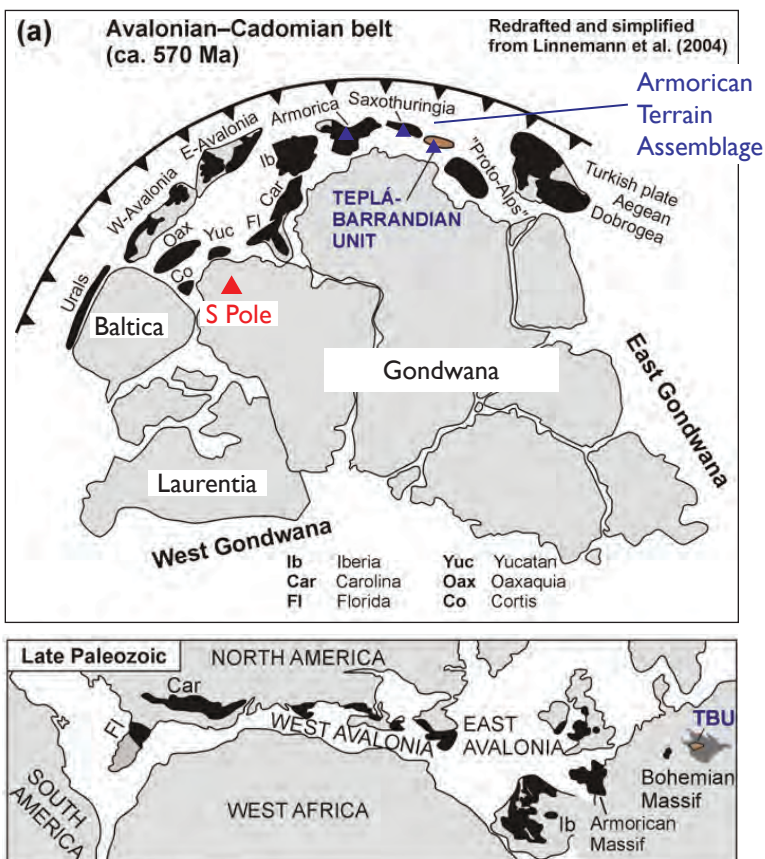

Figure 3. Plate reconstruction at the time of the Cadomian orogen (top). The Iapetus Ocean is starting to open between South America, Baltica and Laurentia.

The bottom reconstruction shows where the Cadomian micro-plates ended up in the Late Palaeozoic.

At that time the continents were quite different from what we see today in shape and global position. The major continents were **Laurentia**, which consisted of most of North America including Greenland, Scotland and northwest Ireland, **Baltica** containing Scandinavia and Eastern Europe up to the Ural mountains and **Gondwana**, which consisted of Africa, South America, Antarctica, Australia and India.

In addition to these large continents, there were quite some micro-continents present in between, as shown in Figure 3. The nature of these micro-continents varies. Some were slivers of continental crust broken off from larger cratons, similar to present-day Madagascar. Others represent volcanic arcs and/or uplifted sedimentary basins, equivalent to the Indonesian islands at present. The most important of these for the development of western Europe are the Avalon Terrain or Avalonia, the Armorican Terrain Assemblage (also called "Cadomia") and Iberia. Avalonia includes the eastern Appalachians in North America, Southern Ireland, Wales, England, Belgium and Northern Germany. The basement of the Netherlands is also part of this Avalon Terrain. The Armorican Terrain Assemblage is a group of micro-continents including Bohemia, Brittany and Normandy, the Massif Central and parts of Germany (Saxo-Thuringia). All these continents were grouped together at that time in the Northern Hemisphere, with the South Pole located in South America.

The onset of oceanic plate subduction led to progressive accretion of the micro-continents to the large land-mass, and development of mountains from the Urals through North America to the European micro-continents. The style of orogeny is identical to that of the Andes in the present-day, including associated magmatism. At the end of the Cadomian orogeny, the European micro-continents and the Avalon Terrain had become part of the large Gondwana continent assembly (Fig. 4a).

Caledonian orogeny

The Cadomian orogeny did not lead to formation of a supercontinent, and divergence was taking place at the same time as micro-continents were being accreted. In particular, the Iapetus ocean started to open between Baltica and Laurentia from approximately 600 Ma. Even the European micro-plates and Avalonia didn't stay part of Gondwana long, and started to rift away in the early Ordovicium, forming the Rheic ocean basin in between. At the end of the Ordovician the Armorican Terrain Assemblage separated from Gondwana forming a second large oceanic basin, the Palaeo-Tethys, or sometimes referred to as the Massif Central ocean (Fig. 4c-d).

As the Rheic ocean opened, the ocean basin separating Avalonia from Baltica closed, as was the Iapetus ocean separating Baltica from Laurentia (Fig. 4a-c). This large-scale convergence forms part of the assembly of the Pangea supercontinent. From 440 to 420 Ma, the Iapetus ocean closed and Baltica and Laurentia collided in the Caledonian mountain building event. Avalonia collided with Baltica and Laurentia, with Northern Germany and the Netherlands accreted onto the Baltica craton into their current position, and the Applachians accreted onto Laurentia. Scotland was also sutured to England in this event. The resulting Caledonian mountain chain extended from the west coast of Norway and east-coast of Greenland, through Scotland, to the Appalachians.

Variscan Orogeny

The Variscan orogen followed directly on the Caledonian and took place from 440 Ma up to the last tectonic related thermal events around 280 Ma. The Variscan orogeny resulted from the closure of the Rheic and Palaeo-Tethys oceans and the subsequent collision of the Laurentia-Baltica continent with Gondwana.

a. 490 Ma
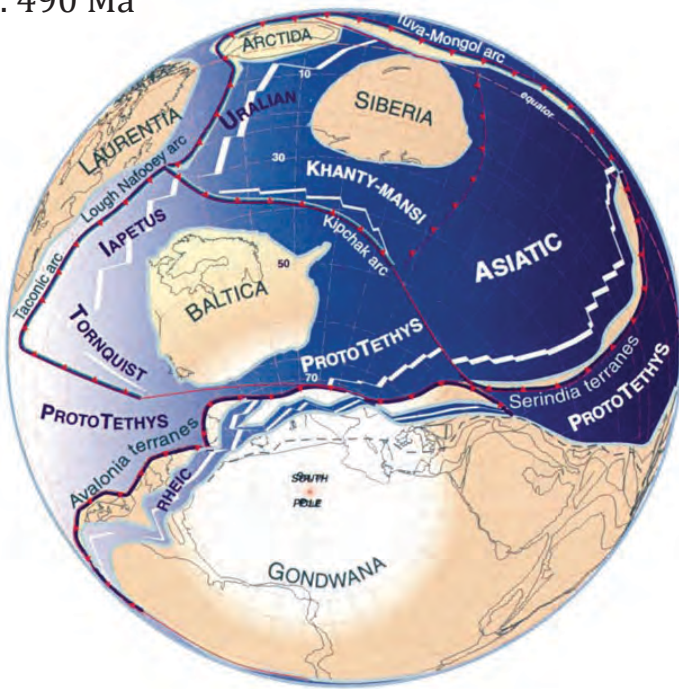
b. 440 Ma
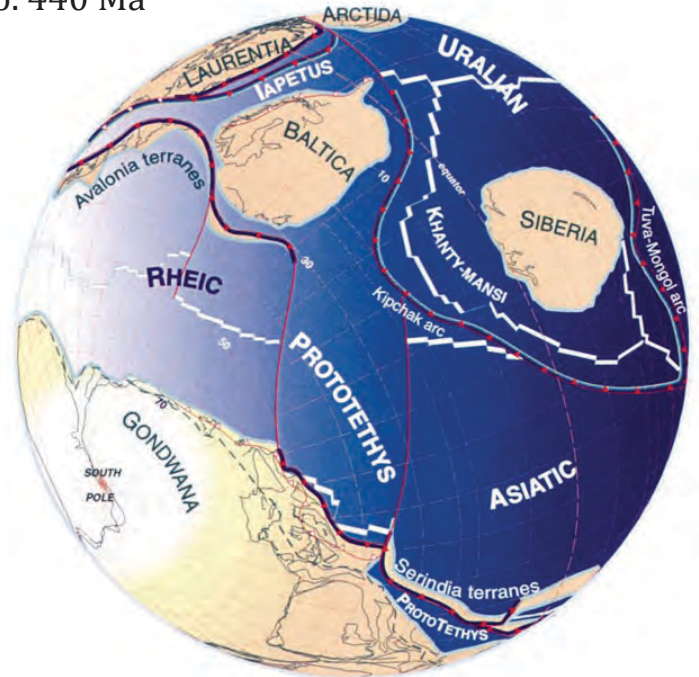
c. 420 Ma
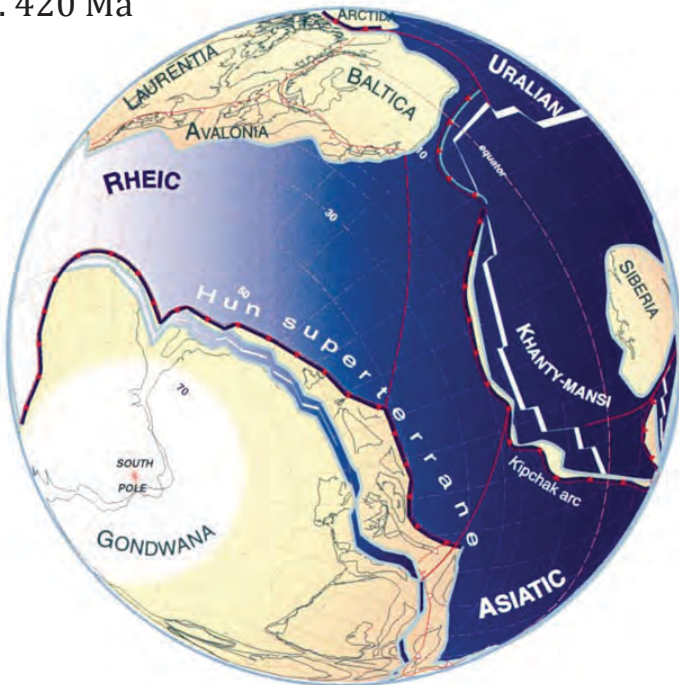
d. 380 Ma
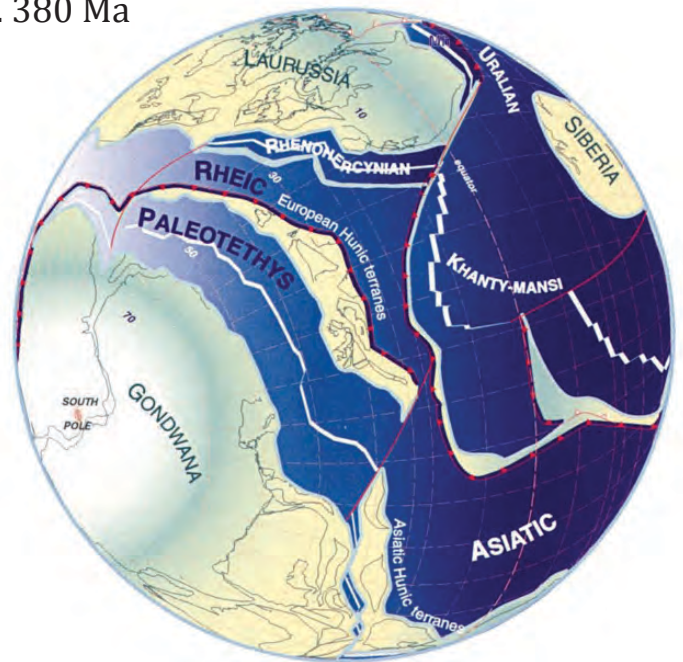
Figure 4. Plate reconstructions showing the European plate arrangements from the Ordovicium to the Devonian. Figures modified after Stampfli and Borel, EPSL 196 (2002) 17-33.

The collision formed a mountain chain extending from the Appalachians in North America to the Mauri-tanides in Northern Africa, as well as a chain from south Iberia through the Massif Central to the Bohemian Massif. In Europe the remnants of this mountain chain can now be found as a large belt in the western part of Iberia, the Armorican Massif and the Massif Central in France, the Ardennes-Rhenish region, Cornwall in the United Kingdom and the Bohemian Massif in Germany, Czechia and Poland.

Variscan tectonic events

The Variscan orogeny (also referred to as Hercynian, Acadian or Alleghanian depending on where you are) started about 440 Ma with the onset of subduction in the two oceanic basins in the region. The largest of these was the Rheic ocean, which was present between the Avalon part of Laurussia (Baltica + Laurentia) and the Armorican Terrain Assemblage (Figs. 4c-d). The Palaeo-Tethys ocean was most likely smaller, 200 km wide in some estimates although the plate reconstructions shown in Figures 4 and 6 suggest it was larger than that. It formed the separation between the Armorican Terrain Assemblage and Gondwana (Fig. 4d).

With the onset of subduction the different parts of the Armorican Terrain Assemblage start to separate and move at different speeds towards Laurussia. Saxo-Thuringia consisting of Central Germany moved north most rapidly together with Bohemia. Moldanubia, consisting of Central France and Central Iberia (which was at time rotated against France) moved north more slowly. Around 350 Ma the Rheic ocean had closed resulting in a collision between these fragments and Laurussia (Fig. 6a), followed at 320 Ma by continent-continent collision between Gondwana and Laurussia. This collision led to suturing of the plates around 300 Ma. This sequence of events is shown schematically in Figure 5.
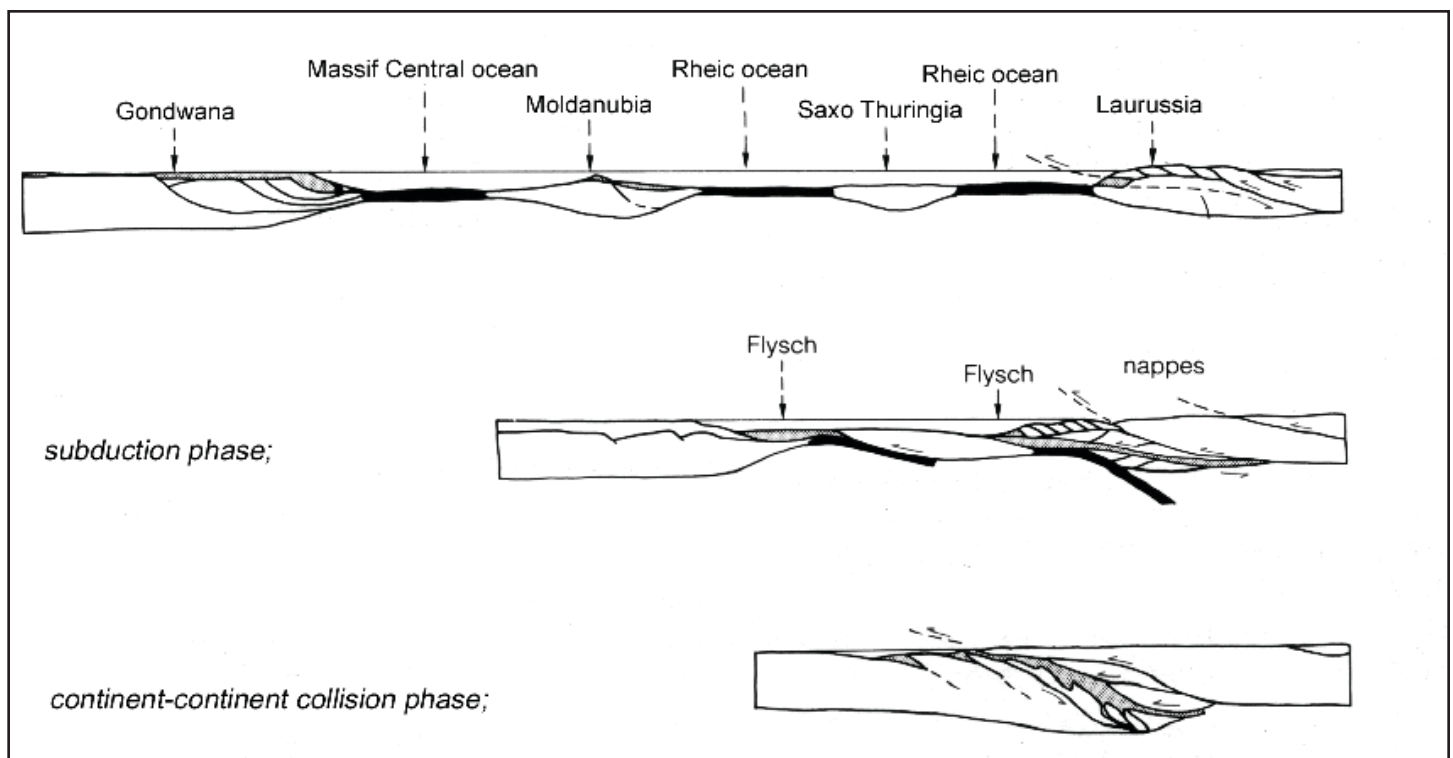
Figure 5. Schematic sections showing the development of the Variscan in Western Europe by the amalgamation of a series of micro-plates separated by oceanic basins.

a. 340 Ma
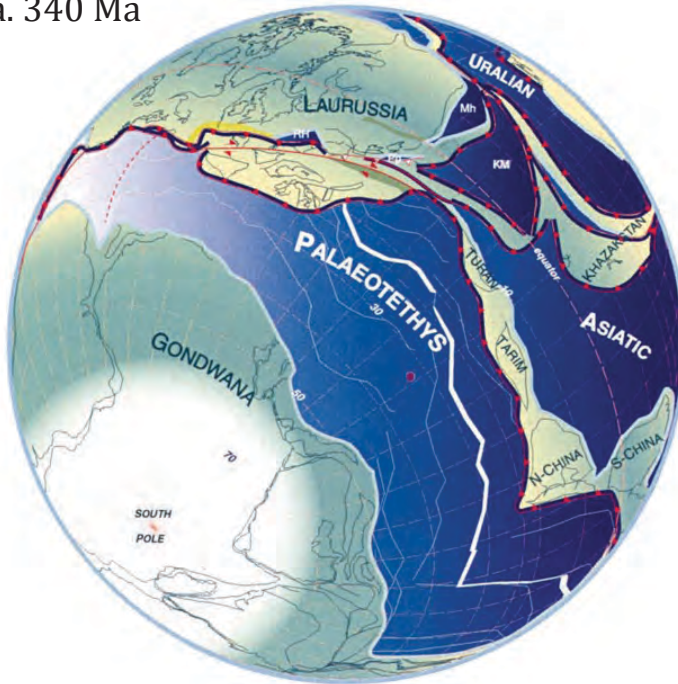
b. 320 Ma
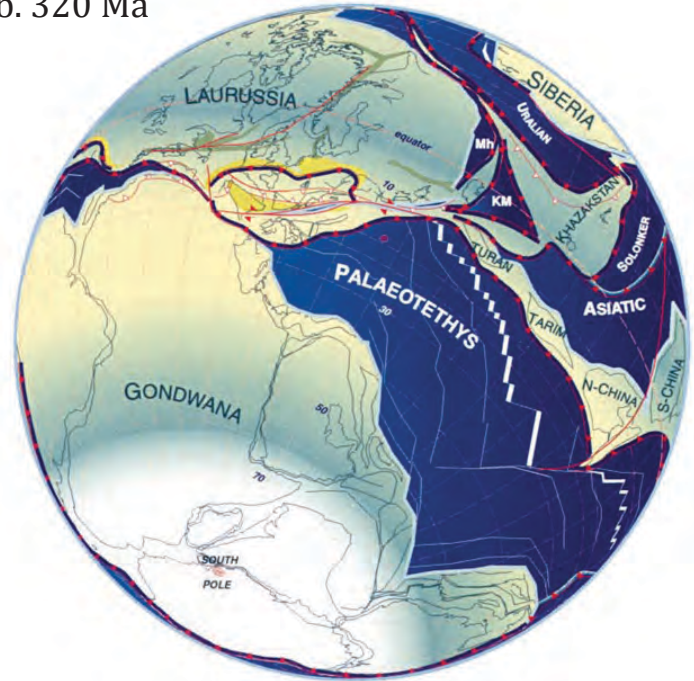
c. 300 Ma
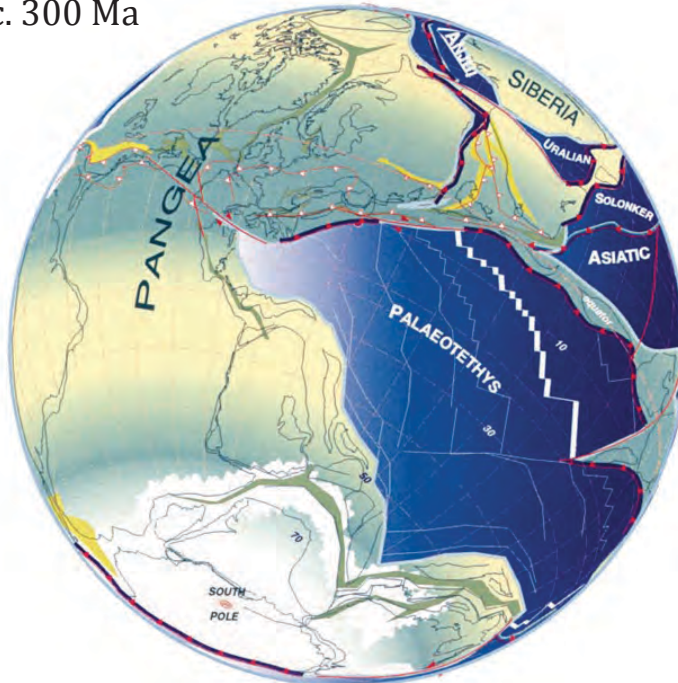
Figure 6. Plate reconstructions showing the European plate arrangements in the Carboniferous. Figures modified after Stampfli and Borel, EPSL 196 (2002) 17-33.

Granitoids

In the continental collision phase of orogens, the crust is thickened to up to two times its normal thickness. This pushes cold continental crust deep into the mantle, where it is heated. Decay of radioactive elements, which are concentrated in continental crust relative to mantle, heat this crustal stack further. This increased heat input into the lower crust results in abundant partial melting and development of large, mostly granitic plutons. These plutons are emplaced in the mid crust, where they can develop contact aureoles. Plutons make up a significant proportion of the mid crustal level of the Variscan in the Massif Central, as can be seen in Figure 2.

The ages of these plutons range from 350 to 280 Ma. Some were syntectonic as shown by elongate pluton shapes or preferred mineral alignments, but most appear to have formed post-tectonically, including the Margeride Granite in the field area. The youngest magmatic dikes associated with this magmatic activity are about 225 Ma in age.

Basin formation and explosive andesite volcanism

The compressional state of the orogen ended at approximately 300 Ma and was followed by a period of gravitational collapse of the mountain belt. This is thought to have been caused by the thickened crust becoming unstable because of weakening, mainly resulting from heating. This collapse led to the formation of intracontinental basins in the late Carboniferous and early Permian, mostly along strike-slip faults, the largest of which is the Grand Sillon Houiller. The basins form where there is a step-over in the strike-slip fault and are generally pull-apart basins.

The basins are mostly short-lived and filled rapidly with peat and alluvial fan and lake sediments. The specifics of these sediments indicate that several of these basins were located in close proximity to glaciers, despite the Carboniferous being a period when conditions were much warmer in Europe. This suggests that these were high-elevation basins. The peat over time transformed into high-grade coal, which was mined extensively in the 18th and 19th centuries, including in the Marsanges and Blassac coal mines in the field area.

Several of these basins also contain a distinct volcanic deposit; a felsic, mostly andesitic, ignimbrite horizon. This unit can be traced throughout Europe, from Denmark to Germany to France, and has been linked to a number of large caldera complexes and smaller volcanoes. The exact origins for this widespread magmatic event are still debated, but it may be related to a (failed) rifting event.

Mineralisations

The Variscan is characterized by an unusual endowment of ore deposits (Fig. 7) when compared to other large orogenic belts including the Caledonian and Alpine, which appears to be linked to the specifics of this orogen, in particular the presence of many micro-continents in between the two large land masses of Laurussia and Gondwana, and their incorporation into the core of the Variscides.

Three main mineralization stages are identified in our field area:

• Stage I: Mo, W, Sn deposits, veins + disseminated
                300-250 Ma
                high temperature 380-275 °C
                spatially associated with granite plutons

Stage II: Sb, Cu, Ag, Pb, Zn deposits, dominantly in veins
                260-230 Ma
                medium temperature 270-150 °C
                temperature trend from Cu-Sb to Fe-Sb to Pb-Zn

Stage III: Fluorite and barite deposits, in veins
                180-160 Ma
                low temperature, as low as 80 °C

The first stage mineralisations are spatially closely associated with the plutons. Their widespread presence and overall similarity in the Variscan chain suggests however that they formed from the interaction of a large scale homogeneous fluid with the fluids expelled from the plutons, rather than from the plutons directly. The main ore minerals that are associated with this stage are wolframite, scheelite, molybdenite and cassiterite.

The second stage mineralisations are characterized by the presence of stibnite (Sb_2S_3). These deposits have no spatial correlation with the granite plutons and formed when the granites were already solidified. Their metal and fluid source has been proposed to be related to devolatisation of the lower crust. The minerals that are associated with this stage are stibnite, berthierite, galena, sphalerite, chalcopyrite and various Pb,Cu,Sb sulfosalts.

The third stage forms the low temperature end of the second stage mineralisations. These mineralisations formed in openstanding fractures near to the surface at very low temperatures. Barite and fluorite are the main minerals that are part of this stage. At the end of the hydrothermal activity the fluorite is dissolved in parts and replaced by quartz.
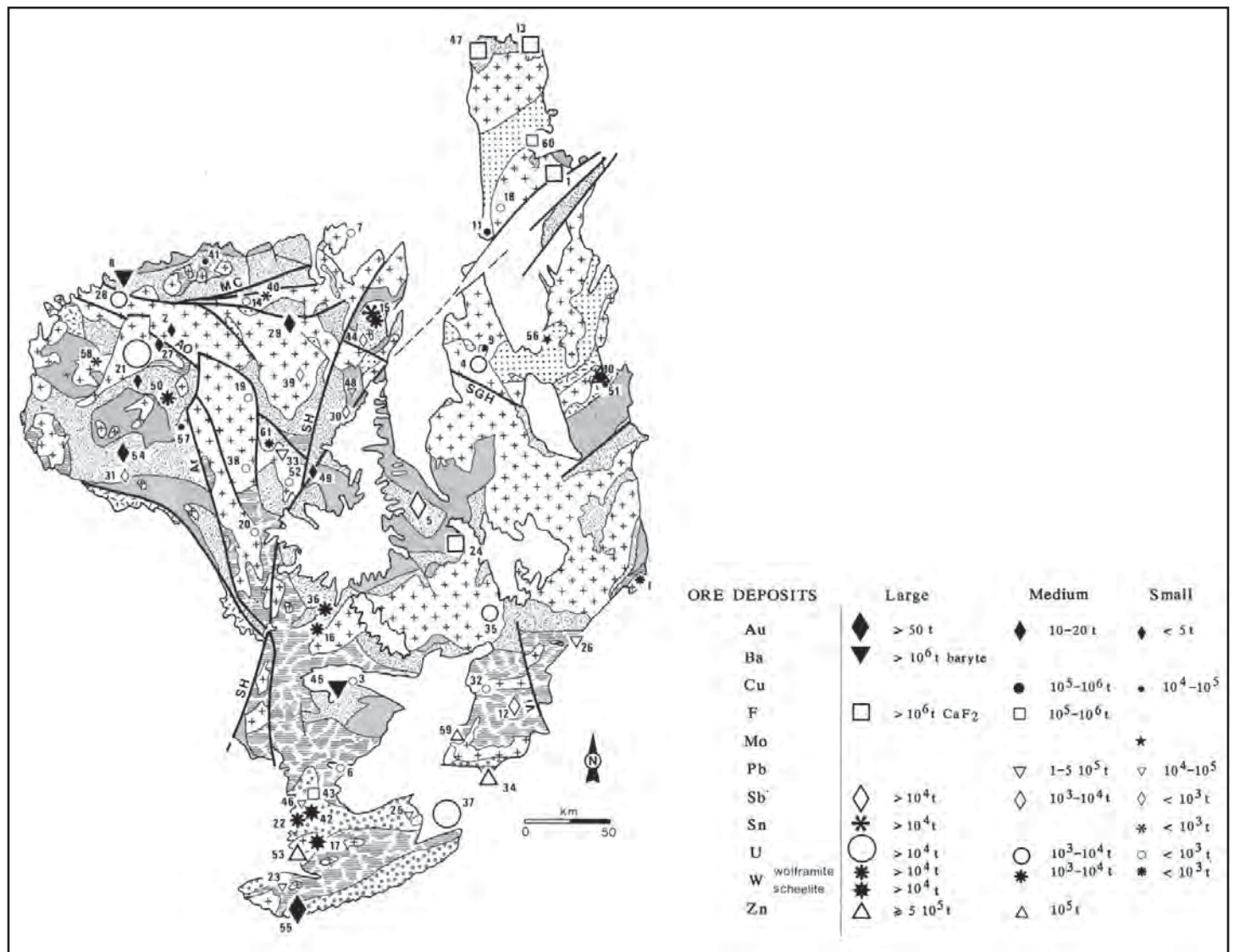
Figure 7. Geological map of the Massif Central showing the diversity of mineralizations found here. The area was a very important mining center from Roman times to the early 20th century.

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Post-Variscan history of the Massif Central

The Pangea supercontinent dominated most of the Carboniferous, but by the Triassic it was already starting to come apart by rifting, and eventual opening of the Atlantic ocean. The rifting led to a rearrangement of the Variscan blocks in Europe, most notably the rotation of Iberia away from the west coast of France to its current orientation. Long-lived erosion levelled the mountains and large sedimentary basins, including the Paris basin were deposited on top of the Variscan basement.

The next major phase in the geological history of the Massif Central starts from approximately 65 Ma with the establishment of a large rift system, the Limagne rift, and emplacement of a mantle plume. It is clear that these events are related, but it is still debated whether rifting and associated thinning of the crust caused mantle upwelling, or mantle upwelling led to extension and rifting.

Volcanism is predominantly mafic in composition, and concentrated on the horsts of the Limagne rift system. Small isolated volcanic centres are most common and widespread, and these produced only one, or a small number of eruptions over a short lifespan. They include spatter cones, maars and tephra rings. Lava-flows with well-developed columnar jointing are also common. A number of larger volcanic centres have developed, most notably the Cantal and Mont Dore complexes. The footprint of the Cantal system makes it the largest volcano in Europe. These large centres have evolved to felsic compositions, including abundant phonolite.

Both the Cantal and Mont Dore systems were glaciated during the last ice age and broad U-shaped glacial valleys can be seen cutting through their structure.
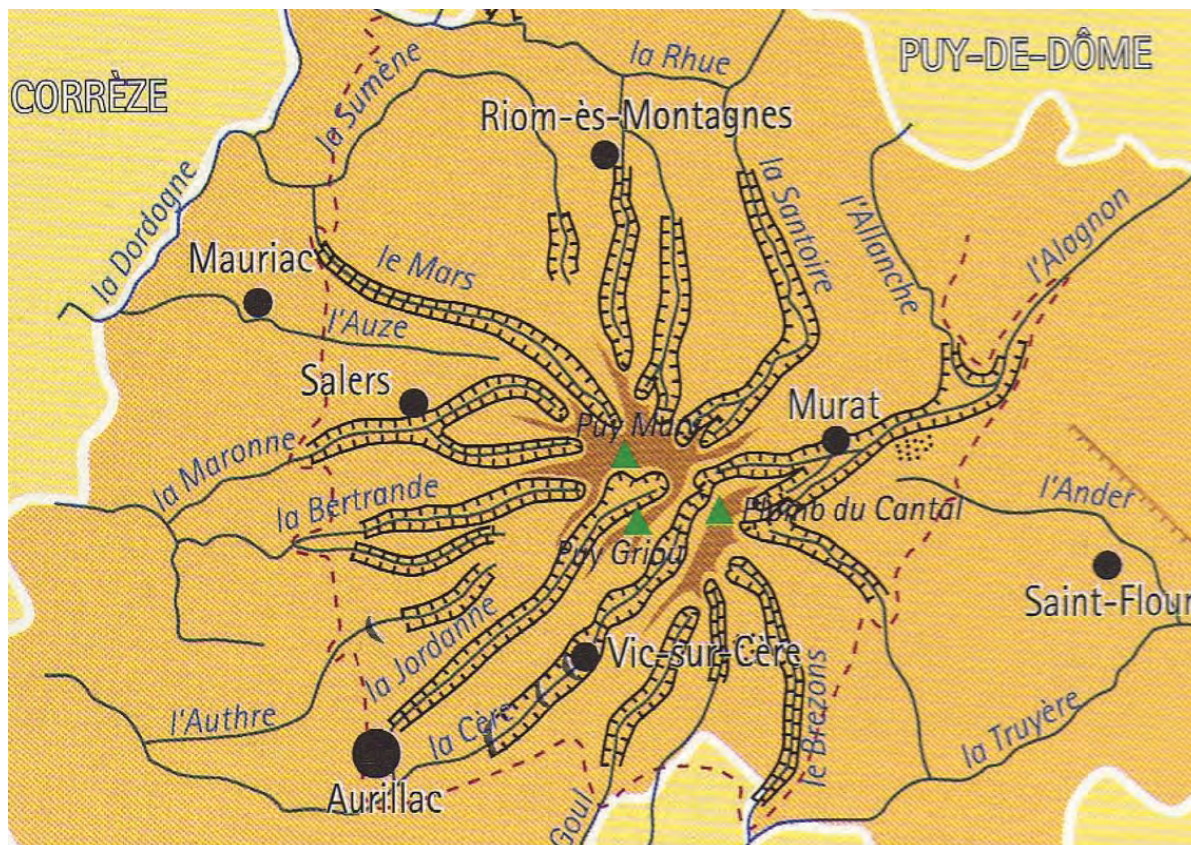
Glacial valleys dissecting the Cantal volcano edifice.

3 geological mapping

The purpose of a geological map is to show the surface geology of an area, including the geological lithologies that are present, their relationships, the geological structure (folds, faults, etc), and any other points of geological interest (e.g. ore veins, mines, quarries, etc.). These maps are made for dissemination and use by others, and as such, they have to obey strict rules of presentation and organization, as you have been taught in Fieldschool 1 and the Field Methods class. A number of key points are summarized below.

General approach

Mapping a metamorphic terrain is commonly more complicated than mapping a sedimentary sequence, because mappable units are generally less continuous and homogeneous. Moreover, retrogression or overprinting, for example next to faults or shearzones, may be present, changing the mineralogy and/or texture of the rocks. Differences between units can also be subtle and may require careful mineralogy checks at each outcrop to make sure that you are still in the same unit (e.g. a kyanite-bearing unit versus a sillimanite-bearing one, or a meta-pelite with and one without staurolite).

There are many approaches to mapping and there is no single one that works best, or works for everyone. Still there are a number of general guidelines;
- Establish your mapping units early, and define them explicitly in terms of the criteria **you** use to separate the unit from all others (mineralogy, mineral proportions, texture, setting, etc). Update your units as you get more familiar with your area.
- Divide the geology in as many units as you can easily distinguish. Obviously one unit is meaningless and 20 is unpractical, but more units allow you to present the geology in greater detail and make it easier to highlight folds and faults. Units that are too thin to plot on the mapscale should be avoided unless they are a marker horizon.
- The two main mapping strategies are mapping **transects** and mapping **boundaries**. Both have their pros and cons. Tracing a boundary will allow you to rapidly delineate a unit on your map and the shape of the boundary provides information on structure. However, you may miss variations within a unit, or miss a unit altogether. In an area with limited exposure or access issues it can also be difficult to trace a boundary. Transects show you all units that are present as well as their internal variability, allow you to make use of the best exposures, for example in roadcuts, and generally give you a better idea of the 3D structure of the geology. However, they require interpolation to connect the geology of the various transects and therefore depend heavily on structural measurements. In the end, a combination is best.
- Do not assume that you will fully understand the geology of an outcrop the first time you visit. You have the time to revisit outcrops as you get more familiar with the rocks in your area. Make use of this! Get familiar with the area and your geology in the first days and map more systematically later on.

Record the geology you observe directly onto a **field map** using coloured pencils, and also include the structural measurements that can help you in understanding the structure. Use bold colours for observations and fainter colours when you infer a certain rock unit, and use the proper map symbols. Your field map is your working map on which you mark all observations, but can also draw hypotheses such as a prediction of where a boundary might go, add notes, such as an area you should visit in the future, etc. You can have several iterations of a field map during the course of a field season and we provide you with plenty of topographic basemaps.

The actual observations, i.e. the hard data, should be transferred to a **tidy map** every evening. This serves several purposes. For one, it safeguards your data should you misplace your field map, but it also allows you to get a quick overview of what areas you have already covered and what areas require additional work, and to get a sense of the distribution of the units and hence the structure of the area. Your final tidy map is one of the things you hand in for the first report, and represents the hard data on which your geological interpretation of the area is based. You use dark *vs.* light colours to denote observed *vs.* inferred geology, show structural measurements, boundaries and important geological features.

The tidy map forms the basis for your **final map**. This final map is similar to your tidy map in that it shows the same information, but unlike the tidy map, no areas should be left blank. In the final map you interpolate between your observations to present a complete, surface covering geological map. In the accompanying text you describe how you interpolated and on what information this is based (e.g. structural measurements, rocks in walls or fields, etc.). The final map represents the culmination of your mapping work.

Structural measurements

Structural measurements help you understand the geological structure of your mapping area and are needed to properly interpolate between your observations in an area without 100% exposure. They also allow you to make crosssections of your map to highlight the 3D geology of your area. Finally, they can help you to locate a unit or boundary when you loose it because of a fault or lack of exposure.

The structures to measure include foliations, lineations, fault orientations, vein orientations, shear zones, uncomformities, fold axes, etc, etc. You should plot the most informative of these measurements onto your maps. Make sure that you remember how to make these measurements using a geological compass, and look at your notes from fieldschool I and/or your Field Methods class if you need a refresher.

Orientation measurements can be recorded in numerous ways and you can use one of two conventions during this fieldschool (make sure to write on page 1 of your notebook what notation you are using and do not switch during the fieldschool!):

1. DDD: **Dip direction and dip**. In this case you report the direction of your dip projected onto a horizontal plane with a value from 0° to 359°, together with the amount of dip. For example, a measurement of 065/45 represents a plane that dips 45° to the NE
2. **Strike and dip.** In this case you report the strike and the amount of dip. To find the strike angle, use the right hand rule: with your thumb pointing in the direction of dip your index finger points to the strike angle. Just to be sure, also record the dip orientation. In this notation, the example above is recorded as 155/45 NE.

The magnetic declination for the field area is +0° 49' (east). With such a small declination it is not necessary to correct your compass.

Notebook

Your field notebook is your most valuable possession during fieldschool. This contains your observations, which are the raw data on which you will later base your maps and your interpretations. In order to be most useful, and for others to be able to extract information from it as well, it needs to be structured, and to strictly adhere to this structure throughout. There is no fixed notebook format and you have the freedom to organize your notes in a format that works for you. However, there is a set of minimum requirements for a good notebook that we expect you to adhere to. Your notebook should FLOAT and hence be:

Factual - Your notes should deal with facts, not wishful thinking. You can definitely write down ideas and hypotheses, but these need to be strictly separated from the observations, and should be clearly marked (for example by writing in a different colour). Also be precise in your statements and avoid terms such as "plenty", "a lot of", "not many",etc.

Legible - Your notes need to be readable by anyone so make sure you write in legible script. Your observations and data essentially don't exist if others cannot read them.

Organized - A good notebook is highly structured and presents information in an organized way. This not only allows the reader to find information easily, it also ensures that you take complete notes at each outcrop and do not forget to record some information that might later be critical when writing your report.

Accurate - You need to be able to trust your notes, so only write down what you actually observe. Some minerals may, for example, be hard to identify in hand specimen, but don't be tempted to "see" them anyway, because if you later decide to define units on the presence or absence of this phase, you will not be able to do that from your notes. Also make sure that sketches are accurate; a reader should be able to locate what you have drawn from your sketch.

Tidy - A tidy notebook allows you to quickly find information. Leave plenty of empty space so you can add notes later,. One of the most common reasons for a cluttered notebook is running out of space, so make sure you bring enough notebooks to the field. One is definitely not enough!

Some additional recommendations on notebook organization:

- Write your name, field address and telephone number/email address on page 1 of your notebook with a plea to anyone who finds it to contact you (in French). Should you loose your notebook, this gives you a fighting chance of being re-united with it.
- Start a new day in your notebook with the date, information on the weather, and the plan for the day; where are you going and what do you aim to achieve. Weather information can be quite helpful, because it is much harder to make good observations during rainy or overcast days.
- Use one side of your notebook for text, the other for drawings, sketches and annotations. You can also put strike-dip measurements on the drawings side, or mark them clearly on the text side (for example by drawing a box around them). Be consistent throughout, and, if you are running out of space, start a new notebook!
- Each locality that you describe is a "station" and should get a sequential station-number. A standard way to number your stations is to use the first three letters of your last name followed by the year and then a three-digit sequence number (e.g. XXX18-001). A station should be marked on your field map and you can also store its GPS coordinates.
- Strictly separate out observations, interpretation and hypotheses. Observations are your raw data and

are always correct, even if your interpretation is off. This makes them the most valuable part of your notes and it should be very clear which parts of your notes are observations. It is good practice to write down ideas and hypotheses, but these need to be clearly marked as such. You can comment on these later by using space on the left side of your notebook.

- Sketches and drawings need a scale, orientation arrow and annotations, as well as a caption. Provide as much detail as necessary. They don't need to be works of art, but need to be understandable by others and be useful. You can draw field overviews, outcrops, structures, samples, etc. It can be useful to give them a sketch number so you can refer to them later in your notes, and your report.
- Use pencil to write and draw. It will rain at some point and ink will be washed out in wet weather. Use coloured pencils in drawings to mark different units.
- Start your notes with large scale observations and move to increasing detail: Station number, location, type of outcrop, state of outcrop (weathering), large scale structures, rock types, mineralogy, mineral-scale structures, etc.
- There is no need to repeat large amounts of information at a next entry if these haven't changed. For example, if you are tracking a unit boundary, it may suffice to just give a structural measurement at each station. Still, it is good practice to state that nothing has changed from the previous station.
- End a day's notes with a short summary of what you have observed and a list of things to follow up.
- Notebooks do get lost and it can be a catastrophe if you loose your notes halfway through a field season. To avoid this, make pictures of your notebook pages each evening when you get back from the field.

We do not use a digital notebook during this fieldschool, but it can be useful to store the GPS coordinates of your stations digitally or tag pictures with their coordinates so you can go back to them easily.

Your notebooks will be graded and this grade becomes part of the overall course grade. The criteria we use to grade notbookes are follow the recommendations for a good notebook as set out above.

Map symbols

observed boundary

inferred boundary

suspected boundary

strike and dip 42

horizontal orientation

vertical orientation

lineation with dip 36

syncline

anticline

anticline with plunge

fault

thrust

Notebook examples

Location _Massif Central_ Date _12-05-2016_
Project / Client _mapping_

May 12: Good weather, sunshine with light breeze. Minor rain overnight. Plan to go to SW of mapping area to check out ridge seen yesterday: could be basalt flow.

Station FGS16-015: Roadoutcrop of ~50m length, 2m high on road from Chilhac to Paulhaguet. Good exposure but rocks are weathered and covered by soil. The rocks are foliated with a steeply dipping foliation. No variation in rock type along the outcrop. Rocks are friable because of weathering, but can still find fresh pieces.

Rock has a schisteous texture with crenulation defined by the micas. Micas consist of musc + biot (mm-sized) and wrap around qtz + feldspar (1-2 mm diameter). About 50% mica and 50% qtz + fsp. Found one small (2 mm diameter) red garnet. No staurolite or Al-silicate, but could be obscured by weathering.

Interpretation: This is the same schist unit as seen in station FGS16-002, but more weathered.

Station FGS16-016: Outcrop in drainage ditch next to the road, a little further along the road towards Chilhac from previous station.

Same unit, even more weathered here.

Station FGS16-017: Outcrop on ridge above the village of Chilhac = ridge seen yesterday.

Rock is fresh and consists of finegrained grey basalt with columnar jointing and mineral-filled vesicles.

Location _____ Date _____
Project / Client _____   Scale _____

foliation: 123/67 NE
119/72 NE*

* should be better because less weathered

Need to check the area in between to confirm they join up. Orientation is very different!

foliation: ~130/70 NE

Location _____ Date _____

Project / Client _____ Scale _____

Location _____ camp 2 _____ Date _July 21, 2014_

Project / Client _'SEGMENT - GEUS'_

Camp 2: Flat area on top of the island run to longish lake. Nice and flat with moss cushion and great views to glacier and icebergs. Only problem is fresh water. Lake ok but full of small critters.

Goals: ① detailed study of UM's, meta-anorthosim and rubies

② check metasediments and their related to boxormed gneisses.

July 21: Sunny and hot. Little wind and lots of bugs. Will traverse island to get overview of geology and check out meta seds.

station viin 020   Outcrop next to lake and camp continuous to other side of camp. Rocks consist of well foliated felsic gneiss little fields of discuich ated

coord: 65° 36.943 N
       38° 28.429 W

stringes of pegmatite or partial melt? very regularly spaced. They are foliated and folded in with but they postdate their host gneiss.
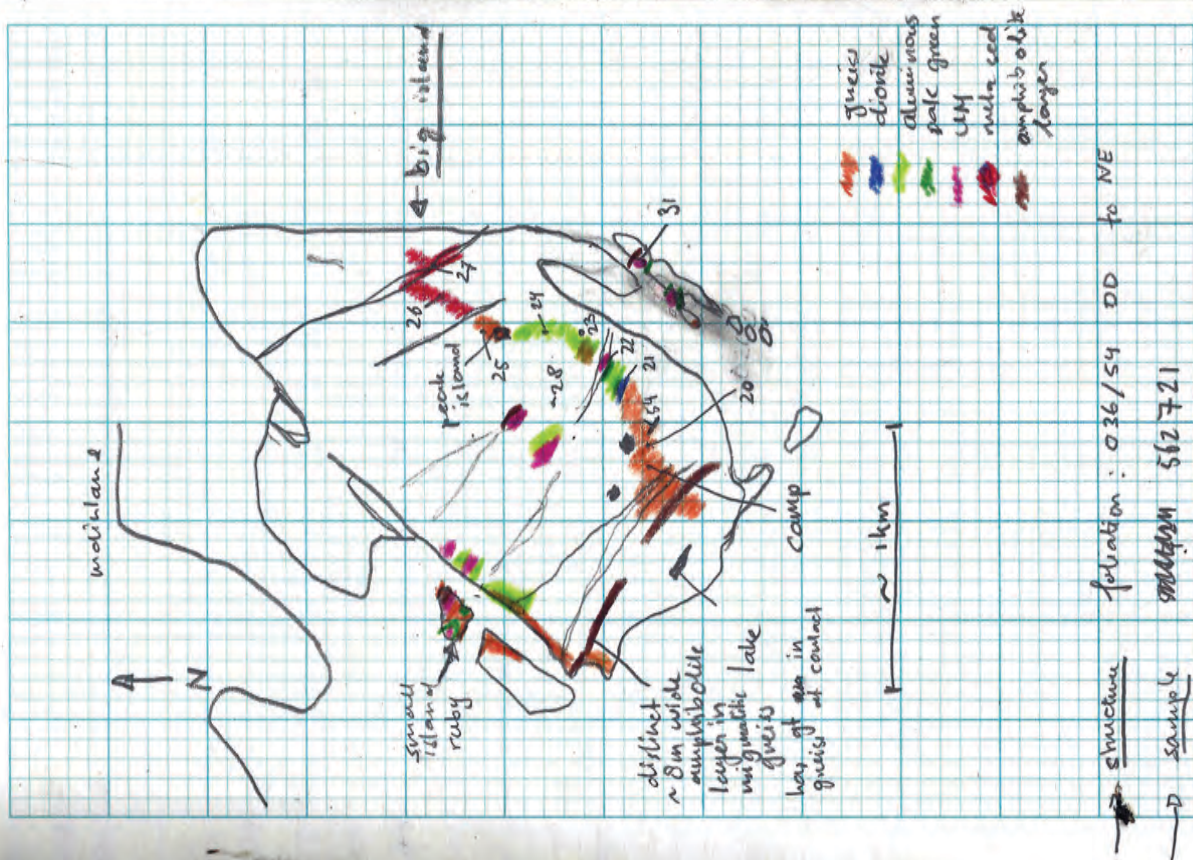
4 geochemical mapping

Geochemistry is concerned with understanding the behaviour of elements and chemical compounds within the major systems of the Earth. The concept of a geochemical cycle plays a central role as it summarizes these major systems and the processes that determine transport of elements and compounds among them (see Fig. 8). In this field course, we focus on element mobility during weathering and transportation, and its links to bedrock geology.
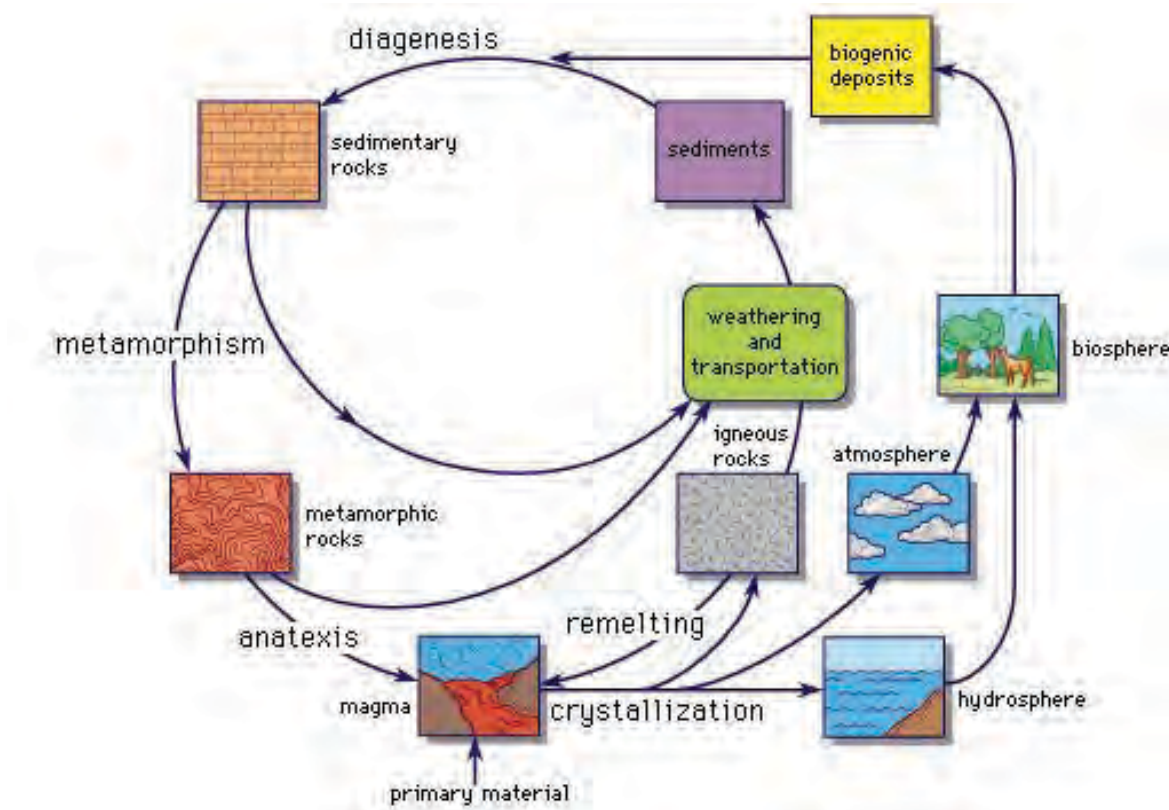
Figure 8. A cartoon of the global geochemcial cycle.

In order to better understand these processes and their spatial variation, a geochemical sampling campaign of river water, river sediment and soils will be conducted. In a field laboratory, the waters are analyzed for pH, conductivity, sulfate, nitrate and fluoride, and the stream sediments and soils for trace elements including Ba, Fe, As, Cr, Pb and Co. Finally, geochemical maps are created that reveal regional patterns of the concentrations of these elements and which allow for links with, amongst others, bedrock geology, land use and human disturbance to be explored.

In the field, each group is responsible for designing the best sampling strategy in their field area, conducting a comprehensive sampling of river waters, river sediments and soils, preparing samples for analysis (drying and sieving of solid samples) and analyzing samples for major and trace elements in the field laboratory. To increase efficiency, the samples from all groups are prepared and analyzed together. However, you will only interpret data from your own field area for the final report.

The regional geochemical study will be based on stream water, stream sediment and soil sampling. Soils are generally locally derived and soil samples therefore most strongly reflect the local geology. In contrast, sample media like stream water and sediment represent composite samples of the upstream drainage area, because they have been derived from a larger area than just the sample site. Smaller streams with less discharge and high up in the drainage basin will commonly more closely reflect the local environment, whereas large rivers show an averaged signal of the complete upstream drainage basin. These various sample media thus serve different purposes; if we are interested in detailed local phenomena, soil samples are most useful, whereas if we are looking for broader trends or want to investigate a large area, composite stream waters and sediments should be our samples of choice. Finally, heavy mineral concentrates will be collected at selected sites by panning, as these can provide valuable information on metamorphism and the presence of mineralisations.

The general approach taken during the geochemical mapping is shown in Figure 9. Subsequent aspects of the mapping and their practical aspects are worked out in the next paragraphs. Background information about geochemical mapping, average compositions of rocks and minerals, (chemical) weathering, transport can be found in the Appendices.

Sampling	Sampling of soils, river sediments and water. Record field site parameters, measure water pH, EC and temperature.
Analyses	Soils and sediments are dried and sieved. Together with water samples they are analysed for major and trace elements.
Data processing	Data assessment is conducted to check data quality and element behaviour. Concentrations are visualised in geochemical maps.
Interpretation	Spatial distribution of concentrations is interpreted in light of basement geology, topography, land use, and disturbances.
Follow-up	Geochemical anomalies are investigated to determine their cause by re-visiting the sample site
Reporting	The interpretations are reported and integrated with geological and geophysical findings.

Figure 9. Overview of the general approach taken in the geochemical mapping part of the fieldschool.

Sampling

Garbage in = garbage out. This statement more than anything captures the importance of careful sampling; if your samples are bad, any data you will get are worthless, and meaningful interpretation of your data will not be possible. Don't cut corners in sampling as you'll pay for it when it comes to writing your report!

Sampling strategy

Sampling itself may look straightforward, but the way a sampling campaign is designed is of importance for later presentation and interpretation of results. Depending on the main goal of the sampling campaign, the following broad types of sampling designs can be distinguished:

- **Random sampling:** sample locations are located randomly over the area. This type of design is useful when no information about the area is *a priori* available and one wants to get an unbiased impression of average concentrations.
- **Grid sampling**: sample locations are located in a grid with spacing of equal distances. This type of sampling is very labour intensive but useful when one wants to accurately interpolate values in order to make a continuous map of concentrations over the area.
- **Judgment sampling:** based on *a priori* knowledge about the area, specific locations are chosen. This approach is obviously logistically favourable and can be used to study a specific part or system within the area. It therefore results in biased estimates of overall concentrations.

For regional geochemical mapping, a random sampling approach is preferred. However, not all randomly selected streams may be appropriate for sampling, for example because of lack of water, garbage at the sample site, no access to the stream, etc. Moreover, lower order streams (see Fig. 10) are more closely linked to local phenomena and are therefore preferred. In reality, regional field sampling is therefore closer to a judgement sampling approach. This does introduce a bias in the data.
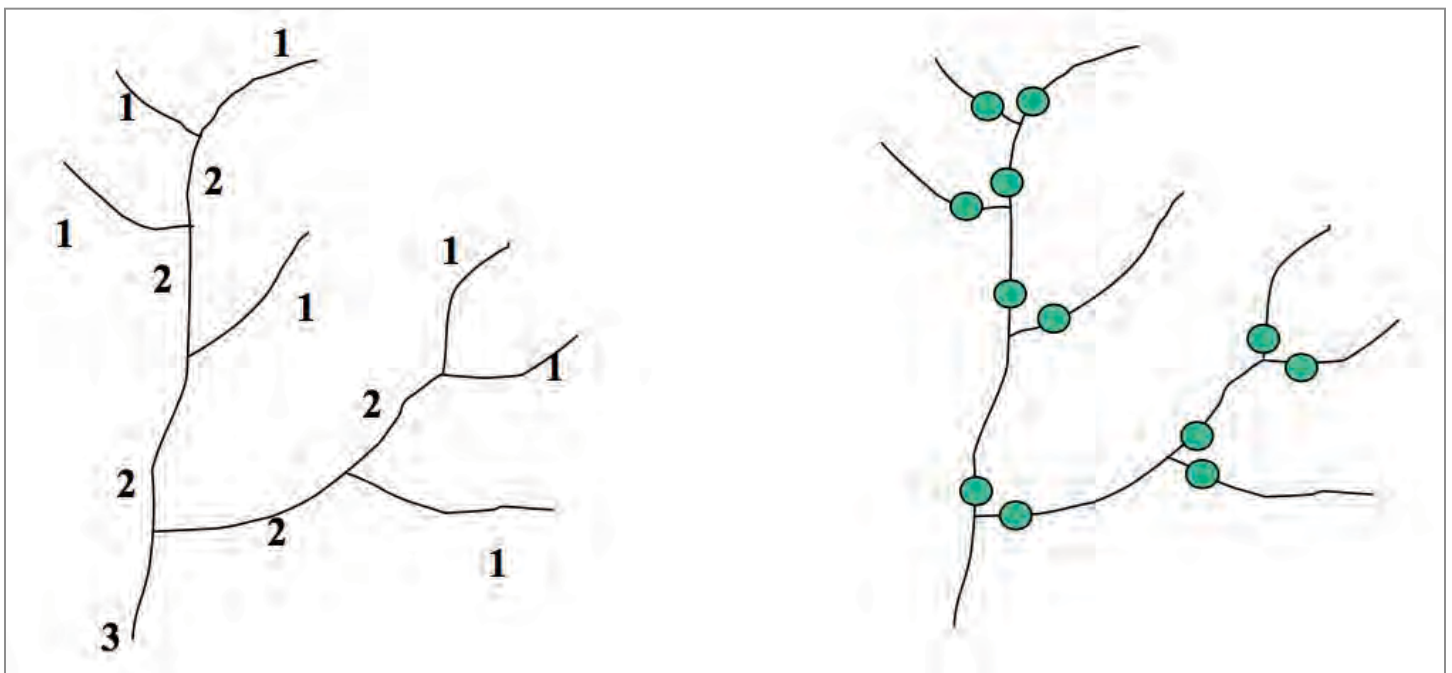
Figure 10. Classification of streams in terms of stream order (first, second and third order streams shown) and appropriate sampling locations (right).

Each group is responsible for designing a sampling plan for their field area with the aid of the topographic map and based on their understanding of the local geology. First and second order streams should be targeted (Fig. 10), because higher order streams sample large drainage areas making it potentially difficult to link their compositions to local factors. There is no point in sampling the Allier to understand your area!

In the exploration part of the fieldschool, you will use a grid sampling approach instead. This will allow for optimal interpolation of concentrations among the sample locations, so that a contoured geochemical map can be prepared. This approach is much more labour intensive and cumbersome and is therefore only applied to smaller areas and follow-up studies, for example, when regional mapping identifies an anomaly.

Given that a geochemical map should give an overview of regional patterns, it is necessary that the small-scale variability (e.g. variation within one sampling location) is significantly smaller than the regional variation. In order to test whether this is indeed true, it is common practice to collect field duplicates. Field duplicates are samples collected close to the original sample location (commonly within 50 m.). ***During the field course, every 10th sample location is sampled in duplicate, which should be clearly recorded in the field form (see Appendix VI).***

Sampling procedures

A water and stream sediment are collected at each location for the regional survey whereas a soil sample is collected at each grid intersection for the exploration survey. In addition a number of field observations and field measurements are made and recorded on the field forms (see Appendix VI).

Regional survey:

Field measurements	pH, conductivity (EC), temperature (°C), discharge (dm³/s)
Stream water sampling	• clean bottle and cap by rinsing three times with the stream water prior to filling • collect only clear water (avoid suspended matter) with bottle opening facing downstream • if the stream is dry, collect only a sediment sample
Stream sediment sampling	• Collect sediment from the active stream bed using a plastic scoop • Collect preferentially the finer material without litter or large organic parts • Store sample in a Kraft paper bag, expel any water before closing

Exploration survey:

Field measurements	soil electrical conductivity (self potential)
Soil sampling	• Remove the humus layer and collect (top)soil using a plastic scoop • Collect preferentially the finer material without litter or large organic parts • Store sample in a Kraft paper bag • Close the sampling hole back up

Upon your return form the field:

Bookkeeping	• Log samples and their locations in the lab computer database and on a GIS map • Transfer field observations and measurements to the database • Check that all samples are accounted for
Sample storage	• Water samples are collected in the analysis in-tray • Stream sediments and soils are put in the oven for drying

Note: if you suspect a sample to be anomalous, for example because you saw ore minerals at the sample site, or sampled just downstream of a village, mark these samples and hand them in separately to avoid cross-contamination.

Soil and stream sediment samples are dried in their Kraft paper sampling bags to remove all moisture and are subsequently sieved to obtain the –80 mesh fraction. This fine fraction generally caries the majority of the trace elements.

Sampling packing lists

Regional survey sampling materials will be handed out at the start of the fieldwork. Each group should make sure that they have the following materials with them during sampling days:

- field notebook
- tablet with cover and pen
- 2 printed regional survey sample forms
- a waterproof felt pen / marker
- 25 large paper sample bags (stream sediment and soil samples)
- 4 small paper sample bags (heavy mineral concentrates)
- 1 plastic scoop
- 1 coarse sieve (sediment and soil samples)
- plastic bottles (25 large ones or 50 small ones)
- combined pH-EC-T meter
- 2 plastic garbage bags
- a sturdy shopping bag
- 5 ziplock bags
- gold pan
- overview geological map and topomap
- camera (to take pictures of interesting features at a sample site)

Aim to collect approximately 50 samples in your regional survey with a good coverage of your area, its geology, and any geological points of interest that you may have identified. You will have a vehicle at your disposal for one sampling day to reach outlying areas and fill in the sampling.

For the exploration survey, geochemical sampling is combined with on-site geophysical measurements along grid lines. Each group should make sure to bring the following:

- field notebook
- 3 printed grid sample forms
- a waterproof felt pen / marker
- 40 large paper sample bags
- 1 plastic scoop
- 2 plastic garbage bags
- a sturdy shopping bag
- compass
- rope and measuring tape
- pink toilet paper (for use as flagging tape)
- multimeter
- copper cable
- 3 soil electrodes in soaking box
- GPS to record the coordinates of the start and end positions of each line

Data analysis

In order to interpret the results of the laboratory analyses we will use a number of procedures and statistical techniques. Some of these are simple and familiar such as calculating the mean and standard deviation, while others are more specific to geochemistry, like log transformations and kriging (a few are outlined below). The staff will prepare the statistical analysis of the data and their visualization on geochemical maps. This is because the details of the procedures used are beyond the scope of the fieldwork and insufficient computing facilities are available to let each group conduct their own processing. However, we encourage you to ask questions about the processing and presentation of the data, and will gladly plot any figure or geochemical distribution map that you may desire in addition to the most common ones that we provide.

Outliers

Outliers are samples with extreme values that you would not expect to find by chance for a given data distribution; they are so unlikely that we regard them as not being part of the data range. Normally these samples are rejected from the data set before doing further statistical analyses, because they are regarded as being part of a different data population. However, in a regional geochemical survey or exploration project, these samples are actually very interesting, because these are deviations from the norm and may indicate the presence of a mineralization, pollution, or other disturbance of the natural background. They are therefore included in the data presentation, but are processed separately. We normally consider a value as an outlier if it is more than 2.5 or 3 standard deviations away from the mean.
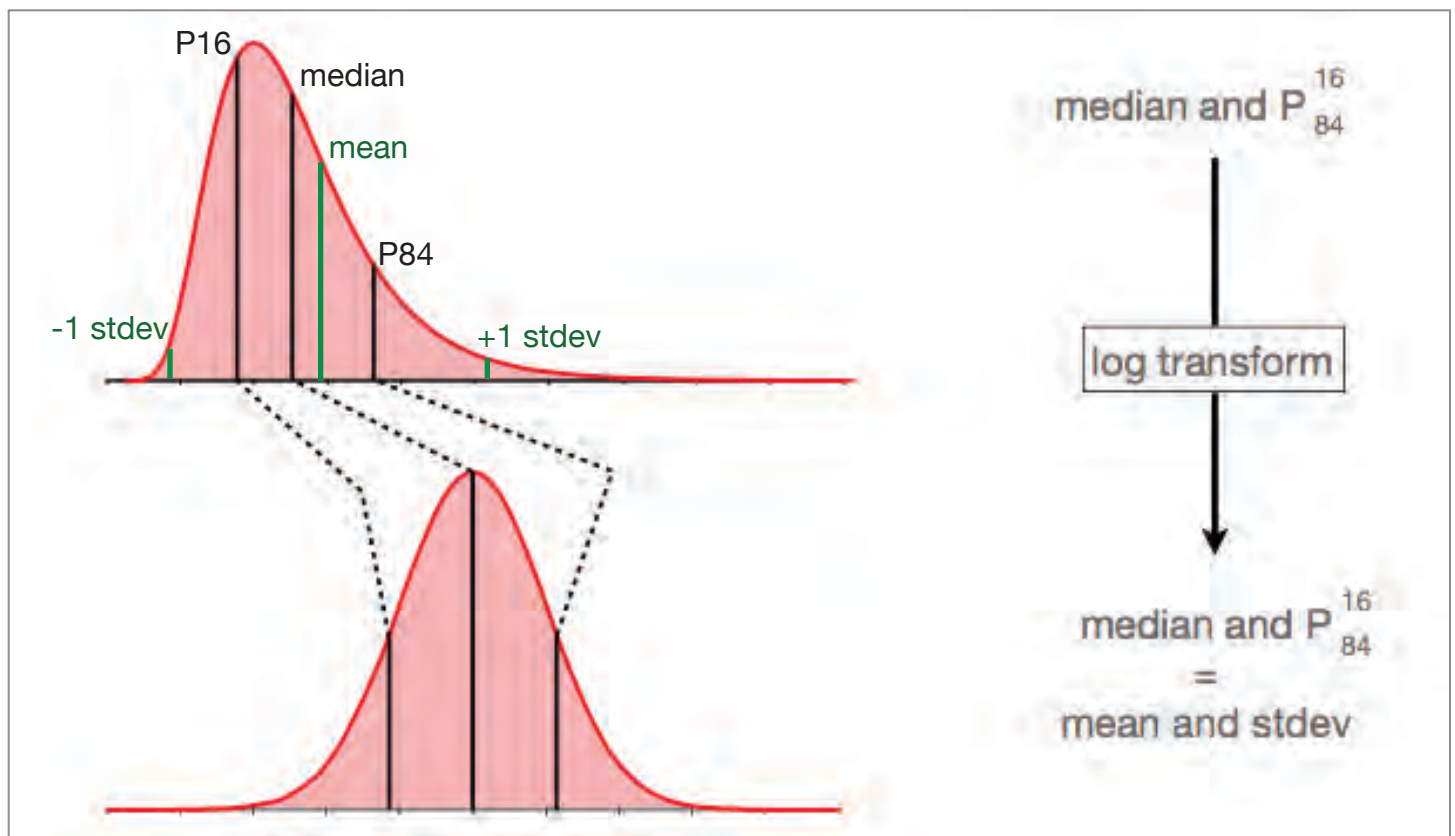
Figure 11. Geochemical datasets commonly show a tail to high concentrations. In such cases, the mean ± 1 stdev does not provide a good description of the data, and the median with a percentile window is much better (we use the 16 to 84 percentile range, because that covers the same 68% of data as ± 1 stdev). An alternative is to log-transform the data and to process them as log-transformed numbers, because the log transformation largely removes the skew as can be seen in the bottom figure, and now mean ± stdev describe the data well.

Log transformations

Most statistical techniques assume that the distribution of a variable is symmetric, i.e. there are an equal number of samples above and below the mean. This type of distribution is called "normal" or Gaussian". However, trace element data from geochemical sources are often asymmetric with a tail to high concentrations, because extremely high values can be observed, but extreme low values cannot, because concentrations below 0 are obviously meaningless. This causes distributions to be "skewed" (Fig. 11). In these cases, the mean and standard deviation (which is based on the mean) are not good descriptors of the data, and we should use the median and interquartile range (IQR) instead. Alternatively, we can log-transform the data, which removes the skew to a large extent and avoids it affecting further statistical analysis. This latter approach is commonly preferred in geochemistry and we will use it here.
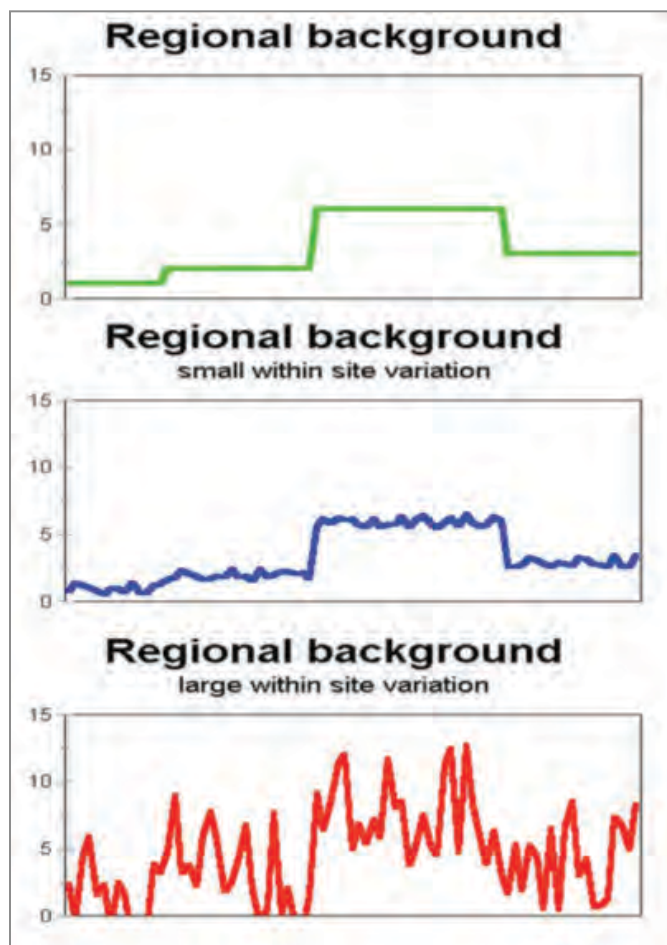
Figure 12. Geochemical surveys are intended to quantify the regional compositional variability. To be able to do so the local variability, i.e. the heterogeneity at the sample site, and the analytical uncertainty, need to be smaller than the regional signal you are looking for; the signal to noise ratio needs to be larger than 1. This is no longer the case for the bottom figure, in which case no regional signal can be discerned and only noise remains.

Data quality

Measurements are never exact, but will have uncertainties coming from many different sources. Some of these uncertainties cause a bias (a shift in concentration) and can be difficult to quantify, such as those resulting from the wrong calibration of an instrument. Others are random and can be quantified by setting up a good sampling design and using statistical techniques. The two most common sources of uncertainty in geochemical surveys are *analytical* and *sample heterogeneity*.

Analytical uncertainty results from small random errors in the analytical method. These can generally not be avoided, but they should be normally distributed and are therefore not a major issues as long as they do not overwhelm the regional signal. Sample heterogeneity or field variance is the uncertainty in concentration resulting from variability in the sample material. For example, one scoop of sediment might have a little

more garnet than another, resulting in a different composition. Again, this source of uncertainty cannot be excluded and it is important to quantify it to make sure that variability at a sample site does not exceed the variability between sites, because this would make the regional survey approach invalid (Fig. 12).

Both the analytical and field uncertainty can be quantified by taking duplicate samples. For field variance, these duplicates are taken in the field at sites that are a little apart (generally less than 50 m) with both samples taken in an identical way. These samples are processed and analyzed separately. Analytical duplicates are made in the lab by analyzing the same sample two times. In both cases, the duplicates are not analyzed sequentially, but rather mixed in with all samples to randomize their analysis time and provide a true estimate of the uncertainty.

In order to properly understand and interpret the regional variability in compositions, the concentration variations among sample sites need to exceed the analytical and sample uncertainty; the signal needs to exceed the noise (Fig. 12). In general, at least 80% of total data variation should be attributable to regional differences in order to produce meaningful maps.

Kriging

To create a concentration contour map from our exploration grid requires knowing the concentrations at every intermediate location, and hence interpolating. There are many methods of estimating the concentrations at these intermediate positions, the simplest of which takes the proportional contribution of adjacent points based on a lever-rule. In geochemistry and exploration we commonly use kriging. This method uses the fact that samples close to the interpolated point contain a lot of information on its concentration, whereas samples further away contain progressively less, until a cutoff is reached where more distant samples do not provide any information anymore. The similarity between points progressively further apart is used as the weighting factor in calculating the concentration at the interpolated point. A big benefit of a kriging approach is that you also obtain the uncertainty on the interpolated concentration, which allows you to go back and take additional samples in those parts of the map where the uncertainty is highest.

Bubble plots

The sample density that you will attain for your regional geochemical survey is insufficient for meaningful interpolation to make contour maps. Instead, element concentrations will be spatially presented in bubble plots. These plots show a circle at each sample site scaled to the concentration, and overlain on a topographic map or the geological map that you will prepare. This allows for quick visual interpretation of data. Aside form concentrations, element ratios, pH, EC, or other field observations can also be plotted.

5 Fieldwork reports

The fieldwork is evaluated in two parts: **1.** A midterm evaluation after two and a half weeks based on your notebook, your field and neat maps, and your cross-sections; **2.** A final report in which you present an integrated interpretation of your geological mapping, regional geochemical survey and exploration soil survey is to be handed in at the end of the fieldwork. There is a dedicated day to work on each report, but preparatory work in the evenings prior to this will be required.

The two main reports are handed in as a group and represent the grades for EPSC 331 and 341, respectively. In addition, notebooks and field participation are marked individually. Participation is 10% and notebooks 15% of the final grades.

In addition, you will hand in your introductory geological transect at the end of the first week (map + cross-section + notebook). Although not formally graded, we will provide feedback on your notetaking and on the quality of your geological mapping. This is purposely planned early so you can take these suggestions into account when collecting and recording the data for your mapping.

Midterm report

This report focuses on the geological aspects of the fieldwork, notably your mapping, which should be complete by this time. It also aims to provide you with feedback on your notetaking, although we will provide preliminary feedback earlier. The following items are to be handed in at this time:

- **Notebooks** - Each student has to hand in their own notebooks, which should contain a complete record of observations made by the group during mapping. For the regional geochemical survey and exploration component a group notebook can be kept, but for the mapping part each person has to take their own notes. Notebooks are evaluated on FLOAT (see section 3) and completeness.
- **Field, neat and final maps** - Each group hands in their field maps and neat + final map with legend. The maps are evaluated on correctness of geology, presentation and use of correct symbols, consistentcy with notes, detail and coverage. This is evaluated for each group as a whole.
- **Cross-section** - This cross-section through your mapping area is to highlight its 3D structure along a line that best shows all its characteristic features (it is allowed to have up to 2 kinks). Choose this line carefully and project your structural measurements onto your cross-section line using a Stereonet. One section is to be handed in per group, and it is evaluated on correctness, internal consistency, choice of sectioning line, correct use of symbols, detail, and correct projection of structural measurments. Use colour, a scale, compass arrow and locate it on your geoligical map.

- **Map description** - A short written report that presents your geological map, the units that you have identified and the criteria used to differentiate them, the 3D structure of your maping area, the relative chronology of your units, and any geological points of interest that you have identified (e.g. mines). One report is to be handed in per group, consisting of:
    - A short introduction (half a page max) of the area describing topography, weather, land use, etc.
    - A description of the geology, including the various units present, their defining characteristics, their relationships, their relative age, their metamorphism and metamorphic grade, and their structure (4 pages max). Refer often to your geological map and the cross-sections. You can also include photographs and sketches (these do not count towards the page limit).
    - An interpretation of your area including a discussion of its geological history (one page).
    - An appendix with geological points of interest in your area.

The various parts of this midterm report are weighted as follows: notebooks (15%), maps (20%), cross-section (10%), and map report (35%). In addition, your field participation is taken into account and adds the final 10% to the grade.

Final report

In this report you integrate your results from the geological, geochemical and geophysical parts of the field-work to arrive at a complete understanding of the area. You have a day at the end of the fieldwork to write this report, but we srongly advise that you discuss the various aspects within your group as you go along. The geological report, its maps and its cross-sections are an annex to this final report. These are not re-evaluated and do not need to be amended. You should (often) refer to this report in the final report, because you need the geological information to interpret your other results. One final report is handed in per group and it will consist of the following parts:

- **General introduction** - A brief (half a page) introduction into your group's area, describing its location, topography, land use, geology, and other relevant information.

- **Regional survey** - This section discusses the results of your stream sediment and water sampling project and links these to the geological map you have made for this same area. The report is to be approximately 4 pages in length excluding figures, and adress the following:
    » outline of the aims of the project with the briefest of summary of the methods used
    » a summary description of your data, including the characteristics of each variable (typical concentration, min and max values, data distribution, etc.). Also include your field observations in this.
    » a description of the spatial distribution of your data with presentation of the bubble plot maps that you have decided to show in the report for field measurements, water analyses, and sediment data.
    » discussion of the spatial distribution of your concentrations and interpretation of these in light of the bedrock, topography, land use, and disturbances (if any).
    » a brief report on any follow-up work you conducted.

- **Exploration survey** - In this section you discuss the results of the exploration grid soil survey, combining field observations with geochemical concentration and geophysical property maps. This part should be about 3 pages in length, excluding figures and tables, and include:
    » outline of the aims of the project with the briefest of summary of the methods used
    » a summary description of your data, including the characteristics of each variable (typical concentration, min and max values, data distribution, etc.). Also include your field observations and geophysical measurements in this.

» a discussion and interpretation of the spatial distribution that you observe for your geochemical and geophysical data and how this links to local geology, topography, mineralizations, etc.

• **Conclusions** - A two-page synthesis that combines all observations made in the various parts of this fieldwork (including the mapping) and presents a holistic view of the field area. Here you present your understanding of the field area, what it represents geologically, its setting and history, and the evidence that leads you to these conclusions.

The final report will be graded in Montreal using the following weighting factors: Regional survey (35%); Exploration survey (30%); Other sections (10%); Notebooks (15%); Field participation (10%). We will evaluate the report on your depth of understanding of the area and your ability to integrate the different field components.

6 Appendices

I. How to make a transect

General rules for drawing cross-sections

- A profile is intended to show the 3D geological structure of an area along a line that highlights the most representative features of the area. Your line should be straight, although it is allowed to have up to 2 kinks to best show the geology. However, if you make observations along a curved road, your section should be a straight line along that road with observations *projected* onto it.
- Ideally, the line of section is drawn perpendicular to the strike of folded strata, or close to it.
- The topographic profile along the line of section should be constructed carefully. Sections should be drawn with limited vertical exaggeration (1:5 is generally a good maximum exageration for a hilly terrain, it should not resemble the Alps!). Remember that geometries and dips are distorted when there is vertical exaggeration - adjust your measured dips accordingly!
- You will need to convert your measured dips to apparent dips where the line of section is not perpendicular to the strike of a unit (see below on how to do that using your Steronet).
- In areas of unmetamorphosed, stratified rocks, stratigraphic thickness may be assumed to be constant unless there is evidence to the contrary.
- Contacts must conform to dips, but watch out for unconformities.
- Intrusive rocks may either crosscut or be conformable with adjacent rocks. Assume crosscutting until you find evidence for conformity.
- Make sure your section is legible, accurate and shows your interpretation clearly.
- Your cross-section should have a scale, legend and compass orientation.
- Remember: the cross-section is a representation of the same geological model contained in the map so the section and map must be consistent. Relative timing and spatial relations must be the same.
- To test a cross-section, consider whether the deformation is geologically plausible. If you retro-deform the section, does it restore to a balanced state?

Procedure for drawing cross sections

- Choose a line of section on the map. Try to orient it perpendicular to the average unit strike. Locate it so that it shows the details and characteristic features of your mapping area!
- Plot the topography. The west or north end are typically on the left by convention. Use a strip of paper to record the positions of topographic contours along the line of section. Transfer these to a piece of graph paper. Leave enough space to allow the section to be projected to around 1000 m below the surface.
- Locate geologic contacts on the topographic profile. Again, use a strip of paper to record the position of contacts and locations of strikes and dips. Note any contacts that approach, but do not cross the line of

section. Make sure to label the units and faults with names or symbols.

- Project measurements onto the line of section along their strike and plot their dips on the topographic profile. Calculate apparent dips if the strike direction is >20° different to the strike of the line of section by using your Stereonet (see below). Use measurements close to your line of section wherever possible and when strikes and dip vary locally, choose an 'average' value to represent these. Measurements should also be drawn at the same elevation at which they were measured, which can be below or above the topography of the section line.
- To constrain major structures, focus on one or two contacts to begin with. Project them to depth and above the topographic profile. THINK: Are they folded/faulted? What method is appropriate for constructing the shapes of the structures? Plunging folds should be projected along the strike of the fold hinge and will intersect the plane of section at an elevation that depends on their dip (use trigonometry to determine this from the distance between measurement and line and the fold hinge dip).
- Examine, consider and revise your interpretation (if necessary). Is the section restorable? Is the section admissible (does it make geological sense)?
- Fill in the rest of the units on the section. Remember a restorable section typically has constant unit thickness – is this a fair assumption based on your field observations?
- Ink in your final copy using the appropriate colors for different lines and dashing lines where uncertain. Color units lightly, add labels, title, explanation etc. Dash contacts where uncertain. Your section is to be a piece of geological artwork, so spend the time to show as much information as possible. Draw the trend of the foliation within units, schematically highlighting variations in foliation intensity and (isoclinal) folding, use dots to indicate areas of, for example, partial melting within a unit, etc etc.

Projecting data into the cross sections using your Stereonet

- Calculate the apparent dip of the projected data by plotting the plane of the section (straight line for a vertical plane) and a great circle representing the strike-dip measurment onto a Stereonet. The intersection marks the apparent dip – read off the angle (rake or pitch) by rotating the stereonet so the plane of section is N-S and count in from the edge (see Fig. 13).
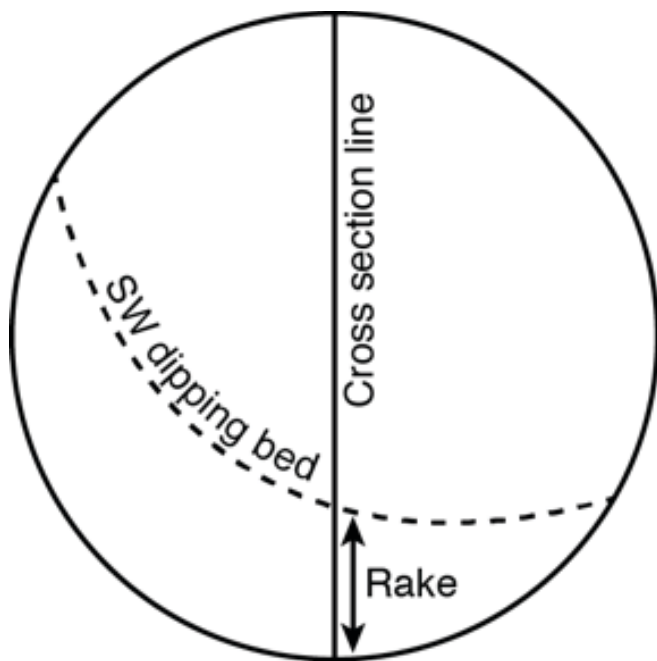

Figure 13. Stereonet showing how to find the apparent dip (rake) of a unit in the plane of section. Make sure to count in the rake when the line of section is aligned N-S on the stereonet.

II. Geochemical mapping: an overview

Geochemical mapping is a scientific endeavour in which the spatial distribution and variability of elements at the earth surface is delineated, with a scale or resolution appropriate to the problem at hand. The application of geochemical mapping has proven very useful in geological and environmental problems.

In the 1960s the main purpose was to supplement geological information and provide geochemical data of crustal evolution and ore forming processes. The data collected were helpful to more clearly define variations in lithology, composition and structure of the bedrock and were of importance in identifying new metalliferous mineralizations, especially in areas lacking surface exposure.

With regard to environmental problems, relations were observed between trace element levels and the diseases in crops, animals and man. For instance, large densely populated areas suffer from high concentrations of fluorine in drinking water, causing severe incidences of fluorosis. Elsewhere disorders are associated with a deficiency of essential trace elements like iodine. In the 1980s and 1990s geochemical mapping activities therefore more and more focused on environmental applications instead of prospecting. As the natural variability of geochemical background levels became better known, it was recognized that in order to identify and quantify anthropogenic pollution it is necessary to have a map of the natural background. For example, Cu concentrations will be naturally elevated in an area underlain by black shales, compared to carbonate basement, and a higher intervention limit should thus be set.

The role played by trace elements in biological processes also emerged when analytical techniques had developed to such an extent that it was possible to measure their concentrations accurately and precisely in organic matter. It was thus established that elements includign Co, Mo, Cr, Se, F, Sn, and V are essential to many living organisms. However, at higher concentration the same elements commonly become toxic, e.g. Se. Thus for many elements there is an optimum range of concentration. Outside this range potentially harmful effects may be observed caused by either a deficiency or excess of the elements in question.

Chemical species are present in different phases and forms in soil, dust, and waters. Some of which are not directly available to living organisms, due to a relatively strong bonding with a solid phase. Geochemistry cannot only identify the total amount of each species but also the amount that is bioavailable. Important controls on the element speciation and mobility are the hydrogen ion activity ($\sim$pH), redox potential (abundance of oxidating compounds), abundance of complexing agents, organic matter and biological activity. Recent developments show great progress in understanding the behaviour and effects of chemical species in the environment.

Many approaches have been used in the geochemical mapping practice. Sometimes the procedures are optimised for particular species in a particular region, often limitations are set by the available funding. As mentioned before the environmental aspects have recently become more and more important. In these cases the emphasis is often on those species that are considered to be especially relevant for the quality of the different environmental compartments.

Hence, extensive geochemical surveys have been conducted, resulting in large databases. However the applied methodologies vary to a great extent, which make it cumbersome to compare different geochemical atlases and databases. These variations entail the sampled medium (stream sediments, soils, waters etc), the selected size fraction for analysis, the analytical methods used, the techniques of interpolation etc. Despite these difficulties it is evident that variations in geochemical background values are considerable, and that valuable information is obtained that is of great use in many fields of investigation.

III. Average compositions of Earth materials

There are broad trends in the compositions of different Earth materials from basalts to granites to lime-stones to coal. These general trends are very useful when trying to interpret geochemical maps, and they also allow for defining testable hypotheses of interpretation (e.g. if you think a high Si area is caused by the presence of granite in the basement, it should also be high in Li and Be). These general compositional trends can be defined *a priori* from the known geochemical behaviour of the elements, for example the par-tition coefficients of elements between fractionating minerals and residual melt, which indicates that ba-salts prefer Mg, Ni, Co, and V, whereas a rhyolite formed from this basalt by fractional crystallisation should be enriched in elements including Si, K, Li, B, W, etc. However, a more common approach in geochemistry is to define the characteristic compositions of these materials by analysing very many samples of this mate-rial, and values for a number of Earth materials are shown in Tables 1 and 2 below.

Average concentrations based on hundreds or even thousands of analyses may appear as the ultimate truth, but the opposite is actually the case and these averages are hotly debated, with debate focusing on what samples are to be included, and what mixing ratios should be applied for composite reservoirs such as the crust. Sampling will always concentrate on those locations that are easily reached and geochemically interesting to analyse, and may therefore not be representative at all. Taking an average of the data present in the literature might therefore bias the result as samples that are out of the ordinary are often reported instead of the normal ones. Besides this bias, the classification of rocks into mafic and ultramafic, for exam-ple, is arbitrary. An ultramafic rock with 47 wt% silica will be chemically much more similar to a mafic rock with 49 wt% silica than to the average for all ultramafic rocks. The data given should therefore only be used to get an idea of the order of magnitude of elements in different rocks. Most of these chemical signatures are obvious, such as the high concentrations of Ca in limestone or Si in sandstones and by looking at these signatures elements with similar (geo)chemical behaviour can be easily recognized, such as Mg and Co.

Table 1. Average concentrations in mg/kg of the relevant elements in various rock types (from Reimann and Caritat, 1998).

ppm	Ultramafic	Basalt	Granite	Sandstone	Graywacke	Shale/Schist	Limestone	Coal
Si	201000	227000	337000	403000	323000	288000	31000	34000
Al	20000	83000	73000	37000	71456	91000	4000	21000
Ti	3000	10000	3000	1500	4316	6000	400	1000
Mg	208000	46000	5000	7000	13900	16000	4000	2600
Fe	94000	86000	20000	10000	41300	55000	5000	10000
Ca	25000	74000	9000	13000	18600	22000	380000	5000
Na	6000	20000	25000	17000	22300	13000	6000	900
K	5000	8000	33000	11000	16600	27000	3000	3500
Ba	5	330	600	300	426	550	90	250
Co	110	45	4	0.3	15	20	0.1	10
Cr	2300	250	10	35	88	100	5	20
Cu	40	90	12	2	24	45	6	20
Pb	0.05	4	20	10	14.2	22	5	20
Sb	0.1	0.2	0.3	0.05	-	1	0.15	2
Sn	0.3	0.9	3.6	0.6	-	5	0.3	8

Table 2. Median values (mg/kg for soil and stream sediment, mg/l for stream and rain water) of relevant elements in various Earth compartments (after Reimann and Caritat, 1998).

ppm	Soil	Stream seds	Stream water	Pristine rain	Polluted rain
Si	280000	298000	6	< 0.1	< 0.1
Al	80000	88000	0.3	0.003	0.11
Ti	4000	5100	0.003	-	-
Mg	9000	11200	4.1	0.02	0.04
Fe	35000	37200	0.04	< 0.01	0.04
Ca	14000	12900	18	0.05	0.1
Na	10000	14800	6.1	< 0.1	0.3
K	14000	23100	2.3	0.05	0.09
Ba	500	490	0.02	0.0005	0.0011
Co	10	15	0.0002	0.00002	0.012
Cr	80	64	0.0007	< 0.0002	0.0005
Cu	25	19	0.003	0.0005	0.23
Pb	17	26	0.003	0.0006	0.006
Sb	0.5	2	< 0.0001	< 0.00003	0.0003
Sn	4	3.3	< 0.00001	-	-

Considering the issues encountered in averages for rocks, it should not be surprising that averages for soil and stream sediments are even harder to determine. These will of course be strongly dependant on the bedrock on which the soil forms and the lithologies encountered by the stream. The uncertainties on these values are therefore huge. They are however very useful if you want to determine the amount of material stored in the soil or water sediments globally when studying geochemical cycles. The composition of rainwater also strongly depends on the location where it is sampled and is governed by factors like proximity to the coast, dust, pollution and climate.

The values given in the above tables should thus be used with care, but can give you an idea of the chemical signatures that are to be expected in various rock types. Comparing the analyses of your soil, sediment and water samples to those in the tables could furthermore point you to obvious enrichment or depletion of specific elements, which may be related to geology.

A number of samples from the field area have been analysed and their bulk compositions are given in Table 3. Although these are samples from the actual bedrock and should therefore give the best indication of their composition, these analyses are for only one sample, which may or may not be representative for the unit it is from. Nonetheless, these data are very useful for identiying the characteristic differences among the major units in the field area and to interpret your geochemical survey maps.

Table 3. Bulk rock compositions for samples from the major lithological units of the field area as determined by XRF and ICP-MS. For most unit, only one sample was analysed

Unit	Margeride Granite	Basalt/ Basanite	Celoux/ Pinols	Bt-Sil Lower Gneiss	LAC leptynite	LAC amphi- bolite	LAC ultra- mafics	Upper Gneiss Unit	Lower Schist Unit
Major element (values in mass percent)									
SiO_2	68.01	43.75	71.00	49.30	65.50	47.78	38.80	66.84	53.10
Al_2O_3	14.74	12.75	13.80	27.00	14.95	15.75	3.70	15.75	24.52
Fe_2O_3	3.15	13.03	2.91	9.93	6.88	11.93	8.01	6.11	8.58
MnO	0.06	0.20	0.04	0.12	0.10	0.17	0.10	0.06	0.13
MgO	1.60	10.63	0.92	2.43	1.65	7.71	37.90	2.21	2.28
CaO	1.11	10.06	1.23	0.38	2.20	8.41	0.90	0.96	0.26
Na_2O	2.65	3.90	3.71	0.59	3.25	2.28	0.10	1.80	1.46
K_2O	4.99	1.46	2.87	3.35	3.80	1.22	0.00	3.15	4.70
TiO_2	0.46	2.28	0.40	1.09	0.90	2.20	0.20	0.77	1.08
P_2O_5	0.23	0.80	0.21	0.05	0.10	0.35	0.00	0.12	0.10
Minor and trace elements (values in mg/kg)									
Ba	813	513	522	612	n.a.	338	n.a.	807	846
Co	26	40	n.a.	n.a.	n.a.	54	n.a.	14	n.a.
Cr	n.a.	354	101	n.a.	n.a.	171	n.a.	93	105
Cs	28	0.5	n.a.	n.a.	n.a.	6	n.a.	7	n.a.
Cu	5	37	10	n.a.	n.a.	n.a.	n.a.	n.a.	53
Ga	21	13	22	n.a.	n.a.	n.a.	n.a.	26	33
Nb	14	63	17	21	n.a.	22	n.a.	15	23
Ni	14	289	9	n.a.	n.a.	280	n.a.	35	20
Pb	40	4	33	n.a.	n.a.	n.a.	n.a.	n.a.	98
Rb	262	41	126	167	n.a.	46	n.a.	140	200
Sb	n.a.	0.1	9	n.a.	n.a.	n.a.	n.a.	n.a.	25
Sc	9	22	6	n.a.	n.a.	18	n.a.	n.a.	27
Sr	213	699	186	82	n.a.	213	n.a.	176	112
Th	19	5.7	13	n.a.	n.a.	n.a.	n.a.	22	18
U	12	1.7	n.a.	n.a.	n.a.	n.a.	n.a.	4	5
V	48	n.a.	32	n.a.	n.a.	145	n.a.	122	140
Y	21	22	25	40	n.a.	25	n.a.	35	34
Zn	61	101	52	n.a.	n.a.	78	n.a.	n.a.	139
Zr	154	196	212	227	n.a.	144	n.a.	334	234

n.a. means not analysed

IV. Weathering

Weathering is the main process by which the geochemical signature of bedrock is transferred to soils, sediments and stream waters, including any local geological features such as mineralisations or intrusions. Different rocks show different susceptibility to weathering, which is both a function of the resistance of their constituent minerals to weathering and the type of weathering reactions that takes place.

Mineral	Lifetime (years)
Quartz	34,000,000
Muscovite	2,700,000
Forsterite	600,000
K-feldspar	520,000
Albite	80,000
Enstatite	8,800
Diopside	6,800
Nepheline	211
Anothite	112
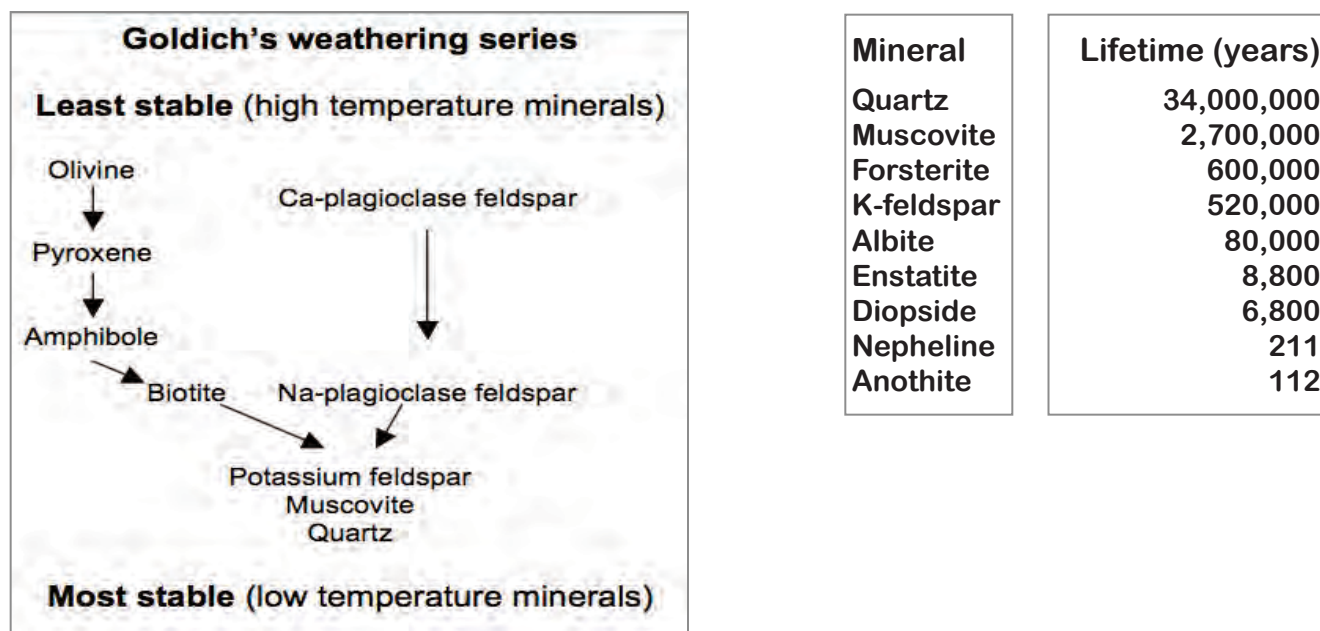
Figure 14. High P-T minerals are more susceptible to weathering because they are further away from their stability field at surface conditions as shown by the Goldich weathering series (left) and the lifetime of 1 mm sized grains of various minerals in a pH = 5 weathering environment (right).

Mineral stability

The Goldich's weathering series qualitatively describes silicate mineral stability in the weathering environment (see Fig. 14). In general, minerals which form at high temperature and pressure are least stable, and weather most quickly because they are farther from their "zone of stability", or the conditions under which they formed. Minerals that form at lower temperatures and pressures are most stable. Another way to represent this is to look at the lifetime of various minerals in a weathering environment, which is shown below on the right. The same mineral sequence emerges, with the exception of forsterite.

Examples of weathering reactions

Dissolution is the simplest type of mineral-water reaction and does not require the presence of dissolved components in the fluid to enable the reaction. For example for halite:

$$NaCl_{(s)} \leftrightarrow Na^+_{(aq)} + Cl^-_{(aq)}$$

Upon contact with oxygen from the atmosphere minerals can be oxidized, especially when moisture is available to facilitate the reaction. A variety of minerals can be oxidized, from biotite (its Fe^{2+}) to oxides (mainly Fe^{2+}, but also Mn^{2+} and a variety of other elements with variable valence) to sulfides, where both the S^{2-} and any Fe^{2+} that is present can be oxidized.

A typical oxidation reaction for pyrite is:

$$FeS_2 + 15\ O_2 + 14\ H_2O \rightarrow 4\ Fe(OH)_3 + 8\ SO_4^{2-}{}_{(aq)} + 16\ H^+{}_{(aq)}$$
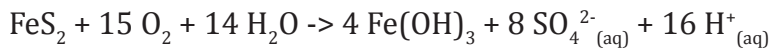
Note that this weathering reaction generates acid, which can facilitate other weathering reactions as shown below. The presence of small amounts of pyrite can therefore lead to greatly sped up weathering for a variety of minerals, and sulfide-bearing parts of an outcrop are generally the most heavily weathered.

Hydrolysis is similar to dissolution, but it differs in that the water chemically reacts with the dissolved ions produced, for example for calcite/limestone governed by carbondioxide:

$$H_2O + CO_{2\ (g)} \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$
$$CaCO_3 + H^+ \leftrightarrow Ca^{2+} + HCO_3^-$$
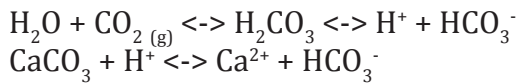
The weathering of a rock consisting of a number of different minerals will be by a combination of these reactions and may involve intermediate, or secondary, minerals. If we look at a typical granite, for example, consisting of the primary minerals K-feldspar, Na-rich plagioclase, quartz, biotite, muscovite and acessory phases such as tourmaline, we will observe the following:

- The feldspars will first undergo hydrolysis to form kaolinite (a clay mineral) and Na and K ions:

$$2\ KAlSi_3O_8 + 9\ H_2O + 2\ H^+{}_{(aq)} \rightarrow Al_2Si_2O_5(OH)_4 + 2\ K^+{}_{(aq)} + 4\ H_4SiO_{4\ (aq)}$$
$$2\ NaAlSi_3O_8 + 9\ H_2O + 2\ H^+{}_{(aq)} \rightarrow Al_2Si_2O_5(OH)_4 + 2\ Na^+{}_{(aq)} + 4\ H_4SiO_{4\ (aq)}$$
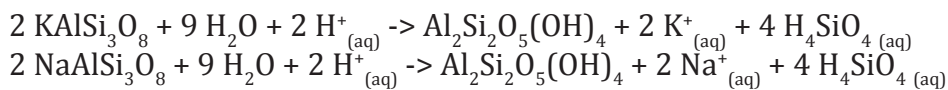
Depending on the environmental conditions (e.g. pH and fluid composition) the weathering reaction may form other minerals such as gibbsite and montmorillonite instead of kaolinite.

- The biotite will undergo hydrolysis to form clay minerals (kaolinite) and oxidation to form iron oxides:

$$K[Mg,Fe]_3[AlSi_3]O_{10}OH_2 + 10\ H^+{}_{(aq)} + 0.5\ O_2 + 6\ H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2\ K^+{}_{(aq)} + 4\ Mg^{2+}{}_{(aq)} + 2\ Fe(OH)_3 + 4\ H_4SiO_{4\ (aq)}$$
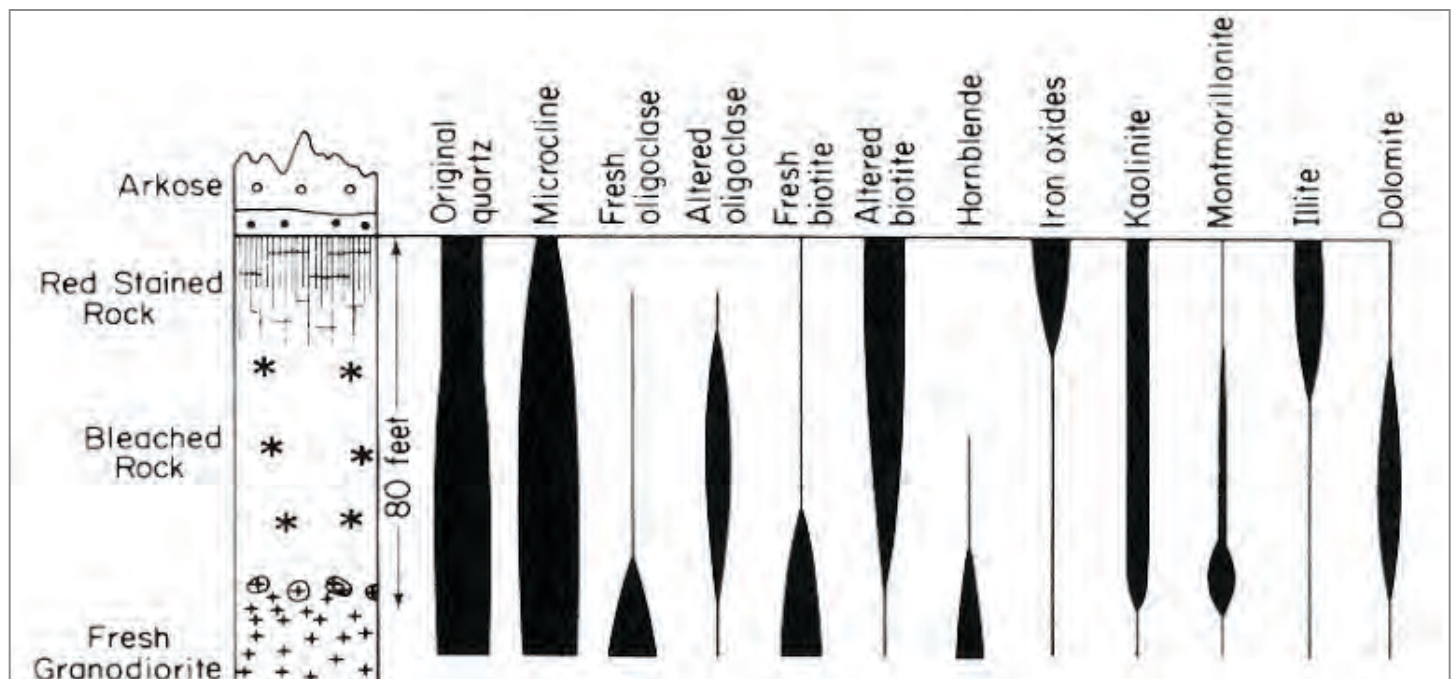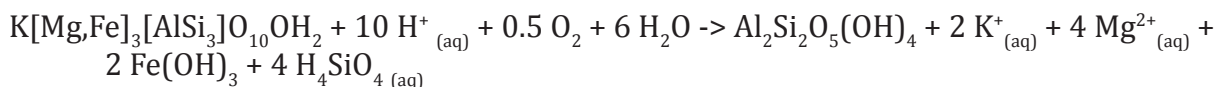
Figure 15. Weathering profile through a soil developed on a granodioritic basement showing the progressive disappearance of its primary minerals and their replacement by secondary phases.

• The quartz, muscovite and accessory phases such as zircon and tourmaline will remain as residual minerals because they are very resistant to weathering.

A weathered granite will thus mainly consist of clay minerals, muscovite and quartz, with smaller amounts of secondary Fe-oxides and resistant accessory phases including tourmaline, see also Fig. 15.

V. Transport of major and trace elements

Transport of major and trace elements as studied during the field course is governed mainly by the movement of water (groundwater and streams). Therefore, some general knowledge about the hydrology and hydrological pathways is useful (see Fig. 16).
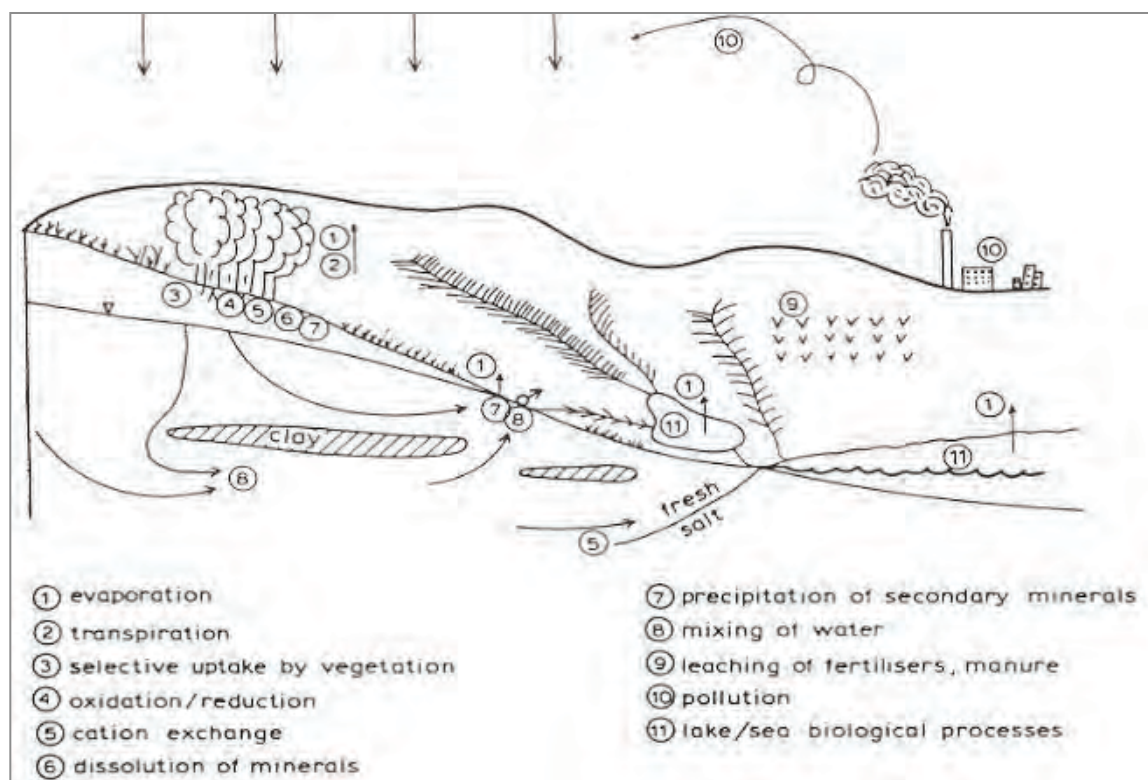
Figure 16. Overview of the processes in the hydrological cycle.

Transport of the elements released from bedrock by weathering takes place in two ways; as **dissolved** elements and as **suspended** material. Unsurprisingly, the "soluble" elements are mainly transported as dissolved ions, and this includes Ca, Mg, Na, K, and Li. Minor elements including Zn, Ni, Pb, but also Al and Fe are dominantly transported as part of the suspended material load of the water. The suspended material includes clay minerals, organic matter and iron/aluminium-oxyhydroxides, and elements transported with this suspended material can either be part of these minerals, or be adsorbed onto them (for example the REE onto FeOOH and AlOOH).

Some common soil forming minerals including clay-minerals (kaolinite, illite, montmorillonite) and iron and aluminium-(oxy)hydroxides have so-called functional groups on the surface of the individual mineral grains. Organic material, such as humic acids, also have surface functional groups. These functional groups can be seen as reactive sites all over the surface and arise most often due to charge imbalances of the crystal structure. These reactive sites are commonly negatively charged and as a result they attract positive ions such as Ca^{2+} or Zn^{2+} and most importantly H^+.

It should be stressed that the adsorption of (positive) ions is not permanent (i.e. the ions are not part of the inner crystal structure). Adsorption depends on the characteristics of the surface sites (and therefore of the mineral or organic phase involved) but also on the presence of other ions in the (soil) solution. Especially the concentration of H^+ (pH) is of major importance to the amount of adsorbed ions. We explicitly make use of adsorption processes during acid-extraction of soil and sediment samples in laboratory analysis, where a large amount of H^+-ions is added in order to "remove" others ions and bring them into solution (especially trace elements). This is called acid-extraction.

During the process of weathering, minerals with little or no surface functional groups (e.g. feldspars) are transformed into clay minerals and iron and aluminium (oxy)hydroxides plus a large amount of dissolved major ions like Na^+, K^+. Thereby, small amounts of trace elements are released like Zn^{2+} and Pb^{2+}. The extent to which these ions are absorbed increases in general from monovalent ions (K^+, Na^+, Li^+) to major divalent ions (Ca^{2+}, Mg^{2+}) to trace elements / transition metals (Zn^{2+}, Pb^{2+}, Cu^{2+}).

The concentrations of elements in steam waters and stream sediments depends on a number of factors, including the transporting capacity of the water (dependent on pH and Eh, *cf.* Fig 17a), the weathering rate of the bedrock (*i.e.* how quickly you can supply elements), and the amount of water being discharged (the higher this is, the more the weahering signal is diluted). This latter factor is very important and is an additional reason to focus on smal discharge streams (lower order streams) in your regional survey. Fig 17b shows the combined effect of water discharge and bedrock susceptibility to weathering on concentrations.
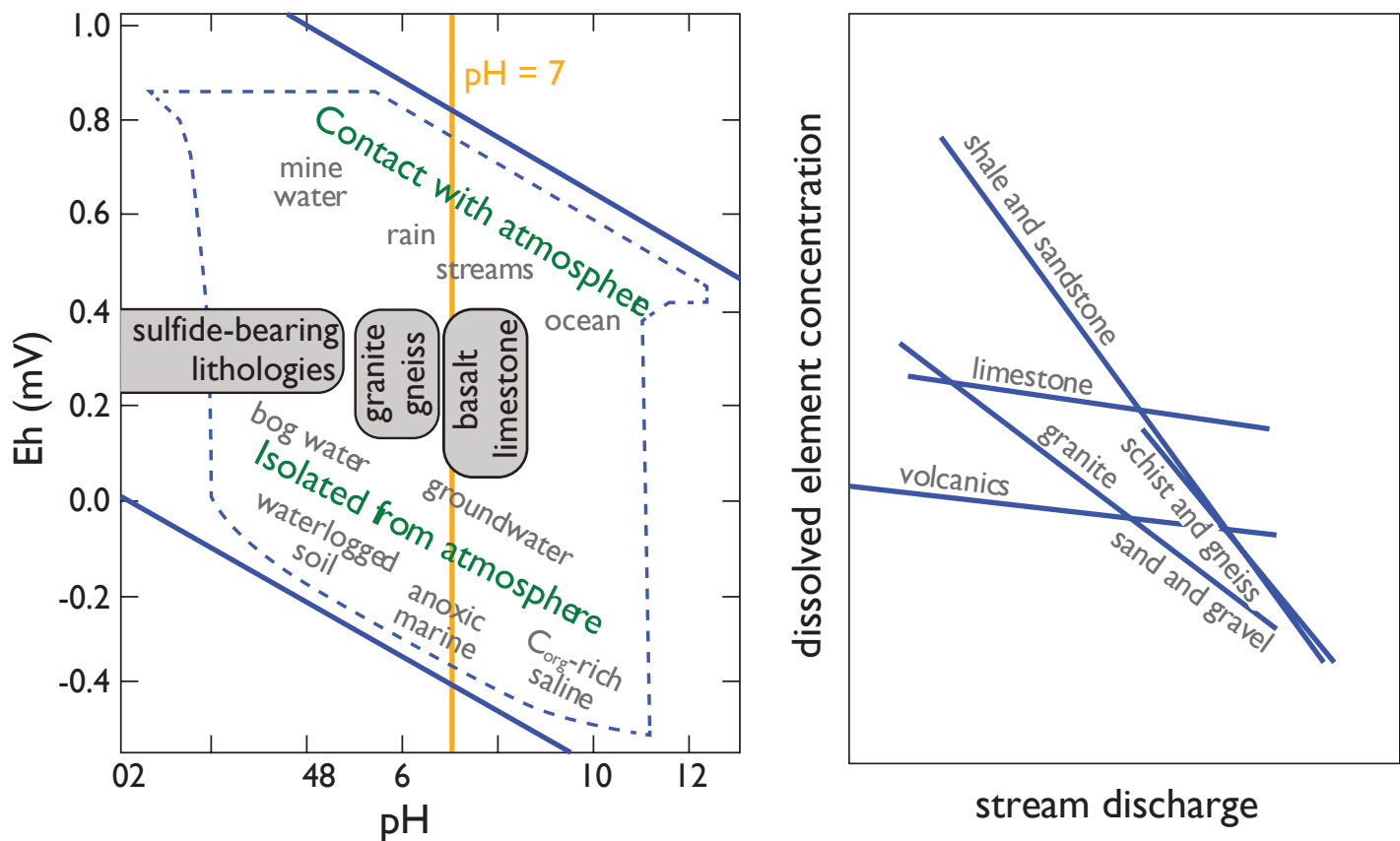
Figure 17 a) pH and REDOX conditions of natural waters. The upper and lower bounds are defined by the stability field of H_2O. The grey boxes indicate the pH of waters interacting with certain lithologies. b) Effect of dilution by increasing stream discharge on the total signal derived from various rock types. Easily weathered rocks maintain high concentrations as discharge increases whereas the signal of gneisses rapidly decreases.

Point sources (*e.g.* pollution or an ore vein) will disrupt the background bedrock weathering imprint on their local soils, and this can be transported by groundwater and soil movement to streams where it can be picked up in water and sediment analyses (Fig. 18). Such disturbances are called anomalies, because they cannot be explained by normal weathering. By tracing the anomaly upstream, it can be approximately located, but to find its exact location generally requires a grid soil survey (Fig. 19).
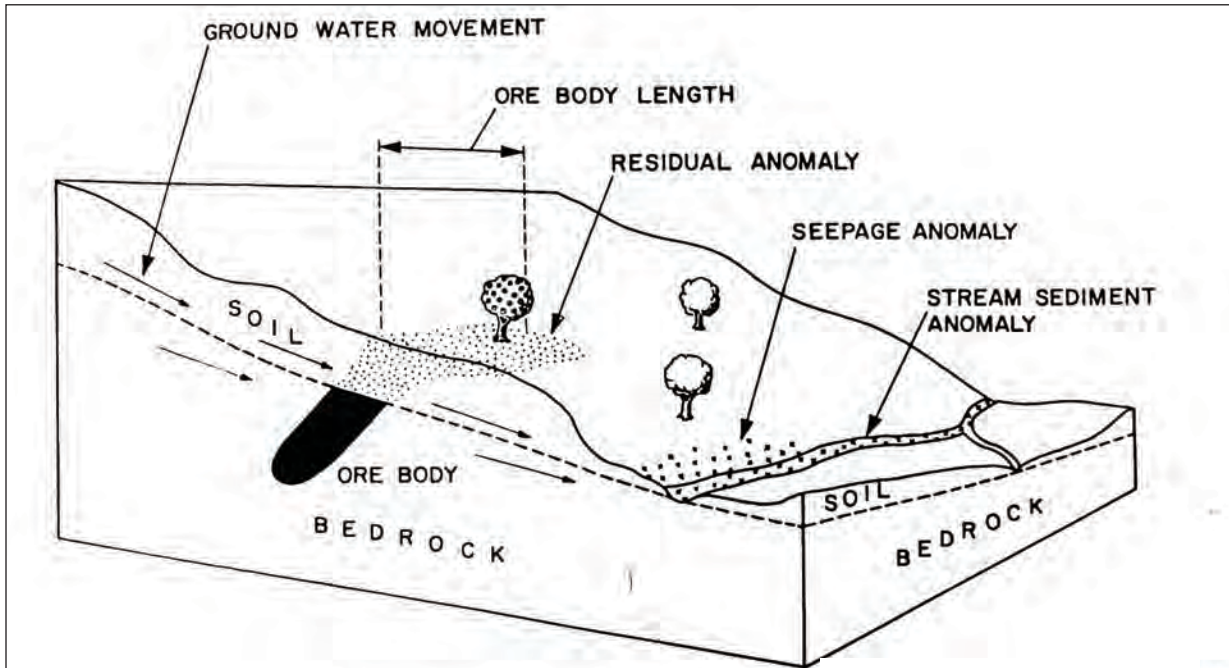
Figure 18. Diffusion of a local anomaly into the environment by groundwater flow and soil movement. The dissolved ions eventually end up in the stream water and the particles, and any elements adsorbed onto them, in the sediment.
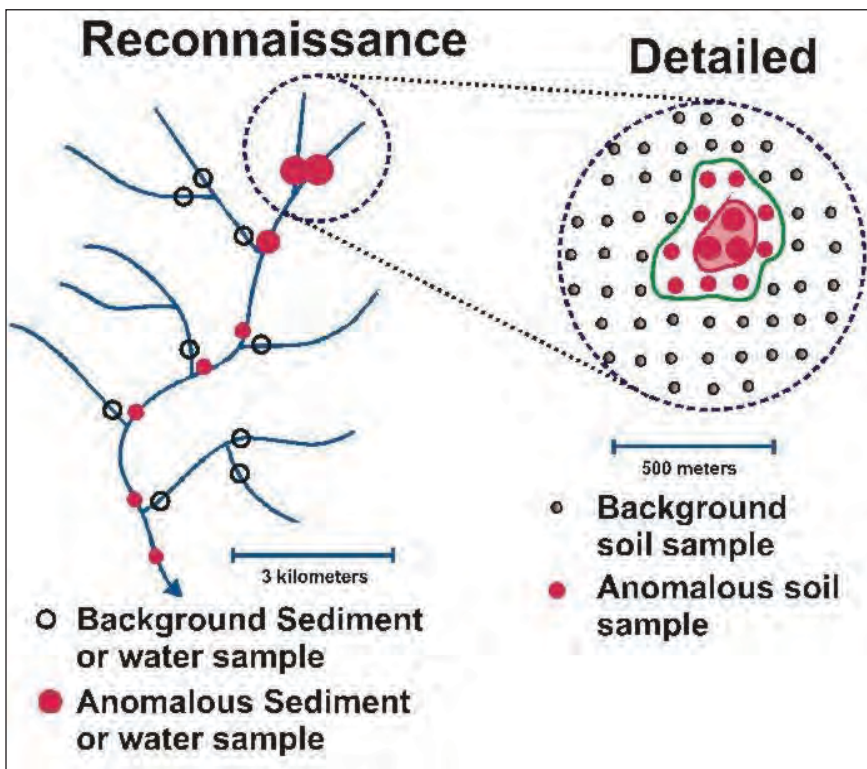
Figure 19. Tracing a stream anomaly upstream leads to the source catchment area to be identified. Further localisation of the anomaly is achieved in a detailed soil survey conducted along a grid.

VI. Field measurements, forms and sample codes

During sampling for your regional geochemical survey, a number of field parameters need to be recorded. We will supply you with a tablet to do so using the QField GIS application (as well as paper forms for back-up). The QField application shows a topographic basemap of the area on which your location is plotted as recorded by the internal GPS. When you add a sample location by clicking on the GPS location, a form opens and you can enter the field parameters. Tablets do fail and all sample locations should also be plotted onto a topographic field map with their corresponding sample number. In addition to the field form, notes can also be entered in your notebook (one per group is sufficient), including special observations and comments. All tablet data need to be transferred to the Fieldschool database in the evening.

Regional sampling field form							

Group:
Date:
Weather:

Group members:

Station							
Sample							
Type							

Nearest village							
Elevation (m)							

Geology code							
River order							
Stream width (dm)							
depth (dm)							
Stream flow rate (dm/s)							
pH							
T (°C)							
EC (µS/cm)							

Type of sediment							
Land use							
Disturbance							
Duplicate							
Heavy minerals							
Photo no.							

Comments							

Explanation of field form parameters

Station and sample numbers: Use station numbering as used in your geological mapping (see the geological mapping section for details) but use a different prefix, for example by combining the first letters of each group member's first name. Use sequential sample numbers in the format assigned to your group:

Group 1	A001 to A999
Group 2	B001 to B999
Group 3	C001 to C999
Group 4	D001 to D999
Group 5	E001 to E999

If you are taking a field duplicate at the site, label this by adding an "F" to the end of the sample number for the duplicate sample (e.g. D004F). Similarly, analytical duplicates will be marked with an "A" at the end of the sanple code in the lab.

Type: Indicate the type of samples taken at the location - water, sediment, water+sediment, soil,

Nearest village: Nearest village indicated on the topographical map

Elevation: Estimate elevation (in meters) of sample location from the topographical map or read it off from your GPS (note however that GPS measurements of elevation are not very accurate)

Geology-code: indicate the geology-code of the sample location in terms of: (1) schist, (2) gneiss, (3) ultramafic (4) volcanics, (5) granite, (6) others (indicate).

River order: List the order of the river (1st, 2nd, 3rd or $>3^{rd}$). Note that river of higher than 3rd order should generally be avoided in sampling.

Stream dimension and discharge: Estimate the discharge of the stream by measuring its width and depth and the water flow rate.

pH: Measure the pH of the water using the handheld pH meter.

EC: Measure the electrical conductivity of the water (μS/cm). Do not use decimal numbers.

T: Measure the temperature of the water using your handheld meter (˚C).

Type of sediment: Describe the sediment, use: fine, coarse, gravel, soil, organic-rich, other (describe).

Land user: Land use at the sample site and its immediate surroundings - pasture, forest, agriculture, built-up, wasteland, other (describe).

Disturbance (yes/no): List whether there is any disturbance of the natural setting at the sample site or immediate surroundings. Provide details in the comments section and/or your notebook.

Duplicate (yes/no): Indicate whether the locations are sampled in duplicate.

Heavy minerals (yes/no): Indicate whether a heavy mineral concentrate has been collected at the site

Photo number: Give the image number of any photographs you have taken of the sample site (optional, but can be useful, especially for disturbed sites or where you expect an anomalous concentration).

Comments: list observations that you think might impact the interpretation of the sample, such as the presence of mineralisation, garbage in the stream, proximity of a road, etc.

Grid sampling field form

Group: Group members:
Date:
Weather:

Sample no.							
Line no.							
Line position							

Self-potential	1	3	1	3	1	3	1	3
in mV	2	4	2	4	2	4	2	4

Comments				

Line details

Line no.		Start GPS		
		End GPS		
Elevation (m)				
Orientation		Land use		

Line details

Line no.		Start G
		End GI
Elevation (m)		
Orientation		Land u

Explanation of field form parameters

Sample numbers: Use sequential sample numbers in the format assigned to your group:

Group 1	GP001 to GP999	Group 4	GT001 to GT999
Group 2	GR001 to GR999	Group 5	GU001 to GU999
Group 3	GS001 to GS999		

If you are taking a field duplicate at the site, label this by adding an "F" to the end of the sample number for the duplicate sample (e.g. GT004F). Similarly, analytical duplicates will be marked with an "A" at the end of the sanple code in the lab.

Line number: The number of the line as counted from the origin.

Line position: The sequential point along the line from its start.

Self potential (mV): Measure the soil self potential at the sample site using the multi-meter. Self-potential measurement are taken at closer spacing than samples for geochemicla measurement.

Comments: list observations that you think might impact the interpretation of the sample, such as the presence of mineralisation, garbage in the stream, proximity of a road, etc.

Line details: List the elevation of the line (lines should be parallel to the height contours), its compass orientation, a GPS coordinate (in DD°MM'SSS" format) at the start and end of the line and its dominant land use - pasture, forest, agriculture, built-up, wasteland, other (describe).

VII. Geophysical survey techniques

Physical properties of earth materials

Before introducing the methods of applied geophysics, a brief review of the properties of earth materials that can be directly or indirectly mapped will illustrate why these methods are important for a wide range of subsurface studies. The range of values for the physical properties measured by applied geophysical methods is shown schematically in Figure 20. Electrical conductivity (or, resistivity) can be as low as 10^{-5} $[^S/_m]$ (or, 105 Ωm) for igneous rocks and as high as 10^4 for graphite. Density on the other hand has a relatively narrow range from 1 to less than 10 $^g/_{cm^3}$. These ranges are important in determining the sensitivity of a measured property to the underlying rock property. For example, a very small change in fluid saturation can lead to a big change in measured electrical resistivity, while a small change in mineral composition or porosity leads to a relatively minor change in density. The relationship between the measured physical properties and the derived rock or soil properties is a central issue for applied geophysics. Ultimately the usefulness of an interpretation of a field survey depends on the accuracy of this relationship. For purposes of a qualitative introduction to this aspect of applied geophysics Table 4 shows the degree to which the measured property is related to the property of interest. The rock properties ("target", derived) are located in the left hand column of Table 3 and the physical properties measurable with the geophysical methods are located across the top. The shaded matrix entries indicate the degree to which the measured property is dependent on the properties of interest. The scale is subjective and is only to be used qualitatively in the following discussion.
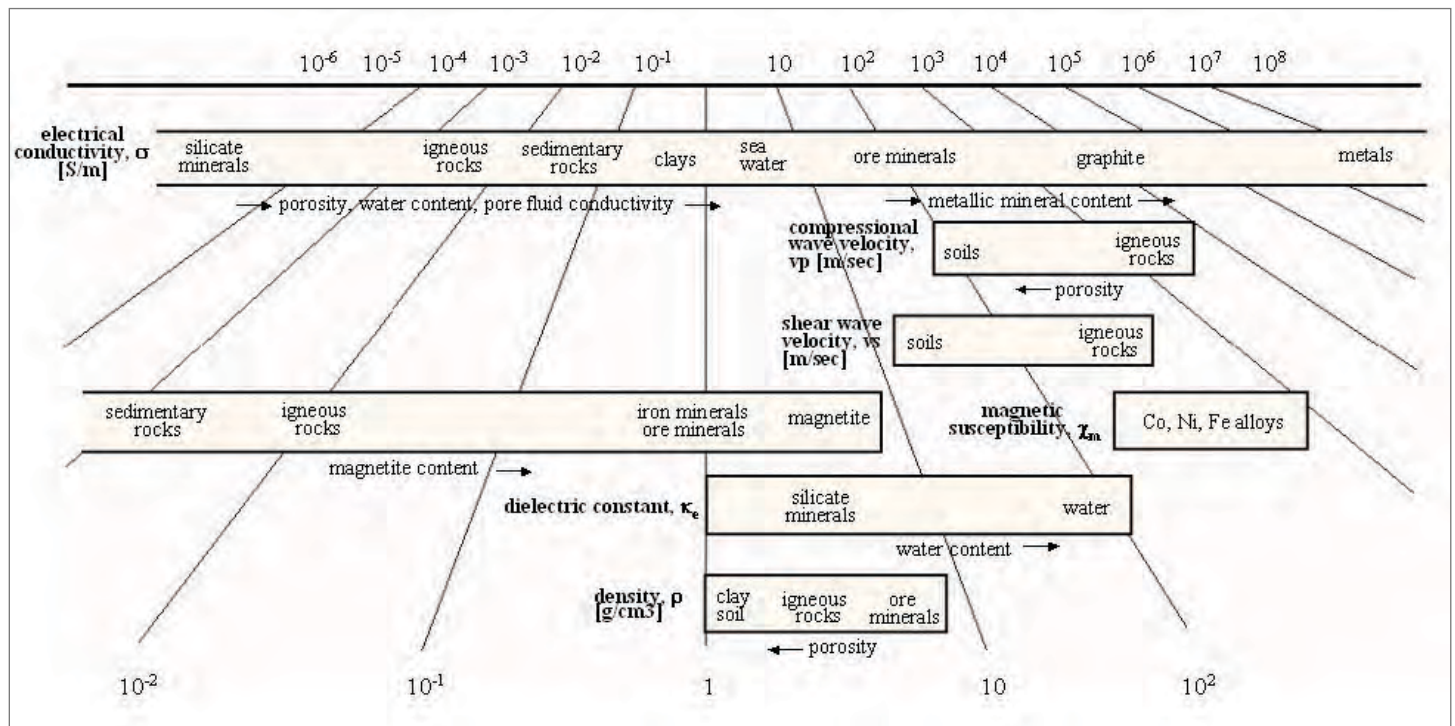
Figure 20. Typical range of Earth material physical properties.

It is important to note, by scanning down the columns, the extent to which the measured property depends on many of the derived properties. Velocity depends on water content, porosity, clay content and the elastic and mechanical properties. Electrical conductivity depends on porosity, saturation, pore fluid conductivity, and clay content. An equally important point is that the derived properties usually depend on several of

the measured properties. Water content is strongly related to dielectric constant, conductivity and velocity, while metallic objects may be detected by their magnetic susceptibility conductivity and possibly density but not much else. These horizontal associations in the matrix chart point out the importance of using multiple methods to reduce the ambiguity in determining the properties of interest. The joint measurements usually narrow the range of desired properties that are compatible with the data.

Table 4. Relationship between measured and target (derived) physical properties of solid earth materials.

PHYSICAL PROPERTY

TARGET	Density	Magnetic Susceptibility	Electrical Resistivity	Dielectric Permittivity	Seismic Velocity
Porosity (pore,fracture)	strong	none	strong	moderate	moderate
Permeability	none	none	weak	weak	weak
Water content	moderate	none	strong	strong	moderate
Oil content	moderate	none	strong	strong	moderate
Water quality	none	none	strong	none	none
Clay content	weak	none	strong	weak	moderate
Magnetic mineral content	moderate	strong	weak	none	none
Metallic mineral content	strong	none	strong	none	moderate
Metallic object	strong	strong	strong	none	moderate
Mechanical properties	moderate	none	moderate	weak	strong
Subsurface structure	moderate	moderate	moderate	strong	strong

strong	moderate	weak	none

Degree of relationship

The self-potential method

Most Earth materials, from rocks to soils to sediments, are electrical insulators and do not let current pass easily. However, the presence of moisture, in particular a free fluid phase, can drastically increase the conductivity. This is because fluids contain ionic species such as Na^+, Ca^{2+}, Cl^- and $CuSO_4^-$, $H_3SiO_4^-$, etc, which can transport charge, and the fluid therefore becomes a conducting medium. As would be expected, the conductivity increases as the concentration of these ionic species increases and salty brines are thus much more conductive than pristine melt waters.

It is not only fluids that can carry electrical current in the Earth, some minerals are also conductive. This includes native metals, such as Cu, which are found in highly reducing environments. Many sulfide minerals, and some oxides, are also conductors, or at least not as much of an insulator as most silicate minerals. Finally, graphite, common in meta-pelites and black shales, is highly conductive.

The potential of these differences in conductivity was realized in the mid 20th century as a tool to explore for metallic and sulfidic ore deposits, and has proven highly successful. In more recent times, focus has

shifted to using conductivity to search for groundwater resources, or to detect seepage and water leaks. In the last decade, the technique has seen somewhat of a revival, because it works exceptionally well to explore for graphite, which is quickly becoming an important commodity in the quest for making ultra-clean graphene, as well as in geothermal exploration.

A variety of electrical parameters is measured, including conductivity, resistivity, and self-potential. The first two require an active source with current being injected into the soil at one point and then measured in a (radial) grid around the injection site. The source can be a battery, or a truck-mounted generator. Active source techniques allow for more control and a greater variety of measurements and are therefore preferred in commercial and large-scale surveys. However, the requirement of a current source cannot be met everywhere, and we will not be electrocuting the ground in this fieldschool. Instead, we will use the potentials that are naturally present; self-potentials.

Self-potentials are generated in a number of ways, but mainly by the flow of groundwater, and therefore provide an especially powerful tool in groundwater and geothermal resource exploration. The technique has also proven highly successful in ore exploration. It is thought this is for two main reasons: 1. Oxidative weathering of a sulfidic ore will produce a current, because this is a REDOX process; and 2. The fractures and alteration zones associated with ore deposits provide preferential passageways for groundwater, and thus lead to a correlation between groundwater flow and mineralisations.

In our grid exploration survey we will use the self-potential method to compliment the geochemical sampling. The self-potential survey will be carried out along the same lines as the geochemical sampling, but at a closer spacing of measurement points. The self-potential method uses non-polarizing electrodes consisting of a Cu electrode submerged in a saturated Cu-sulfate solution, which makes contact with the ground through a porous ceramic point. One or two electrodes are used as a reference and remain at the same position throughout the survey. The other electrode is the roaming electrode and is moved from measurement point to measurement point. The electrodes are connected by insulated Cu wire and the self-potential is measured using a high impedance voltmeter in between the electrodes. The electrodes are placed in a shallow hole that is dug down to where the soil or sediment is moist. It is left for approximately 5 minutes to equilibrate before a measurement is taken.

The voltage that is measured by the self-potential technique is not necessarily generated shallowly, but the measurement penetrates to the subsurface. This is generally a good thing, because it allows for groundwater and/or mineralisations to be detected underneath a cover (see Figure 21 below). It is possible to invert the data collected to estimate the depth of the anomaly, be it an ore vein or a groundwater reservoir, although we will not do this during the fieldschool.

The self-potential technique is sensitive to disturbances in the ground electrical field, which can have a number of sources. Lightning is an extreme example, with faulty buried electrical wiring and proximity to electrified train tracks more common problems. Because these leak currents can be transient, the reference electrode would not be constant over time and spurious results may be generated. It is therefore good practice to re-measure one roaming station at the start and end of each survey line.

Another potential issue is variations in water flow, which can be brought about by rain, or surveys on non-level terrain (with groundwater flow towards the valley). Survey should not be conducted in the rain, or shortly after, and a new reference value will need to be obtained. In order to minimize the effect of topography, lines should be surveyed parallel to the height contours, and multiple electrodes at different elevations can be connected into an overall average reference electrode.
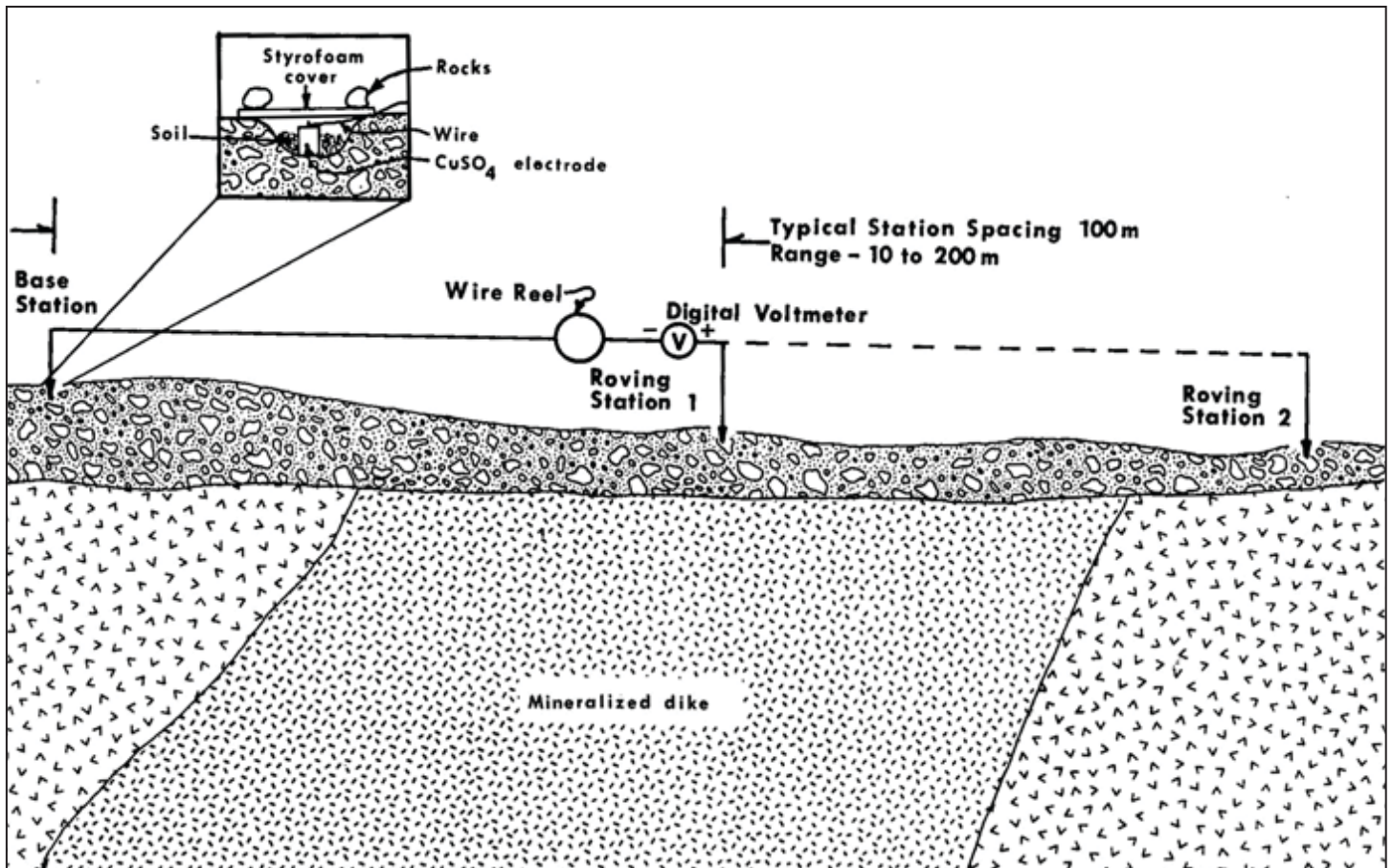
Figure 21. Typical measurement setup for a self-potential survey with a reference and roaming electrode. By convention, the roaming electrode is connected to the + pole of the voltmeter.

VIII. Useful figures
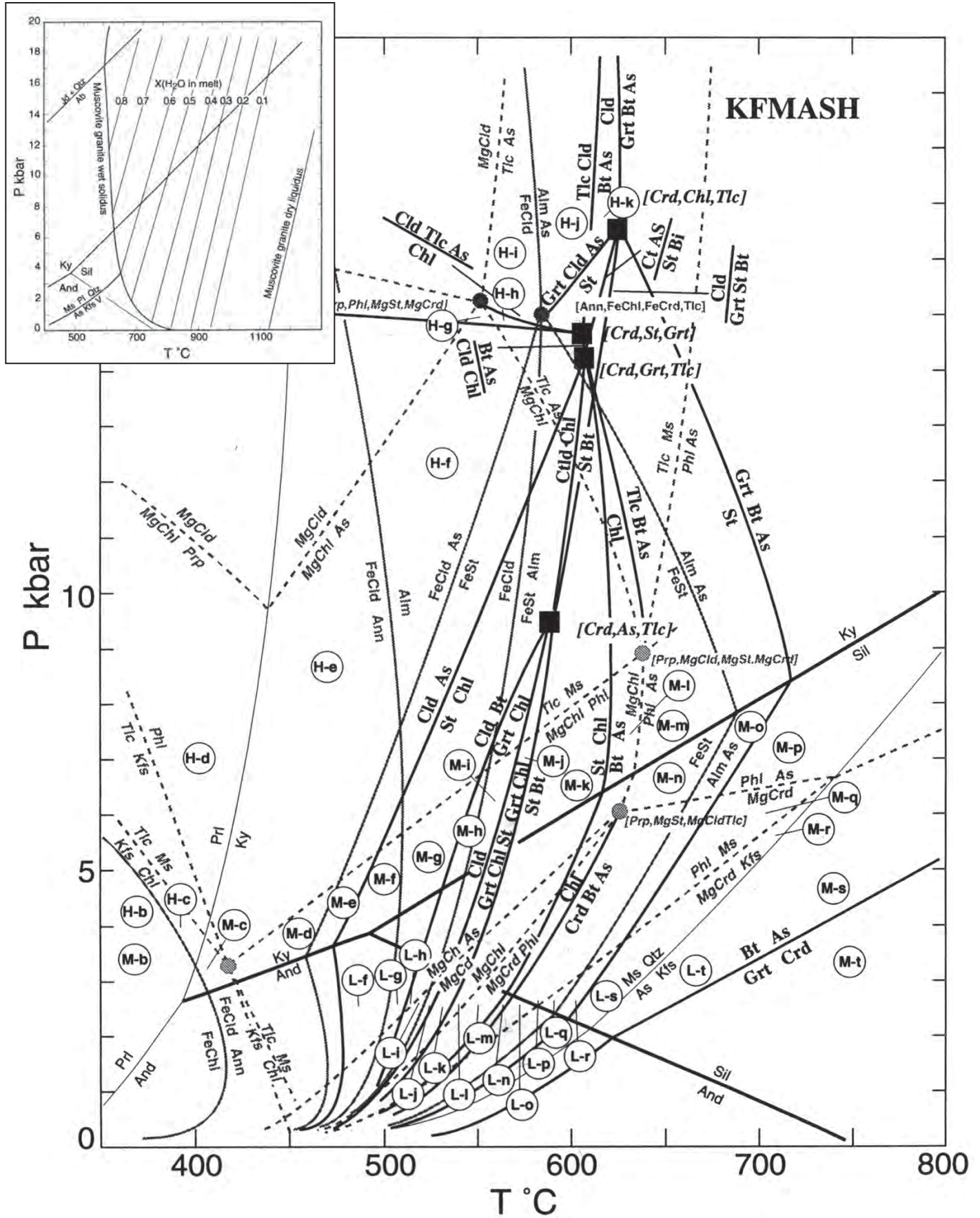
Metamorphic facies	Greenschist		Amphibolite		
Mineral zoning	Chlorite	Biotite	Garnet	Staurolite	Sillimanite
Metamafites					
Albite	▬▬▬▬ ·····				
Albite-oligoclase		····· ▬▬▬	▬		
Oligoclase-andesine			▬▬▬▬		
Andesine				▬▬▬	▬▬▬
Epidote	▬▬▬▬▬▬▬▬▬		▮		
Actinolite	▬▬▬▬▬▬ ·····				green and brown
Hornblende		blue-green	green		
Chlorite	▬▬▬▬▬ ··				
Calcite	···········				
Biotite		green-brown ▬▬▬	brown ▬▬▬▬▬▬		····
Muscovite	····················				
Quartz	····················				
Metapelites					
Chlorite	▬▬▬▬ ·····				
Muscovite	▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬				
Biotite		▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬			
Garnet			▬▬▬▬▬▬▬▬▬▬▬		
Staurolite				▬▬▬	
Alumosilicate				andalusite	sillimanite ······
Chloritoid	·····				
Plagioclase	clastic		oligoclase		
Quartz	▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬				
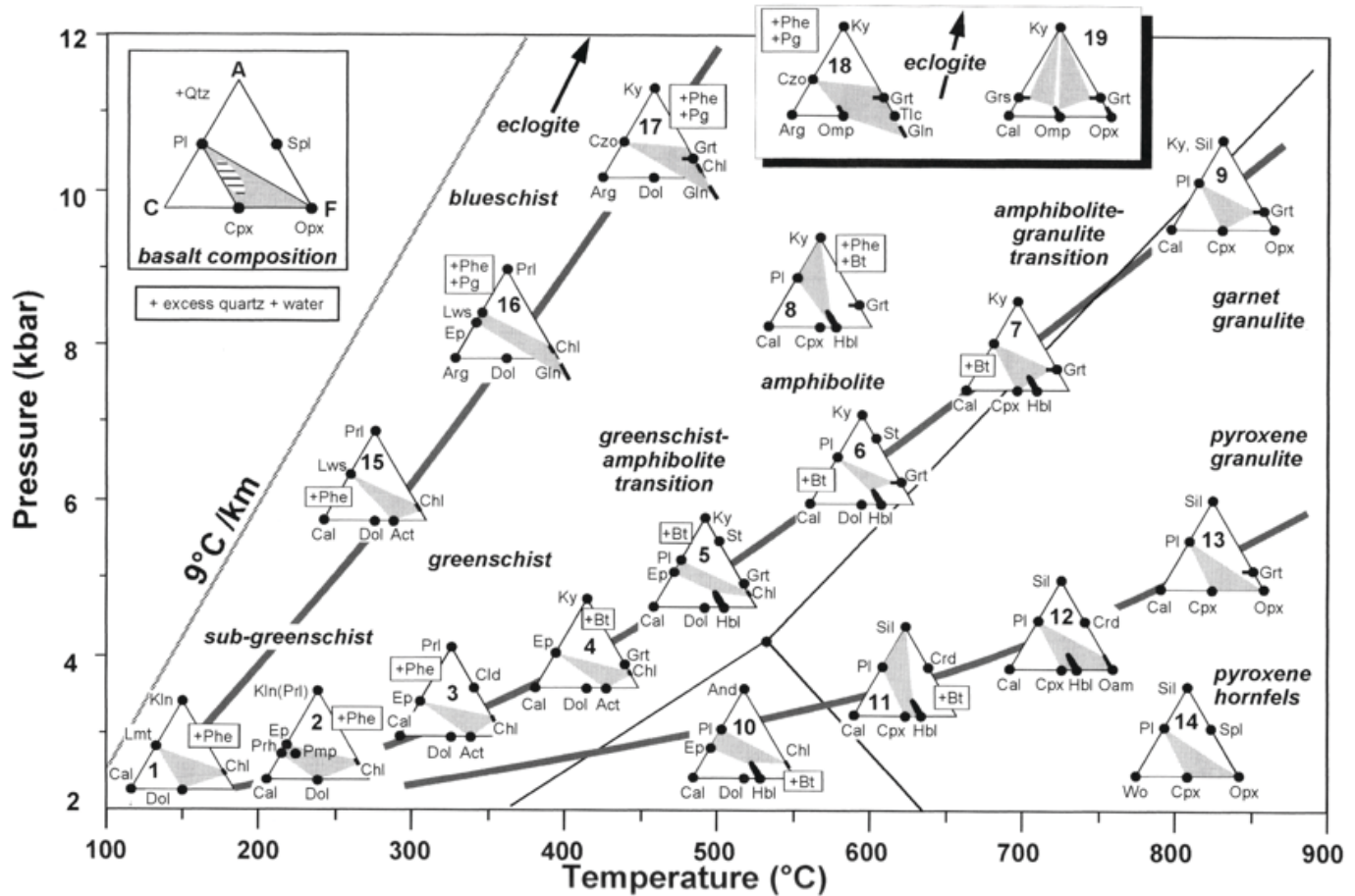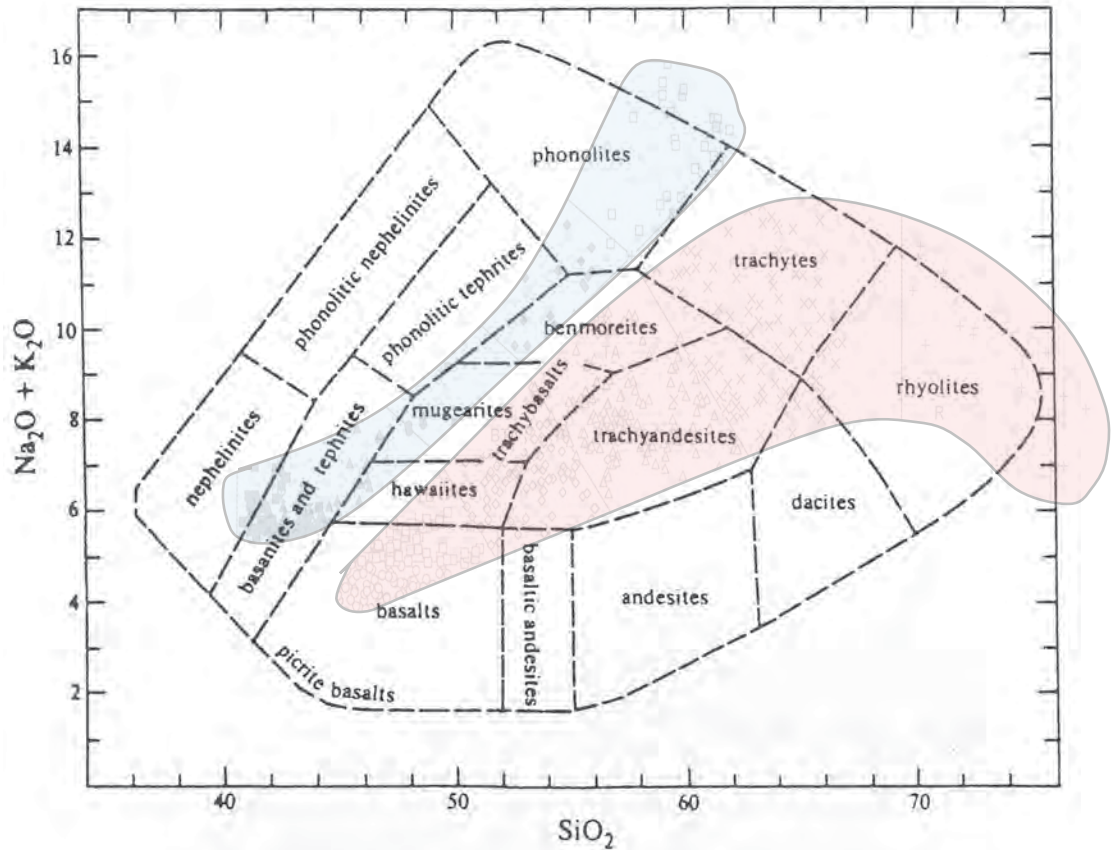
TABLE 1. *Nomenclature and mineralogy of Massif Central volcanics*

Names*	Phenocrysts†	Groundmass†
Saturated series		
Alkali basalt (Ankaramite)	ol cpx mt (ilm)	ol cpx mt ilm plag ap foid
Hawaiite Leucobasalt (Labradorite) (Trachybasalt) (Basalt demi-deuil)	cpx Ca-plag ap amph mt ilm (ol)	cpx plag mt ilm ol ap alkfsp amph
Mugearite Doreite (Mesocratic trachyandesite)	cpx plag amph ap mt ilm (alkfsp) (bio) (opx)	cpx plag mt ilm ap alkfsp
Benmoreite Sancyite (Leucocratic trachyandesite) Latite	plag alkfsp cpx amph bio ap mt ilm (opx)	cpx plag mt ilm ap alkfsp (crist) (trid)
Trachyte (Domite)	alkfsp bio cpx plag amph ap mt ilm sphene zircon (opx)	alkfsp bio cpx plag mt ilm ap (trid) (crist)
Rhyolite	alkfsp cpx mt ilm plag (amph) (bio) (pyrr) (sphene)	alkfsp plag cpx ap amph trid crist zircon
Undersaturated series		
Basanite	ol cpx mt	ol cpx mt foid (amph) (bio) (alkfsp)
Tephrite Ordanchite	cpx plag amph mt haüyne ap (alkfsp)	cpx plag mt ap
Trachyphonolite Miaskitic phonolite (Subalkaline phonolite)	alkfsp plag cpx amph haüyne nosean sodalite zircon sphène mt	alkfsp foid ap cpx amph bio plag
Phonolite Agpaitic phonolite (Hyperalkaline phonolite)	alkfsp cpx sodalite analcime neph plag amph	alkfsp ap cpx amph plag neph analcime mos lav

* Names in bold type are current usage (international); names in parentheses are no longer in use in the context of the Massif Central.
† ol, olivine; cpx, clinopyroxene; mt, magnetite; ilm, ilmenite; amph, amphibole; bio, biotite; plag, plagioclase; alkfsp, alkali feldspar; opx, orthopyroxene; trid, tridimite; crist, cristobalite; ap, apatite; neph, nepheline; foid, feldspathoid; mos, mosandrite; lav, lavenite; pyrr, pyrrhotite.

55

Modifié d'après BROUSSE et BELLON (1983)

Légende:
- Volcanisme alcalin tertiaire péri-alpin
- Principales failles des zones du rift péri-alpin
- Principaux décrochements
- Zone orogénique alpine
- Volcanisme calco-alcalin tertiaire des Alpes occidentales

0   50   100   150   200 km

Principales provinces et ages du volcanisme alcalin du Massif Central Français (Ma: millions d'années)

1 - Chaîne de la Sioule (5 à 1 Ma)
2 - Chaîne des Puys (150 000 à 3500 ans)
3 - Limagne (15 à 2 Ma)
4 - Mont Dore (2,5 à 0,2 Ma)
5 - Cézallier (8 à 3 Ma)
6 - Cantal (11 à 3 Ma)
7 - Aubrac (9 à 6 Ma)

8 - Causses (14 à 2 Ma)
9 - Forez (15 à 13 Ma)
10 - Deves (2,7 à 0,6 Ma)
11 - Velay 14 à 1 Ma)
12 - Vivarais (35 000 à 10 000 ans)
13 - Coirons (8 à 5,5 Ma)
14 - Escandorgue-
Languedoc (3,5 à 0,8 Ma)

0   50   100 km

D'après Nehlig P. Et Traineau H. (1998)

Cantal

La carte géologique simplifiée du Cantal.

- Basaltes supracantaliens
- Phonolites
- Dépôts de coulées de débris
- Dépôts d'avalanche de débris
- Formations cendro-ponceuses
- Coulées et pyroclastites trachyandésitiques et trachytiques
- Basaltes infracantaliens
- Sédiments oligo-miocènes

Chaîne des Puys

Bowen's thermal valley
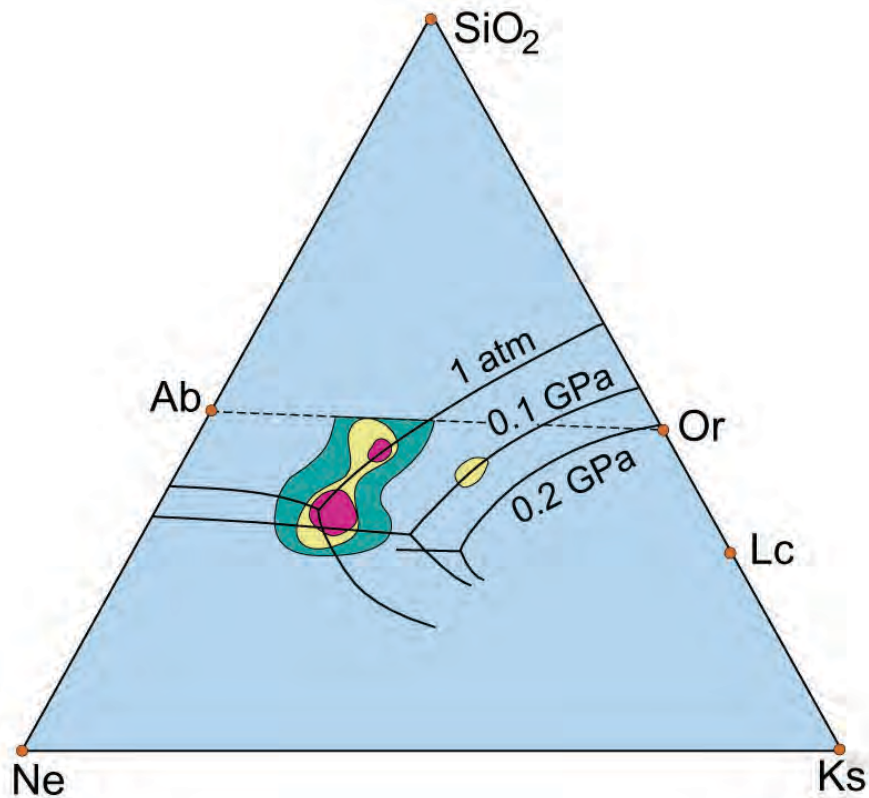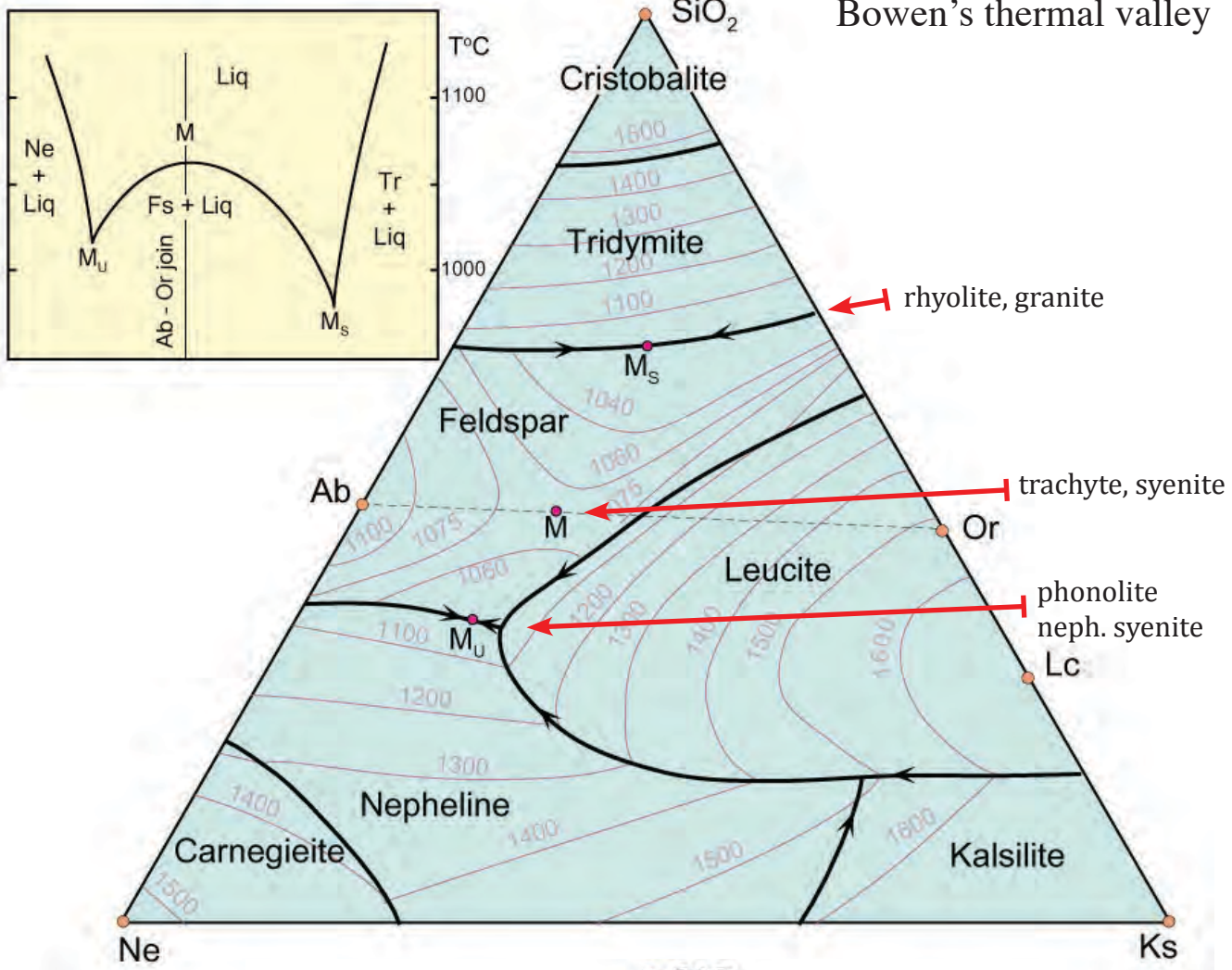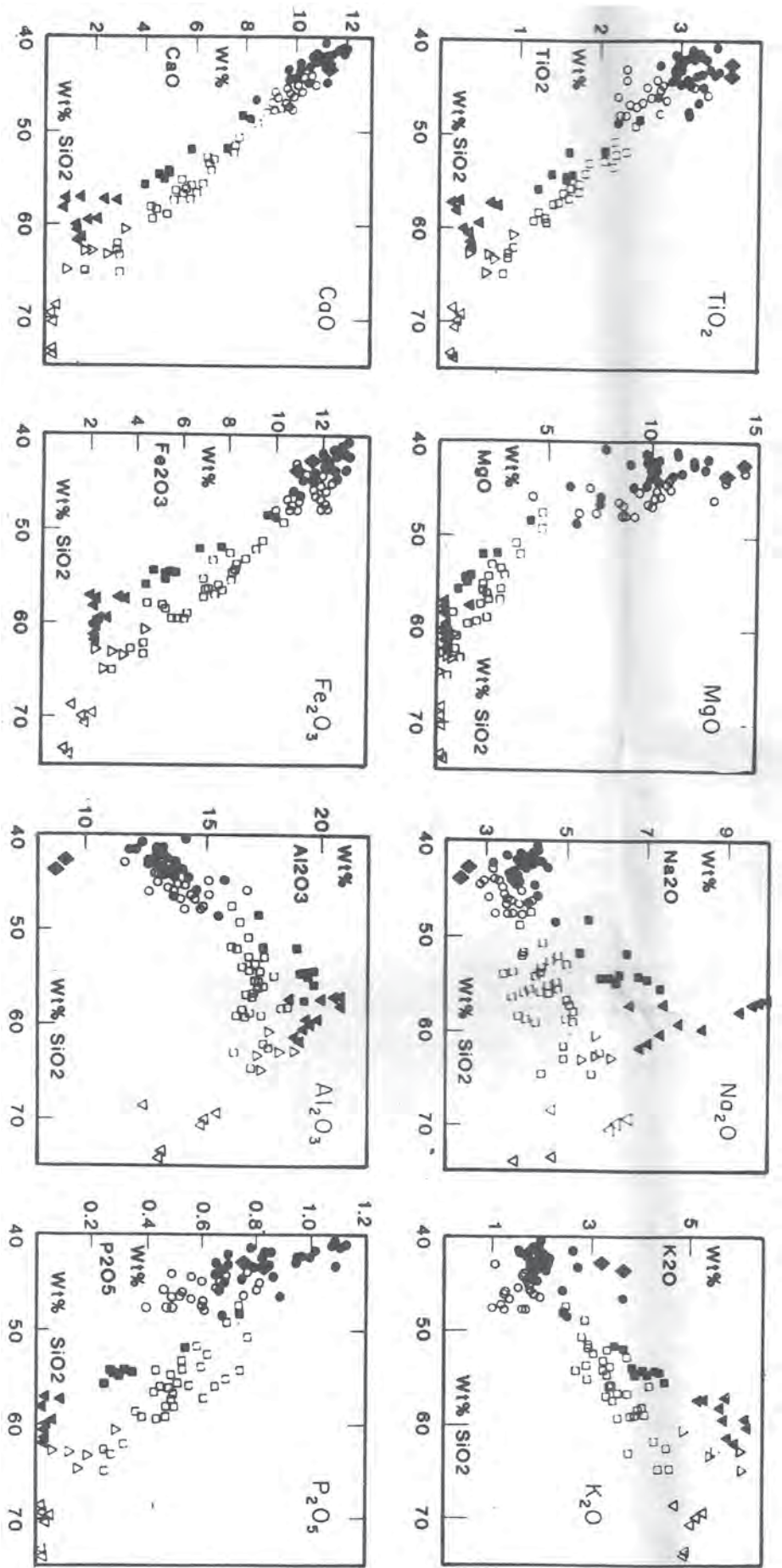
Key to symbols: ♦, nephelinites; ●, basalts; ■, tephrites; ▼, phonolites; ○, basalts; □, trachyandesites; △, trachytes; ▽, rhyolites; ×, Mont-Dore rhyolites and phonolites (Brousse 1961); Velay trend from Berger et al. (1976); Chaine des Puys trend from Maury et al. (1980); UC, Massif Central upper-crustal granites; LC, Massif Central lower-crustal granulites; (H. Downes and A. Leyreloup, unpublished data.) LC*, glass analyses in partially fused lower-crustal xenoliths from the Andes (R. S. Thorpe, personal communication, 1984).
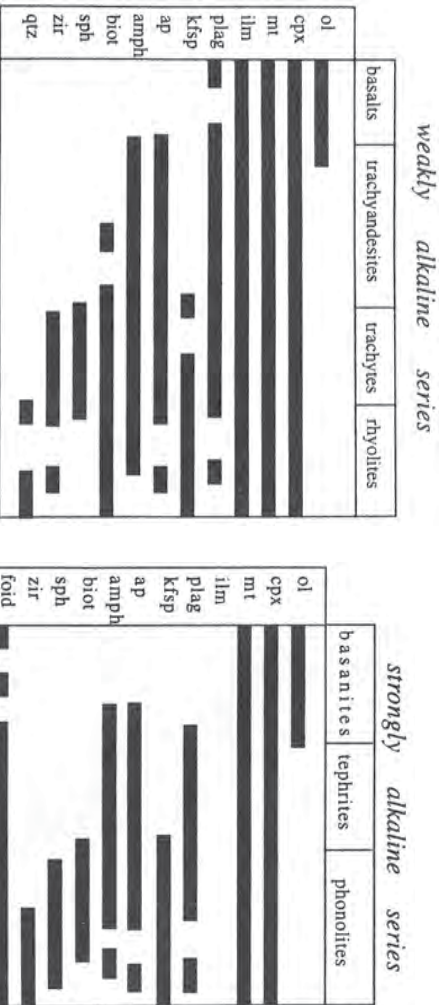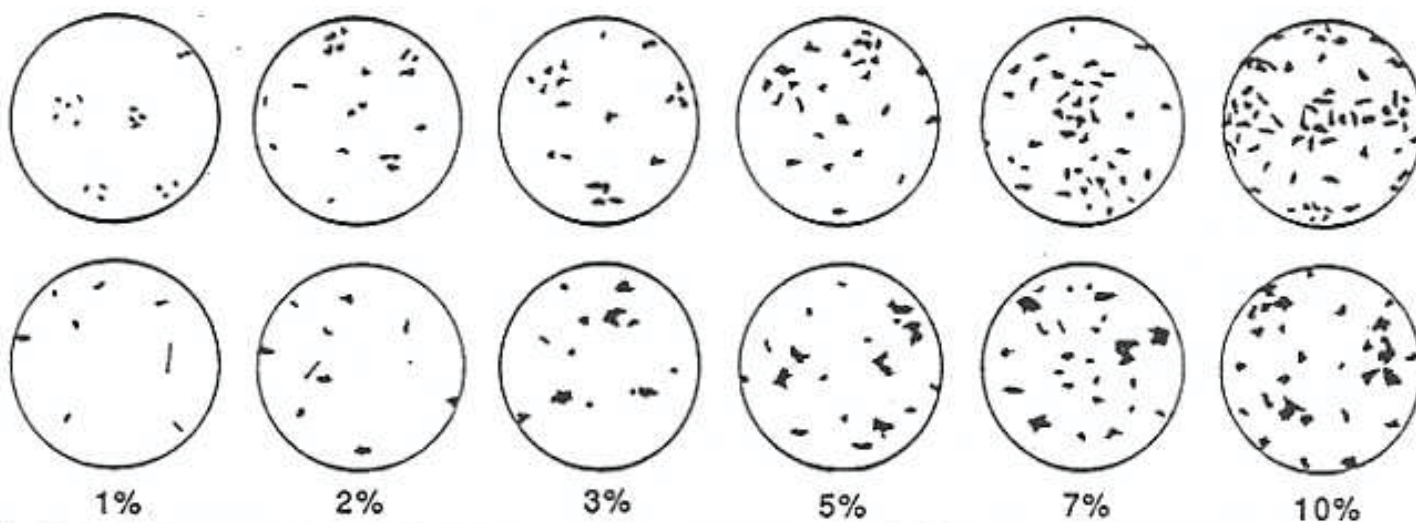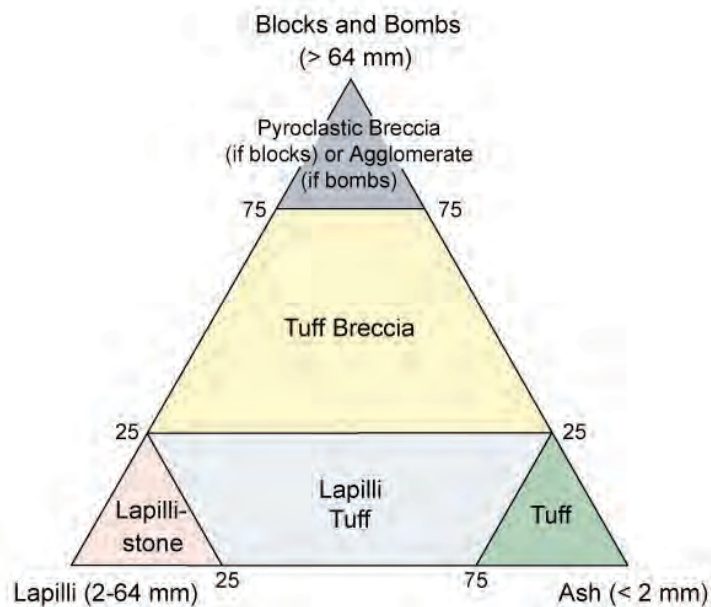
Volume percentage estimator

2009 GEOLOGIC TIME SCALE
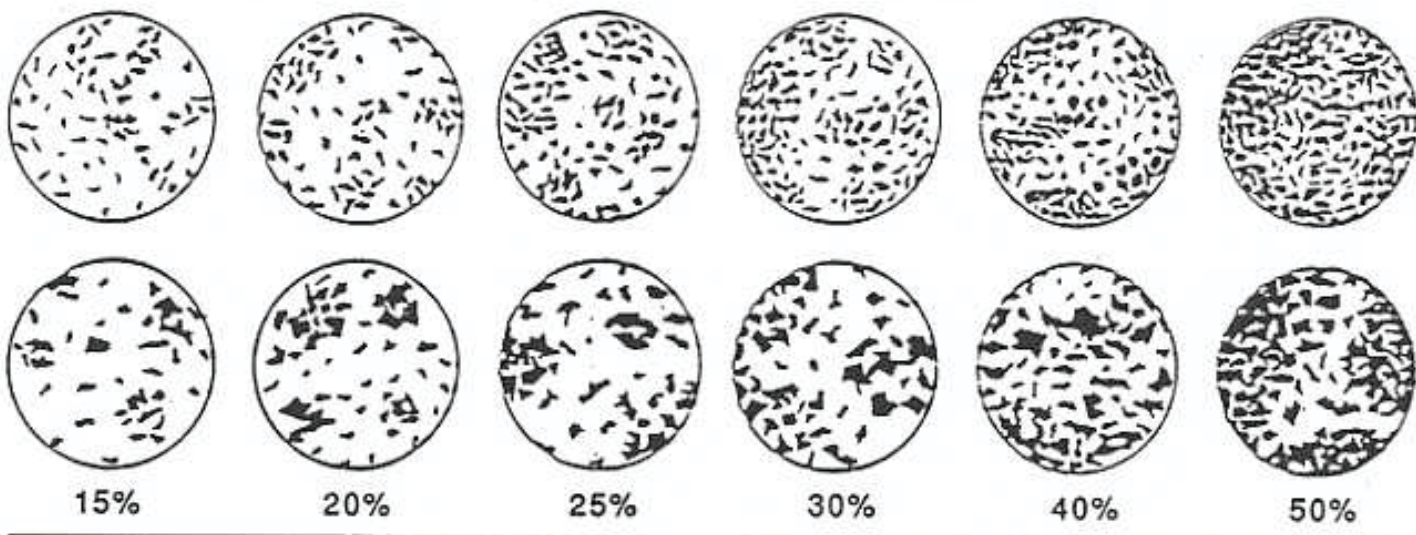
Crystal Structures

- Cubic, face centered
- Cubic, body centered
- Cubic
- Hexagonal
- Monoclinic
- Orthorhombic
- Tetragonal
- Rhombohedral

	meters	dm	cm	mm	μm	nm	Å
1Å =	10^{-10}	10^{-9}	10^{-8}	10^{-7}	10^{-4}	10^{-1}	1
1nm =	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-3}	1	10
1μm =	10^{-6}	10^{-5}	10^{-4}	10^{-3}	1	10^3	10^4
1mm =	10^{-3}	10^{-2}	10^{-1}	1	10^3	10^6	10^7
1cm =	10^{-2}	10^{-1}	1	10	10^4	10^7	10^8
1dm =	10^{-1}	1	10	10^2	10^5	10^8	10^9
1m =	1	10	10^2	10^3	10^6	10^9	10^{10}

Legend:
- Alkali Earth
- Alkaline Earth
- Rare Earth
- Other Metals
- Non-Metals
- Halogens
- Transition Metals
- Metalloids
- Noble Gases

Symbol key:
- Atomic Number
- Atomic Weight
- Symbol
- Kα Energy (+)
- Lα Energy (+)
- Mα Energy (+)
- Crystal Structure

Periodic Table of Elements

Group headers: IA, IIA, IIIB, IVB, VB, VIB, VIIB, VIII, IB, IIB, IIIA, IVA, VA, VIA, VIIA, VIIIA

Z	Symbol	Element	Atomic Weight	Kα	Lα	Mα
1	H	Hydrogen	1.008			
2	He	Helium	4.003			
3	Li	Lithium	6.941			
4	Be	Beryllium	9.012	0.108		
5	B	Boron	10.811	0.185		
6	C	Carbon	12.011	0.277		
7	N	Nitrogen	14.007	0.392		
8	O	Oxygen	15.999	0.523		
9	F	Fluorine	18.998	0.677		
10	Ne	Neon	20.180	0.848		
11	Na	Sodium	22.990	1.040		
12	Mg	Magnesium	24.305	1.254		
13	Al	Aluminum	26.982	1.486		
14	Si	Silicon	28.086	1.740		
15	P	Phosphorus	30.974	2.013		
16	S	Sulfur	32.066	2.307		
17	Cl	Chlorine	35.453	2.622		
18	Ar	Argon	39.948	2.957		
19	K	Potassium	39.098	3.313		
20	Ca	Calcium	40.08	3.691	0.341	
21	Sc	Scandium	44.956	4.090	0.395	
22	Ti	Titanium	47.88	4.510	0.452	
23	V	Vanadium	50.942	4.952	0.511	
24	Cr	Chromium	51.996	5.414	0.573	
25	Mn	Manganese	54.938	5.898	0.637	
26	Fe	Iron	55.847	6.403	0.705	
27	Co	Cobalt	58.933	6.929	0.776	
28	Ni	Nickel	58.70	7.477	0.851	
29	Cu	Copper	63.546	8.040	0.930	
30	Zn	Zinc	65.39	8.637	1.012	
31	Ga	Gallium	69.72	9.250	1.098	
32	Ge	Germanium	72.61	9.885	1.188	
33	As	Arsenic	74.922	10.542	1.282	
34	Se	Selenium	78.96	11.220	1.379	
35	Br	Bromine	79.904	11.922	1.480	
36	Kr	Krypton	83.80	12.649	1.586	
37	Rb	Rubidium	85.468	13.393	1.694	
38	Sr	Strontium	87.62	14.163	1.806	
39	Y	Yttrium	88.906	14.955	1.922	
40	Zr	Zirconium	91.22	15.776	2.042	
41	Nb	Niobium	92.906	16.617	2.166	
42	Mo	Molybdenum	95.94	17.481	2.293	
43	Tc	Technetium	(98)	18.368	2.424	
44	Ru	Ruthenium	101.07	19.282	2.558	
45	Rh	Rhodium	102.906	20.217	2.696	
46	Pd	Palladium	106.42	21.180	2.838	
47	Ag	Silver	107.868	22.166	2.984	
48	Cd	Cadmium	112.41	23.135	3.133	
49	In	Indium	114.82	24.209	3.286	
50	Sn	Tin	118.71	25.272	3.443	
51	Sb	Antimony	121.76	26.359	3.604	
52	Te	Tellurium	127.60	27.471	3.768	
53	I	Iodine	126.905	28.615	3.937	
54	Xe	Xenon	131.29	29.779	4.109	
55	Cs	Cesium	132.905	30.971	4.286	
56	Ba	Barium	137.33	32.196	4.465	0.779
57	La	Lanthanum	138.906	33.441	4.650	0.833
58	Ce	Cerium	140.12	34.717	4.839	0.883
59	Pr	Praseodymium	140.908	36.031	5.033	0.929
60	Nd	Neodymium	144.24	37.358	5.229	0.978
61	Pm	Promethium	(145)	38.725	5.432	1.032
62	Sm	Samarium	150.36	40.118	5.635	1.081
63	Eu	Europium	151.97	41.534	5.845	1.137
64	Gd	Gadolinium	157.25	42.992	6.056	1.185
65	Tb	Terbium	158.925	44.476	6.272	1.240
66	Dy	Dysprosium	162.50	45.997	6.494	1.293
67	Ho	Holmium	164.930	47.534	6.719	1.347
68	Er	Erbium	167.26	49.100	6.947	1.405
69	Tm	Thulium	168.934	50.730	7.179	1.462
70	Yb	Ytterbium	173.04	52.382	7.414	1.521
71	Lu	Lutetium	174.967	54.078	7.654	1.581
72	Hf	Hafnium	178.49	55.801	7.898	1.644
73	Ta	Tantalum	180.948	57.450	8.145	1.709
74	W	Tungsten	183.85	59.305	8.396	1.774
75	Re	Rhenium	186.207	61.122	8.651	1.842
76	Os	Osmium	190.2	62.989	8.910	1.910
77	Ir	Iridium	192.22	64.896	9.174	1.978
78	Pt	Platinum	195.08	66.834	9.441	2.048
79	Au	Gold	196.967	68.804	9.712	2.120
80	Hg	Mercury	200.59	70.806	9.987	2.191
81	Tl	Thallium	204.38	72.869	10.256	2.268
82	Pb	Lead	207.2	74.969	10.550	2.342
83	Bi	Bismuth	208.980	77.091	10.837	2.419
84	Po	Polonium	(209)	79.272	11.129	2.505
85	At	Astatine	(210)	81.513	11.425	2.585
86	Rn	Radon	(222)	83.771	11.725	2.665
87	Fr	Francium	(223)	86.098	12.029	2.747
88	Ra	Radium	226.025	88.480	12.338	2.830
89	Ac	Actinium	227.028	90.880	12.650	2.915
90	Th	Thorium	232.038	93.382	12.967	2.991
91	Pa	Protoactinium	231.036	95.886	13.288	3.077
92	U	Uranium	238.029	98.434	13.612	3.165
93	Np	Neptunium	237.048	100.800	13.941	3.253
94	Pu	Plutonium	(244)	103.320	14.275	3.344
95	Am	Americium	(243)	105.970	14.615	3.435
96	Cm	Curium	(247)	108.737	14.961	3.539
97	Bk	Berkelium	(247)	111.676	15.309	3.634
98	Cf	Californium	(251)	114.778	15.661	3.731
99	Es	Einsteinium	(252)	16.018	3.829	
100	Fm	Fermium	(257)			
101	Md	Mendelevium	(258)			
102	No	Nobelium	(259)			
103	Lr	Lawrencium	(260)			

IX. Common minerals

silicate minerals:

Olivine	$(Fe,Mg)_2SiO_4$
Clinopyroxene	$Ca(Fe,Mg)Si_2O_6$
Orthopyroxene	$(Fe,Mg)_2Si_2O_6$
Amphibole	
Edenite	$(Na,K)Ca_2(Mg,Fe)_5Si_7AlO_{22}(OH)_2$
Gedrite	$Mg_5Al_2Si_6Al_2O_{22}(OH)_2$
Hornblende	$Ca_2Mg_4AlSi_7AlO_{22}(OH)_2$
Feldspar	
albite	$NaAlSi_3O_8$
anorthite	$CaAl_2Si_2O_8$
K-feldspar	$KalSi_3O_8$
Quartz	SiO_2
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$
Muscovite	$KAl_3Si_3O_{10}(OH)_2$
Chlorite	$(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$
Kaolinite	$Al_4Si_4O_{10}(OH)_8$
Garnet	
Spessartine	$Mn_3Al_2(SiO_4)_3$
Almandine	$Fe_3Al_2(SiO_4)_3$
Pyrope	$Mg_3Al_2(SiO_4)_3$
Grossular	$Ca_3Al_2(SiO_4)_3$
Sillimanite	Al_2SiO_5
Andalusite	Al_2SiO_5
Kyanite/Disthene	Al_2SiO_5
Staurolite	$(Fe^{2+},Mg)_2(Al,Fe^{3+})_9O_6[(Si,Al)O_4]_4(OH)_2$
Cordierite	$(Mg,Fe)_2Si_5Al_4O_{18}$ .n H_2O
Zircon	$ZrSiO_4$
Sphene/Titanite	$CaTiSiO_4(O,OH,F)$
Tourmaline	
Dravite	$NaMg_3Al_6Si_6O_{18}(BO_3)_3O_3(OH,F)$
Schorl	$Na(Fe,Mn)_3Al_6Si_6O_{18}(BO_3)_3O_3(OH,F)$
Epidote	$Ca_2(Al,Fe)_3(SiO4)_3(OH)$
Vesuvianite	$Ca_{10}(Mg,Fe)_2Al_4Si_9O_{34}(OH)_4$
Serpentine	$Mg_3Si_2O_5(OH)_4$
Talc	$Mg_6Si_8O_{20}(OH)_4$
Natrolite	$Na_2Al_2Si_3O_{10}$. $2H_2O$
Nepheline	$NaAlSiO_4$
Leucite	$KAlSiO_4$
Sanidine	$(Na,K)AlSi_3O_8$
Sodalite	$Na_8Al_6Si_6O_{24}Cl$
Nosean	$Na_8Al_6Si_6O_{24}SO_4$

sulfide minerals:

Pyrite	FeS_2
Arsenopyrite	$FeAsS$
Boulangerite	$Pb_5Sb_4S_{11}$
Bournonite	$PbCuSbS_3$
Molybdenite	MoS_2
Sphalerite	ZnS
Galena	PbS
Stibnite	Sb_2S_3
Chalcopyrite	$CuFeS_2$

oxide minerals:

Spinel	$MgAl_2O_4$
Magnetite	Fe_3O_4
Ulvospinel	Fe_2TiO_4
Hematite	Fe_2O_3
Ilmenite	$FeTiO_3$
Rutile	TiO_2
Cassiterite	SnO_2
Wolframite	$(Mn,Fe)WO_4$
Scheelite	$CaWO_4$
Corundum	Al_2O_3

carbonates:

Calcite/aragonite	$CaCO_3$
Witherite	$BaCO_3$
Strontianite	$SrCO_3$
Dolomite	$CaMg(CO_3)_2$
Ankerite	$Ca(Mg,Fe)(CO3)_2$
Siderite	$FeCO_3$
Cerussite	$PbCO_3$
Malachite	$Cu_2(CO_3)(OH)_2$
Azurite	$Cu_3(CO_3)_2(OH)_2$
Smithsonite	$ZnCO_3$
Magnesite	$MgCO3$

evaporites:

Gypsum	$CaSO_4.2H_2O$
Anhydrite	$CaSO_4$
Halite	$NaCl$
Celestite	$SrSO_4$
Sylvite	KCl
Bischofite	$MgCl_2.6H_2O$
Carnallite	$KMgCl_3 \cdot 6(H_2O)$
Kieserite	$MgSO_4 \cdot H_2O$
Borax	$Na_2B_4O_7.10H_2O$

uranium minerals:

Autunite	$Ca(UO_2)_2(PO_4)_2.10H_2O$
Torbernite	$Cu(UO_2)_2(PO_4)_2.10H_2O$
Uraninite	UO_2

other minerals:

Apatite	$Ca_5(PO_4)_3F$
Monazite	$(Ce,La,Th)PO_4$
Xenotime	$(Y,Yb)PO_4$
Fluorite	CaF_2
Anglesite	$PbSO_4$
Barite	$BaSO_4$
Gibbsite	$Al(OH)_3$
Goethite	$FeO(OH)$
Graphite/Diamond	C
Gold	Au

Gemstones:

Agate	calcedony quartz
Amethyst	quartz
Aquamarine	emerald (beryl)
Opal	amorfe quartz
Citrine	lemon colered quartz
Sapphire	corundun
Tiger's eye	quartz
Ruby	corundom
Topaz	$Al_2SiO_4(F,OH)_2$

7 Logistics

Fieldwork staff

Vincent van Hinsberg • McGill University
Galen Halverson • McGill University
Thilo Behrends • Utrecht University
Simon Vriend • Utrecht University
Arnold van Dijk • Utrecht University

Address

Gîte Rêve de Rivière
Rue du Pont
Lavoûte-Chilhac
43380 France

Fieldwork dates

First field day: May 7, 2018
Last field day: June 3, 2018

Emergency phone numbers

Ambulance, Police, Fire department: **112**
Emergency field contact: Vincent   **+1 514 607 8112**

Langeac hospital: Hôpital Pierre Galice,   +33 (0)4 71 74 59 00
Doctor (Langeac): Maison de Santé, 2 Rue Dumas, +33 (0) 4 71 77 77 10
Dentist (Langeac): Maison de Santé, 2 Rue Dumas, + 33 (0)4 71 77 77 10
Departmental telephone number: +1 514 398 6767
Langeac and Brioude have several pharmacies
More info on services in Langeac can be found at *www.ville-langeac.fr*

Field schedule

Day	Date	crosssection 1 day	mapping 6 days	regional survey 6 days	exploration 3 days
Sat	May 5	Arrival Clermont-Ferrand (afternoon)			
Sun	May 6	day off			
Mon	May 7	introduction to the field area			
Tue	May 8	introduction to the field area			
Wed	May 9	introduction to the field area + mine visit			
Thu	May 10	green	orange		
Fri	May 11	green	orange	blue	
Sat	May 12	excursion Chaîne des Puys			
Sun	May 13	day off			
Mon	May 14		orange	blue	
Tue	May 15		orange	blue	
Wed	May 16		orange	blue	
Thu	May 17		orange	blue	
Fri	May 18		orange	blue	
Sat	May 19	excursion sedimentary basins			
Sun	May 20	day off			
Mon	May 21		orange	blue	red
Tue	May 22		orange	blue	red
Wed	May 23		orange	blue	red
Thu	May 24		orange	blue	red
Fri	May 25	mapping report writing			
Sat	May 26	excursion Mt. Dore or Cantal			
Sun	May 27	day off			
Mon	May 28			blue	red
Tue	May 29			blue	red
Wed	May 30			blue	red
Thu	May 31			blue	red
Fri	June 1			blue	red
Sat	June 2	final report writing			
Sun	June 3	student excursion			
Mon	June 4	Departure Clermont-Ferrand (morning)			

Notes