BASIC PRINCIPLES OF GEOLOGICAL AND THEMATIC MAPPING

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with co-authors

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PREFACE

This guidebook has been compiled in aid of field geological and thematic mapping activities at 1 : 50,000 scale. In practice, the geological maps should be readable and consistent, which requires a series of steps and a logical build-up to realize such map outputs.

The guidebook has been prepared based on the experience of joint field mapping activities of geologists from the Czech Geological Survey and Geological Survey of Ethiopia between 2015 and 2018 as a result of development projects funded by the Czech Development Agency in the framework of the Development Cooperation Program of the Czech Republic in Ethiopia.

These projects were designed to assess geological and environmental hazards based on geological and related geo-scientific maps. An effort has been made to maintain the traditional techniques in the field of geological survey and research combined with recent advances in geoscience methods and approaches. These methods and approaches will contribute to the comprehensive knowledge of geological environment in Ethiopia with many practical applications.

This manual is not intended to replace the standard field geological mapping guidebooks and other locally adopted standards, but rather complement it by bridging with the current demand of users. It is strongly believed that the wider professional community will benefit from the use of this guidebook.

Kryštof Verner

1) INTRODUCTION

Geological mapping is a step-by-step process, which culminates in a compilation of a geological map. Up on completion of the geological map, applied maps of various thematic objectives are more efficiently compiled. The objectives of basic geological mapping are to describe and depict the geological composition and structure in a particular area and subsequently to serve as the basis for depicting mineral occurrences, prognostic evaluation of industrial and non-industrial raw materials, groundwater resources assessment and delineation of geological hazards and geological factors affecting the environment.

Libraries and internet are full of texts about field, graphical, laboratory or computer techniques on how to collect, process and publish geological data. However, geological mapping cannot be learnt in lecture halls or in laboratories alone. It should be strongly supplemented with precise field observation where also continued experience is gained from every natural encounter in the process. Geological mapping covers wide spectrum of techniques from natural science to field and laboratory data analysis, handcraft, and imagination and curiosity and practicality. Any two geological maps cannot be identical as each geologist reflects different style and expression of his viewpoint, making geological mapping also kind of an art.

The data gathered and the maps compiled are normally intended to serve the needs of the state and public administration, in particular for decision making when planning civil works, and formulating policies on energy, minerals resources and environmental protection. These data are also made available for use by educational establishments, museums, foundations, and public service organizations, as well as by the private sector.

The geological maps can be used for academic reasons (how our planet and life were formed) but in fact geological maps are essential for economic development not only of individual countries but the whole continents.

1.1 Geological map

Geological map is a scaled-down representation and interpretation of the structure of selected area of the upper part of the Earth crust usually drawn on the topographic base map. Geological map shows (using various colours and symbols) the distribution of different kinds of rocks, and boundaries between them that would be seen on the Earth surface if the soils were removed.

The function of geological and derived maps is:

- to explore natural resources (raw materials, groundwater, surface waters, geothermal energy, etc.).
- to locate rocks of particular age, lithology, structure ….
- to reconstruct geological history of an area.
- to estimate composition and character of soils.
- to identify geological hazards.

- to estimate physical parameters of rocks for engineering geology.
- to locate/identify sites with bedrocks suitable for waste disposal.
- to solve theoretical and applied problems leading to advances in geology and the earth sciences in general.
- to teach geology and related disciplines.

1.2 Types of geological and thematic maps

Geoscience maps are commonly divided according to scale and purposes.
Division of geological maps according to the scale:

- 1 : 10,000,000 and smaller – maps of entire continents or the Earth on a single sheet;
- 1 : 1,000,000 to 1 : 5,000,000 – synoptic maps of continents or countries;
- 1 : 500,000 – maps of countries, provinces or states;
- 1 : 200,000 and 1 : 250,000 – regional maps;
- 1 : 25,000 and 1 : 50,000 – detailed geological maps in well-investigated countries;
- 1 : 10,000 and larger – standard scale for field surveying and detailed investigation.

Purposes of geological maps are closely related to their scale. While maps of smaller scale provide overview information about large geological units and regional tectonics, maps of larger scales illustrate distribution of rocks and specific geological features in a greater detail.

According to the content of maps, the following can be distinguished:

- Geological base map depicts distribution of the geological units and rocks including the Quaternary cover. Usually at a scale of 1 : 25,000 to 1 : 75,000.
- Geological map of the bedrock (solid) depicts pre-Quaternary geological units in the mapped area.
- Tectonic map shows the orientation and character of lithotectonic units and tectonic features governing the geological structure of the mapped area.

The described maps are the base for derived and specialized maps, which could be:

- Geophysical map.
- Geochemical map.
- Map of mineral resources.
- Hydrogeological map.
- Map of engineering-geological zoning.
- Map of geodynamic phenomena.
- Soil map.

2) TOPOGRAPHIC BASE MAP

2.1 Characteristics of the topographic map

A topographic map provides information on the existence, location, and the distance between natural and human-made features on the Earth's surface. It also indicates variations in the terrain, heights of natural features, and the extent of vegetation cover. Therefore, topographic base maps have many purposes, but the prime purpose is to give a graphical two-dimensional representation of the defined portion of the Earth's surface.

The International Cartographic Association defines Topographic Maps as follows: Topographic maps are maps of various scales which incorporate variety of information. The basic coverage (state large-scale map series) is based on measurements done in the field and/or from aerial photographs. Derived topographical maps (of medium and small scales) are prepared by reduction and generalization from the original basic maps.

In short, it can be said that a topographic map is a graphical representation of the three-dimensional configuration of the Earth's surface in two dimensions. It shows the size, shape and distribution of landscape features, and presents the horizontal and vertical positions of those represented features. The features in topographic maps can be divided into four major groups:

Relief: Depicted with contour lines or by shaded relief.

- A **contour line** is a line joining points of equal elevation on a surface. Elevations are given in meters (or feet) above mean sea level. Every point along a contour line has the same exact elevation. Contour lines can never cross each other. A contour line must close on itself. Some contour lines will have their elevation marked next to them, but not in all cases. In order to calculate the height of any contour line, you need to know the contour interval. An easy way to recognize real world slopes on the map is to think of the distance between contour lines on the topographic map where the lines represent certain constant elevation value. If the distance between contours is very far apart, it indicates a gradual increase in elevation and hence low slope or flat terrain. If the lines are on the other hand too close to each other, the change in elevation occurs very quickly, indicating a steep slope or terrain.
- A **shaded relief** is a specific type of terrain representation that uses colours and shading to show heights and features on the map. Shading on a topographic map is used to give it a more realistic view. Mountains actually look like mountains instead of just contour lines.

Water features: they represent oceans, lakes, rivers, streams, swamps, springs etc. A river network is a mandatory feature that makes it easy to navigate the map.

Vegetation: they represent wooded and cleared areas. Topography for geological maps is usually used without forests, because the green colour of forests would distort the colours of individual geological unities.

Cultural features: they represent all the human-made features: buildings, roads, railroads, land boundaries, etc.

Topographic maps usually show a geographic graticule (a network of longitude and latitude lines on a map or chart that relates points on a map to their true locations on the Earth) and a coordinate grid (network of parallel and perpendicular lines superimposed on a map and used for reference) for better finding of relative and absolute positions of mapped features.

2.2 Coordinate systems

Coordinate systems are frameworks that are used to define unique positions. The coordinate system that is most commonly used to define locations on the three-dimensional Earth is called the geographic coordinate system. It is a three-dimensional reference system that locates points on the Earth's surface. The unit of measure is usually decimal degrees. A point is described by two coordinate values: latitude and longitude (Fig. 1). Latitude is defined as the angle formed by the intersection of a line perpendicular to the Earth's surface at a point and the plane of the Equator. Latitude values range from –90 to +90 degrees. Points situated north of the Equator have positive latitude values, while points lying south have negative values.

Lines of latitude are also called parallels because a particular value of latitude forms a circle parallel to the Equator. A meridian is formed by a plane that passes through the point and the North and South poles. The longitude value is defined by the angle between that plane and a reference plane. The reference plane is known as the prime meridian. The most common prime meridian passes through Greenwich, United Kingdom. Longitude values range from –180 to +180 degrees with negative values lying west of prime meridian.

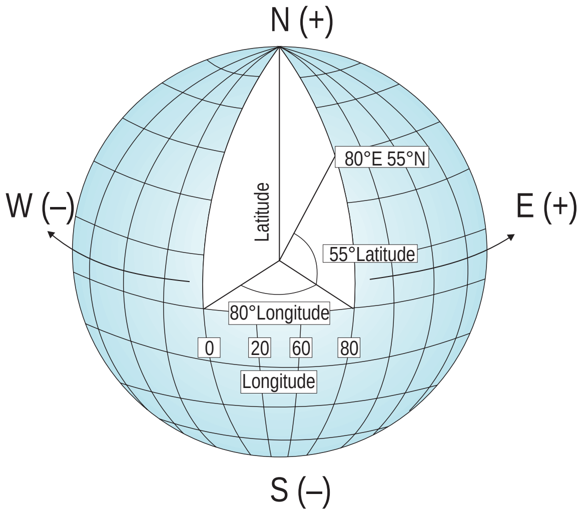

Figure 1. *Explanation of latitude and longitude (https://www.ibm.com/support/knowledgecenter/en/SSEPEK_10.0.0/spatl/src/art/0sbp5004.gif).*

A projected coordinate system is a two-dimensional representation of the Earth. It uses Cartesian coordinates based on linear units of measure. It is based on a spherical earth model and its coordinates are converted to x, y coordinates on the flat projection.

The intersection of the x and y axes is the origin and usually has coordinates of (0, 0). The values above the x axis are positive, and the values below the x axis are negative. The lines parallel to the x axis are equidistant from each other. The values to the right of the axis are positive, and the values to the left of the y axis are negative. The lines parallel to the y axis are equidistant. Mathematical formulas are used to convert a three-dimensional geographic coordinate system to a two-dimensional flat projected coordinate system. The transformation is referred as a map projection.

Map projections are classified by the projection surface used, such as conic, cylindrical, and planar surfaces. Depending on the projection used, different spatial properties will appear distorted. Projections are designed to minimize the distortion of one or two of the data's characteristics: the distance, area, shape, direction, or a combination of these properties might not be accurate representations of the data being modelled.

There are several types of projections available. While most map projections attempt to preserve some accuracy of the spatial properties, there are others that attempt to minimize the overall distortion. The most common types of map projections include:

- Equal area projections preserve areas and distort shape, angle, and scale.
- Conformal projections preserve angles; the area of the map is distorted. Conformal projection includes Transverse Mercator projection.
- Equidistant projections maintain the scale along one or more lines, or from one or two points to all other points on the map. If you go outside the data set, the scale will become more distorted.

Ethiopian topographic maps use projected coordinate system Adindan / UTM zone 37N with parameters:

WKID	20137
Projection	Transverse Mercator
False Easting	500000
False Northing	0
Central Meridian	39
Scale Factor	0,9996
Latitude Of Origin	0
Linear Unit Meter	–1
Geographic Coordinate System	GCS Adindan
Angular Unit	Degree (0,0174532925199433)
Prime Meridian	Greenwich (0,0)
Datum	D Adindan
Spheroid	Clarke 1880 RGS
Semi-major Axis	6378249,145
Semi-minor Axis	6356514,87
Inverse Flattening	293,465

2.3 Magnetic declinations

True north is a geographical direction represented on maps and globes by lines of longitude. Each line of longitude represents direct north and south travel. Compass, on the other hand, direct you to magnetic north. It is a point in the arctic regions of Canada that is continually shifting location based on the activity of the Earth's magnetic fields. There is a difference between true north on a map and the north indicated by your compass. That difference is called the magnetic declination and is measured by the angle between true north and magnetic north when plotted on a map. If the magnetic north deviates from the geographic to the right, it declares a positive deviation (δ) called declination angle (Fig. 2), if to the left, it becomes negative. If both directions match, the declination is 0 degrees, and if they are exactly opposite, the declination is 180 degrees.

Magnetic declinations vary from place to place, depending on the intensity of the Earth's magnetic fields. Magnetic declinations in Ethiopia were between +0° 25' and +2° 41' in 2017. The accurate calculation of the magnetic declination value for a particular location in Ethiopia can be used by the service at: https://www.ngdc.noaa.gov/geomag-web/

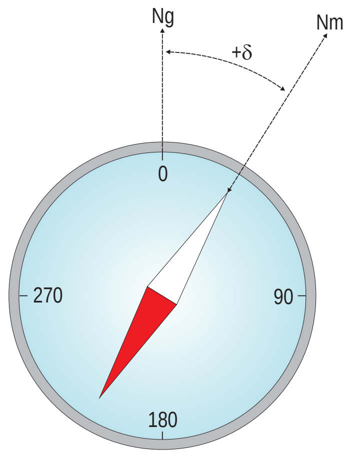

Figure 2. *Magnetic deviation δ from geographic north (https://en.wikipedia.org/wiki/File: Magnetic_declination.svg).*

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3) REMOTE SENSING IN GEOLOGICAL MAPPING

Implementation of remotely sensed data and their interpretation can provide a cost effective method for geological mapping purposes. Most of the Earth`s surface is covered by digital elevation model (DEM) data, Landsat, Aster and other satellite imagery, which are freely available. The aim of this contribution is to provide basic information on data types, which could be used for geological interpretation. Morphology could be easily visualized using DEMs in the form of coloured elevation maps combined with shaded relief. Also, Landsat TM (Thematic Mapper, ETM – Enhanced Thematic Mapper, ETM+) band 5 and panchromatic band, and radar images (such as Radarsat or ERS – European Remote Sensing satellite) can help to understand morphology. Some lithologies (rock types) could be identified from morphology, but DEM is mainly used for structural interpretation. The best approach for identification of lithological features, such as lithological boundaries or hydrothermal alteration zones, is to combine RGB composites from visible and infrared bands of optical satellite imagery, such as Landsat and ASTER, which are available for free download on USGS and NASA servers. There are many sophisticated methods, which can be used to enhance and identify lithologies from optical imagery. Some of them are mentioned below. Their thorough description is beyond the scope of this short guidebook; geoscientists needs to ask remote sensing specialists for assistance. This guidebook is focused essentially on the basic methods, which are effective for mapping and available to any geoscientist having very basic GIS and remote sensing skills.

3.1 Digital elevation models (DEMs)

The best spatial resolution of DEMs for the geological mapping at a scale of 1 : 50,000 is 10–30 m in pixel size. Good quality data are Aster DEM and SRTM3, both available free on USGS/NASA servers. LIDAR data based on laser scanning are usually too detailed (cm–dm in pixel size) and not so useful for identification of geological features at such scales (1 : 50,000).

Rock types can be accessed by morphological interpretation of the data, as different rock types have specific depositional landforms and respond to the effects of erosion differently. Patterns and shapes on the image directly relate to the characteristics of rock types when comparing drainage systems, shape of valleys, or specific geomorphologic features. Before such an approach, the climate of the area should be studied.

Sedimentary rocks are usually stratified due to the variations of depositional conditions and display banded appearance, which may interfere with the nature of pyroclastic rocks. These are however mostly discernible by their proximity to volcanic centres or volcanic rocks. The bedding orientation in the sedimentary rocks generally determines the appearance of the rocks on the surface giving an idea of their dip and strike angle. Less compacted, finer grained, or carbonate-cemented sequences are more prone to erosion. Coarse clastic sediments display V-shaped valleys, a widely spaced drainage pattern and are usually jointed. Fine clastic rocks frequently contain stratification, which is very thin. At a macroscopic scale, fine clastic sediments form homogenous units up to hundred meters thick. A dendritic pattern of the drainage system is characteristic. These sediments are more prone to erosion and usually form negative topographic features.

Extrusive igneous rocks (lavas and domes) pose a huge problem in front of an image analyst because they are usually interbedded with sediments and pyroclastic rocks. The differentiation between sediments and volcanic rocks can be solved if we can observe associated volcanic landforms, such as relics of cones (Fig. 3) or lava flows. A larger problem is the discrimination between the pyroclastic products and the volcanic rocks themselves. The exact determination of pyroclastic rocks from their volcanic counterparts typically needs field checking. Areas covered by volcanic rocks display dendritic pattern of drainage system and stand out as positive topographic features.

Intrusive igneous rocks form different shapes on the images according to the form of the intrusion from small elongated dykes to large plutons. They are usually jointed due to the cooling processes and effects of shrinkage. Being formed by resistant rock forming minerals, they stand out as positive topographic features (Fig. 4). This is not always the rule. For example, granites are prone to erosion in arid regions due to the differences in coefficients of thermal expansion between quartz and feldspar. Acidic to intermediate rocks do not display prominent regular jointing pattern, which discerns them from sandstones, and often form onion exfoliation patterns. Basic and ultrabasic rocks exhibit similar patterns as granitic rocks except for being much darker in tone.

Metamorphic rocks form compact units with almost no jointing patterns. The drainage systems are finely spaced and dendritic. Metamorphic provinces form positive topographic reliefs. Most metamorphic rocks display compositional banding representing their original layering of sedimentary or igneous origin or redistribution of the rock constituents during metamorphism (Drury 1997). The rocks are typically intensively foliated and folded,

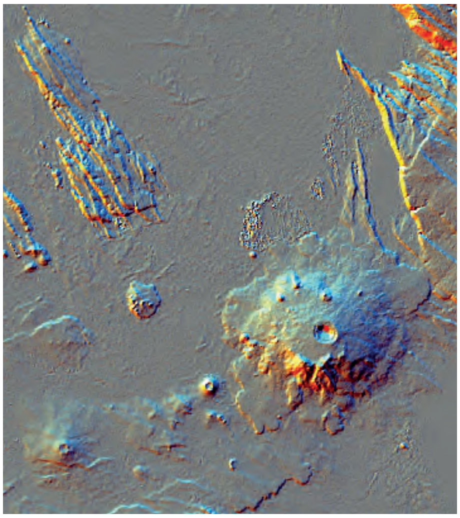

Figure 3. *Shield volcano Dema'ali Terara, Afar depression, NE Ethiopia. Note NW striking normal faults of Red Sea Rift system. Map is 40 km wide (multidirectional shaded relief map generated from ASTER DEM).*

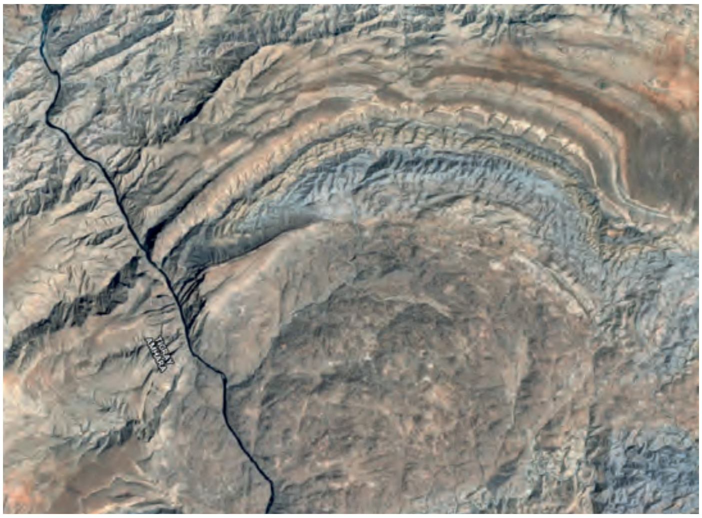

Figure 4. *An example of granitoid intrusion (rounded body bottom centre) into folded Proterozoic metasediments. 60 km south of Axum, northern Ethiopia, optical satellite imagery in true color, image is 15 km wide (©2018 DigitalGlobe by Google).*

which results in complex structures. The variations of composition can only be enhanced by strong chemical weathering typical in humid regions.

3.2 Tectonic interpretation of remotely sensed data

Structural characteristics of an area can be accessed on remotely sensed images by interpretations of linear features. Satellite images allow the recognition of features because of their large synoptic view of an area that otherwise would be difficult to follow and interpret during field campaigns. The shape of the platy geological features on the Earth´s surface is determined by their dip angles. Except for thrust, most faults dip steeply and form straight lineaments relatively unaffected by topography. This rule can be applied generally – steep structures have straight expressions on the Earth`s surface (veins, alteration zones, etc.) There are, however, also other possibilities how the linear features can be interpreted in remotely sensed data; from being actual faults, dykes, steep or vertical strata, to roads and data artifacts. Neotectonic faults (Fig. 3) can be identified by (1) their morphology, forming asymmetric ranges with one side corresponding to breaks in slope or scarps, (2) the displacement of late Neogene rocks and boundaries between them, structural or erosional surfaces, and (3) the occurrence of straight lines of several tens of kilometres in length. Images must be systematically compared with geological maps in order to carefully separate the scarps formed by fault planes (active) from those resulting from differential erosion of contrasted lithology (ancient). The active fault scarps, even eroded, are much higher and longer than the scarps formed by lithological contrasts.

Identification of kinematic indicators (strike-slip, normal or reverse fault): Strike-slip faults have rectilinear traces and they locally bound push-up hills or extensional basins at step-over or bends of the fault trace. They can be associated with typical patterns such as tail-crack or horse-tail structures at fault ends. Reverse faults have sinuous traces and they are associated with half-cylindrical-shaped hills of the uplifted blocks due to drag folds deforming ancient planar erosion surface in the hanging wall. Normal faults are recognized by the following geomorphic features: (1) they generally have a widely arched trace, concave (mainly) or convex toward the footwall, in contrast to the strike-slip faults, whose trace is generally straighter; (2) they bound tilted plateaus (tilted blocks); (3) similarly to the case of strike-slip faults, they are not related to half-cylindrical-shaped hills corresponding to recent drag folds, which accompany active reverse faulting. Mapping of the recent folds, the synclines, forming lowlands filled with sediments and the anticlines corresponding to regularly-shaped elongated hills is also possible. It is important to point out that this approach provides information on the finite strain, but not on its detailed history. Faults usually develop in conjugate directions where one direction can be dominant. The recognition of conjugate fault systems allows for general estimation of the maximum and minimum principal stress axes orientation. Faults represent local weaknesses in the Earth's crust and become eroded easily so that they form linear depressions often followed by streams, which is recognizable on digital terrain models. The higher water saturation of fault zones provides excellent environment for plants that may grow along the fault line and enhance its discernment. However, as a rule, other geologically significant features such as truncations, displacements of lithological units or direct field checking should support the statement that a linear feature in an image represents a real fault structure. Active faulting in an area may be beneficial for the recognition of faults as it may produce specific landforms like headless valleys, facetted spurs, shutter ridges, offset streams or sag ponds.

As shown in the previous paragraphs, morphological aspects of a terrain (Fig. 5 and 6) serve as indicators for assessing geological situation when viewed and analysed in remotely sensed datasets. That is why the investigation of morphostructural features plays an important role in geological image analysis.

For the purposes of structural interpretation, in addition to DEMs also radar satellite data can be very helpful (Radarsat, ERS). They are especially helpful in areas with dense vegetation cover, because they can penetrate vegetation and show soil/rock surface. Radar interferometry is also used for the measurement of small vertical displacements of the surface. In radar interferometry, two images of the same place are taken at different times and merged afterwards. The merging of the two images shows the ground displacement (if any) that would indicate movement that has occurred between the time the two images were taken. The tectonic displacement, landslide movement, subsidence or aggradation of sediments could be detected by such interferometric methods.

3.3 Optical imagery

Images used for geological interpretation usually underwent several phases of pre-processing. These include georeferencing and/or map transformation to reduce spatial distortion and to fit to available map data; spatial filtering to „clean“ poor quality data or radar images, or to sharpen image. After this pre-processing, methods of image enhancement are applied to increase spectral information in the image, i.e. to increase „colour contrast“, which means increasing the number of colour hues representing

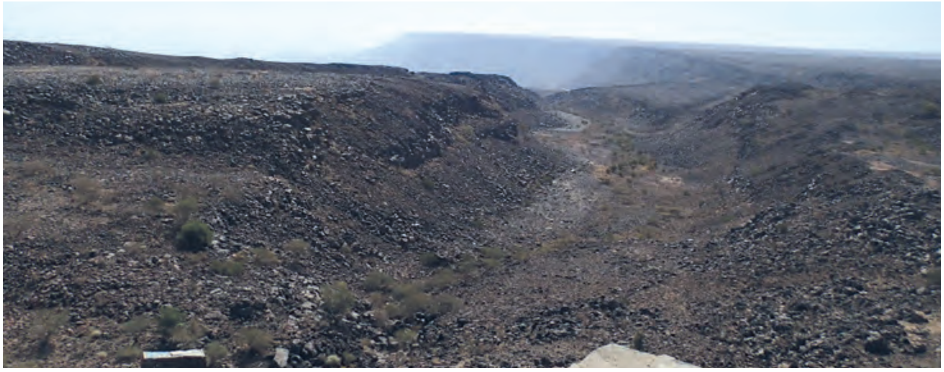

Figure 5. *NNE striking normal fault escarpments of the Main Ethiopian Rift system, east of Dobi Graben, Afar Depression, NE Ethiopia.*

Figure 6. *NW striking Dobi Graben normal fault escarpments, which are part of the Red Sea Rift system, Afar Depression, NE Ethiopia. Note also salt deposits in the graben basin and small alluvial fan (left).*

different lithologies. These methods can include different algorithms of histogram stretch of all dataset or subset or masked area (it can be very effective for enhancing selected lithologies), principle component analysis and decorrelation stretch. More advanced methods of image processing involve algebraic operations with spectral bands (to reduce topographic correlation and to increase spectral/lithological information), calculation of specific mineral and vegetation indices, unsupervised and supervised classification.

Panchromatic images (black and white panchromatic band of Landsat) are usually acquired in visible range of electromagnetic spectra (VIS), so we can see the Earth surface similarly to how we observe it by human eyes but in grey scales; light rocks would be expressed by light shades, dark rocks with dark shades; such images are good for interpretation of morphology, morphotectonics, some lithologies and Quaternary deposits. True colour composite images such as e.g. **Landsat** bands **321** displayed as RGB composite are of a similar importance.

Multispectral images (Fig. 7) such as Landsat or ASTER have also bands in SWIR (short-wave infrared) range of electromagnetic spectra; Landsat bands 4, 5, 7, ASTER bands 3 to 9. These are not percepted by human eyes, but there are distinct absorption or reflectance features of some important minerals and rocks in these bands (spectra). These bands are most suitable for interpreting most lithologies (Tab. 1).

Thermal infrared (TIR) bands (Landsat 6, ASTER 10 to 14) show surface temperature. Differences in temperature are dependent mainly on thermal capacity of the material (rock), overall absorption in VIS and SWIR and sun exposure. Thermal capacity is highly influenced by water content in soils and rocks. TIR bands are therefore used mainly to interpret silicate-rich rocks (which have poor absorption features in VIS and SWIR) and in hydrogeology.

Table 1. Landsat spectral bands, wavelengths and applications

Landsat band TM/ETM/ ETM+	wavelength	Application
TM 1	0.45–0.52 μm (blue)	Soil/vegetation discrimination; identification of urban areas; prominent reflectance of water (the only band for mapping shallow water sediments, in other bands water has high absorption, i.e. very low reflectance – almost black), snow, halite.
TM 2	0.52–0.60 μm (green)	Vegetation and agricultural mapping; some rocks and minerals (chlorite, epidote, serpentinite, some volcaniclastic rocks,..).
TM 3	0.63–0.69 μm (red)	Plant species discrimination (based on absorption of chlorophyll); Fe hydroxides and colloids (Fe soils); identification of urban/cultural areas.
TM 4	0.76–0.90 μm (near infrared)	Identification of plant species, vegetation stress, biomass content; contouring water (based on absorption); soil moisture.
TM 5	1.55–1.75 μm (mid IR)	Fe oxides; absorption of gypsum; sensitive to moisture in soils and vegetation; contouring clouds and snow cover.
TM 6	10.4–12.5 μm (thermal IR)	Vegetation stress and soil/rock moisture identification based on thermal emission; thermal mapping (urban areas, water, silicate minerals).
TM 7	2.08–2.35 μm (mid IR)	Minerals and rocks identification; especially clay minerals; prominent absorption of gypsum; identification minerals with bonds Al-OH, Mg-OH, C-O; also sensitive to vegetation moisture.

For understanding and mapping vegetation cover, the most suitable way is to use visible and near-infrared bands (VNIR) **Landsat 432** or **ASTER 321** bands (as RGB false colour composite – vegetation is in red). To enhance different lithologies and soil types, the most used band combinations are **Landsat 531** or **ASTER 421**, which enables the identification of several Fe minerals, shallow water sedimentary bodies, snow and halite in Landsat only. Band combinations of Landsat 753 or ASTER 542, 642, 742, 842 and 942 work with bands sensitive to clay minerals (Landsat 7, ASTER 5, 6, 7, 8, 9). These are good for soil mapping, or e.g. hydrothermal alteration zones are expressed here in yellow and brownish-yellow colours (because they are abundant in clay minerals and Fe oxides). In **ASTER** bands **468** (RGB), kaolinite and alunite zones may be expressed in pink and evaporites in white.

There are just a few spectral bands in multispectral images and while the number of minerals and rocks to be identified are too many, therefore it is not usually possible to precisely identify lithology. The solution is to follow a strategy by trying various band combinations to map lithological boundaries – a different colour often represents different lithology. Images could significantly help with mapping lithological unit boundaries at the scale of approx. 1 : 50,000 (notice pixel size at about 30 m). Details on units/structures and particular lithologies must be checked in the field. But spectral mapping has limits. It is quite common that rocks with similar composition but different texture (granite, rhyolite, arcose) end up showing no significant difference in tone or colour in the image meaning, they can appear with similar colours because of similar composition. On the other hand, a very significant spectral (colour) expression of two rocks may represent only a minor change in mineralogy (e.g. clayey sandstone, Fe-oxide rich sandstone, organic rich sandstone) and for the purposes of geological mapping, these rocks should rather be a part of one unit.

There are also other freely available data, which could be used for geological mapping, such as: DigitalGlobe optical satellite imagery in visible range available via GoogleMaps or GoogleEarth.

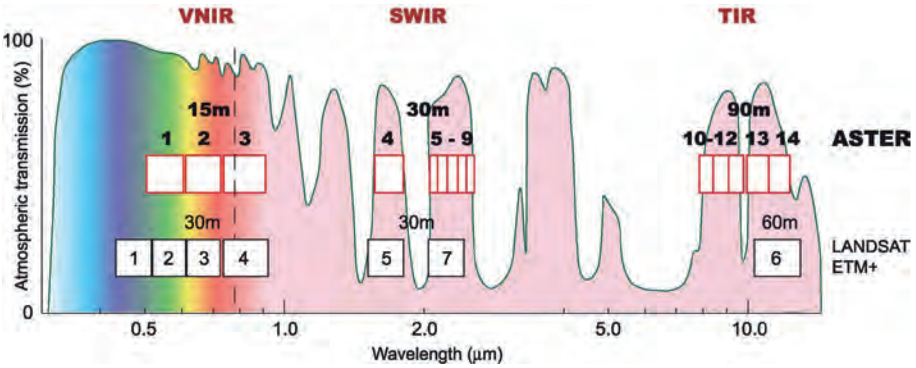

Figure 7. *Diagram showing atmospheric transmission vs. electromagnetic wavelength, position of Landsat and ASTER spectral bands are indicated (NASA/USGS).*

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Jordan G., Meijninger B.M.L., van Hinsbergen D.J.J, Meulenkamp J.E., van Dijk P.M. (2005): Extraction of morphotectonic features from DEMs: Development and applications for study areas in Hungary and NW Greece. International Journal of Applied Earth Observation and Geoinformation 7 163–182.

Saintot A, Angelier J, Chorowicz J. (1999): Mechanical significance of structural patterns identified by remote sensing studies: a multiscale analysis of tectonic structures in Crimea. Tectonophysics 313 187–218.

Snyder N. P., Whipple K.X, Tucker G.E., Merritts D.J., (2000): Landscape response to tectonic forcing: Digital elevation model analysis of stream profiles in the Mendocino triple junction region, northern California. Gelogical Society of America Bulletin 112 (8): 1250–1263.

On-line resources:

Data

https://www.google.com
https://www.google.com/earth/
https://landsat.gsfc.nasa.gov/
https://landsatlook.usgs.gov/
https://glovis.usgs.gov/
https://earthexplorer.usgs.gov/
http://www.esri.com/software/landsat-imagery
https://search.earthdata.nasa.gov/search
http://www.tectonique.net/tectask/index.php?option=com_bookmarks&Itemid=4&mode=0&catid=22&navstart=0&search=*

Textbooks/Courses

http://www.nrcan.gc.ca/node/9309
https://www.esri.com/training/

Software

https://engineering.purdue.edu/~biehl/MultiSpec/download_win.html
https://qgis.org/en/site/forusers/download.html
http://www.esri.com/products
http://www.harrisgeospatial.com/SoftwareTechnology/ENVI.aspx
https://www.hexagongeospatial.com/products/power-portfolio/other-producer-products/er-mapper

4) PARTS OF THE GEOLOGICAL MAP

A sheet of the base geological map (Fig. 8) consists of the geological map itself, including Quaternary formations. It is supplemented by the obligatory information to be placed on one side of the map. This must include:

- Number and name of map sheet.
- Legend to the geological map.
- Lithostratigraphic scheme.
- Geological cross-section.
- Summary of geological mapping.
- Synoptic description of regional geological units.
- Map sheet index.

According to the need, the map can be supplemented by other optional appendices such as geophysical, stratigraphic or lithological schemes, 3D model of the relief, etc.

Basic parts of the map sheets are the frame with the geological map itself, key to the map outside of the map frame, and a map sheet index. These basic parts are completed by text information and supplementary graphical information all outside the map frame.

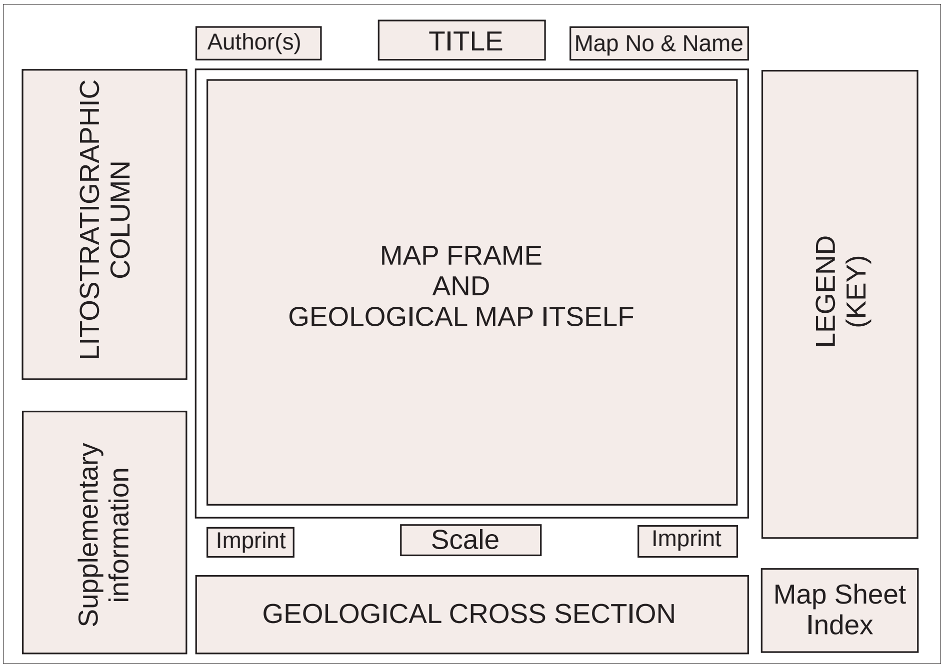


Figure 8. *Schematic layout of the sheet of the geological map.*

4.1 Geological map

Geological map is fixed in the frame, which corresponds to the boundary of the topographic base map and bears information about the coordinate system. The local state grid is usually drawn based on WGS84 datum.

The geological map depicts and interprets the geological structure of the Earth's surface, including sediments forming the Quaternary cover and anthropogenic deposits. It is a compilation of lithological, stratigraphic and structural observations of the bedrock and the overlying Quaternary deposits, supplemented by selected tectonic, palaeontological, hydrogeological and geodynamic data, together with information concerning mineral resources. Information depicted on the geological map at large scales includes:

- Areas of rocks units defined in terms of lithostratigraphy, chronostratigraphy, petrology, tectonics, Quaternary deposits, and the geological contacts between them.
- Anthropogenic deposits.
- The lines of faults and other tectonic elements on the Earth's surface.
- Zones of contact metamorphism and hydrothermal alteration.
- Important zones of eluvium and products of fossil weathering.
- Important geodynamic phenomena.
- Active and abandoned surface mine workings, adits, and shafts of underground mines.
- Important springs of fresh groundwater and mineral waters.
- Sites of important palaeontological finds.
- Position of important boreholes.
- Important geological localities.
- Lines of geological cross-sections.

4.2 Legend (Key)

The legend must include all features shown on the geological map, the geological cross-section and the lithostratigraphic column. If some of these features appear only in the lithostratigraphic column or in the geological cross-section, then this should be indicated in the text describing the individual items of the legend.

The legend is divided according to regional-geological and chronostratigraphic principles. Classification of separate groups of units within individual chronological sequences or in regional geological units is indicated by headings above the respective groups.

Individual items in the legend are indicated by consecutive numbers that will be the same as those given to the appropriate paragraphs in the explanatory notes. The units in the legend are arranged in the order of age from the youngest to the oldest. The key to geological symbols forms an integral part of the legend. This is shown below the last rock unit.

Lithostratigraphic units, rocks and other geological features depicted in the legend are distinguished by a combination of colour, hatching, index and symbols. The symbols and colours used should follow the international standards. Graphic depiction of individual items in the legend is supplemented by basic stratigraphic and petrographic descriptions.

The names of rocks and their regional geological, chronostratigraphic and lithostratigraphic classification are based on international standards and the terminology. The names given to rocks in the legend, in the lithostratigraphic column and in the explanatory notes must be the same.

4.3 Text information

The upper part of the map sheet could be organized in two rows and contains:
- Name of the map set and type of map (in two rows).
- Name of editor(s) (up to three names).
- Official number and name of the sheet in the state map series.

The lower part of the map sheet contains imprints and scale. The scale in text and graphical form is completed by information about contour interval and indication of magnetic declination and imprints. Imprints contain technical information.

Left imprint contains:
- Name of editor and quotation of the map.
- Co-authors (names).
- Editor-in-Chief and Technical Editor (name(s)).
- Technical processing (name(s)).
- Approval (name of responsible person, date).

Right imprint contains:
- Information about map projection and coordinate system.
- Copyright for topographic base.
- Copyright for geological data.
- Name of workplace, year of processing.
- Number of prints.

4.4 The lithostratigraphic scheme

The lithostratigraphic column shows the stratigraphic (chronostratigraphic) sequence of lithostratigraphic units observed on the surface or, based on drilling data and geophysical measurements, inferred to be present on the map sheet down to a depth of approximately 1 km, even if these units do not appear at the surface on the map or in the geological cross-section. The separate geochronological columns are compiled for different lithotectonic units.

As a rule, the lithostratigraphic column includes only sedimentary, extrusive and the low-grade metamorphic rocks arranged according to their relative ages and the law of superposition. In areas with a complex tectonic structure, it is desirable to compile a separate lithostratigraphic column for each tectonic unit.

Igneous and metamorphic events could be depicted in separate columns if the age is known.

Lithostratigraphic units are arranged in the column according to stratigraphic sequence in accord with the actual International Stratigraphic Chart of the International Commission on Stratigraphy (http://www.stratigraphy.org). If the local lithostratigraphic units cannot be correlated with chronostratigraphic units of the International Stratigraphic Chart, then reference should be made to a published regional stratigraphic column.

Estimated thickness of a unit and important stratigraphic hiatus, fossils, fossil soil or weathering horizons are also depicted.

4.5 The geological cross-section

A geological cross-section without vertical exaggeration is constructed to depict the inferred geological structure to a depth of 1–2 km (according to scale). This will vary depending on the characteristic features of the geological structure of the mapped area.

If possible, the line chosen for the geological cross-section should run perpendicular to the strike of the principal structures and rock units shown on the map sheet, passing through important elevations and boreholes. The section can be bent to pass through chosen points or significant topographic features, but unnecessary bends in the line of section should be avoided. The total length of the geological cross-section must not be longer than the length of a diagonal of the given map sheet. Starting and terminal points should be placed on the map margins. The starting point is situated in the more western part of the cross-section.

All rocks, geological boundaries of units and tectonic structures crossed by the line of the section should be depicted. The Quaternary cover is only shown when thick enough to be depicted at the scale of the cross-section.

4.6 List of authors

The names of geologists who have contributed to the original mapping of the sheet are shown together with the areas for which they are responsible. Sectors newly mapped, updated or taken from other sources should be distinguished. The individual areas are numbered. Under each of these numbers, the name of the contributor and the period during which the mapping was done are shown in the accompanying legend.

4.7 Summary of the geological units

The defined regional geological units and important faults shown on the map sheet are summarized here. Terms used should match those used in the legend to the geological map.

4.8 Map sheet index

The index map depicts position of the map sheet in State topographic base map and the scheme consists of two parts. The first part depicts the distribution of map sheets of the smaller scale within the territory of the State showing the map sheet on which the given base map lies. The second part shows the position of the given map within the small-scale map sheet.

5) DATA SOURCE

The data needed for compilation of a geological map vary in scale and purpose of the map. In general, they are (1) archival from the previous research and new data originated during the mapping process directly in the field or in laboratories.

Archival data are important for the preparation of geological project. They comprise older maps and reports, publications, boreholes, analytical or geophysical data, aerial photos as well as satellite imageries. They are available in the State geological archives and in archives of geological companies in printed, and more frequently also in digitalized versions.

5.1 Field data

Geological mapping is the process of making observations of geological phenomena in the field and recording them. Following the definition of a geological map, the field data are crucial for the map compilation. The information recorded in the field must be factual, based on objective examination and made with an open mind. Field documentation comprises:

- Documentation in a topographic map.
- Field notebook.

Documentation in a topographic map

The primary objectives of geological mapping are to locate and identify contacts between the rocks and geological units.

Traversing is a basic method of geological mapping. It is made by walking a more or less predetermined route from one point to another, plotting the geology on the way. The rocks (formations) exposed in the field in the form of outcrops or fragments are marked on topographic map by colours or agreed symbols as a line (track) along the traverse. Quaternary cover is marked as an area. The information is completed by a handmade pencil remarks as the position of reference point, tectonic symbols, geomorphological features related to geology, springs, man-made excavations and other supplementing data. Concurrently, traverse could be saved as a track in GPS device or using suitable application in Smart Phones.

Geological (mapping) tracks should be oriented perpendicular to the main geological structures on a map and are organized in two stages. The orientation of regional geological structures is depicted from the older general maps or from the satellite imagery. During the first stage, regional transects are conducted to reveal the main mappable lithological and lithostratigraphical units (formations) and boundaries between them. In the second stage, more detailed information is collected by a combination of traversing (going perpendicular to the contacts) and contact followings (tracing boundaries between different rocks formation).

The distance of individual traverses depends on the map scale and complexity of terrain and geological structure of the area. Generally, it is at least one hundredth of the scale. It means that on a map at a scale of 1 : 50,000, the distance between traverses is 500 meters at maximum.

Field notebook

Field notebook and pencil is as important as hammer or geological compass for a geologist. The purpose of the field notebook is to expand information in the field map. Localization, geological data, geomorphological observation, number of samples and its labels, remarks about terrain accessibility, hand-made pictures as well as non-geological information are recorded in the notebook. The most important part of the notebook is the description of various kinds of geological exposures. The notebook must be consequently linked with the field map by unique label for each reference point.

Together with the remarks in the map, records in the notebook will form the basis of fair copy of the geological map and written report. These data are also stored in geological archives for future geological works. It means that the notebook must be well-organized and legible.

Some geological companies replace standard notebooks by documentation cards with predefined fields (Fig. 9), which are useful mostly in ore prospecting, geochemical exploration, mineral exploration or in applied geology.

5.2 Laboratory data

Laboratory work follows the field work and helps to classify rocks and to reveal their genesis and age. Samplings differ according to the used method. As a standard, the rocks are generally described on the outcrop based on visual observation (basic composition, colour, grain size, texture), supplemented by sampling for documentation as well as thin section analysis if needed at later stage.

GEOLOGICAL SURVEY OF THE MONGOLIAN ALTAI

Sheet No.	Point No.	N	E	Z

Type of outcrop:	Localisation:	Author:
Type of sample:		Date:

Valley:	Stream gradient:	Grain size:

Fm.	Rock	Grain size	Composition	Alteration	Tectonics

Ore minerals:	Fossils:
Other observations:	

Figure 9. *An example of a field documentation card used by the Czech Geological Survey in Mongolia.*

All samples and results should be related to the reference points and are stored in separate tables according to the methods used.

According to the results of laboratory works, the classification of rocks are decided and interpret the origin and evolution of the rocks. Geological mapping uses a variety of analytical techniques to classify and interpret the origin of rocks:

- Determination of the mineral composition of rocks.
- Determination of the chemical composition of minerals.
- Determination of the chemical composition of rocks.

Methods of determination of the mineral composition of rocks

The choice of sample for a thin section depends on the grain size of rocks and structure of the rock (e. g. foliation). Fresh samples of about 6 × 9 × 3 cm size are generally preferred. Hand specimens for structural studies should be oriented in the field. For the mineral separation, usually samples weighing 2 to 10 kg in total are prepared.

(a) Thin section is about 0.03 mm thick sliver of rock glued on glass slide. Except the rock, it can be made of mineral or soil and was used with a polarizing petrographic microscope (standard cover thin section) or electron microprobe (polished thin section). Thin section is used for identification of the mineral composition of rocks and abundance of minerals in the rocks (modal composition).

Polished thin sections are different from the thin section in that they are extra ground to create smoother surface removing even smaller irregularities. These are usually not covered with glass cover but directly put under microscope for observation through reflected light from the top rather than transmitted light from underneath the stage of the microscope, as in the case of think sections. These are used mostly for opaque minerals and also for electron microprobe analysis of specimen under direct bombardment with electron beams.

(b) For **separation of minerals** from unconsolidated sediments or crushed rock, we use several methods such as magnetic, gravitational, flotation and partial dissolution techniques (isolation or concentration of a certain type of grains from the sample). For example, heavy minerals are fractionated using a heavy liquid (e.g. lithium heteropolytungstate, LST, with density of 2.85 g/cm^{-3}). Mineral grains are examined in both transmitted and reflected light modes using binocular microscope. Selected grains are usually sufficient for XRD, WDS or EDS analysis.

Methods of determination of the chemical composition of minerals

For the precise classification of rocks and for the interpretation of evolution of hydrothermal veins, information about the chemical composition and chemical zonation of mineral phases are useful. All analytical data must be fully documented in the database and linked with hand specimen and thin sections.

(a) X-ray powder diffraction (XRD) is useful for identification of monomineral crystalline phases (with a grain size up to several mm) and identification of fine-grained mixture of minerals such as clays. Only several grams of mineral phases are sufficient (sample is ground to fine powder).

(b) An **electron microprobe** (EMP) is used to determine the chemical composition of minerals in polished thin sections. The thin section surface is bombarded with an electron beam and emitting x-rays from a small area (few microns) at wavelengths characteristic for the elements being analysed. For interpretation of X-rays, WDS or EDS detectors can be used. An energy-dispersive (EDS) detector is used to separate the characteristic X-rays of different elements into an energy spectrum. For providing fundamental compositional information, it is useful to create element composition maps (show the spatial distribution of elements in a sample). This method allows simultaneous analyses of multiple elements in short time, although with low precision. A wavelength-dispersive (WD) spectrometer is used to isolate the X-rays of interest for quantitative analysis. The advantage of WDS is the better sensitivity in comparison to EDS.

(c) The **Mössbauer spectroscopy** is used to examine the valence state of iron, (Fe, Fe^{2+}, Fe^{3+}), as well as the type of coordination polyhedron occupied by iron atoms. We need several grams of pure mineral phases (sample is ground to fine powder).

(d) Optical cathode luminescence permits optical examination of polished thin sections. Cathode gun (special equipment for optical microscope) bombards the sample with a beam of high-energy electrons, which generate luminescence in minerals without Fe (e.g. feldspars) and allows us to see textures and compositional variations.

Methods for determination of the chemical composition of rocks

According to the whole-rocks chemical composition, types of rocks, their genesis and evolution are determined. For the geochemical analysis, fresh chips of rocks are usually prepared, weighing 2 to 10 kg (depending on the grain size and homogeneity of samples). In the laboratory, samples are ground to a fine powder and homogenized. Laboratories usually use jaw crushers to reduce sample particle size and finally, the sample is pulverized in an agate planetary mill to a grain size < 0.063 mm (for the analysis, we need only 5 to 20 g).

(a) The X-ray fluorescence (XRF) works on wavelength-dispersive spectroscopic principles. It is a relative low-cost and widely used method for bulk chemical analyses of major (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P), minor and trace elements (in abundances >1 ppm; Ba, Ce, Co, Cr, Cu, Ga, La, Nb, Ni, Rb, Sc, Sr, Rh, U, V, Y, Zr, Zn) in rocks and soils. Measurements by XRF are carried out directly on the solid material (about 1 g of the powdered sample was pressed to the tablet). The detection limit is 10 ppm for W using XRF, and 0.05 ppm for W using ICP-MS.

(b) Instrumental Neutron Activation Analysis (INAA) is used to determine the concentration of major, minor and trace elements. A sample is subjected to a neutron flux and radioactive nuclides are produced. Comparison of the intensity of gamma rays (product radioactive nuclides decay) with those emitted by a standard permit is necessary for a quantitative measurement of the concentrations of various nuclides (analyse numerous elements simultaneously). The main advantage lies in very low detection limits and small sample sizes (1–200 mg), but several elements (Y, Rb, Sr, Y, Nb, and Zr) are better determined by other analytical methods (XRF).

(c) Inductively Coupled Plasma Mass Spectrometry (ICP-MS) combines a high-temperature Inductively Coupled Plasma source (converts the atoms of the elements in the sample to ions) with a mass spectrometer (Ag, As, Au, Bi, Cd, Cu, Hg, Mo, Ni, Pb, Sb, Se, Tl, Zn, Ba, Be, Co, Cr, Cs, Ga, Hf, Nb, Ni, Rb, Sc, Sr, Ta, Th, U, V, W, Y, Zr, REE).

(d) Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) is used for the simultaneous detection of multiple elements. Samples are introduced into the plasma during a process that produces excited atoms and ions. The constituent elements can be identified by their characteristic emission lines, and quantified by the intensity of the same lines. A high sensitivity is typical (low limit of detection for the majority of elements is 10 ppb or lower) and elements that are difficult to analyse in atomic absorption spectrometry such as Zr, Ta, rare earth elements (REE), P and B can be easily analysed.

(e) Atomic absorption spectroscopy (AAS) is an analytical method based on the absorption of UV or visible light by gaseous atoms. The sample becomes atomized by injecting a solution into a flame. Atoms in the flame absorb the wavelength sent by the source of light. The absorption of light from a hollow-cathode lamp is proportional to the concentration. Generally lower detection limits than in ICP-OES.

(f) Other methods of analysis of geological materials are CV AAS (Cold vapour atomic absorption spectrometry), DCP AES (Direct current plasma atomic emission spectrometry), DCP AES (Direct current plasma atomic emission spectrometry), ETAAS (Electrothermal atomic absorption spectrometry), FAAS (Flame atomic absorption spectrometry), FAES (Flame atomic emission spectrometry), HG AAS (Hydride generation atomic absorption spectrometry), IC (Ion chromatography), ICP AES (Inductively coupled plasma atomic emission spectrometry), ID ICPMS (Isotope dilution inductively coupled plasma mass spectrometry), ID TIMS (Isotope dilution thermal ionization mass spectrometry), LA ICP MS (Laser ablation inductively coupled plasma mass spectrometry), PGAA (Prompt gamma activation analysis), PIXE (Particle-induced X-ray emission), RNAA (Radiochemical neutron activation analysis), and TIMS (Thermal ionization mass spectrometry).

Further reading

Rollinson R. (2014): Using Geochemical Data: Evaluation, Presentation, Interpretation. Routledge, 384 pp.
White M. W. (2013): Geochemistry. Wiley-Blackwell, 668 pp.

5.3 Palaeontology

Paleontological data are crucial for stratigraphic ranking of sedimentary strata and depiction of palaeoenvironmental conditions during sedimentation. Macrofossils could be preliminarily identified in the field, but for precise determination, cleaning and separation of fossils from the host rocks is important. The process of cleaning, repairing and removing excess rock from a fossil is known as preparation. Generally, only preliminary cleaning or trimming is done in the field, so that more careful preparation work may be done later in the laboratory. Final determination of particular species and their stratigraphical age must be done by experts.

Micropalaeontological studies providing a large amount of information about the floral or faunal assemblage. Laboratory processing is very important. Different sample preparation techniques for a micropalaeontological analysis can be used depending on the required result. For palynomorphs, calcic plankton or diatomites very different procedures and chemicals are used. The most important techniques include:

- Washing and sieving
- Disintegration in liquids
- Leaching in chemical solutions.

Further reading

http://www.geotop.ca/upload/files/publications/cahiers-de-laboratoire/Micropal_Methods_2010.pdf
http://www.jpaleontologicaltechniques.org/
http://preparation.paleo.amnh.org/
http://paleobiology.si.edu/fossiLab/projects.html
http://preparation.paleo.amnh.org/assets/Madsen1996Microvertebratepreparation.pdf

5.4 Data archive

Geological maps and reports are traditionally stored in national geological archives, which are massively scanned and converted to the PDF (Portable Document Format) documents. Maps are digitalized and converted to the form of GIS-compatible products, which allows them to be available on line.

Laboratory data are commonly stored in a table form that can be easily linked with the GIS projects. The most complicated task is the processing of field geological data conversion into the usable database, mainly because the fact that field notebooks contain a lot of unclassified information. In all cases, the relational database (a set of related tables) is the most preferred tool for storing the geological field data and which can also be linked to a GIS database. There are many professional or open-source software systems available (commercial: ArcMap and ArcSDE; freeware PostgreSQL rel. database with the PostGIS extension, Q-GIS package, etc.).

The structure of the database (hierarchy of individual tables) depends on the purpose of the field work (geological mapping, ore prospection, geochemical exploration, mineral exploration, hydrogeological investigation, geo-hazards zonation, pedological mapping etc.). But some attributes such as the localization and the rock description are common in all cases. While there exist various professional software used in ore prospecting or mining (e. g. Surpac, RockWare, Vulcan, Micromine, Petrel etc.), a universal database or system for general geological mapping purpose are missing.

The basic conceptual scheme representing the field data record is shown in Fig. 10. All the arrows in the diagram represent 1:N relations. It means that more than one rock can be exposed at one site, and we have more than one structural measurements or samples in one rock.

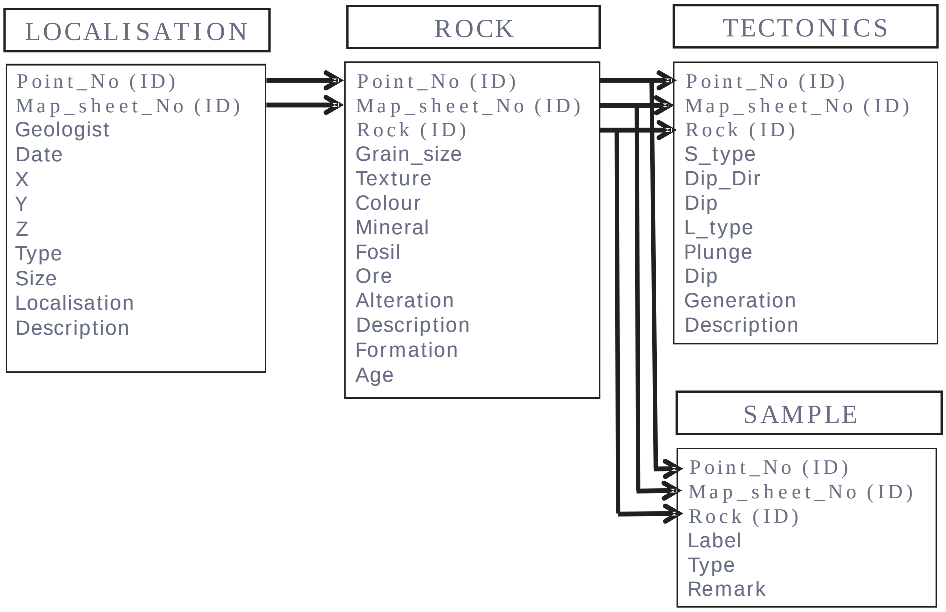


Figure. 10. *Diagram of the tables and their relationships in the database of geological reference points.*

6) GEOLOGICAL FIELD TECHNIQUES

Fulfilling essential, basic field equipment and psychological readiness are two important qualities ever since the first prospectors started geological mapping, with open eyes and mind to make notice of precise field observation. The basic geological equipment are geological hammer, geological compass that possess inclinometer and bearing measurement functions, topographic base map and the field notebook together with pencils. Pocket or handheld GPS device (including applications in Smart Phones) help with the orientation in the field and precise localization of geological documentation.

Geological documentation is a basis for the compilation of geological map; it should be precise, legible and complete, especially in remote areas where it might be impossible to return back to. Traditionally, rock outcrops are subjects of geological documentation, but in poorly exposed areas, documentation of boulders and rock fragments in debris is alternatively employed. The number of documentation points in the map depends on the complexity of geological structure and is usually defined by standards of the local geological authority. Description of the outcrop, starts with a general overview, looking at the main rock types, boundaries between them and dominant structural phenomena. Then study and description of rocks and structures in detail including hand-drawn sketches and photographs are made. Sampling is always conducted in the end. The contents of exposure description include:

- Localization.
- Description of rocks and contacts.
- Tectonics.
- Samples.
- Sketches and photographs.

The description of exposure should follow the structure shown in documentation table in Fig. 10.

6.1 Localization

Localization must be marked (cross is the most common symbol) in the field map and linked with the description in the notebook by a unique Identification code (numbers and letters) label.

Point No is a label, which must be unique in the frame of a map sheet or a project. In the ideal case a combination of letter(s) which can indicate the author's name and incremental number (e.g. *KV001*) should be used.

Coordinates obtained by handheld GPS device can be written in WGS format (decimal degrees are ideal for GIS processing or in the local coordinate system).

Localization defines the type of outcrop (rock, road cut, river bank, block, debris, stone pit, shaft, spring, well, etc.), size (length/height/width), position (distance and azimuth) related to the important geographical point named in a map sheet.

Description summarizes an overview of geological phenomena and relationships between rocks observed on outcrops.

Using Global Position System (GPS)

Location of documentation points and tracks on a map can be time-consuming, especially in the general map, forest or rugged terrain. The excellent tool for effective orientation in the field is represented by the Global Position System (GPS). The usage of hand-held GPS device has become wide-spread since May 2000 when the directive of President Bill Clinton and the U.S. Government ended the Selective Availability of GPS that intentionally degraded civilian accuracy on a global basis. Global Positioning System is based on receiving radio signals from orbiting satellites. GPS is a constellation of 24 or more satellites flying 20,350 km above the surface of the Earth. Once a GPS device knows its distance from at least four satellites, it can use geometry to determine its location on the Earth in three dimensions.

The modern hand-held devices can receive signal not only from the U.S governed GPS, but also from the Russian system GLONAS. GPS-enabled smart phones are typically accurate within 5 m. High-end users boost GPS accuracy with dual-frequency receivers can enable real-time positioning within a few centimeters, and long-term measurements at millimeter scale.

The first meters accuracy, availability and pocket size made the GPS an attractive tool for a mapping geologist in:

- Precise localization of documentation points.
- Recording of geological traverses with remarks on rocks.
- Precise location of boundaries between units.
- Storing of geological data (including map) for using them in the field.

The standard coordinate system of GPS is WGS 84, but the setting of device allows using many other projection and geographical coordinate systems. Every GPS device manufacturer provides software for the communication of device with PC. Google Earth by Google is the easiest way how to see the field GPS data on a map or satellite imagery. Modern GIS software enables direct communication with GPS data in GPX format and professional processing of data.

GPS provided Smart Phones can offer greater comfort in using a suitable GPS application (e.g. Soviet Military Maps, Oruxmaps, Locus), which allow downloading various topographic and satellite maps and are able to communicate with a geological database more easily than the standard GPS.

GPS-based electronic devices are tools effectively improving the geological field work, but it is not worthy to absolutely rely on it. Paper map, notebook and pencil are still the best recording media in the field.

6.2 Rock and lithological description

Rocks

Rock is a basic unit of geological mapping, but in many cases, single rocks are not mappable at a given scale and are grouped into geological (lithostratigraphic) units. In most cases, only part of a geological unit is represented by just one rocks type at an outcrop.

Rock name when finally confirmed should conform with the international classification scheme (Appendix 3) and that name should be used to archive in the relevant database, while descriptive field names should be kept only in field notebooks ("*red spotted massive rock*").

Grain size description and classification should correspond with the international standard being used differently according to the origin of the rocks such as in cases of crystalline: massive, fine-, medium-, coarse-grained and in case of sedimentary rocks: clay, silt, sand, gravel.

Texture is dependent on mutual relationships (size, arrangement and homogeneity) of rock forming particles.

Colour is subjective and influenced by hydrothermal and weathering processes. Nevertheless, colour is characteristic for some rocks and formations.
The composition of rock is described according to the rock-forming **minerals** visible by a naked eye or using lens, occurrence of **ore minerals** and hydrothermal **alterations**.
In sedimentary rocks, the composition of rock and **fossil** fragments should be described.

Formation (a geological unit composed of a specific sequence of rocks) and **age** (if known) should fit with the regional classification of an area. Working (temporary) names are common in field notebook which should be formalized as the mapping progresses. Additional information completes the **Description** of a rock.

Lithology

Rock descriptions are the essential part of geological mapping. This work combines all field and laboratory observations. The name of rocks and mineral composition recorded in the field notebook of documented outcrops can sometimes differ from the laboratory results, in particular those of mappable rocks (a rock that can be distinguished in the field by a naked eye).

In all cases, each rock and relationships between recognized rocks must be systematically described on the outcrop. The description of lithology must proceed from the oldest to the youngest. Describe the colour of weathered and fresh rocks. Note the degree of weathering and/or alteration, mineral composition, texture, grain size and the relationship between grains. Finally, choose an appropriate name for each rock on the outcrop (Appendix 3). The name of the rock should be descriptive (e.g. porphyritic medium-grained red muscovite-biotite granite). According to the results of laboratory works, we can choose the final name of rocks and interpret their origin.

6.3 Tectonics

Field observation and precise description of structural elements including the insight to their relationship is a key to drawing a geological map. Generally, small-scale structures (bedding, foliation, fold, joint, lineation etc.) can be seen at the outcrop, while regional structures (faults, synclines, anticlines, domes etc.) are depicted mainly by geological mapping or interpreted based on the remote sensing data. Planar (**S type**) and linear (**L type**) structures are distinguished among the small-scale elements.

There are two dominant ways how to measure the orientation (position towards geographic North) of tectonic elements (Fig. 11). The easiest method is to measure **dip-direction** and **dip** for planar elements and **plunge-direction** and **plunge** for linear elements (all in degrees) in one-step by the Freiberg type of geological compass.

As many observed planar structures and associated linear fabrics as possible should be measured from every locality documented in the field. Planar structures commonly encountered might include bedding, cleavage, foliation, lineation, fold limbs, joints, etc. and linear fabrics could be any of sedimentary or metamorphic lineation, linear preferred orientation of magmatic minerals, fold axis, striations on fault planes, etc.

The measurement can be plotted as a tectonic symbol in the field map showing the trend: strike and direction in case of planar fabric and plunge direction in case of linear fabric and each labeled with dip amount in degrees. Measurement in the field of any structural record should be written following the format, dip direction/dip (e.g. 180/45) in field notebook. Traditional abbreviations are used for the description of various types of structures. S is the general label for planes, L for lineation, B for fold axis, D for dislocation and J for joints.

It is important to observe relative relationships between structures and to reveal various generations (e.g. S_0, S_1, S_2) of structural elements.

Field structural measurements and data processing

Brief summary of basic methodological approach to geological structures description is given in this sub-section including interpretation and the overall assessment of tectonic pattern of the mapped area. These data are essential for the geological map, cross-section and lithostratigraphic scheme processing.

Fabrics or structures in rocks are divided into primary and secondary ones. The **primary fabrics** are associated with the genesis of the rock predominantly visible in the sedimentary and igneous rocks (e.g. bedding, magmatic foliation). **Secondary fabrics** (metamorphic foliation, cleavage) can be identified mainly in the metamorphic rocks. There is also a specific group of superimposed fabrics, usually observed in all types of rocks (e.g. cleavage, shear zones, faults and joints) which are of brittle-ductile and brittle nature. The origin of superimposed structures is mainly associated with the changes of regional stress field.

Fabrics are also divided as (a) **structures of sedimentary units**, (b) **ductile structures** including the fabrics of metamorphic and igneous rocks, (c) **brittle-ductile structures** (e.g. low-temperature shear zones) and (d) **brittle structures** (faults and joints).

Fabrics and structures in the geological map

Based on the shape parameters, planar and linear structures are distinguished:

- Planar structure is a descriptive (non-genetic) term for any planar structural elements in the rocks (bedding, foliation, layering, compositional banding, cleavage, fault plane, etc.).

- Linear structure is a descriptive (non-genetic) term for any linear element visible in the rocks. Several types of lineation in the rocks can be distinguished (e.g. mineral lineation, elongation lineation, crenulation lineation, etc.).

Classification based on the type (character) of structures:
- Sedimentary structures are formed during the formation of strata and they reflect either linear or planar preferred orientation (e.g. sedimentary bedding).
- Magmatic structures are formed during the flow of minerals or rock fragments or crystallization of magma after its emplacement. It marks the preferred spatial orientation of rock-forming minerals and lithic fragments (linear, planar), which are created by different processes in the presence of melt. Magmatic structures show the absence of deformation and recrystallization (e.g. magmatic foliation, magmatic lineation).
- Metamorphic structures are formed due to the recrystallization and/or the deformation under ductile or brittle-to-ductile conditions. The geological map should depict metamorphic or deformation fabrics such as metamorphic foliation and/or lineation, cleavage, fold axis, etc.

All the structures described above should be displayed with special oriented symbols at the corresponding positions to those observed in the map. This point mark carries the information about the strike, dip-direction and dip angle and the type of structure.

Brittle structures such as faults and fault zones are marked in the map by linear tectonic marks, which reflect the trend of the structure in the map. The known size of fault dip or even the orientation of striation is depicted by a point tectonic mark. This point mark carries the information about the strike, dip-direction and dip angle of the planar structure, and possibly also the kinematics (sense of movement, such as normal fault, reverse fault, strike-slip fault) and the accompanying deformational features (e.g. mylonitization).

Faults can either be observed, inferred or obscured. When tectonic boundaries are precisely identified and documented, mutual displacement of lithological boundaries will show up. Tectonic boundaries can be observed in the field or verified and documented by technical or geophysical methods and are drawn on the map with solid lines. Inferred faults can be drawn even when not sufficiently verified, as long as an apparent justification can be made from the structural relations. Obscured faults are, on the other hand, drawn to depict the estimated course of faults below the younger undeformed sedimentary cover often traced as a broken or a dashed line on the map.

The spatial orientation of structural elements is described in the form of dip-direction and dip angle. This description is supplemented with references to orientation diagrams in Lambert equal-area projection on the lower hemisphere, where all characterized tectonic data should be graphically illustrated.

Field structural data record format

Two conventions how to display the structural data exist (Fig. 11):
- Direction of dip (0 to 360°) and angle of dip (0–90°); for example: 269/45.
- Strike-direction given as azimuth (0 to 360°) followed by dip angle (0–90°) and the direction of dip given as the cardinal direction; for example: 143/76 SW. Provided that the planar structure is defined by using two angles (dip-direction and dip), the intersection line of the generally inclined geological structure with the hypothetical horizontal plane "h" is referred to as the trend (strike) of the geological planar structure

(Fig. 11). On the other hand, the intersection of the vertical plane "v" perpendicular to the geological planar structure direction is referred to as the dip direction. If the dip direction extends the vertical plane and marks its intersection with a horizontal plane, then the dip direction of geological surface is the azimuth of the intersection line (angle in the range 0–360°). The dip of geological surface is the angle between the horizontal plane and geological surface (measured in the vertical plane, ranging between 0–90°). Linear structure is defined by two angles (plunge-direction and plunge). The hypothetical vertical plane "v" is parallel to the lineation. Then the plunge-direction is defined as the azimuth of intersection line between "v" plane and horizontal plane (angle measured in the 0–360° interval). The plunge is the angle between the intersection line and linear structure (measured between 0° and 90°).

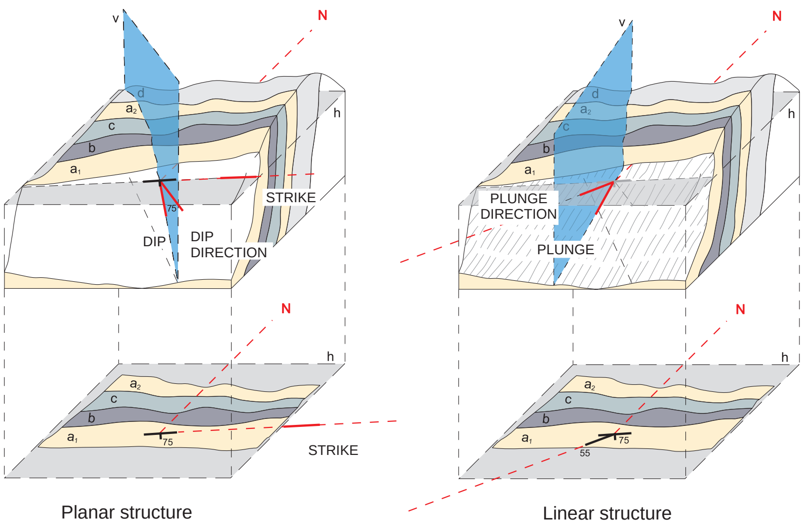


Figure 11. *The principle of measuring the orientation of linear and planar structures and their presentation on the geological map.*

A uniform terminology must be used when describing the structures and fabrics in accordance with the use of tectonic marks on a geological map. Structures of brittle-to-ductile and brittle tectonics are described for all units altogether. Exceptions are for extensional joints in the bodies of igneous rocks, which should be described separately.

Evaluation and presentation of structural data

Field structural data can be evaluated by several software such as for example SPHERISTAT and STEREONET using the Equal-Area projection (Tab. 2) to the lower hemisphere. Both are easy-to-use utility for entering structural field measurements (either axial or polar vector) in a tabular form and can be plotted in a variety of ways: on a stereonet, on a map using a structural symbol set, or on a circular (rose) diagram. Each plotting method creates additional advantages to extract more information from the data set.

Usually, one structural element (e.g. metamorphic foliation) is displayed in one diagram. If the differentiation of partial development stages of one structural element (e.g. types of metamorphic foliation) is necessary, it can be made graphically (by assigning particular colours).

All tectonic diagrams should conform to certain logical grouping to clearly show differences in partial structural domains.

Table 2. Characteristics of the equal-area projection

Projection	How Projected	Advantages	Drawbacks	Uses
Equal Area	Draw arc from a point on sphere to the plane	Area conserved, moderate distortion	Curves are complex	Structural geology, for the statistical analysis of spatial data

http://www.uwgb.edu/dutchs/structge/labman.htm
Spheristat TM 3.1 *http://www.pangaeasci.com*
Stereonet 8 *http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html*
SG2PS *(Sasvári and Baharev, 2014)*
OATools *(Kociánová and Melichar, 2016)*

Planar fabrics

Two alternatives are used to plot planar fabrics on the lower hemisphere of the equal-area stereographic projection, mainly depending on the amount of field data. These are either circles (arcs) or poles. Poles are the projections of orthogonal lines to the planar fabrics on the lower hemisphere stereographic projection.

Circles (arcs) are traces of the lines of intersection between the planar geological structural surfaces and the lower hemisphere stereographic projection, which can be used to plot in cases where only few data measurements are made and to show some relations between structures such as fault planes and kinematic indicator linear features appearing as points on the fault planes (striations). **Poles to Planes** are used alternatively when a large amount of field structural data are used. Hence, imaginary lines drawn perpendicular to the measured planar surface form a dot when they intersect the lower hemisphere stereographic projection after passing through the planar surface at right angle plotting on the opposite side of the stereogram (Fig. 12). This consistent mechanism allows plotting several measurements to show in one diagram.

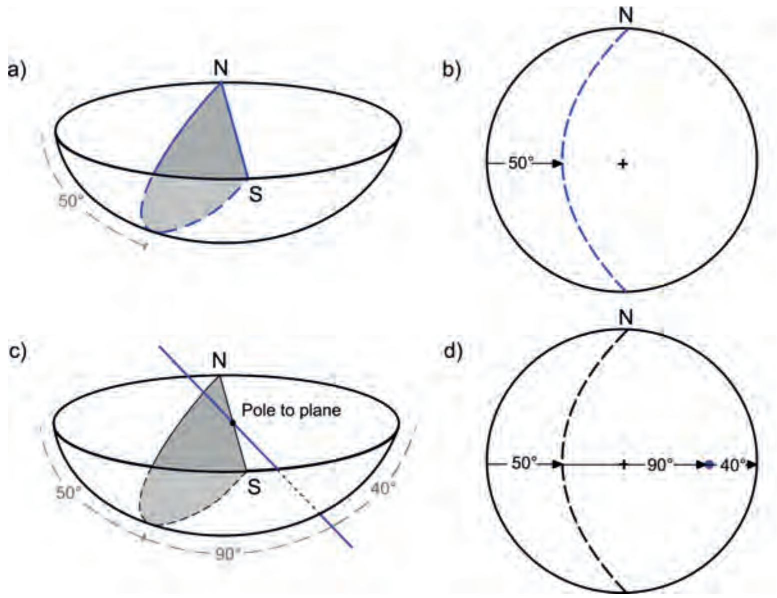


Figure 12. *Projection of N–S striking and 50° W dipping plane. (a) – Oblique view; (b) – Equal-area projection. Projection of the pole toplane; (c) – Oblique view; (d) – Equal-area projection (after Rowland et al. 2013).*

Steeply dipping planar structures are hence represented by points (poles) that lie closer to the edge of the stereographic projection plane (equator), which is opposite to the sense of the case in the great circle plots. On the other hand, planar features that are gently dipping or subhorizontal will have the poles to their planes plotted near the center of the stereographic projection plane (equator).

Linear fabrics

When the structures to be displayed are linear features, these are directly represented as dots on the stereographic projection (Fig. 13).

Points are dots plotted on the lower hemisphere equal-area stereographic projection plane (equator) for linear features. It must be distinguished from poles to planes mentioned previously as those are the projections of imaginary lines orthogonal to the planes being represented, which are introduced to avoid cumbersome display of arcs representing planar features (Fig. 13).

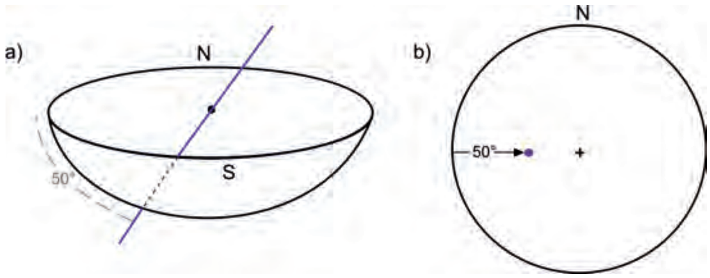


Figure 13. *Projection of a line plunging 50° to the west (after Rowland et al. 2013).*

In this case (linear features represented as dots), however, as the orientations of actual linear features are presented, they must be seen and/or considered differently. These are the intersections of actual linear features when viewed directly projected down onto the lower hemisphere of the stereographic projection forming a dot on the equatorial plane. Points located near the centre of the circle hence correspond to lineations with steep inclination or plunge, while those plotted near the edge of the stereographic projection plane (equator) are lineations having gentle or horizontal plunge.

Rose diagrams are used to summarize and highlight frequent measurements in the space of the principal **directions** or **azimuth.** Examples of these types of data include dips of joints, bedding planes, etc.

Further reading

Davis H. G., Reynolds J. S (1996): Structural geology of rocks and regions. John Wiley & Sons, 776 pp.

Haakon F. (2010): Structural geology. Cambridge University Press.

McClay K. R. (2013): The mapping of geological structures. John Wiley & Sons, 168 pp.

Kociánová, L., Melichar, R. (2016). OATools: An ArcMap add-in for the orientation analysis of geological structures. Computers & Geosciences, 87, 67-75.

Ramsay J. G., Huber M. I. (1987): Modern structural geology. Academic Press, Vol. 2.

Ramsay J. G., Lisle R. J. (2000): The techniques of modern structural geology. Academic Press, Vol. 3.

Sasvári, Á., and Baharev A. (2014) „SG2PS (structural geology to postscript converter) – A graphical solution for brittle structural data evaluation and paleostress calculation." Computers & Geosciences 66 (2014): 81-93.

Rowland, S. M., Duebendorfer, E. M., Schiefelbein I. M.. Structural analysis and synthesis: a laboratory course in structural geology. John Wiley & Sons, 2013.

https://www.fault-analysis-group.ucd.ie/

http://structural-geology.org/

https://en.wikipedia.org/wiki/Geological_compass

6.4 Sampling

Sampling is an important part of any geological work, including mapping. Firstly, samples serve for the comparison of similar rocks from different outcrops. Secondly, they are collected for subsequent laboratory analysis. The size and quality of a sample depends on the laboratory analysis. Laboratory results help to describe and distinguish rocks and geological units depicted on the map.

A sample should be labelled by a point number (by a permanent marker on the rock). Paper label (and a note about the sample in notebook) must be completed by information about the **type** of sample (petrography, geochemistry, physical properties, palaeontology, palaeomagnetism, radiometric dating, etc.), the name of geologist and date of sampling (Fig. 14 and 15). More samples from one outcrop used for the same purposes should be **labelled** by an additional letter (e.g. *KV001-A*).

6.5 Illustrations and photographs

Good illustration and photographs complete the geological description of an outcrop in the field, but the most important role of a picture is to display the relationship of rocks, tectonic features and their relationships, position of samples and photographic details.

Sheet No.	**Point No.**
Type of sample:	
Date:	**Author:**

Figure 14. *An example of a sample card used by CGS in Mongolia.*

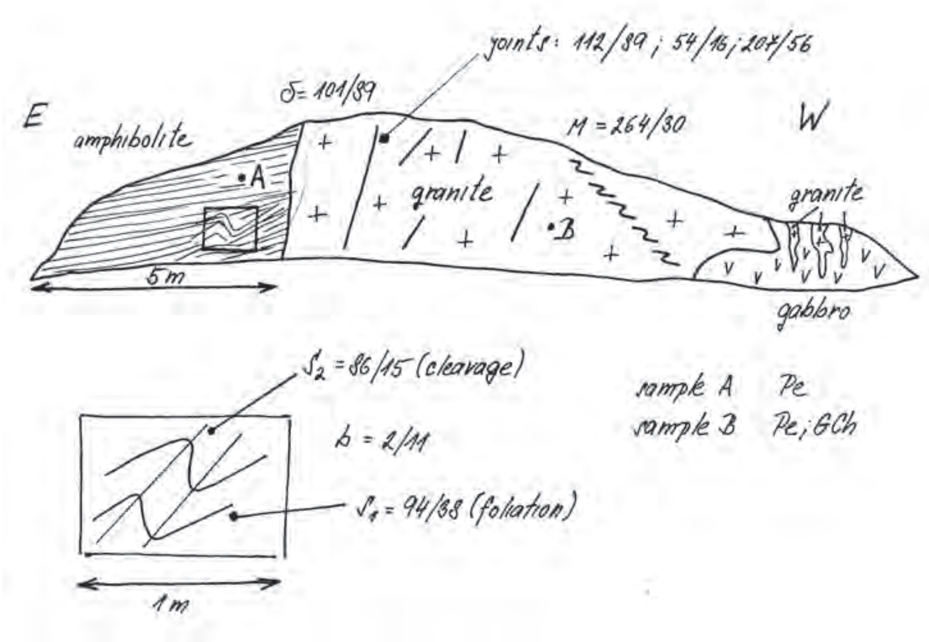
Figure 15. *An example of a sample label used for geochemical prospection in the Lesser Caucasus.*

The picture is schematic (Fig. 16) and should contain at least:

- Scale and orientation.
- Situation of rocks distinguished by various hatching.
- Character of boundaries by various lines.
- Position of important structural elements with their orientation.
- Situation of samples.
- Situation of details.
- Text remarks.

Photographs do not replace illustrations, but supply them. An overview picture of the outcrop and photographs of important textures and structures all should be made; besides, it is also useful to make a macro photograph of rocks during the map compilation. The scale is an important part of each picture. Do a remark in notebook with a number of snap shots for the arrangement of photos, which could be subsequently linked with database.

Figure 16. *An example of outcrop illustration.*



7) COMPILATION OF GEOLOGICAL MAP

A geological map is a scaled-down diagram of the Earth`s surface based on available and surveyed field data record. Generally, the geological map must be as close as possible to the real world and be comparable and legible. To produce such maps, the geologist should stick to sets of rules concerned with field observations, field data processing and final compilation of the map.

Map compilation is a process of interpreting factual data in space and time, and eventually plotting the results on plain sheet of paper. It means that much of the information gathered during the mapping is not transferred to the manuscript. The general rule is to show any features which add to the understanding of the geology and geological history, and to omit those that do not. The criterion of what to show is mainly a matter of common sense and experience.

Among the parts of the geological map, geological legend must be compiled at first.

7.1 Legend

Legend is a column in the map, which explains the meanings of all colours, hatches, lines and symbols used to represent geological features on the geological map, cross-sections and lithostratigraphic column.
Assembly of the legend to the geological map take the following into consideration:

a) The legend must include all features shown on the geological map, the geological cross-section and the lithostratigraphic column. If some of these features appear only in the lithostratigraphic column or in the geological cross-section then this should be indicated in the text describing the individual items of the legend.

b) The addition (sub-division) of separate groups of units within individual chronological sequences or in regional geological units is indicated by headings above the appropriate groups.

c) Individual units are indicated by consecutive numbers that will be the same as those given to the appropriate paragraphs in the explanatory notes.

d) The units in the legend are arranged in order of age from the youngest to the oldest. In the case of sedimentary rocks, the name of the formation/member and the affinity to the appropriate lithostratigraphic unit will be given; the petrographic designation in plural should follow. The Quaternary rocks are characterized according to their genesis and lithology. In the case of alluvial terraces, their local affinity (e.g. Leku) or their geomorphological position (e.g. lower terrace) can also be given. If the relative ages of magmatic rocks are not known, they should be classified in order from acid to basic types. Metamorphic rocks are arranged in order from granulites and metamorphosed ultrabasic rocks through orthometamorphic rocks, varied interbedded parametamorphic rocks, migmatites, migmatised rocks and parametamorphic rocks.

e) Each unit is depicted by a combination of colour, hatching, and an index correlated with the fundamental lithological and petrographic characteristics of the rocks that form it. The petrographic characteristics of magmatic and metamorphic rocks are given in the singular in the following order: grain size, texture, mineral composition and the name of the rock. Attributes such as migmatised, leucocratic, hybrid, etc. are given immediately in front of the name of the rock. Transitions from one rock to another (e.g., metamorphosed granite – orthogneiss), and the occurrence of specific minerals up to 5 modal % (e.g., with garnet), information about intercalations or interbeds that are not possible to map (e.g. with intercalations of quartzites), are given after the name of the rock. The traditional name of the rock can also be given in brackets (e.g. Daleti granite, compact gneiss, diabase).

f) The petrographic characteristics of the rock as shown in the legend (up to 105 characters), should be the same as in the lithostratigraphic column and in the explanatory notes.

g) Geological symbols form an integral part of the legend. They are given after the last rock unit and are marked by consecutive numbers. There is a specific order as follows: contacts of geological units, faults and other tectonic features, eluvium, geodynamic phenomena, important fossiliferous sites, mineral occurrences and mine workings, waters, important boreholes and numbered geological localities, lines of geological cross sections.

The legend is organized as the combination of regional and chronostratigraphic hierarchy from youngest to oldest geological units. Regional and chronostratigraphic headings separate geological units depicted on a map into logical blocks.

Chronostratigraphic units are bodies of rocks, layered or unlayered, formed during a specified interval of geological time and have the following hierarchy:

- Erathem
- System
- Series
- Stage

Regional units are units with similar geological evolution and composition and which are related to a specific region. The hierarchy of regional units follows:

- Regional system
- Region
- Province
- Area

7.2 Elements of Geological map

Geological units

The basic part of the legend is a **geological unit** – an element which is mappable and distinct from one another. There is a little bit different comprehension of the geological unit in sedimentary/volcanosedimentary areas and in magmatic/metamorphic complexes.

In sedimentary/volcanosedimentary complexes, **lithostratigraphic units** are defined as bodies of rocks, bedded or unbedded, that are defined and characterized on the basis of their lithologic properties and their stratigraphic relations.

The basic subdivision of lithostatigraphic units (http://www.stratigraphy.org/) is:

- Group – two or more formations.
- Formation – the primary unit of lithostratigraphy.
- Member – a named lithologic subdivision of a formation.
- Bed – a named distinctive layer in a member or formation.
- Flow – the smallest distinctive layer in a volcanic sequence.

A **lithodemic unit** is a defined body of a predominantly intrusive, highly deformed, and/or highly metamorphosed rock, distinguished and delimited on the basis of rock characteristics. In contrast to lithostratigraphic units, a lithodemic unit generally does not conform to the Law of Superposition. Metamorphic rocks are parts of a larger complex or suites. Intrusive rocks could be separated according the shape and size into:

- Dyke – a platy body with sharp boundaries.
- Pluton – the general term for a body composed of igneous rocks.
- Batholith – a variable and large mass of intrusive igneous rocks, usually composed of plutons and dykes.

Symbols

Symbols are crucial for legibility and appearance of a map. The extent of geological units is expressed as a coloured area. The faults and boundaries between rocks are represented by lines. Symbols indicate the position and character of point geological features. All graphical elements of the legend are numbered by ordinal numbers individually for each map sheet.

Geological units are represented in the legend by the following elements described below.

- Lithological description of unit.
- Coloured box with hatch.
- Index.
- Ordinal number.

The characterization of a geological unit in the legend has a descriptive (petrographic character), completed by genetic information for Quaternary sediments and volcanoclastic rocks.

Expression of geological units differs slightly for lithostratigraphic and for lithodemic units:

(a) Lithostratigraphic unit: colour, grain size, composition, characteristic attribute, name of rock(s), supplemental information.

(b) Grain size, texture, mineral composition, name of rock(s), supplemental information.

Colours and hatches

Colours commonly express, the age and hatches the lithology, in a geological map. For igneous and volcanic rocks, colours are used to contrast with the surrounding units. Colours and hatches should conform to the international standards and many of them are a part of the default library of ArcGIS.

If the geological map has many map units, it is sometimes impossible to maintain the standard geological age colours. Colours should be chosen so that the map has the closest credibility with the standard and be legible in the following aspects.

- Showing contrast and clarity of map units and symbols.
- Showing ages or age relationships of map units.
- Matching or approximating colours and patterns used on nearby or adjacent maps to maintain consistency and continuity of colours and patterns among the maps in a region.
- Showing structural relationships of map units.
- Using colours that are light enough for easy legibility of the base map.
- Do not forget that the map should be appealing to sight.

Web pages with international standards:

http://www.stratigraphy.org/index.php/ics-chart-timescale
https://engineering.purdue.edu/Stratigraphy/charts/rgb.html
http://pubs.usgs.gov/tm/2005/11B01/pdf/
https://ngmdb.usgs.gov/fgdc_gds/geolsymstd/fgdc-geolsym-patternchart.pdf

Index

The index of a geological unit is used for unique identification of a legend unit in a map.

Generally, the index is composed of a body which expresses the main stratigraphic and lithological information and symbols in lower and upper cases, which characterize supplemental signs. In addition, in volcanic and sedimentary units, numbers are also assigned according to relative superposition.

The index building slightly differs for sedimentary, volcanic, igneous and metamorphic rocks and it is composed of a body of index and symbols in upper and lower cases. The principles of index assemblage are summarized in Tab. 3 and the list of symbols used in index construction is given in Appendix 1.

Map symbols

Map symbols express aerial, line and point geological phenomena superposed on the geological units:

- Lithological (unit) boundaries.
- Tectonic lines.
- Structural elements.
- Palaeontological symbols.
- Superposed geological and geodynamic phenomena.
- Occurrence and exploitation of raw materials.
- Hydrogeological elements.
- Documentation symbols.

A summary of the most common map symbols is summarized in Appendix 2. A library in default symbols of ArcGIS is available. A comprehensive catalogue of symbols was published by USGS or BGS:

https://pubs.usgs.gov/tm/2006/11A02/.
https://ngmdb.usgs.gov/fgdc_gds/geolsymstd.php
http://nora.nerc.ac.uk/3221/1/RR01001.pdf

Table 3. Principles of the creation of a geological index for various kinds of rocks, for symbols see Appendix 1

Sedimentary rocks	
${}^{te}_{li}So^{1}_{ls}$	
Body of index S – system o – series (if known) 1 – lower, 2 – middle/upper, 3 – upper	**Symbols in upper and lower cases** te – expressive sign (*characteristic texture, mineral, colour, admixture, matrix, texture, genesis, grain size etc.*) li – dominant lithology ls – lithostratigraphic or regional unit

Volcanic rocks	
Coherent volcanic rocks	**Pyroclastic rocks**
${}^{te}_{mi}rSo^{1}_{ls}$	${}^{ge}rSo^{1}_{ls}$
Body of index r – rock, small letter of Greek alphabet S – system o – series (if known) 1 – lower, 2 – middle/upper, 3 – upper, (used according to the stage of knowledge)	**Symbols in upper and lower cases** te – texture mi – characteristic mineral ge – genetic type ls – lithostratigraphic (regional) unit

Plutonic rocks	Metamorphic rocks
${}^{te}_{gs}rSmi_{ls}$	${}^{te}_{gs}\mathit{R}mi_{ls}$
Body of index r – rock, small letter of Greek alphabet S – system (if known) mi – significant minerals	**Body of index** *R* – rock, large (orthometamorphite) or small (metasediment) letter in italic mi – significant minerals
Symbols in upper and lower cases te – texture or other expressive sign (colour) gs – grain size ls – lithostratigraphic or geological unit	**Symbols in upper and lower cases** te – texture or other expressive sign (colour) gs – grain size ls – lithostratigraphic or geological unit

Organization of legend

The first version of the legend should be prepared before the first reconnaissance trips to the field based on archive data. This graphic hand-made temporary legend is subsequently improved by the knowledge obtained during the geological mapping and nearly finalized during the preparation of the fair-copy of a geological map.

The graphic form of legend is insufficient for GIS processing and information from it must be transformed to a structured table. Every geological unit depicted in a map is described in one row with list of headings (Tab. 4).

Table 4. Structure of the legend table for further GIS processing

			Chronostratigraphic units				*Regional units*			*Lithostratigraphic units*		*Technical projection*			
LEG_ID	ORDER	Unit_DSCR	ERATHEM	SYSTEM	SERIES	STAGE	REGION	PROVINCE	AREA (UNIT)	GROUP	FORMATION	INDEX	COLOR_NO	HATCH_NO	HATCH_CO

7.3 The lithostratigraphic scheme

a) The lithostratigraphic column shows the sequence of sedimentary units observed or inferred to occur on the map sheet, even if these units do not crop out on the map or in the geological cross-section. The column can also include metamorphic and effusive rocks if their observed or inferred chronostratigraphic positions are known. The column also shows any hiatus in the stratigraphic succession, weathering profiles, soil horizons, facies variations, occurrences of fossils, etc.

b) The rocks are arranged in a column 2 cm wide with a maximum length of shorter edge of map. The maximum thicknesses of individual units, formations and members are indicated by figures marked in the stratigraphic column. The interval in the stratigraphic column allocated to monotonous units should not be too great, but in the case of thin units, the thickness should be as such to allow the text describing their characteristics to be incorporated.

c) The inclusion of all chronostratigraphic information is an integral part of the lithostratigraphic column.

d) In areas with a complex tectonic structure, it is desirable to compile a separate lithostratigraphic column for each tectonic unit.

7.4 Fair copy map

Fair copy map (draft map) is a first comprehensive interpretation of archive, observed field and laboratory data. Fair copy map can be a hand-drawn sketch or it can be drafted using appropriate software. All factual data and documents should be well-organized. These data are represented mainly by:

- Topographic base map.
- Remote sensing data.
- 3D model.
- Field map.
- Map of small-scale (regional) tectonic elements (bedding and foliation preferably).

- Field documentation, preferably in a database.
- Laboratory results.
- Archive documents.

Much of the information gathered during the mapping is not transferred to the manuscript. The general rule is to show any features which add to the understanding of the geology and geological history, and to omit those that do not. The criterion of what to show is mainly a matter of common sense and experience.

Sequence of geological map compilation

- Compilation of legend.
- Compilations of lithostratigraphic scheme.
- Preparation of a topographic map with a trace of geological transects and oriented tectonic symbols.
- Interpretation of faults from satellite imagery and 3D model.
- Contouring of the Quaternary cover.
- Interpretation of platform cover and its boundaries within underlying rocks.
- Contouring of the intrusive rocks.
- Interpretation of boundaries in pre-platform units.
- Situation of subsequent geological symbols.
- Compilation of geological cross-sections.

Principles

Regardless of the fact that all contacts are not exposed everywhere in reality, all round contacts should be depicted on the geological map but with different line styles distinguishing confirmed contacts and extrapolated contacts. The geologist needs to interpret the map from visible contacts and outcrops. Aerial and satellite imageries can help to reveal regional structures and geomorphological map, while 3D model can help with deciphering of faults, linear or dome structures.

The geological map is made from strata and is drawn from younger to older layers with observance of two basic rules, which are the principles of superposition and crosscutting and V-rule.

Principle of superposition states that in any undisturbed sequence of rocks deposited in layers, the youngest layer is at the top and the oldest at the bottom, while each layer being younger than the one beneath it and older than the one above it.

Principle of crosscutting relationships says that feature that cuts across another rock unit is the younger geological feature.

The outcrop patterns of rocks on the surface of the Earth are results of the intersection of geological plane elements (rock boundaries, bedding, foliation, fault plane etc.), often dipping and folded, with an irregular, curved land surface. Understanding of the intersection pattern is fundamental for the visualization of geological structures in a map.

The **V-rule** helps to predict and understand patterns of the intersection between planar geological structures and land surface and says that a dipping surface that crops out in

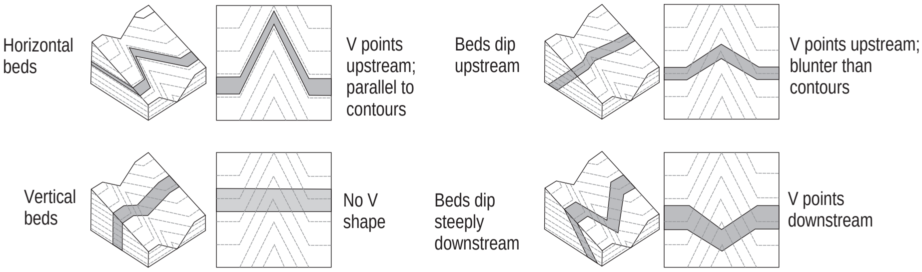


Figure 17. *Schematic expression of the V-rule in block diagrams and maps.*

a valley or on a ridge gives rise to a V-shape outcrop. The way of the outcrop patterns depends on the dip of the geological surface related to topography (Fig. 17).

Further reading

http://academic.brooklyn.cuny.edu/geology/leveson/core/topics/time/froshlec8.html
https://www.fault-analysis-group.ucd.ie/
http://seoe.sc.edu/segchapter/sites/sc.edu.segchapter/files/attachments/97936453-Geological-Structures-and-Maps.pdf
http://earth.leeds.ac.uk/geology.html

8) EXPLANATION NOTES TO GEOLOGICAL MAP

The explanatory notes (report) provide and extend information about the important geological features identified during the geological mapping; these are summarized in the following notes.

A report enables to understand the significance of geological features that are depicted on the map and described in the legend.

Structure of the report could vary but a common standard is as follows:

- Title.
- List of contents.
- Abstract.
- Introduction.
- Main body (Geology).
- Conclusion and recommendation.
- Reference.
- Appendix.

8.1 Title page, contents and abstract

Title page shows what the report is about, who prepared it and when. The first title page informs the reader about the name of the report including the name and number of the map sheet, editor, organization and year of publishing. The second title page extends this information (e.g. the name of the project, working team, cooperative organization). Moreover, this page has the name and signature of the project (chief) geologist and of the advising or reviewing geologist, if any.

List of contents shows the organisation of chapters in the report.

The abstract starts on a separate page following the contents and summarize the results of the reported work. It must be written at last, following the formulations of ideas and conclusion of the report. The length should not exceed one page.

8.2 Introduction

The introduction puts the work into the context of time, space, bounding conditions and objectives. The chapter briefly defines the geographic position of the map sheet and its position with respect to the administrative divisions of the country. The introduction should also give a brief review on vegetation, land use, transportation and economy of the region.

A review of techniques and procedures which were used is organized in a sub-chapter of the introduction. It is completed by numbers of reference points, samples, thin sections, analysis etc. Topographic base maps and remote sensing data are briefly characterized here as well.

Units and abbreviation used in the text are explained here.

8.3 Main body

The main body of the report is composed of few obligatory chapters:
- Review of previous work.
- Regional context of geology and stratigraphy.
- Geological and petrological characteristics of units.
- Tectonics.
- Geological evolution (history).

These chapters could be completed by optional chapters such as:
- Geophysics.
- Geochemistry.
- Mineral resources.

Review of previous work

The summary of previous geological investigations and surveys is given specifically concerning the area covered by the map sheet. When referring to these earlier studies in the text, attention should be drawn to the specific contributions made for the understanding of geology of the map sheet.

Regional geology and stratigraphy

This section provides information about the identity and distribution of the main geological units depicted on the map sheet in a regional frame.

A brief description of the individual units and their mutual relationships in time and space should be provided:
- Geological definition.
- Geographical position.
- Geological boundary and relationship with adjacent units.
- Basic lithology.
- Stratigraphy and age.

The section should also contain a synoptic map on which the major regional geological units are depicted. The scale of the synoptic map can be variable, but it should be the same for one edition of map sheets. The range of 3 × 3 map sheets with a described map in the centre is well-tried.

Geological and petrological characteristics of units

This chapter describes individual units depicted in the legend of the geological map.

The structure follows the form of the legend and consists of paragraphs describing the character and types of rocks composing the geological units and formations found in the area of the map sheet.

Individual units are described in chronological order, starting with the oldest and proceeding to the youngest. This is the reverse of the sequence shown in the legend.

Bodies of rock that could not be depicted on the map because of their small dimensions should be described under the heading of the main unit in which they occur.

The descriptions of individual units in the legend should include the following structured information:

Name – number and full name of the geological unit (rock or group of rocks). This will be the same as that given in the legend of the geological map.

Geographic extension – distribution of the geological unit on the map sheet with a reference to the topographic base map.

Representative locality – an outcrop (borehole) characteristic for the given rock type defined in the legend within the map sheet.

Shape and thickness – geometry of bodies formed by the individual rock units defined in the legend.

Boundaries – the description of relationships to adjacent rocks, geological formations or lithostratigraphic units for which the footwall and hanging wall boundaries (if known) are to be defined.

Lithology – macroscopic and microscopic description of the rocks given in the legend, taking account of variations in rock facies or lithostratigraphic units that cannot be depicted on the map sheet because of their small dimensions. The description is usually accompanied by photos of typical outcrops, specimens and thin sections.

Age of rock or **lithostratigraphic unit** – include the reference to geochronological data and/or important biostratigraphic results.

Origin – summary of ideas concerning the origin and development of the rocks, character of the sedimentary environment, etc.

Tectonics

Structural data are described within a tectonic (lithotectonic) unit, which is defined based on common structural features, lithological composition, origin and tectonic development in time. The tectonic unit has clearly determined boundaries with its surroundings; the boundaries can be transgressive, intrusive, and deformational (ductile to brittle).

The description of structural features should be done in the successive order, i.e. from the oldest to the youngest (spatially and/or temporally), in the range of varying scale from regional to local, from ductile to brittle, from high- to low-temperature structures; and in size ranging from mesoscopic to microscopic. Moreover, the known or supposed relationship between structures and fabrics must be characterized with regards to the character and orientation of tectonic unit boundaries.

To describe all the types of fabrics, the following must be specified:

- Character (planar, linear and linear-to-planar).
- Intensity.
- Spatial orientation (principal directions).
- Genesis (regional, local, relict).
- Kinematic pattern (senses of movement such as dextral, sinistral, normal, reverse, etc.).
- Mutual relations between individual fabrics (superimposition).

Descriptions are often organized sequentially for the different modes of structures. Hence, brittle and ductile deformations are described usually starting with ductile deformations followed by brittle deformations. The planar fabric (foliation) encompasses the type of foliation such as compositional banding, schistosity, cleavage or bedding in some cases accompanied by the lineation observed on foliations. Faults and joints are described as brittle structures. All planar and linear structures described are accompanied by the stereographic plots of the measured data in the field.

The description of regional tectonic features of the mapped area in the report appears in the introduction part where only regional trends are broadly and generally outlined without a detailed account. Specific descriptions of each group of structural features are described based on the direct field observation without any interpretation or implication in the detailed section of the report such as the geological structures section. The description must include the extent of observation (such as outcrop scale, hand-specimen scale), orientation measurements, qualitative description of appearance of the structures, and distribution of the structures in various rocks on the observed outcrop.

The stereographic plots of measured structural trends, sketches and photographs should be incorporated along with the descriptions and clearly labeled with scale and orientation. Photographs and sketches should be labeled with orientation or view direction and the locality that the illustrations show. Temporal and geometrical relationships between the structures are also described in this section based on the field observation. All names of places described in the report are expected to appear in at least one of the maps in the report or in the main geological map attached. The interpretation of tectonic development of the mapped area is given in the final part of the chapter.

Geophysics

This chapter provides an assessment of geological units or rock types in terms of their physical parameters based on geophysical surveys and laboratory measurements. It makes use of archival as well as new measurements obtained by airborne, ground and laboratory geophysics. Petrophysical, regional gravimetric measurements, airborne geophysics (magnetometry and radiometry and/or gamma spectrometry) and detailed ground measurements (gravimetry, magnetometry, gamma spectrometry, seismic, geoelectric methods) are all used for the purpose of geological interpretation. It takes account of geophysical patterns at regional and local scales, reflecting the lithology and structure of geological units, and the mineralization in the area as well as hydrogeological and geodynamic phenomena etc.

Geochemistry

In this chapter, an account of the geochemical features of individual types and groups of rocks occurring on the map sheet will be given. Particular attention should be paid to the influence of rock geochemistry on the environment. Both existing archived data and new analyses obtained from the samples collected during the mapping program are used for this purpose.

Whole rock analyses, including the determination of organic matter, are used for characterization and classification of rock units depicted on the map. A combination of analyses of rocks, soils and stream sediments is used to assess the influence of lithology on the environment. The relationship between the geochemistry of individual rock types and sequences and surface geochemical anomalies, if any, form the basis for interpretation of geological data and implication for environmental contamination or use as base line background data for future consideration in environmental studies is paramount importance.

Mineral resources

In this chapter, a summary of the known mineral occurrences, deposits, inferred mineral resources and showings located within the mapped area is given. It also contains brief information concerning the main mining and mineral processing facilities as well as data on mining operations and production available at the date of compilation. The chapter also provides a basic geological description of all new discoveries and recently inferred mineral resources.

This sub-heading is divided into the following sections:
- Metallic minerals.
- Fossil Fuels.
- Humolites (peat, humic coal).
- Non-metallic minerals.
- Industrial minerals and rocks.

Each type of mineral raw material should be described separately in this sub-chapter. Mineral resources consisting of several commodities (e.g., clays, kaolin, bentonite, limestones), should be described separately, preferably in individual paragraphs. The following structure of this sub-heading is recommended:
- Geological setting and the mode of formation.
- Quantitative parameters of the mineral resource.
- Uses and potential uses of the mineral raw material.

Individual mineral deposits are arranged in the text according to their size and economic importance.

Geological evolution of the area

In this chapter, a simple description of the geological history of the mapped area is given. The development of different geological units should be described in order starting with the oldest formations and proceeding to the recent. Some discussion about the origin and distribution of mineral resources, aquifers, geomorphology and geodynamic phenomena should be included. The data from earlier studies will be integrated with the results of the new geological survey.

The chapter is divided into sub-headings or paragraphs, in which the geological development of the mapped area is progressively reconstructed. Endogenic and exogenic processes including sedimentation and development of basin fills, tectonic deformation and metamorphism, and the succession of magmatic events should be described in the chronological order. The sources of geochronological and palaeontological ages for magmatic, tectono-metamorphic and sedimentary events must be listed. If the PT conditions for metamorphic assemblages in the area of the map sheet have been determined, these should be included and, if appropriate, a PT-t path for the metamorphic history of the mapped area can be constructed. Attention should be drawn to the gaps in information essential for the reconstruction of certain stages of geological development of the mapped area and its environs. The discussion of the wider questions of regional geological evolution is not the purpose of this sub-heading. If some units occurring on the mapped sheet are not sufficiently characterized, stratigraphically classified and/or dated outside the mapped area, this should be taken into account.

8.4 Reference

Reference should contain a list of all published papers and unpublished reports or manuscripts and maps used in compilation of the map and the accompanying explanatory notes.

Citation includes the author`s name, year of publication; full title; publication of series, if appropriate; volume and part numbers; publisher; pagination; and information that will enable a person to get a copy of the citation if it is “unpublished report”.

Use a consistent format for citation, avoid abbreviations wherever possible. Reference management software effectively helps. See for comparison: https://en.wikipedia.org/wiki/Comparison_of_reference_management_software.

8.5 Appendix

This part of the explanatory notes contains essential data and information that could not be included under appropriate chapters or paragraphs. Typical inclusions are laboratory test data, sedimentological logs, palaeontological reports etc.

Further reading

Berkman A. D. (2001): Field geologists´manual. The Australian institute of mining and metallurgy, 395 pp.

Lisle J. R. (2004): Geological structures and maps. Elsevier, 106 pp.

Lisle J. R., Brabham P., Barnes J. (2011): Basic Geological Mapping. Willey-Blackwell, 217 pp.

Maltman A. (1990): Geological maps and introduction. VNR, 84 pp.

9) HYDROGEOLOGICAL MAP

The hydrogeological map displays hydrogeological information of a given area with respect to the geological structure, hydrogeological, geothermal and hydrological objects. The map is accompanied by explanatory notes. All features expressed on the map should be documented (inventoried). The map documentation consists of a description of all natural and/or man-made features contributing positively or negatively to status of the natural resources. The numbered documented points are shown on the map using symbols from the legend. The aim of the hydrogeological map is to provide information about aquifer – aquiclude / aquitard system, type of permeability of aquifers and their productivity (qualitative and quantitative hydrogeological character of lithological units) and existing water points.

Types of hydrogeological maps

Hydrogeological maps can be divided using the scale and specific contents:

- 1 : 2,000,000 and 1 : 1,000,000 – small-scale hydrogeological maps showing the general location of aquifers / aquitards and a broad picture of the surface drainage.
- 1 : 250,000 – medium-scale regional hydrogeological maps showing considerable amount of data with inserted maps, which enhance information about the area (rainfall, physiography, chemistry, etc.).
- 1 : 50,000 – large-scale detailed hydrogeological maps in the areas with large amount of hydrogeological data and demand for detailed hydrogeological information.
- Specific hydrogeological maps (well-documented field hydrogeological map, aquifer vulnerability map, etc.).

9.1 Components of hydrogeological map

A sheet of the hydrogeological map comprises the hydrogeological map itself, which is supplemented by the obligatory information to be placed on sides of the map. This must include:

- Number and name of a map sheet.
- Hydrogeological scheme (vertical aquifer scheme).
- Scheme of the main basins.
- Legend to the hydrogeological map.
- Map sheet index.
- Summary of hydrogeological mapping.

Basic parts of the map sheets include a frame with the hydrogeological map itself and a key to the map outside of the map. They are completed by text information and supplementary graphic information out of the map frame. According to the requirements, the map can be supplemented by other optional appendices such as scheme of hydrochemistry, etc.

Hydrogeological units

The basic hydrogeological map expresses the main hydrogeological units based on the integration of hydrogeological character of the main geological units. In the case of a hydrogeological map, the permeability of hydrogeological units is the main information shown on the map. It is compiled based on the combination of two basic types of data and information: (a) type of permeability – qualitative characteristic (e. g. porous, fissured aquifers) map, or (b) value of transmissivity ($T = m^2/d$), specific yield of wells (q = l/s.m) and yield (Q = l/s) for wells and/or springs – a quantitative characteristic. The type of permeability is expressed by a specific colour and quantitative characteristic are expressed by the intensity of the colour using principle that the higher the value, the more intensive the colour (see article legend).

All lithological units that appear on the geological map are shown in plain (area) colour, whether being aquifers or non-aquifers. The colour and its intensity depict the basic qualitative and quantitative characteristics of hydrogeological units. The hydrogeological units are arranged (lined up) from the most potential (porous) aquifer to the most impermeable aquiclude and aquifers with specific conditions in concordance with the description in the explanatory notes. The legend for groundwater and rocks is shown in Appendix 4.

Lithology

The lithology of strata in outcrops is represented by a hatch printed in grey colour. Examples of geological symbols for the hydrogeological map are in Appendix 4.

Hydrogeological symbols and marks

Detailed hydrogeological information is shown by the use of colours, lines and symbols, printed in various colours. The detailed hydrogeological information is shown by the use of symbols, and occasionally by lines and symbols printed in various colours. Numerical figures, in the same colours, may be added for clarification, e.g. to put the values on contours. The different colours and groups are as follows:

1. Groundwater dynamics and springs (Violet).
2. Groundwater quality and temperature (Orange).
3. Surface water and karst hydrography (Blue).
4. Man-made features and alterations to the natural groundwater regime (Red).
5. Aquifer thickness and limits of certain features (Dark green).
6. Geological, tectonic and stratigraphic information (Grey).

1. Groundwater dynamic and springs (violet)
The groundwater dynamic features mainly consist of the following features:

- Groundwater level contours.
- Groundwater flow direction.
- Main groundwater divide.
- Limit of the area with confined groundwater.
- Cold springs, based on their yield, should have diameter appropriate to the yield > 25, 5–25, 0.5–5, 0.05–0.5, < 0.05 l/s.
- Thermal spring (temperature over 30 °C) – temperature in orange colour is added to an appropriate spring symbol.

Note: the springs with no information about the yield have a uniform symbol – a circle of 3 mm in diameter with a cross rotated by 45°.

2. Groundwater quality and temperature (orange)
Groundwater quality (salinity of TDS above 1.5 g/l) and temperature (above 30 °C) is expressed in orange colour. The thermal areas are shown in the map by orange hatching (see Annex).

3. Surface water and karst hydrography (blue)
Surface water and karst hydrography are coloured in blue. The most important and frequent symbols are as follows:

- Stream with perennial and intermittent flow.
- Main surface water divide (13 catchments) and secondary (tertiary) water divide.
- Symbol for river gauging station (see Appendix 4).

4. Man-made hydrogeological features (red)
Man-made features show mainly the following symbols:

- Ponds and dams.
- Dug wells and water holes.
- Boreholes based on their yield should have diameter appropriate to the yield > 25, 5–25, 0.5–5, 0.05–0.5, < 0.05 l/s. The wells with thermal water (temperature over 30 °C) – T in orange colour is added to an appropriate well symbol.
  Note: boreholes with no information about the yield have a uniform borehole symbol of 3 mm in diameter with a cross rotated by 45° in black colour.

5. Aquifer thickness and limits of certain features (dark green)
These features are specific for each map sheet and consist mainly of contours of aquifer thickness and limits of certain features which are not shown in other groups.

6. Geological information (grey)
Geological information in the hydrogeological map consists of structural elements that are printed by lines and various symbols derived from the geological map (faults, anticlines, volcanic cones and craters).

Legend

The proposal for the legend is mainly based on provisions for the International Legend to the Hydrogeological Map by International Association of Hydrogeologists (see Further reading). The legend to the hydrogeological map is standardized for each hydrogeological unit of the Ethiopian territory.

The items of the legend to the hydrogeological maps include three main groups of graphical information: colour, hatching (pattern), and symbols (indexes). Each item has a number, graphical expression and text description.

The graphical expression of the legend is presented in four main sections as follows:

- Background information (black colour) representing topographical data (names of villages and towns, roads, state and regional boundaries, latitude grids, etc.).
- Groundwater and rocks – aquifers and non-aquifers (various colours).

- Lithology (grey colour ornaments).
- Representation of detailed data (various colours) such as wells, springs, hydrological measurements etc.

Scheme of main basins

The position of the sheet within a basic surface water basin system (13 main basins within the state territory) should be expressed in the scheme. The width and length of the scheme is 15 × 15 cm (at a scale of approximately 1 : 10,000,000).

Hydrogeology scheme (vertical aquifer scheme)

The hydrogeology scheme (vertical aquifer scheme) shows a sequence of existing or inferred aquifers and aquicludes /aquitards of the area and the main groundwater circulation systems. The scheme can be prepared for each important hydrogeological system shown on the map in the case of complicated hydrogeological settings (several different multi-layered systems on one sheet of the map). The hydrogeological system is shown in concordance with the legend of the map. The addition of a hydrogeological scheme to the hydrogeological cross-section is preferable as it shows the hydrogeological system and circulation of groundwater in greater detail. The width and length of the scheme is app. 15 × 15 cm and the scales of axis could be different (it is out of the scale).

Hydrochemical map

The map of hydrochemistry can be presented as one of the inserted maps or as a separated main map. The principles for the compilation of both maps are the same and are described further.

Map sheets index

The position of the map sheet in the State topographic base map (national mosaic). It helps to locate geographical position of the sheet. The width and length of the scheme is 15 × 15 cm (at a scale of approximately 1 : 10,000,000).

Authors information

It includes the information about the chief compiler and other participants in the compilation and mapping of the sheet.

Cartographic information

It includes projection type, scale, and other information acquired from the original topographic map for the compilation of the hydrogeological map.

9.2 Hydrochemical map and scheme

Hydrochemical map shows hydrochemical types of water (groundwater, surface and rainwater and the most important qualitative parameters such as Total Dissolved Solids (TDS) and chemical components exceeding the standards for drinking water. The data for the compilation of hydrochemical map results from the laboratory chemical analysis.

The chemical composition of groundwater is the combination of results of the composition of water that enters the groundwater reservoir and reactions with minerals in the rock. Several factors influence the groundwater chemistry in recent years; apart from the natural processes, which are a controlling factor of the groundwater quality, the effects of pollution such as nitrates and acid rain also have a significant contribution.

Main unit

The main map shows the hydrochemical types of groundwater in appropriate colours (full colours and screens), idealized contours of TDS and pie charts of surface and rainwater.

Groundwater chemistry

Groundwater chemistry evaluated from the point of view of groundwater origin within a hydrological circle is shown on a standard hydrochemical map. These maps are prepared based on the hydrochemical types of groundwater. The hydrochemical type of groundwater is defined by its cation and anion composition expressed in Meq%. Hydrochemical types are further classified based on Meq% representation of individual cations and anions implementing the scheme as follows:

- Basic hydrochemical type (full colour) – all of the main cations and anions have a content higher than 50 Meq%.
- Transitional hydrochemical type (horizontal stripes) – the content of the main cation and anion ranges between 35 and 50 Meq%, or exceeds 50 Meq% for one ion only; a dominant ion combination is expressed by the relevant coloured stripes (screen) in the horizontal position, the second ion is expressed by an index (e.g. Mg).
- Mixed hydrochemical type (vertical stripes) – the contents of cations and anions are not greater than 50 Meq%, and only one ion has a concentration greater than 35 Meq%; this type is expressed by the relevant coloured stripes (screen) in the vertical position.

Hydrochemical types of groundwater are expressed in full colour and /or using screens. An area of a hydrochemical type is delineated and expressed on the map by the relevant colour if three water points of the same type occur close to each other. The colours and screens used for various hydrochemical types are shown in Annex 3.

Rain and surface water chemistry

Hydrochemistry of waters additional to groundwater (rain and surface water such as rivers, dams, lakes and ponds) are represented in the hydrochemical map by pie charts. The diameter of a circle shows the total dissolved solids and colours show different ions (see Appendix 4).

Hydrochemical symbols and marks

Symbols (springs, wells and dug wells) are printed appropriately in black colour. Other most important and frequent symbols for the hydrochemical map are shown in Appendix 5.

Legend

The legend is presented in four main sections as follows:

- Background information (identical to the hydrogeological map).
- Groundwater chemistry.
- Rain and surface water chemistry.
- Representation of detailed data.

Scheme of main basins

The position of the sheet within a basic surface water basin system (13 main basins within the state territory) should be expressed in the scheme. The width and length of the scheme is 15 × 15 cm (at a scale of approximately 1 : 10,000,000).

Shaded relief

The shaded relief scheme is shown on the map because the groundwater chemistry (typology) results from water rock interaction as well as the geomorphological position of aquifers (plateau, escarpment, rift valley floor, etc.). The width and length of the scheme is 15 × 15 cm (at a scale of approximately 1 : 10,000,000).

Map sheets index

Position of the map sheet in the State topographic base map (national mosaic). It helps to locate the geographical position of the sheet. The width and length of the scheme is 15 × 15 cm (at a scale of approximately 1 : 10,000,000).

Cartographic information

Projection, scale, and other information from the original topographical map used as a base for the compilation of the map.

Author information

These include information about the chief compiler and other participants in the compilation and mapping of the sheet.

9.3 Data for hydrogeological mapping

The data and information needed for the compilation of hydrogeological maps differ based on the phase of the mapping activity. In general, hydrogeological mapping has three phases: desk study, filed work and data assessment (post field work).

DESK STUDY (PRE-FIELD WORK – PHASE 1)

Collection and study of:

- Topographical maps (Ethiopian Mapping Agency).
- Existing geological and hydrogeological maps at a scale of 1 : 2,000,000, 1 : 1,000,000 1 : 250,000 and 1 : 50,000 and hydrogeological and geophysical studies (Geo-sciences Mapping and Geo-information Center of the Geological Survey of Ethiopia, library of the Ministry of Water Resources, Energy and Irrigation).

FIELD WORK (PHASE 2)

The collection of primary and secondary data consists of:

- Filed data inventory (primary data) of boreholes, springs, dug wells and water holes (Tabs. 5–8).
- Sampling of ground, surface and rain water and field pH, temperature and electrical conductivity (EC) measurements (other parameters like fluorides, etc.).
- Well drilling reports (secondary data) from water bureaus at federal, regional, zonal and woreda levels as well as private sources (particularly for the boreholes and dug wells inventoried during the field work).

Field data recording (field notebook, inventory sheets). These sheets are used for a long time and data from the inventory sheet are used for the compilation of maps.

Table 5. Borehole inventory

Borehole ID	BH, SBH and number
Identification	Name of owner, Woreda, Zone, Region
Coordinates	UTM: X, Y, Elevation (using GPS)
Drilled by	Drilling company or who ordered drilling (water bureau, NGO drilling report collection) and year
Topography	Plain, depression, valley, slope
Depth of BH	Depth in (m)
SWL/DWL	Static/dynamic water level at the date of visit/ confined (artesian) condition (m)
Q	Yield at the date of visit (l/s)
T	Transmissivity from pumping test (m^2/d) – mainly taken from drilling report
Aquifer	Geological unit (visible or from a geological map)
Pump	Submersible, hand pump
Development	Kind of development (reservoir) and protection (fencing)
Measurements	Temperature, pH and EC as a basic field measurement
Remark	Odor, taste, turbidity, fluctuation of certain characteristics, sampling, etc.

Table 6. Spring inventory

Spring ID	CS, HS and number
Identification	Name of owner, Woreda, Zone, Region
Coordinates	UTM: X, Y, Elevation (using GPS)
Topography	Plain, depression, valley, slope (slope break)
Spring type	Depression, contact, artesian, fracture, karst
Eye	Single, multiple, seepage
Q	Yield at the date of visit (volumetric measurements are required) (l/s)
Permanence	Perennial, intermittent
Aquifer	Geological unit (visible or from a geological map)
Development	Kind of development and protection (developed – concrete box)
Measurements	Temperature, pH and EC as a basic field measurement
Remark	Odor, taste, turbidity, fluctuation of certain characteristics, sampling, etc.

Table 7. Dug well inventory

Dug well ID	DW and number
Identification	Name of owner, Woreda, Zone, Region
Coordinates	UTM: X, Y, Elevation (using GPS)
Dug by	Construction company, who ordered the construction (water bureau, NGO digging report collection) and year
Topography	Plain, depression, valley, slope
Depth of DW	Depth in (m)
SWL/DWL	Static/dynamic water level at the date of visit (m)
Q	Yield at the date of visit
Diameter	(m)
Lining	Concrete tubes, masonry, partial at the surface, without
Aquifer	Geological unit (visible or from a geological map)
Pump	Hand pump, rope and bucket, etc.
Development	Kind of development and protection
Measurements	Temperature, EC and pH as a basic field measurement
Remark	Odor, taste, turbidity, fluctuation of certain characteristics, sampling, etc.

Table 8. Water hole inventory (a typical water point in desert areas in a dry wadi bed)

Dug well ID	WH and number
Identification	Name of owner, Woreda, Zone, Region
Coordinates	UTM: X, Y, Elevation (using GPS)
Depth	Depth in (m)
SWL/DWL	Static/dynamic water level at the date of visit (seasonal fluctuation)
Renewal	Renewed each year in the area (at the same place)
Aquifer	Geological formation (visible or from a geological map)
Measurements	pH, temperature and EC as a basic field measurement
Remark	Odor, taste, turbidity, fluctuation of certain characteristics – groundwater level fluctuation, sampling, etc.

The data during the field inventory are filled into "Inventory sheet" and are transferred into digital table format (MS Excel) files, which can be used for the compilation of map using ArcGIS. Finally, the data are transferred into text format and published in Appendix of explanatory notes.

Field equipment and sampling

The basic field equipment and purpose for field use is shown in the following list in Tab. 9.

Table 9. Field equipment

Material / equipment	Purpose
Topographic maps at an appropriate scale	Visualization of different topographic and geomorphological features and assessment of access roads
Landsat ETM imagery	
SRTM data	
Garmin 12 channel GPS	Acquiring position of water points
Provisional geological and hydrogeological maps	Reference / base map during the field work
Portable pH and EC meters	Field measurement of water samples
Solutions of known pH (4,7,9.2) and concentration of dissolved solids (KCl) of 1N concentration	Calibration of measuring devices
Distilled water	Washing of electrodes of pH and EC meters to prevent inappropriate results of measurements
Plastic sample bottles	Collection and storage of water samples
Geological hammer	Chip rock samples
Camera	Taking photographs of various features
Reports and literature	Review of existing data from the study area
Stationary material	Miscellaneous field and office work
Computer with various software	Analysis and presentation of collected data
4WD vehicle	Traveling during the field work

Sampling is an important part of any hydrogeological study including mapping. A sample has to be labeled by a point number. The quality of a sample depends on the laboratory procedure/standards. The water samples should be delivered into laboratory as soon as possible.

Some important terms for field inventory

- A spring is a concentrated flow of groundwater appearance at the ground surface. The type of springs can be defined based on the rock structure, discharge, temperature and variability.
- Seepage is a non-concentrated flow of groundwater at the ground surface forming a swamp area, pond with or without an outlet.
- Depression spring occurs where the groundwater table intersects the ground surface.
- Contact spring occurs where a permeable layer is underlain by a less permeable layer.
- Artesian spring occurs where groundwater leaks under pressure through the overlying confined layer.
- Fracture springs occur where groundwater is discharged directly from fissures and fractures of hard rocks.
- Karst spring occurs where groundwater is discharged directly from karst openings or from a cave.
- Perennial spring discharges groundwater throughout the year.
- Intermittent spring discharges groundwater only during some part of the year.
- Hot springs (warm springs) discharge groundwater with a temperature exceeding the normal temperature of local groundwater.
- Unconfined aquifers – where groundwater level varies based on the configuration of terrain and/or recharge and discharge areas.
- Confined aquifers (artesian) / where groundwater is under pressure by an overlying confining (less permeable) layer and after drilling through this confining layer, the groundwater level rises above the bottom of the confining layer. In some cases groundwater can overflow the well head.

DATA ASSESSMENT (POST-FIELD WORK – PHASE 3)

The compilation of the map and writing of explanatory notes consist of:

- The compilation of the hydrogeological map consists of a) the main map, b) legend and c) supplementary (inserted) maps, implementing GIS.
- Written explanatory notes consist of the assessment of hydrology, hydrogeology (definition of aquifers/aquitard system), hydrochemistry and groundwater resources, when a part of a complex map set including geological and other maps. In case the hydrogeological map is compiled as a separate map, full contents of explanatory notes are given in further.

Some important terms for the data assessment:

- Groundwater contours are connecting the piezometric surface of groundwater levels in wells, springs and the level of surface water in gaining rivers.
- Gaining river – a river recharged by groundwater.
- Losing river – groundwater recharged by water from a river.
- Bank storage – the volume of groundwater stored in aquifer (mainly alluvial) during the flood period.

- Base flow – stream flow originating from groundwater discharge into stream channel.
- Aquifer – a unit capable of transporting and storing groundwater under the normal hydraulic gradient.
- Aquitard – less permeable units in the study area (the vertical cross section).
- Aquiclude – a geological unit incapable of storing and transmitting a significant quantity of groundwater under the normal hydraulic gradient.

9.4. Explanatory notes to the hydrogeological map

Written explanatory notes to a hydrogeological map describe the hydrology (hydrometeorology), hydrogeology (the definition of aquifers/aquitard system), hydrochemistry and groundwater resources of the map sheet additional to basic data as a geological map.

Hydrology (hydrometeorology)

- Rainfall, resulting in adopted rainfall to the map sheet.
- Other climatic characteristics (temperature, relative humidity, wind speed, sunshine hours, evapotranspiration (data collected from National Meteorological Centre or FAO data from www.crop.wat.com).
- Rivers and lakes consist of development and flow describing the basin and sub-basins of the map sheet and result in the adopted specific runoff and specific baseflow calculated by Kille and separation hydrograph methods (data collected from Hydrology Department of the Ministry of Water Resources, Energy and Irrigation).

Hydrogeology

This chapter refers to the previous work and the definition of aquifer / aquitard / aquiclude system of the map sheet. Based on the previous mapping experience from Ethiopian territory, the following geological units forming different aquifers and aquitards were defined:

- **Units with porous permeability**, where groundwater is accumulated in and flows through pores of an unconsolidated or semi-consolidated material. Porous materials are represented either by alluvial and lacustrine sediments with subordinate colluvial and eluvial sediments developed in depressions of lakes and/or along valleys of former and existing rivers or by pumiceous pyroclastic, resedimented pumice and unwelded tuff materials (a polygenetic infill of depression).
- **Units with fissured permeability**, where groundwater is accumulating in and flows through the fractured part of volcanic and sedimentary rocks. The porosity of lava flows may be high, but the permeability is largely a function of secondary structures (joints and fissures) within the rock. The permeability of lava flows tends to decrease in geological time. The pyroclastic rocks between lava flows are generally porous, but usually less permeable due to poor sorting. They can be represented by impermeable unwelded tuff in some parts of the volcanic sequence. Hence, extensive volcanic ash beds may form semi-horizontal barriers to water movement (infiltration) resulting in the lower productivity of basaltic units located at greater depth. Layers of paleosoil of various thicknesses in between lava flows are also less permeable and usually consist of clay material on the one hand, whereas layers of fluvial and lake sediments and

pumiceous pyroclastic materials between various lava flows can considerably enhance the yield on the other hand.

- **Units with karst permeability**, where the groundwater is stored in fissures across the whole thickness of rock units, the permeability can be enhanced by karstification along some fissures. Solution phenomena and karstification of carbonate rocks are controlled by the drainage base level, which may be represented by a perennial stream and/or by an impervious formation inside the limestone (e. g. marlstone, gypsum, shale) and/or by rocks underlying the carbonate aquifer. The rock is presumably dissolved the most rapidly in the zone between the highest and lowest positions of the water table.
- **Units with mixed fissured and porous permeability** – volcanic rocks are often mixed with sediments accumulated in between two lava flows representing subsequent volcanic episodes. The porous sedimentary material is represented by river and lake sediments and/or relatively thick layers of unwelded tuffs, ash flows and pumiceous pyroclastic material. These intercalated porous materials do not act as independent aquifers, but they form a mixed fissured and porous multilayered aquifer together with the volcanic rocks with fissured permeability. The permeable porous sediments in between lava flows form a body that can accumulate large volumes of groundwater by draining the surrounding fissured aquifers and contribute to the yields of wells developing groundwater from this mixed aquifer. Groundwater is under the water table more frequently under semi-confined conditions.
- **Basement rocks** represent fissured aquifers of low potential and were defined as a separate group, because they have a specific hydrogeological character and cover large areas of the Ethiopian territory. The groundwater in the basement rock is practically stored completely in the fractured zones and the weathered mantle of the parent rocks. The depth of fractured aquifer zones is generally no more than 50–70 m below the surface. The fractures tend to close at depth. The faults and joints in igneous rocks are nearly vertical, except for narrow fractures, which are more or less parallel with the rock surface and exfoliation. The greatest permeability is found in the sub-soil zone within the partly decomposed rock. Wells tapping this zone have yields roughly an order of magnitude greater than in the fresh rock.
- **Units with limited groundwater resources** (aquitard) are lithological units (additional to basement rocks) with different permeability, where groundwater is stored and transmitted through specific lithological parts of the unit and/or through specific (open) fissures, which are not closed by clay of other materials. Groundwater can be reached by individual wells and most of the springs have intermittent and/or seepage character.
- **Units with essentially no groundwater resources** (aquiclude) are lithological units where groundwater is neither stored nor transmitted through the rock under ordinary hydraulic gradients. Groundwater development for a limited individual water supply is very difficult and even impossible in places. These are groundwater resources with poor or no exploitation potential and may be represented by Mesozoic gypsum and shale, Tertiary trachyte domes or Quaternary obsidian and pitchstone. The units with essentially no groundwater resources are expressed on the hydrogeological map in dark brown.
- **Shallow and limited aquifers** where groundwater is accumulated in and flows through pores of an unconsolidated material are represented by a) eluvium (an in situ weathered material derived from volcanic and basement mother rocks) and by eluvial soils, slope deposits and landmass of landslide; b) alluvial soils in small accumulation of mixed

alluvial and other sediments in intermountain depressions. These shallow and limited aquifers with shallow groundwater for local use (private dug wells) provide a variable amount of water based on thickness variation and proximity to recharging areas.
- **Specific confined aquifers;** their character can be shown in the map. One of the examples is an extensive aquifer immediately underlying a thin (more than 5 m) "impermeable" cover, which can be found in northwestern Ethiopia, where aquifer developed in the Adigrad sandstone is covered with marlstone, which has a confining function to the aquifer (Adi Ramets map sheet).

It is recommended to assess the quantitative data of individual aquifers using a simple statistical analysis such as a histogram showing the yield frequency of springs and wells. In case of insufficient data for a particular aquifer, it is possible to use an analogy from the surrounding maps and/or from a map at a different scale.

Hydrochemistry

The chapter describes the hydrochemistry of natural water and presents the water types and their relationship based on a scheme used for the compilation of a hydrochemical map.

The water quality for various purposes is defined as:
- For drinking purpose using the Ethiopian standard published in the Negarit Gazeta No. 12/1990 and The Guidelines of Ministry of Water Resources published in 2002.
- Aagriculture (Sodium Absorption Ratio – SAR, EC values – salinity criteria, and livestock watering.
- Industrial use (requirements for various industrial processes, corrosion and incrustation hazard).

Groundwater resources assessment

The assessment of water resources of the map sheet is based on the data listed in Tab. 10.

Table 10. Assessment of water resources

Element of water resources	Input data
Precipitation	Adopted depth of rainfall in (mm)
Total water resources – map	Adopted value of specific runoff in (l/s.km^2)
Renewable groundwater resources, active aquifers	Adopted value of specific baseflow in (l/s.km^2)
Static groundwater resources in fissured aquifers	Considering 5% open spaces and 100 m saturated thickness
Static groundwater resources in porous aquifers	Considering 15% porosity with a saturated thickness of 20 to 100 m

Remark: the saturated thickness can vary sheet by sheet.

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10) GEOLOGICAL RISKS AND GEOMORPHOLOGY MAP

Definition of Geological hazard map

The geological hazard map displays information about geodynamical conditions and hazardous phenomena in the studied area related to the geological and geomorphologic setup. It represents a basic source of information for urban or rural planning and sustainable development, thus securing lives and property against dangerous geological processes. Moreover, it is also suitable for civil engineering and the environmental protection. The map is accompanied by explanatory notes. All features expressed on the map should be documented. The map documentation consists of a description of all natural and/or manmade features.

Methodology of Geological hazard mapping

Geological hazard mapping has the following phases:
- Desktop study of existing data and literature.
- Geomorphologic analysis of remote sensing and topographic data.
- Field work.
- Synthesis of archived data, remote sensing interpretation, field data into final geo-hazard map.

10.1 Desktop study

Desktop study includes a collection and evaluation of all relevant geological, structural, lithological, pedological and geomorphologic data in technical reports, publications, and archival maps at a relevant scale.

Interpretation of Remote Sensing and Topographic data

The quality and scale of topographic and distance data should match the scale and purpose of the resulting map. Basic topographic data should be in greater detail or at least at the same scale as the resulting map (if available). Topographic and remote sensing data include a wide range of data with different types of information:
- **Basic topographic data** indicate the slope gradient, terrain configuration and drainage patterns, infrastructure and settlements.
- **Aerial photographs** allow the identification of topography, drainage pattern, geomorphologic feature, land-use and relations to other factors. Careful study of a given area of terrain with the aid of oblique aerial photographs and vertical stereo pairs can yield significant information on the type of landforms, including the indications of superficial processes. A review of recent and past aerial photographs

of the area should be undertaken whenever possible for the analysis of evolution and impact of geodynamical processes on the surface.

- **DEM (digital elevation model)** displays the 3D visualization of terrain. The slope analysis and hypsometry can be derived from DEM. These data can be used for geomorphologic interpretation, slope failure analysis, modeling water flow for hydrology or mass movements and other geological applications. The very accurate Digital Elevation Model should be applied also in flat terrains. For example, the LIDAR technology can produce high-resolution terrain maps even where the forest cover gets in the way of traditional photography and the products are very clear and detailed DEM. It allows a detailed geomorphologic and geodynamic interpretation in flat areas (flood plains, alluvial fans) as well as in the zones with dense vegetation cover.

Geomorphologic interpretation of remote sensing and topographic data

Morphometric shapes of the relief can be parametrically derived from the remote sensing data, by which it is possible to express and quantify the individual geomorphological landforms occurring in the given territory.

Individual types of relief define different geomorphologic landforms, which can be considered afterwards for the processes where they occur. The geomorphologic interpretation of the structural, denudation and accumulation landforms will be characterized by occurrence, spatial relations and geomorphologic setting. Terminology of Goudie (2014) is applied for the definition of geomorphologic landforms. During the interpretation, it is necessary to focus especially on the types of landforms with a high occurrence of dangerous surface processes such as recent and fossils landslides, retreating escarpments, erosional landscape with badlands and gullies, alluvial fans, flood basins as well as morphological expressions of tectonic, seismic and volcanic activity (fault escarpments, ground fissures, lava flows). It is also appropriate to include a multi-temporal analysis in the geomorphologic interpretation for the reconstruction of the evolution of nature systems. The multi-temporal analysis can be applied for the prediction of the future evolution of nature system as well. Characteristics of geomorphologic landforms with regards to mutual interactions of anthropogenic impacts should be obtained by the interpretation and checking of the field work later.

10.2 Field data collection

The main task of the field work is to verify the results of interpretations of remote-sensing data and document significant phenomena regarded to the geological hazard.

The subjects of the documentation are:

Geomorphology of a given territory – changes in topography and surface form, morphometric information, occurrence of gullies in erosion surface, occurrence, type and geometry of fluvial channels, occurrence of slope failure indications, quantitative measurements (e.g. slope angle).

Lithological characteristics of bedrocks and superficial cover and character of soils – lithological type, thickness bedding geometry, strike and dip, character and density of discontinuities, the degree of weathering or alteration types, geotechnical characteristics (if available).

Character and description of geodynamical features – indications of geodynamical features of alluvial processes (erosion, accumulation of material, avulsion, flooding), slope processes (landslides, rock-falls, mass movements) as well as post-volcanic processes have to be described. The classification of Varnes (1978) is useful for landslides.

Anthropogenic constructions include open pits, mining and their waste disposal, important linear engineering structures (roads, pipelines, big embankments, bridges, retaining walls, power plants, river dams, regulation of river channels etc.)

The character of the vegetation cover

Slope stability is discussed extensively by. The mechanisms of woody vegetation influence on slope stability can be viewed in two aspects: hydrological and mechanical (Marston 2010). Among the hydrological effects Interception of precipitation by canopy, promoting evaporation and reducing water available for infiltration all have beneficial effects. Strong anchorage of top and deeper soil by vegetation roots thereby also increasing the shear strength of the soil are among the mechanical stabilization mechanisms of vegetation cover. Neverthless in some cases the added weight of vegetation have adverse effect of aggravating slope instability depending on the type of plant (for example Enset in the Ethiopian case) (Temesgen et al 2000).

Land Use

Landslide activity is strongly controlled leading to stagnation of landslide from expanding (Van Beek and Van Asch 2004). Land use influence perceived hazard levels and zonation of an area where especially land use changes involving land abandonment strongly influence vulnerability of an area that is already adversely disposed for instability or degradation due to other physical factors.

Map sheet	Name and number of a map sheet
Location	Municipality, Woreda, Zone, Region
Coordinates	UTM: X, Y, Elevation (using GPS)
Topography, geomorphological setting	Plain, depression, valley, slope, type of landform
Type of geodynamical feature	The origin of a geodynamical feature, classification, geomorphological indication
Length of geodynamical features	Visual estimation in the field, measurement in the field (if available) from topographic data (m)
Width of geodynamical features	Visual estimation, measurement in the field (if available), from topographic data (m)
Depth geodynamical features	Visual estimation, measurement in the field (if available), from topographic data (m)

Activity of feature	Active / Non active / Fossil
Triggering factors	Human intervention or an inappropriate construction, precipitation and saturation, other nature processes; brief interpretation of factors geological unit (visible or from the geological map)
Mitigation	A brief description and the description of proposal how to eliminate a negative impact of a hazardous process.
Land-use	Description of land-use, occurrence of buildings, roads, irrigation infrastructure, type of vegetation
Endangered objects	List of objects that could be endangered by geodynamic processes (buildings, infrastructure, farmland)
Photo documentation	Photos of features and the scheme of situation in the endangered area
Date of documentation	

10.3 Synthesis and transformation of data to general geo-hazard map

Geological hazard map provides a graphical expression of spatial analyses as the occurrence of forms indicating the present-day or historical activity of hazardous geodynamical processes and the spatial assessment of vulnerability as a result of synthesis of the primary documentation data, the interpretation of remote-sensing data and field-work observation.

The geological hazard map consists of layout (Fig. 18) with the following items:

- Original of the map.
- Legend to the map.
- Map sheet scheme .
- Author scheme .
- Tectonic scheme (seismic zoning and epicenters, active fault zones).
- Geomorphologic scheme (basic geomorphologic units).
- Supplementary data (e.g. 3D model, satellite imagery).
- Scale.
- Imprints.

10.4 Explanatory note to the geo-hazard map

Written explanatory notes to the geo-hazard map describe geodynamic processes in the area and their impact to the nature and human activity. The structure of report can attain the following.

Introduction

- A brief description of the area with regards to nature hazard processes, a basic description of geological, hydrological and geomorphological conditions of the area

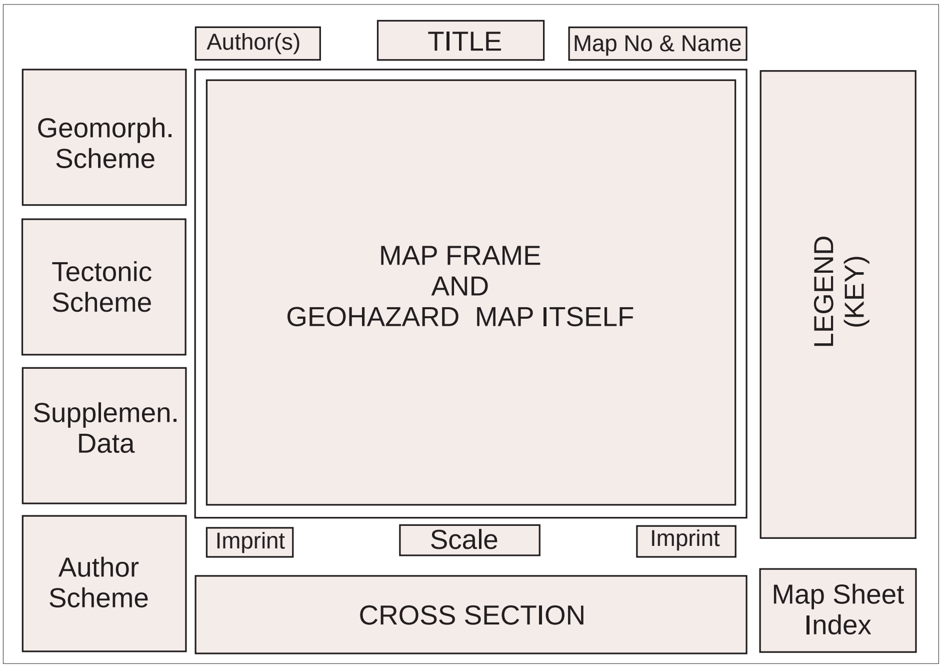

Figure 18. *Idealised layout of Geo-hazard map.*

Endogenous hazard

- Review of seismic hazards – earthquakes, seismic swarms and volcanic earthquakes and their impact. The data are obtained from databases, archived data and previous studies such as: catalogue of earthquakes from the United States Geological Survey (USGS), local seismic networks from Institute of Geophysics, Space Science and Astronomy (IGSSA), Addis Ababa University.
- Review of volcanic hazards – processes and phenomena related to late Pleistocene to Holocene volcanic activity, which consist of indication and evidence of magmatic eruption as well as post-volcanic features. The analysis of volcanic hazards is based on the morphological feature of volcanic landforms, field observations and estimations of volcanic deposits age and archive data resources – final reports (JICA 2012, UN-UNDP), the on-line database (Global Significant Volcanic Eruptions, Database Caldera Collapse) and published data.

Exogenous hazard

- Review of alluvial hazards – a wide range of processes associated with rivers and surface water streams, vertical and lateral erosion, complex processes on an alluvial fan and floodplains, based on the archived data (publications, final reports, hydrological data), previous mapping, geomorphologic features, analysis and field observation with documentation.
- Review of slope processes hazards – mass movement, landslides and slope failure based on the archived data (publications, final reports), previous mapping, geomorphologic features, analysis and field observation with documentation.

Prevention and mitigation measures

- Recommendation and proposals of mitigation and reduction of hazard, steps for the creation of long-term hazard prevention.

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11) SOIL MAP

A *soil map* shows the geographic distribution of different soils in the landscape using soil map units. Soil map is a result of a soil survey.

The *soil* is a topmost part of the Earth's crust, consisting of mineral components, decayed organic matter and living organisms. It is more or less distinctly horizontally zoned, and originates from a regolith and/or unconsolidated mineral and organic sediments. The soil is a complex product of geological, hydrological, atmospheric and biological interactions. The understanding of the nature, properties, dynamics and functions of the soil as a part of landscape and ecosystem is the main objective of *pedology*.

11.1 Soil survey

Soil survey is a systematic study of the soil of an area, including the classification and mapping of the properties and the distribution of various soil *units*. It applies the principles of soil science, geomorphology, theories of soil formation, and the analysis of vegetation and land use patterns.

Soil survey is always conducted with a certain purpose, which can be either general (e.g. soil profiles for the soil characterization) or specific (e.g. sampling to investigate potentially contaminated land). Soil surveying usually comprises five essential steps (Deckers et al., 2009):

1. Background study

All the relevant data for the given area are compiled – former studies and existing maps, aerial photographs, background information concerns the hydrology, geology and lithology, geomorphology and land use.

2. Describing soils in the field, profile study and soil sampling

The assessment of soil variability can be done in different ways: in hilly areas, the soil profiles are sampled according to transect walks from hilltops to valleys, on flat terrain, a systematic grid is recommended. Soil variability is assessed by an auger or soil core sampler, and representative sites are located for soil profile studies. For chemical soil analysis, a disturbed sample is taken from each horizon, or from a specific depth. For physical analysis, undisturbed core samples are needed.

3. Extrapolation and boundary verification.

After the field classification, all observation points are plotted on the base map (topographic map or an aerial photo) along with the landscape features – a conceptual model emerges, linking the distribution of soils to landscape features.

4. Laboratory analysis

The type of analysis depends on the purpose of the survey. The routine analysis comprises the following for each horizon: the particle-size distribution, pH, electrical conductivity, organic carbon and nitrogen contents, cation exchange capacity (CEC), exchangeable bases and phosphorus content.

5. Data crunching, map production, interpretation and reporting.
Once the laboratory data are in a file, the field classification of the soil profile pits can be verified and the soil map can be finalized. The legend of the map is constructed so that it serves its purpose to a maximum extent.

11.2 Soil description and classification

The availability of reliable information on soil morphology and other characteristics obtained through examination and description of the soil in the field is essential, and the use of a common language is of prime importance. The increasing need for internationally accepted rules and systems of soil description led to the development of *„Guidelines for soil description"* (Jahn et al. 2006). Full text free access: http://www.fao.org/docrep/019/a0541e/a0541e.pdf.

These guidelines provide a complete procedure for the soil description and for collecting field data. To help beginners, some explanatory notes are included together with keys based on simple tests and observations. The summary of the *guidelines* is given below.

Before the completion of any actual soil description, it is necessary to take note of some relevant information related to the registration and identification of the soil to be described.

General site information: profile number – date of description – author(s) – soil unit – location – elevation – map sheet number and grid reference – coordinates. The information is necessary for easy referencing and retrieval of the soil description from data storage systems.

Soil profile description

A **soil profile** is a cross-section (cut, pit or trench) through various more or less horizontally oriented features formed by pedogenic processes called *horizons* from the surface down to the *beginning* of the material unmodified by pedogenesis.

The **soil horizon designation** summarizes many observations of the soil description and gives an impression about the genetic processes that have formed the soil under observation.

Four kinds of symbols are used in various combinations to designate horizons and layers:

Capital letters *(H, O, A, E, B, C and R)* – master horizons; **lowercase letters** – specific characteristics of master horizons; **numbers** – vertical subdivisions within a horizon and discontinuities; **special symbols** – layers formed in human-transported material or sequences of horizons having otherwise identical designations.

Horizon boundaries are described in terms of depth, distinctness and shape. In certain cases, they reflect past anthropogenic impacts on the landscape.

A profile can be described additionally with depth intervals of sampling, which do not necessarily correspond with pedogenetically formed horizons (top- and subsoil).

A soil profile description consists of two parts:

- Description of the environment in which the soil occurs: Topography, landform, position, slope, micro-topography, soil-landscape sequential relationships, land use, human influence, vegetation, parent material (unconsolidated material, rock type), rock outcrops, surface coarse fragments, erosion, surface sealing, surface cracks and other surface characteristics, drainage, flooding, groundwater, and/or moisture conditions of the soil.

- Soil horizon description: colour, texture, structure, consistence, rock fragments and artefacts, carbonates content, content of gypsum, readily soluble salts, andic characteristic and volcanic glasses, soil-water status, coatings, biological activity, human-made materials, and/or the degree of decomposition and humification of peat (Tab. 11).

In addition, specific locations, patterns or any other characteristics may be recorded. The surveyor should attempt to classify the soil in the field on the basis of the soil morphological features that have been observed and described.

The final classification is made after the analytical data have become available: *pH value, Calcium Carbonate content, cation exchange capacity, base saturation, organic Carbon content (for an indirect determination of organic matter), total Nitrogen content, C/N ratio, and/or Mehlich III extractable elements (to assess soil nutrient status).*

Soil classification concerns the grouping of soils with a similar range of properties (chemical, physical and biological) into units that can be geo-referenced and mapped.

Soil science, unlike many other scientific disciplines, does not have a universally accepted classification system. Many countries have developed systems to classify their soils, but the results often do not translate well between the taxonomic systems. Attempts have been made through efforts such as the *FAO Legend for the Soil Map of the World, Soil Taxonomy, and the World Reference Base for Soil Resources*.

The World Reference Base (WRB) (IUSS Working Group WRB, 2015) is the international standard for soil classification system endorsed by the International Union of Soil Sciences. As far as possible, diagnostic criteria match the main existing systems, so that the correlation with national and previous international systems is as straightforward as possible.

Full text free access: http://www.fao.org/soils-portal/soil-survey/soil-classification/world-reference-base/en/.

Table 11. The example of the soil profile description – Dystric Nitisol (Profile ID DE164)

Profile photo	Horizon	Depth (cm)	Description
	Ah	0–25	dark reddish brown (5YR 3/4), loam, weak blocky subangular to moderate fine granular, soft fragile consistence, many very fine pores, many very fine and common medium roots, dry, non calcareous, clear wavy boundary to
	AB	25–60	diffuse transitional horizon dark reddish brown (5YR 3/6), clay loam, moderate blocky subangular, broken thin clay cutans, many very fine pores, non-calcareous, diffuse boundary to
	Bt	60–160	dark reddish brown (5YR 3/6), clay, strong very coarse subangular blocky, hard consistence, continuous moderately thick clay cutans, many very fine pores, non-calcareous, abrupt irregular boundary to
	R	below 160	unwelded ignimbrite, ash-rich matrix

11.3 Compilation of soil map

Soil map is a result of a *soil survey*. It delineates areas occupied by different map soil units, where each unit has a unique set of interrelated properties characteristic for the material from which it is formed, its environment and its history (Soil Survey Division Staff, 1993).

The *soil map unit* is the basic geographic component on the soil map. Each *map unit* has a unique *symbol* (numbers or letters, see Appendix 6) on the soil map – *map legend*.

Soil maps created at different cartographic scales require different levels of generalization.

Rules for creating map legends according to WRB soil classification system

1. A map unit consists of

- a dominant soil only or
- a dominant soil plus a codominant soil and/or one or more associated soils or
- two or three codominant soils or
- two or three codominant soils plus one or more associated soils.

Dominant soils represent ≥ 50% of the soil cover, codominant soils ≥ 25 and < 50% of the soil cover. Associated soils represent ≥ 5 and < 25% of the soil cover or are of high relevance in the landscape ecology.

2. The number of qualifiers specified below refers to the dominant soil. For codominant or associated soils, fewer numbers of qualifiers (or even no qualifier) may be appropriate.

3. Depending on scale, different numbers of principal qualifiers are used:
a) For very small map scales (e.g. smaller than 1 : 10,000,000), only the Reference Soil Group (RSG) is used.
b) For next larger map scales (e.g. from 1 : 5,000,000 to 1 : 10,000,000), the RSG plus the first applicable principal qualifier are used.
c) For next larger map scales (e.g. from 1 : 1,000,000 to 1 : 5,000,000), the RSG plus the first two applicable principal qualifiers are used.
d) For next larger map scales (e.g. from 1 : 250,000 to 1 : 1,000,000), the RSG plus the first three applicable principal qualifiers are used.

4. If there are fewer qualifiers applicable than described above, the lesser number is used.

5. Depending on the purpose of the map or according to national traditions, further qualifiers may be added optionally at any scale level. These may be additional principal qualifiers from further down the list and not already used in the soil name, or they may be supplementary qualifiers. They are placed using the above-mentioned rules for supplementary qualifiers. If two or more optional qualifiers are used, the following rules apply:
a) the principal qualifiers are placed first, and from them, the first applicable qualifier is placed first, and
b) the sequence of any supplementary qualifiers added is decided by the soil scientist who makes the map (IUSS Working Group WRB, 2015).

Mapping information can be produced in paper form, or increasingly in digital mapping form by means of a Geographical Information System (GIS), which uses the computer to store and manipulate the data about soils and other related themes.

The *scale* at which the soil data is collected is a reflection of the sampling density – the number of observations taken throughout the survey (Tab. 12).

Table 12. Survey intensity versus scale and sampling density (according to Dent and Young, 1981)

Survey type	Scale	1 cm^2 on the map	Observation density
Very high intensive	1 : 5,000 1 : 10,000	0.25 ha 1.00 ha	1/0.5 ha 1/2.5 ha
High intensive	1 : 20,000 1 : 25,000	4.0 ha 6.25 ha	1/8 ha 1/12.5 ha
Medium intensity	1 : 50,000	25 ha	1/50 ha
Low intensity	1 : 100,000	1 km^2	1/km^2

The data requirement during the field survey is related to the specific objectives of the study and types of land use under consideration. The scale and intensity of soil survey are set in function of the objectives of the evaluation and time/money available. An overview of the types of soil surveys, scale, purpose and methods used is given in Tab. 13.

Table 13. Type of soil survey versus scale, purpose and methods used (according to Dent and Young, 1981)

Exploratory **Scale:** 1 : 500,000 – 1 : 1,000,000 **Purpose:** to establish major soil regions **Methods:** deductions from other maps, geological survey, vegetation records, remote sensing and ground verification
Reconnaissance **Scale:** 1 : 100,000 – 1 : 250,000 **Purpose:** systematic land resources inventory **Methods:** aerial photo interpretation, comprehensive field surveys and land system analysis, profile description and analyses
Semi-detailed **Scales:** 1 : 20,000 – 1 : 50,000 **Purpose:** project feasibility studies, Land use development **Methods:** aerial photo interpretation, intensive field observations, profile descriptions and analysis
Detailed **Scales:** 1 : 10,000 and larger **Purpose:** farm planning **Methods:** very intensive soil augering, laboratory analysis

Traditional soil mapping is conducted with an auger and spade at intervals throughout the landscape. The intervals between the soil survey sites can be defined according to a pre-determined grid (grid-survey) or, more often, are based on the judgement of the surveyor who uses his/her knowledge of the inter-relationship between the soil type and landscape, geology, vegetation, etc. A field soil map drawn in such a way is later digitized and printed. Recent advances in digital soil mapping have produced an alternative means for the soil mapping by correlating the soil properties to ancillary information such as derived from digital elevation models and remote sensing imagery, and by using geostatistics to interpolate the soil between observations at point locations.

Digital soil mapping is the generation of geographically referenced soil databases based on quantitative relationships between spatially explicit environmental data and the measurements made in the field and laboratory (McBratney et al., 2003).

- Digital soil mapping is the prediction of soil classes or properties from point data using a statistical algorithm.
- The digital soil map is a raster composed of 2-dimensional cells (pixels) organized into a grid, in which each pixel has a specific geographic location and contains soil data.
- Digital soil mapping can be used to create initial soil survey maps, refine or update existing soil surveys, generate specific soil interpretations, and to assess risks (Carré et al., 2007).
- It can facilitate the rapid inventory, re-inventory, and project-based management of lands in a changing environment.

Further development in digital soil mapping depends on the effective use of historical soil information, and the development of rapid and inexpensive techniques to make new soil measurements.

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APPENDIXES

APPENDIX 1
Symbols used in build of geological index

CHRONOSTRATIGRAPHIC SYMBOLS

Sytem	Series	Symbol
Quaternary		Q
	Holocene	Qh
	Pleistocene	Qp
Neogene		N
	Pliocene	N2
	Miocene	N1
Paleogene		Ꝑ
	Oligocene	Ꝑ3
	Eocene	Ꝑ2
	Paleocene	Ꝑ1
Cretaceous		K
	Upper C.	K2
	Lower C	K1
Jurassic		J
	Upper J.	J3
	Middle J	J2
	Lower J.	J1
Triassic		T
	Upper T.	T3
	Middle T.	T2
	Lower T.	T1
Permian		P
	Lopingian	P3
	Guadalupian	P2
	Cisuralian	P1

System	Series	Symbol
Carboniferous		C
	Pennsylvanian	C2
	Mississipian	C1
Devonian		D
	Upper D.	D1
	Middle D.	D2
	Lower D.	D3
Silurian		S
	Pridoli	S4
	Ludlow	S3
	Wenlock	S2
	Llandovery	S1
Ordovician		O
	Upper Ordovician	O1
	Middle Ordov.	O2
	Lower Ordovician	O3
Cambrian		Є
	Furongian	Є4
	Series 3	Є3
	Series 2	Є2
	Terrenuvian	Є1
Erathem		
Neoproterozoic		NP
Mezoproterozoic		MP
Paleoproterozoic		PP

SEDIMENTARY ROCKS

Important sedimentary textures and genetic feature (te)	
bd	biodetritic
if	ichnofossil
bi	existence of bitumen
ca	carbonaceous rocks, admixture
cb	cross bedding
dt	detritic
e	eolian sediment, admixture
f	fluvial sediment
fy	flysh sediment
fw	fossil weathering
g	glacial sediments
ch	chaotic texture
co	coral sediments
l	limnic sediments
la	lamination
mv	massive texture
my	mylonitization
bo	biogenic rock
vc	variocoloured
ry	rhytmite
s	spotted
si	silicification
t	tuffaceous admixture

Sedimentary lithology (li)	
a	arkose
b	breccias
d	dolomite
di	diatomite
e	evaporate
cy	clay, claystone
sh	shale
c	conglomerate
l	loess
ld	lydite
s	sandstone
q	quartzite
r	siltstone
ra	radiolarite
ch	chert
m	marl
sg	spongilite
g	gravel
co	coal
li	limestone
w	greywacke

VOLCANIC ROCKS

Coherent volcanic rock (r)	
α	andesite
β	basalt
βα	basaltic andesite
η	basanite
ζ	dacite
φ	foidite
υ	phonolite
ω	picrite, polzenite
ρ	rhyolite
ψ	tephrite
τα	trachyandesite
τβ	trachybasalt
τ	trachyte

Pyroclastic rocks – genetic types (ge)	
b	breccias
ig	ignimbrite
l	lappilistone
la	lahar
p	pumice
s	scoria
t	tuff

Textural and genetic specification of volcanic rocks (te)	
f	fluidal
gt	granulate
la	lamination
an	amygdaloidal
mv	massive
my	mylonitic
p	porphyric
pl	pillow lavas
gs	glassy
v	vitritophyric
vl	variolitic
s	stratification
e	effusive
ep	epiclastic
fr	phreatomagmatic

PLUTONIC ROCKS

Igneous (plutonic) rocks (r)	
ι	aplite
δ	diorite
δq	quartz diorite
ν	gabbro
νδ	gabbrodiorite
γ	granite
γδ	granodiorite
hσ	hornblendite
aν	hyperite
si	quartz vein
χ	lamprophyre
pν	norite
κ	pegmatite
σ	peridotite
γπ	porphyric microgranite
νπ	porphyric microgabbro
γδπ	porphyric microgranodiorite
ξπ	porphyric microsyenite
δπ	porphyric mikrodiorite
pσ	pyroxenite
ξ	syenite, monzonite
ξδ	syenodiorite
ξν	syenogabbro
δ´	diorite dyke
γ´	granite dyke
γδ´	granodiorite dyke
ξ´	syenite dyke

Textures and expressive signs of igneous rocks (te)	
al	alkalic
at	altered
s	schistosed
b	brecciated
en	enclave
l	leukocratic
la	lamination
ml	melanocratic
mv	massive
my	mylonitic
p	porphyric

Grain size (gs)	
m	massive
f	fine-grained
m	medium-grained
c	coarse-grained

METAMORPHIC ROCKS

Metamorphic rocks (r)	
A	amphibolite
s	schist
E	eclogite
e	erlan, calc-silicate rock
ph	phyllite
νA	gabbroamfibolite
Gr	granulite
h	hornfels
v	crystalline limestone (marble)
q	quartzite
$^{m}\beta$	metabasalt
M	migmatite
G	orthogneiss
g	gneiss, paragneiss
S	serpentinite
sk	skarn
m	mica schist
B	greenschist

Textures and expressive signs of metamorphic rocks (te)	
a	agmatitic
ca	carbonatic
f	phlebitic
i	injected
c	cataclastic
l	leucocratic
M	migmatitized
ml	melanocratic
mv	massive
my	mylonitic
n	nebulitic
o	ophtalmitic, augen
la	laminated
po	porhyroblastic
q	quartzitic
s	stromatitic

SYMBOLS OF ROCK-FORMING MINERALS

actinolite	ak	hedenbergite	he	oligoclase	og
albite	ab	hyperstene	hy	olivine	ol
hornblende	h	chalcedona	cl	omphacite	om
analcime	ac	chlorite	c	orthoclase	ok
andalusite	and	chloritoide	cg	plagioclase	pg
andesine	as	jadeite	j	prehnite	pr
anhydrite	ah	calcite	ca	pumpellyite	pu
anorthite	an	kaolinite	k	pyroxene	p
augite	ag	corundum	cr	serpentinite	sr
biotite	b	quartz	q	sericite	s
cordierite	co	kyanite	ky	sillimanite	si
diopside	dp	lepidolite	le	scapolite	sk
dolomite	do	leucite	l	sodalite	so
aegirine	ae	limonite	lm	spinel	sp
enstatite	en	magnetite	mt	staurolite	st
epidote	ep	magnezite	mg	topaz	to
phlogopite	pl	talc	tk	tourmaline	t
glaucophane	gl	melilite	me	tremolite	tr
graphite	gf	muscovite	m	wollastonite	wo
garnet	g	nepheline	n	zeolite	z

APPENDIX 2
The most common geological map symbols

CONTACTS

- Observed/exposed boundary of units and rocks
- Approximate contact (not precisely located within 1/10 of cm at the scale of a map
- Lithological and petrological transition

FAULTS

- Fault observed
- Normal fault
- Fault inferred
- Reverse fault
- Fault concealed
- Thrust fault (nappe)
- Fault showing dip and striation
- Fault with mylonite zone
- Fault showing horizontal movement
- Fault with breccia zone

TECTONIC SYMBOLS

- Strike and dip of beds
- Strike and dip of magmatic foliation
- Subvertical bedding
- Subvertical magmatic foliation
- Subhorizontal bedding
- Bedding overturned
- Lineation with amount of plunge
- Strike and dip of cleavage
- Fold axis with amount of plunge
- Subvertical cleavage
- Subvertical lineation
- Strike and dip of foliation
- Subhorizontal lineation
- Subvertical foliation
- Combine symbol of foliation and lineation

SUPPLEMENTAL SYMBOLS

Reference point, natural	Stone pit
Reference point, artificial	Sand pit
Fossil flora	Clay pit
Fossil fauna	Mine
Block	Mine adit
Laterite	Mine shafts
Landslide	Borehole
Volcanic center	Water well
Mofetta	Spring
	Hot spring

APPENDIX 3

Rocks classification and lithological description

Rocks are classified into three main groups (igneous rocks, sedimentary rocks and metamorphic rocks); for each type, different classification criteria are used.

IGNEOUS ROCKS

The classification of igneous rocks is based on the mineralogy (plutonic rocks), geochemistry (volcanic rocks) and partly also on the texture (pyroclastic rocks). During the description of rocks in the field, other factors such as cooling conditions, magmatic fractionation (cumulates), type of eruption (pyroclastic rocks) and weathering effects should always be taken into account.

The main criteria that could be used to classify igneous rocks are (a) the modal mineralogical composition, (b) chemical composition of rocks, (c) rock texture.

(a) The modal mineralogical composition represents relative proportions of rock-forming minerals in a sample. The mineralogy strongly depends on the chemical composition of the magma and therefore, the modal composition is a good classification criterion for coarse-to-medium-grained plutonic igneous rocks. Individual crystals in the rocks can be easily seen with the naked eye or under microscope. However, volcanic rocks usually contain glass or very fine-grained minerals due to rapid cooling. Frequently, we are not able to readily identify these phases with the naked eye (only phenocrysts, texture and colour are usually visible) or under microscope (volcanic glass is mainly a problem).

PLUTONIC ROCKS

Plutonic rocks are classified according to their modal composition using the QAPF diagram (Fig. A1); Streckeisen 1974; Le Maitre et al. 2002). The corners of the double triangle are Q = quartz, A = alkali feldspar, P = plagioclase and F = feldspathoid. This diagram must be used for the rocks in which the mafic mineral content, M, is lower than 90% (pyroxenite, hornblendite). For the classification, we use the modal amounts of Q, A, P, and F and these minerals must be recalculated to make their sum 100% (Le Maitre et al. 2002).

Alkali granite contains quartz, alkali feldspar, biotite, alkali amphiboles and/or pyroxenes (alaskite may be used for a light-coloured (M ≤ 10) alkali feldspar granite).

Granite consists of quartz, K-feldspar, plagioclase, biotite and/or muscovite and often also garnet, andalusite, tourmaline.

Granodiorite commonly contains quartz, K-feldspar, plagioclase (oligoclase, more rarely andesine), biotite and/or amphibole.

Tonalite and ***quartz-diorite*** consist of quartz, plagioclase (K-feldspar minor) biotite and/or amphibole and sometime also pyroxene (trondhjemite and plagiogranite may be used for a light-coloured tonalite (M ≤ 10)).

Alkali feldspar syenite and ***syenite*** consist of alkali feldspar, biotite, amphibole or alkali amphibole and/or pyroxene.

Monzonite consists of K-feldspar, plagioclase, biotite and/or amphibole (pyroxene).

Monzodiorite and ***monzogabbro*** are separated according to the average composition of their plagioclase (monzodiorite = An < 50%; monzogabbro = An > 50%), typical dark minerals are biotite, amphibole, pyroxene, olivine.

Diorite, ***gabbroic rocks***, and ***anorthosite*** are separated according to the average composition of their plagioclase and the colour index (M less than 10% the rock is typical for anorthosite), typical dark minerals are biotite, amphibole, pyroxene, olivine.

Gabbroic rocks are subdivided according to the relative abundances of their orthopyroxene, clinopyroxene, olivine, and amphibole: **gabbro** = plagioclase + clinopyroxene, **norite** = plagioclase + orthopyroxene; **troctolite** = plagioclase + olivine; **gabbronorite** = plagioclase with almost equal amounts of clinopyroxene and orthopyroxene; **orthopyroxene gabbro** = plagioclase + clinopyroxene with minor amounts of orthopyroxene; **clinopyroxene norite** = plagioclase + orthopyroxene with minor amounts of clinopyroxene; **amphibole (hornblende) gabbro** = plagioclase + amphibole with pyroxene < 5%.

Foid syenite contains foids, alkali feldspar, biotite, alkali amphiboles and/or pyroxenes (the name depends on the most abundant foid, e.g. nepheline syenite, sodalite syenite).

Foid monzodiorite and ***foid monzogabbro*** are distinguished according to the average composition of their plagioclase.

Foid diorite and ***foid gabbro*** are distinguished according to the average composition of their plagioclase (foid diorite = An < 50%; foid gabbro An ≥ 50%). Two special terms may be used; theralite for nepheline gabbro and teschenite for analcime gabbro.

Foidolite (a volcanic equivalent called foidite) has a name according to the most abundant foid that should be present in the name, e.g. nephelinolite.

For plutonic and subvolcanic dykes, the plutonic root name and prefix with the term ***"micro"*** (microgranite) is commonly used.

The plutonic ultramafic rocks are classified according to their content of mafic minerals: olivine, orthopyroxene, clinopyroxene, amphibole, biotite, and various but usually small amounts of garnet and spinel (Streckeisen 1974, 1976). ***Peridotites*** are distinguished from ***pyroxenites*** by containing more than 40% olivine. The **peridotites** are subdivided into dunite, harzburgite, lherzolite and wehrlite. The **pyroxenites** are subdivided into orthopyroxenite, websterite and clinopyroxenite.

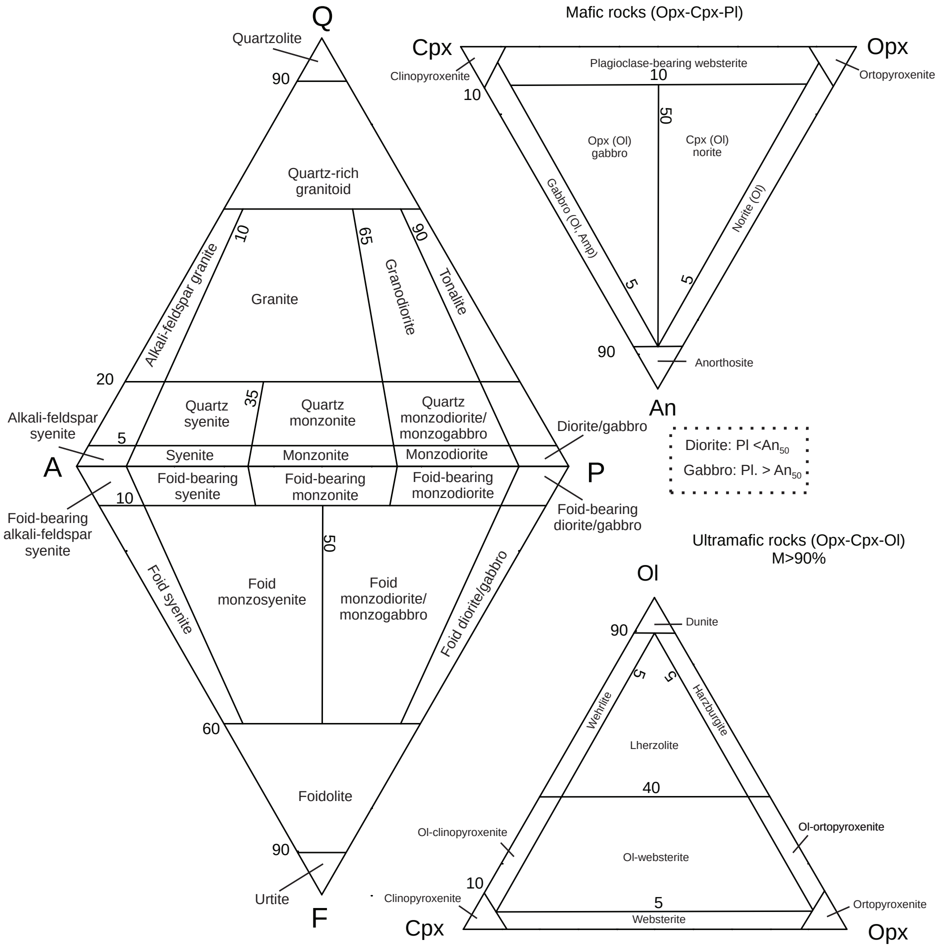

Figure A1. *QAPF ternary diagram used to classify the composition of silica saturated (QAP), undersaturated (FAP) basic (An-Opx-Cpx) and ultrabasic (Ol-Opx-Cpx) igneous rocks (Le Maitre et al. 2002).*

VOLCANIC ROCKS

The classification by QAPF for volcanic rocks can be used only if a mineral mode can be determined (Streckeisen 1978, 1979). The numbers of the fields are the same as those for plutonic rock classification (Fig. A2).

Alkali-feldspar rhyolite, ***rhyolite*** and ***dacite*** contain quartz, alkali feldspar, biotite, amphibole and/or pyroxene. Alkali-feldspar rhyolite is a rhyolite with alkali pyroxene and/or amphibole.

Alkali-feldspar trachyte, ***trachyte*** and ***latite*** are rocks without foids (but nepheline in the CIPW norm is present) and contain alkali feldspar, biotite, amphibole and/or pyroxene. Alkali-feldspar trachyte is a trachyte with alkali pyroxene and/or amphibole.

Basalt and ***andesite*** are divided from each other using colour index and plagioclase composition (andesite = An < 50%; basalt = An > 50%) and contain plagioclase, amphibole, pyroxene and/or olivine, sometimes biotite.

Phonolite consists of alkali feldspar, feldspathoid and mafic minerals. The predominant foid should be added to the root name, e.g. leucite phonolite, analcime phonolite.

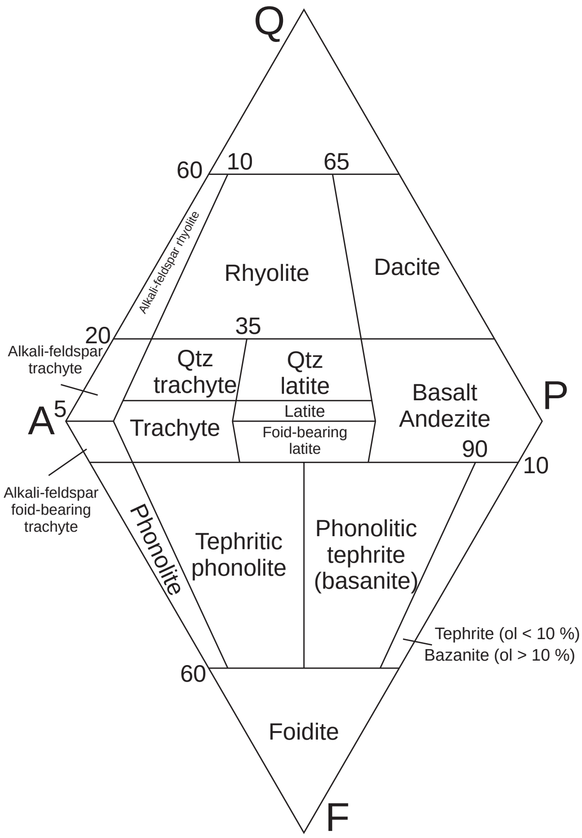

Figure A2. *QAPF ternary diagram used to classify the composition of volcanic rocks (Streckeisen 1978, 1979).*

Basanite and ***tephrite*** are distinguished based on the amount of olivine in the CIPW norm (basanite is a rock with a normative olivine content > 10% and a rock with < 10% olivine is called tephrite).

(b) Chemical composition of rocks reflects the mineral composition of the rocks; though it is not the same frequently (the mineral composition is also affected by PT conditions and fluid composition). Frequently, we use normative mineral composition (calculated from the chemical analysis), which represents hypothetical minerals that could crystallize from magma with the same chemical composition to the rock (e.g. the CIPW norm).

The first major geochemical division is based on Na, K and Si, which yield two groups, the subalkaline and alkaline rocks (Fig. A3a). The subalkaline rocks are subdivided based mainly on the Fe content (Fe-rich = tholeiitic series and Fe-poor = calc-alkalic). Several specific diagrams for the classification of igneous rocks on the basis of chemical composition are published. The common classification is based on the values of Na_2O + K_2O and SiO_2 (TAS) diagram (Le Bas et al. 1986; Fig. A3a). Alternatively, we can use a classification based on trace elements (Pearce 1996; Fig. A3b), which is suitable for partly altered rocks (Fig. A3a).

(c) Rock texture is an important classification criterion for volcanic and volcano-sedimentary rocks. The first textural division concerns an unconsolidated volcanic deposit (pyroclastic (tephra) and hyaloclastic rocks) and coherent volcanic rocks.

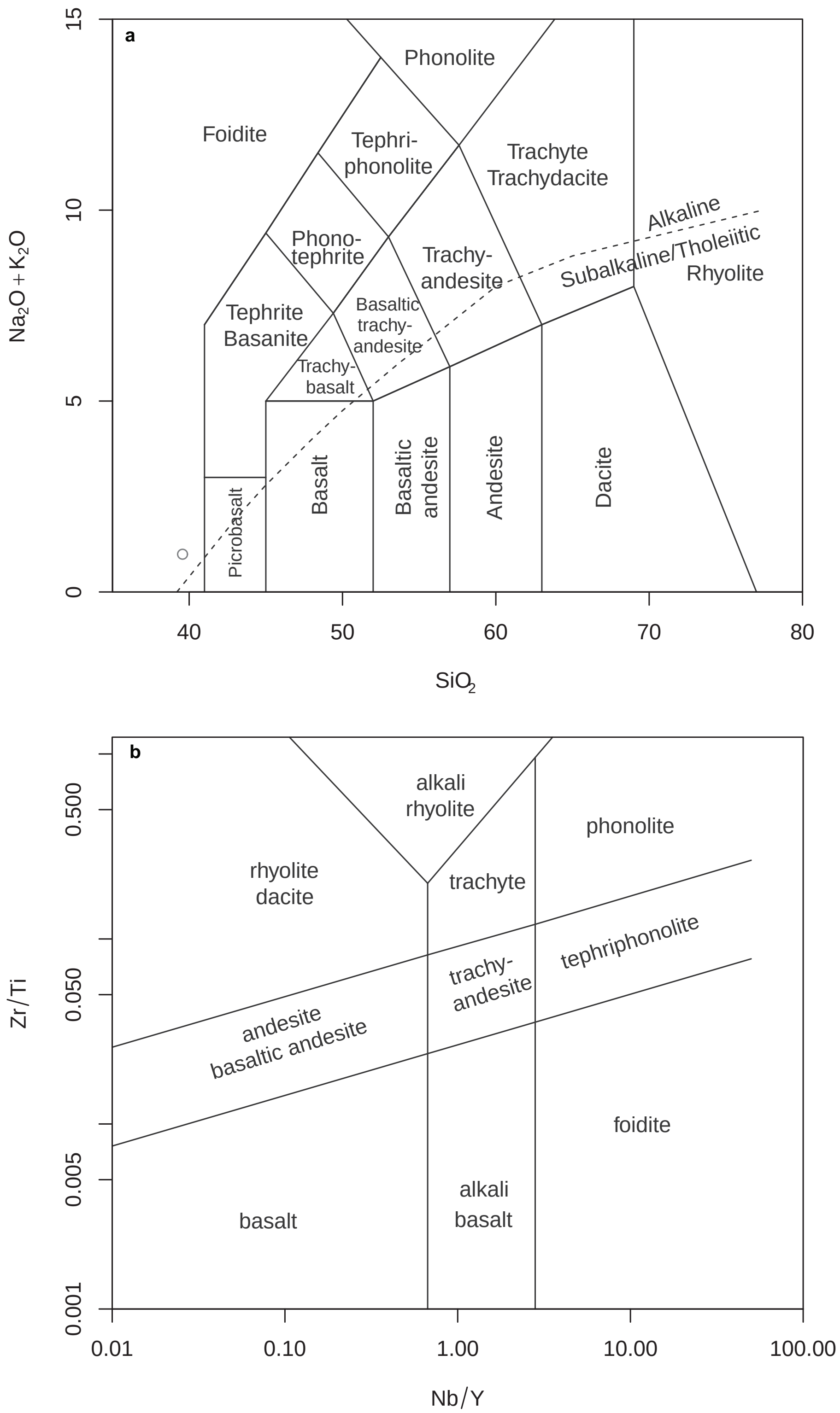

Figure A3. *Discrimination diagrams for volcanic rocks: a – Total Alkalis vs. Silica (TAS) diagram (Le Bas et al. 1986); b – Zr/Ti vs. Nb/Y diagram (modified by Pearce 1996).*

Volcanoclastic rocks are composed primarily of volcanic material. This material may be pyroclastic (fragments derived from magmatic eruptions) or hyaloclastic (fragments formed by thermal shock when hot lava gets to a contact with cool water or as the result of phreatomagmatic eruptions). However, these fragments can be mixed with epiclasts (clasts produced by weathering, and consequently transport of the volcanic rock) and/or sedimentary clasts in various proportions (volcano-sedimentary rocks).

(I) ***Unconsolidated volcanic deposits*** (Pyroclastic and hyaloclastic rocks, Fisher and Schmincke 1984) are commonly formed from fine ash (< 0.063 mm), coarse ash (< 2 mm), lapilli (< 64 mm) and bombs or blocks (> 64 mm) ejected from the volcano. Typical pyroclastic deposits include pyroclastic fall (pyroclastic material sorted in the air and deposited in beds) and pyroclastic flow (pyroclastic material emplaced by lateral flowage as a mixture with hot gas).

Important terms: Scoria is an accumulation of highly vesiculated basic rocks (predominately volcanic bombs) and ***pumice*** is a highly vesiculated acid glass. ***Ignimbrite*** is pumice and/or ash dominated pyroclastic flow deposit (classification according to the grain size, mineralogy (pumice-rich, crystal-rich) and texture (e. g. welded vs. unwelded ignimbrite).

(II) ***Coherent volcanic rocks*** are divided into fragmental volcanic rocks (Fig. A4; tuff, lapilli tuff, lapillistone, tuff breccia, agglomerate) and lava (volcanic rocks and glass). Lava (e. g. basalt, rhyolite) forms volcanic dikes, volcanic laccoliths, intrusive volcanic breccia, lava flow (pahoe-hoe, aa, block lava, massive lava, pillow lava) and lava dome.

Classification of **volcanic glass** depend on the chemical composition, texture and/or color (*obsidian* is acid, non-hydrated glass, generally dark-colored, and has few or no phenocrysts; *perlite* is acidic, hydrated glass characterized by spherical fractured texture).

(III) When the volcanic material has been transported and reworked by wind or water, we use the term ***volcanoclastic deposits*** (e. g. epiclastic sandstone or conglomerate). For rocks, which contain a mixture of pyroclastic, epiclastic and/or sedimentary material, we generally use the term tuffites (75% to 25% pyroclastic or hyaloclastic fragments). Tuffites may be divided according to their average grain size.

(IV) For the ***volcanogenic sedimentary deposits*** (sediments with addition of pyroclastic material, below than 25% pyroclastic or hyaloclastic fragments), we used the adjective **tuffitic** or **tuffaceous** (e.g. tuffitic sandstone).

Tuffites, tuffaceous and epiclastic rocks are produced by a volcanic avalanche (volcanic material possibly mixed with other rocks, emplaced by gravitational collapse from a volcanic edifice and subsequent rapid flowage) and a volcanic debris flow (volcanic material redeposited as water-saturated rock debris that flowed rapidly under the force of gravity = lahars).

Special terms (rocks beyond the presented classification):

Charnockites (e. g. hypersthene granite; Streckeisen 1974, 1976) are characterised by the presence of hypersthene (or fayalite with quartz).

Carbonatites are plutonic or volcanic rocks containing more than 50% modal carbonates (Streckeisen 1978 and Streckeisen and Le Maitre 1979). Mineralogically, they may be distinguished into: Calcite carbonatite (coarse-grained is soviet, and medium to fine-grained is alvikite); dolomite carbonatite (beforsite); ferrocarbonatite; natrocarbonatite (composed of sodium, potassium and calcium carbonates).

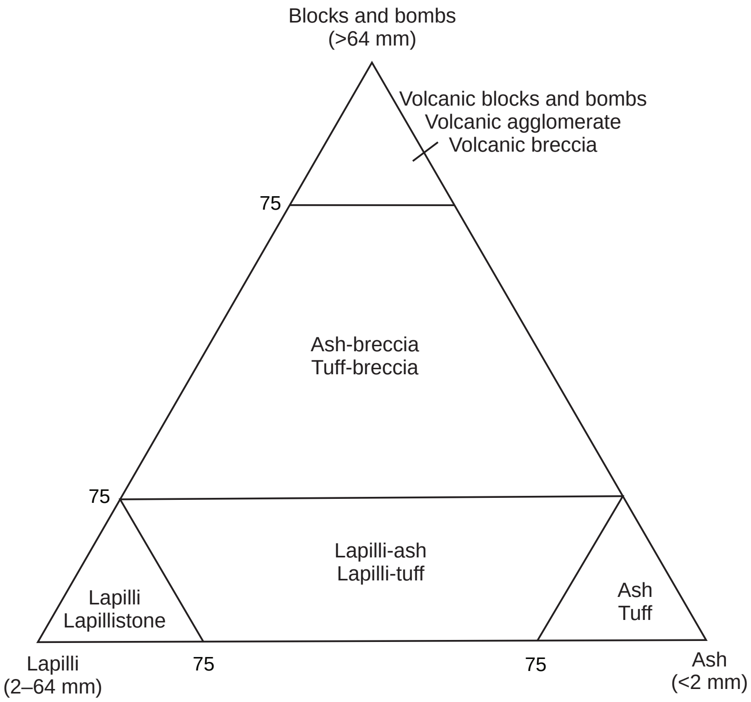

Figure A4. *Ternary diagram of grain size terms for the classification of pyroclastic rocks and fragmental volcanic rocks (modified from Fisher and Schmincke 1984). Top labels = unconsolidated, bottom labels = consolidated.*

The term ***melilite, kalsilite or leucite -bearing*** rocks is used for volcanic (subvolcanic) rocks with >10% modal melilite (kalsilite, leucite).

Kimberlites are ultramafic subvolcanic rocks dominated by primary olivine and carbonate minerals (often also magnesian ilmenite, pyrope, chromium diopside, phlogopite, enstatite and chromite).

Lamproites are ultrapotassic mantle-derived volcanic or subvolcanic rocks (e. g. wyomingite = diopside-leucite-phlogopite lamproite, orendite = diopside-sanidine-phlogopite lamproite).

Lamprophyres are mesocratic to melanocratic subvolcanic rocks (dikes, lopoliths, laccoliths, stocks and small intrusions) with a panidiomorphic texture and abundant mafic phenocrysts of dark mica (*minette* in groundmass orthoclase, *kersantite* in groundmass plagioclase) and/or amphibole (*vogesite* in groundmass orthoclase, *spessartite* in groundmass plagioclase) with or without pyroxene and/or olivine.

SEDIMENTARY ROCKS

Sedimentary rocks (Fig. A5) can be classified on the basis of their composition (mineralogy), grainsize or genesis (origin). The source rocks can be disintegrated into their chemical components (chemical and biochemical sedimentary rocks) or can be broken down into fragments (clastic rocks).

(a) Chemical sedimentary rocks precipitate from solutions without the influence of organic activity. The most common chemical sedimentary rocks are crystalline ones: inorganic carbonates such as travertine or dolostones; cherts composed of microcrystalline quartz; evaporites such as halite, gypsum, and anhydrite; iron oxides such as hematite and limonite.

Clastic rocks	Biochemical biogenical rocks	Chemical precipitates	Volcanoclastic rocks
conglomerate, sand, sandstone, mudstone, shale	limestone, dolomite, coal, phosphorite, chert	ironstone, evaporite	tephra, tuff

Figure A5. *Four principal categories of sedimentary rocks.*

(b) Biochemical sedimentary rocks are formed mostly by the remains of organisms (e. g. shells, corals plant fragments). Most organisms use calcite or aragonite to build their shells or a part of their skeleton and therefore, limestones are a relatively abundant type of sedimentary rocks. The dominant carbonate mineral in most limestones is calcite, but other carbonate minerals such as aragonite and dolomite may be present. The components of limestone are: (I) orthochems (micrite, sparite); (II) allochems = non-skeletal grains (ooids, peloids, intraclasts) and skeletal grains (biofossil = whole fossil, bioclast = particles of fossil); (III) non-carbonate constituents (quartz, chert, clay, phosphate, glauconite).

Also, silica-rich (diatomite), phosphorus-rich (phosphate rocks) or carbon-rich (lignite and coal) biochemical sediments are known.

Transition between biochemical and clastic sediments: a typical example is marl (carbonate-rich mud) or marlstone (carbonate-rich mudstone) containing 25–75% clay (Fig. A6).

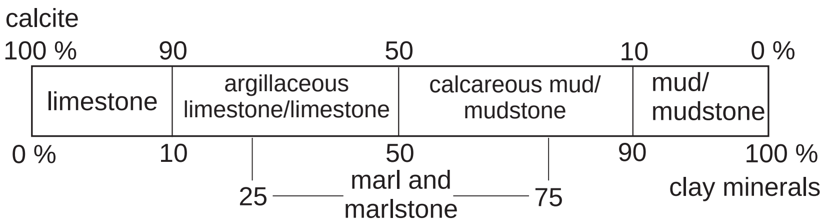

Figure A6. *Scheme of the transition from mud (or mudstone) to lime (or limestone).*

(c) Clastic sedimentary rocks consist of solid rock fragments (mainly siliciclastic or carbonate rocks) and are classified on the basis of grain size (gravel, sand, silt and clay). The clasts are transported as individual pieces by wind, water, ice or gravity-driven processes until the deposition. After the deposition, sediments are compacted (porosity decreases) and cemented by minerals that precipitate from a solution. Grains of sediment, rock fragments and fossils can be replaced by other minerals during diagenesis. The matrix or cement are fine-grained materials deposited along the clastic grains (matrix consists of clay minerals and silt-grade quartz; cement is precipitated around and between grains during diagenesis; common cementing agents are quartz and calcite). Siliciclastic rocks are initially subdivided according to the clast size:

(I) Rudite (psephite) is a rock dominated by fragments greater than 2 mm, being subdivided according to the clast geometry (angular clasts = breccia; subangular, subrounded or rounded clasts = conglomerates) or the petrological composition of clasts (several types of rock fragments = polymictic, only a few varieties of rocks = oligomictic, one type of clasts = monomictic).

(II) Arenite (psammite, grain-sized 0.006–2 mm) is subdivided according to the percentage of a fine-grained matrix versus clasts (Fig. A7; wacke contains more than 30% matrix) and by the mineral composition of the clasts (lithic arenite contains more than 15% clasts of the rock fragments, arcose contains more than 25% feldspar clasts).

(III) Lutite is a rock with a grain size less than 0.06 mm and can be subdivided into aleurite and pelite. **Aleurite** (siltstone or mudstone) is composed of silt-sized particles (0.004-0.06 mm) and a variable content of carbonates (marlstone is defined as a mud-supported carbonate rock). **Pelite** or shale (less than 0.004 mm) consists of mix of flakes of clay minerals and silt-sized fragments of other minerals (e. g. quartz, calcite).

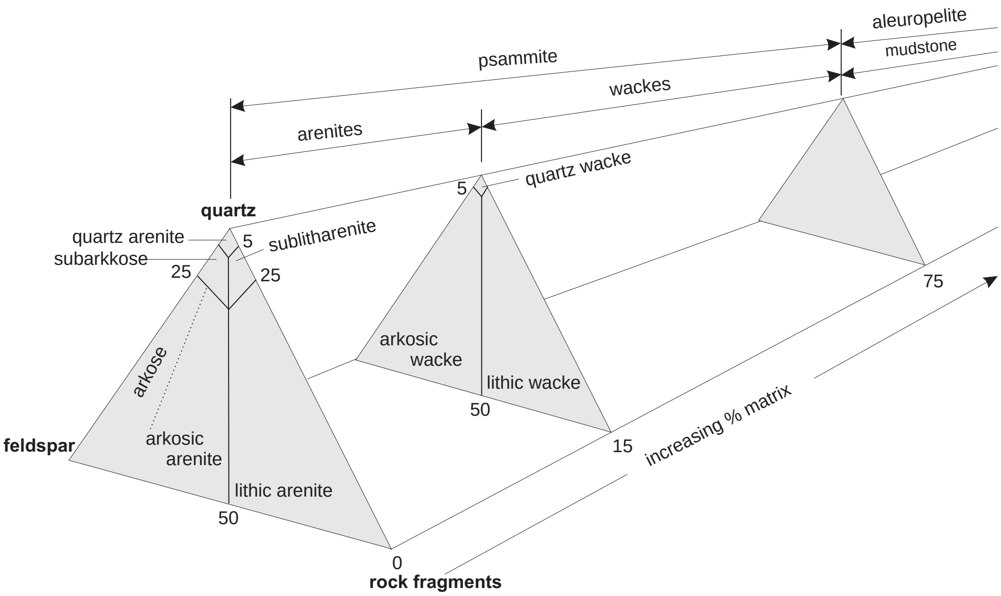

Figure A7. *Classification of the sandstone (modified from Pettijohn et al. 1987).*

METAMORPHIC ROCKS

Metamorphism is a subsolidus process leading to changes in mineralogy and/or texture and often in the chemical composition of a rock (Fettes et al. 2007). These changes occur due to physical and/or chemical conditions that differ from those normally occurring at the Earth´s surface and in the zones of cementation and diagenesis below this surface.

Lower limit of metamorphism: The protolith is subjected to temperatures up to 150 °C and a pressure of 1500 bars. Changes in a deeply buried sedimentary rock may be continuous from diagenesis into recrystallization forming a metamorphic rock.

Upper limit of metamorphism: The rocks reach high degrees of partial melting and have igneous composition and texture (approximately from 650° C to more than 1100° C depending on pressure, bulk composition and the proportion of water in the fluid phase). Metamorphic rocks may coexist under partial melting (migmatites).

Protolith means the original rock before metamorphism. The protolith may be a sedimentary rock, an igneous rock or another older metamorphic rock.

Metamorphic rocks are classified according to their texture, protolith and the type of metamorphism (e. g. metamorphic facies, Fig. A8).

MAIN TEXTURAL TERMS

Hornfels is a non-foliated aphanitic rock having a granoblastic fabric affected by contact metamorphism.

Granofels is a phaneritic rock which has little or no foliation or lineation.

Schist is a phaneritic metamorphic rock that has welldeveloped continuous schistosity.

Mylonite displays a foliation defined by the shapes of deformed mineral grains.

MAIN PROTOLITHE TYPES

Chemical composition of the protolith defines the modal mineralogy of rocks except for the metasomatic rocks (e. g. skarns, amphibolite, gneiss, eclogite, granulite).

Metabasites (amphibolite, eclogite, mafic granulite) are metamorphosed mafic rocks that have lost the original texture and mineralogy (e. g. amphibolite consists of > 75% amphibole and plagioclase and amphibole forms > 30% of the whole rock).

Calc-silicate rocks consist of > 50% calc-silicate (e.g. diopside, plagioclase) and carbonate; marble consists of > 75% carbonate.

Metapelite (paragneiss) consists of quartz + feldspar + mica + aluminous mineral (> 70%), and aluminous mineral plus mica content is > 40% (micaschist, phyllite).

Quartzofeldspathic (orthogneiss, felsic granulite) rocks consist of quartz + feldspar + mica + aluminous mineral (> 70%), and quartz + feldspar > 60% (gneiss).

METAMORPHIC FACIES

(a) Zeolite facies is associated with burial metamorphism and sub-seafloor alteration of the oceanic crust. It represents the transition between diagenesis and prehnite-pumpellyite facies and initiates at temperatures of 150–250 °C and pressures of 0.1–0.6 GPa (Fig. 8). Typical reactions include the transformation of smectite to illite, kaolinite, vermiculite in pelitic sediments, while zeolites, prehnite and albite are produced in metabasites (zeolites also frequently occur in the form of filling vesicles as amygdales in metabasites). Typical rocks: **zeolitic metatuff** (light-colored; relicts of pumices and lapilles; volcanic glass has been replaced by zeolites; mineral assemblage: plagioclase + zeolite + K-feldspar + quartz ± chlorite ± volcanic glass ± pyroxene ± amphibole).

(b) Prehnite-pumpellyite facies is associated with burial metamorphism, sub-seafloor alteration and the upper parts of accretionary wedges at the subduction zones. Metamorphism occurs at temperatures of 250–350 °C and pressures of 0.2–0.7 GPa. The presence of prehnite, pumpellyite, chlorite and stilpnomelane is the most characteristic. Actinolite occurs at higher temperatures and lawsonite at higher pressures. Typical mineral assemblages: **metabasalts**: prehnite + pumpellyite ± chlorite ± albite ± epidote; **metapelites:** illite/white mica + chlorite + albite ± stilpnomelane, metagranodiorites: albite + chlorite ± pumpellyite ± prehnite ± stilpnomelane ± white mica ± titanite ± epidote ± carbonate; **marbles and calc-silicate rocks:** calcite ± dolomite ± prehnite ± albite ± chlorite ± quartz.

(c) Greenschist facies is associated with regional metamorphism at temperatures of approximately 350 to 500 °C and pressures of 0.2–1.2 GPa. The production of abundant chlorite, muscovite and albite is the most characteristic for metapelites, while chlorite, actinolite and epidote are common in basic rocks (greenschists or greenstones, chlorite-rich schists). Biotite and/or garnet occur at higher temperatures in metapelites (phyllites and schists) and metagranitoids. Typical mineral assemblages: **greenschists:** albite + chlorite + actinolite + epidote + titanite ± quartz ± white mica ± calcite ± stilpnomelane; **phyllites:** muscovite + chlorite ± albite ± paragonite ± graphite ± rutile ± carbonate ±

epidote ± K-feldspar ± titanite ± stilpnomelane (low-Al protoliths) ± pyrophyllite (high-Al protoliths) ± chloritoid (high-Al protoliths) ± biotite ± staurolite; **metagranodiorites** and **metagreywackes:** albite + epidote + muscovite + chlorite ± titanite ± stilpnomelane ± actinolite; **marbles** and **calc-silicate rocks:** calcite ± dolomite ± quartz ± muscovite ± albite ± K-feldspar ± chlorite ± zoisite ± talc; **serpentinites:** antigorite ± actinolite-tremolite ± talc ± chrysotile.

(d) Amphibolite facies is associated with regional metamorphism at temperatures of approximately 500–750 °C and pressures of 0.2–1.3 GPa. Changes in mineralogy depend on the protolith composition (e. g. production of hornblende, intermediate plagioclases (oligoclase-andesine), epidote or garnet in basic rocks and garnet, sillimanite/kyanite, biotite, muscovite in metapelites are the most characteristic). Typical mineral assemblages include: **amphibolites:** hornblende + oligoclase ± epidote ± almandine garnet ± titanite ± quartz ± chlorite ± biotite; **gneisses** and **mica schists**: quartz +biotite ± muscovite ± oligoclase ± almandine garnet ± cordierite (low-P) ± andalusite (low-P) ± kyanite (high-P) ± sillimanite (moderate-P, and/or high-T) ± staurolite (high -T) ± graphite ± titanite ± Ilmenite; **orthogneisses:** oligoclase + alkali feldspar + muscovite + biotite ± hornblende; **marbles** and **calc-silicate rocks**: calcite ± dolomite ± quartz ± diopside ± tremolite ± forsterite ± grossular ± amphibole ± clinozoisite.

(e) Granulite facies is associated with orogenic regional metamorphism at temperatures of approximately 700 °C and a pressure range of 0.2–1.5 GPa. Amphiboles and micas both disappear in granulite facies rocks, hornblende dehydrates to form pyroxene and plagioclase, biotite dehydrates to form garnet. Kyanite and sillimanite are often produced from muscovite and biotite. Rocks often undergo partial melting due to the presence of water resulting from dehydration reactions. Typical mineral assemblages include: **mafic granulites**: plagioclase + pyroxene ± hornblende ± garnet ± olivine± quartz; **migmatites**: microcline ± plagioclase ± garnet ± cordierite ± kyanite ± sillimanite ± graphite ± rutile ± ilmenite ± corundum ± spinel; **felsic granulites**: microcline + plagioclase + garnet ± kyanite ± sillimanite ± pyroxene ± hornblende; **calc-silicate rocks**: calcite + dolomite + quartz + diopside + scapolite + forsterite + wollastonite + graphite.

(f) Eclogite facies is associated with orogenic regional metamorphism and subduction zones and occurs at temperatures of approximately 400–1000 °C and in excess of 1.2 GPa (45 km in depth). Eclogites are associated with blueschists or kimberlites or granulites and high-grade amphibolites. Diamond and coesite occur in ultrahigh-pressure eclogites (UHP rocks appear at depths greater than 150 km). Typical mineral assemblages for rocks developed from different protoliths include: **eclogite:** garnet + omphacite ± quartz – no albite, no lawsonite (epidote or grossular garnet are stable); **white schist:** talc + kyanite + phengite (Si-rich muscovite), no chlorite.

(g) Blueschist facies is associated with subduction zones and occurs at temperatures of approximately 200–500 °C and in excess of 0.6 GPa (15 km in depth). Mafic and intermediate rocks are characterised by bluish colour due to the presence of an alkali amphibole (glaucophane). Transition between blueschist- and greenschist in metabasites is as follows: clinozoisite + glaucophane + quartz + H_2O = tremolite + chlorite + albite. Typical assemblages: **blueschist:** glaucophane + lawsonite and/or epidote + albite + titanite ± garnet ± quartz; **white schist:** Fe-Mg-carpholite ± chloritoid ± kyanite + zoisite ± pargasite or phengite ± albite ± quartz ± talc ± garnet; **orthogneisses:** kyanite ± paragonite ± chlorite ± albite ± quartz ± pargasite or phengite; **marbles:** calcite ± aragonite ± dolomite.

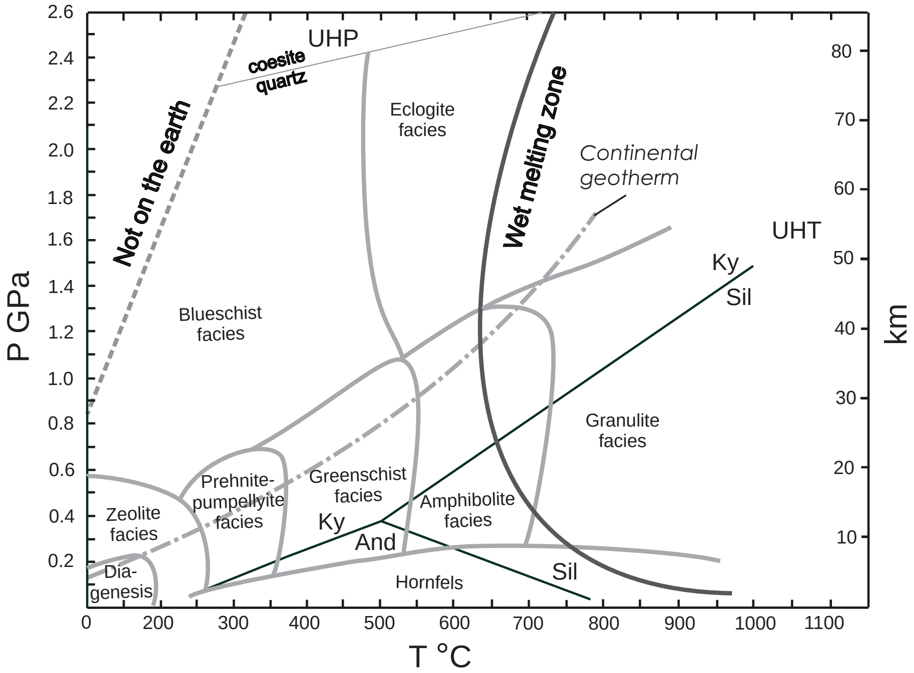

Figure A8. *Pressure–temperature diagram regarding the metamorphic facies, a beginning of the hydrous haplograite melting.*

(h) Hornfels and contact schists are associated with contact metamorphism and occur at temperatures of 250–1000 °C and pressures of 0.05–0.2 GPa. These rocks are described from the thermal aureoles around igneous bodies or are present as xenoliths within igneous rocks (albite epidote, hornblende, pyroxene and sanidine hornfels). Typical minerals for metapelites are andalusite, cordierite, sillimanite, sanidine, tridymite and corundum. S**karns** are specific rock types, which originate from contact metamorphism and metasomatism of limestones. They usually contain abundant carbonates and silicates like andradite, epidote, vesuvianite, diopside and wollastonite.

(i) Mylonites are affected by dynamic metamorphism that is produced along shear zones. They are usually fine-grained with layers. **Cataclasites** are fine-grained rocks (typically less than 0.1 mm) with up to 50% of visible tectonic angular clasts.

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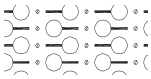
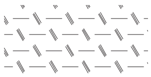
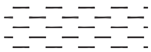
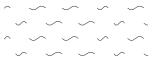
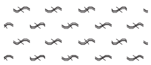
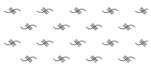
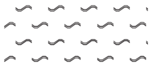
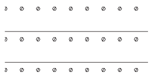
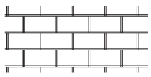
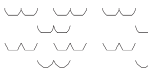
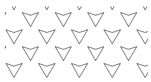
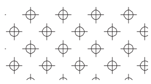
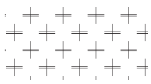
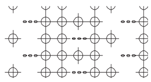
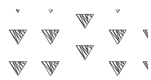
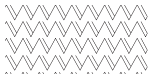
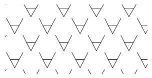
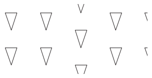
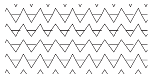
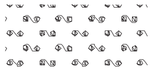
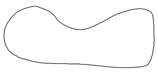
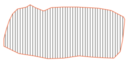
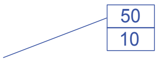
APPENDIX 4
Symbology in hydrogeological map

LEGEND FOR GROUNDWATER AND ROCKS

No. in library	Specification	Colour No.		Aquifer and non-aquifer characteristics (definition)
		R-G-B	H-S-V	
B1	Dark blue	80-197-255	133-164-240	Extensive (larger than 100 km^2) and highly productive aquifers (T = 10.1 – 100 m^2/d, q = 1.1 – 10 l/s.m, Q = 5 – 25 l/s for wells and/or springs) or locally extremely productive aquifers in which the flow is mainly intergranular
B2	Light blue	176-229-255	133-74-240	Extensive (larger than 100 km^2) and moderately productive aquifers (T = 1.1 – 10 m^2/d, q = 0.011 – 1 l/s.m, Q = 0.51 – 5 l/s for wells and/or springs) or local or discontinuous (smaller than 100 km^2) but highly productive aquifers in which the flow is mainly intergranular
B3	Dark green	179-255-64	55-179-240	Extensive (larger than 100 km^2) and highly productive aquifers (T = 10.1 – 100 m^2/d, q = 1.1 – 10 l/s.m, Q = 5 – 25 l/s for wells and/or springs) or locally extremely productive aquifers in which the flow is mainly through a regularly developed system of fissures of sedimentary rocks and karst openings
B4	Light green	224-255-176	55-74-240	Extensive (larger than 100 km^2) and moderately productive aquifers (T = 1.1 – 10 m^2/d, q = 0,011 – 1 l/s.m, Q = 0.51 – 5 l/s for wells and/or springs) or local or discontinuous but highly productive aquifers in which the flow is mainly through a regularly developed system of fissures and joints of sedimentary and volcanic rocks
B5	Brown-red	255-196-176	10-74-240	Extensive (larger than 100 km^2) and low productive aquifers (T = 0.11 – 1 m^2/d, q = 0.0011 – 0,01 l/s.m, Q = 0.051 – 0.5 l/s for wells and/or springs) or fissured aquifers in which the flow is mainly developed in an irregular system of fissures and weathered mantle of a crystalline rock (intrusive and metamorphic rocks) with local and limited groundwater resources
B6	Light brown	255-220-112	30-134-240	Minor aquifers with local and limited groundwater resources (T = 0.01 – 0.1m^2/d, q = 0.0001 – 0.001 l/s.m, Q = 0.005 – 0.055 l/s)
B7	Dark brown	208-156-0	30-240-195	Formation with essentially no groundwater resources
B8	Aquifer colour with brown stripes			Extensive aquifers immediately underlying a thin (more than 5 m) “impermeable” cover; the appropriate aquifer colour should be used crossed by (vertical) brown stripes (1 mm wide and 3 mm separation)
B9	Combination of two aquifer colours			Mixed aquifers with fissured and porous permeability; the appropriate aquifer colours should be used in horizontal 5 mm stripes
B10a B10b	Aquifer with shallow groundwater 10a 10b			Limited aquifers in unconsolidated material (eluvial character (regolith) – yellow B10a, alluvial character – B10b, blue oblique strips) with shallow groundwater for local use providing variable amount of groundwater based on thickness and recharging values

EXAMPLES OF GEOLOGICAL SYMBOLS FOR THE HYDROGEOLOGICAL MAP

Hatch	G-symbol No. in library	Lithology
	Q 22	Clayey sand with gravel – alluvial sediments in general
	Q 32	Clayey soil
	Q 33	Clay
	M 12	Phyllite
	M 19	Mica schist (schist in general)
	M 20	Paragneiss (gneiss in general)
	M 28	Migmatite
	S 12	Sandstone
	S 25	Limestone
	S 37	Tuff without distinction
	S 46	Gypsum
	Vh 13	Granite
	Vh 15	Diorite
	Vh 25	Granodiorite
	V 17	Basalt

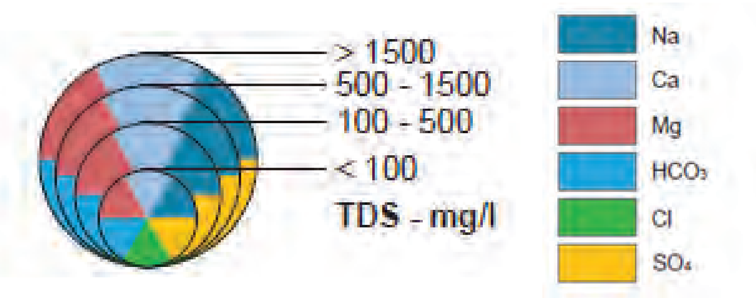
	V 19	Phonolite
	V 44	Ignimbrite
	V 45	Rhyolite
	V 46	Trachyte
	V 49	Scoria (cinder, cinerites)
		Lithological boundary
		Area with an occurrence of thermal water (water with a temperature above 30° C)
		Flow gauging station (mean annual runoff in m3/s – the upper value and catchment area in 1000 km^2 – the lower value)

LEGEND FOR VARIOUS HYDROCHEMICAL TYPES IN THE HYDROCHEMICAL MAP

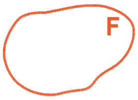
No. in library	Hydrochemical type	Specification	Colour	Classification of type
B1				Basic
B2	**$Ca-HCO_3$**		R-G-B 176-255-255 H-S-V 120-74-240	Transitional
B3				Mixed
B4				Basic
B5	**$Mg-HCO_3$**		R-G-B 232-208-255 H-S-V 180-44-240	Transitional
B6				Mixed

B7				Basic
B8	**$Na\text{-}HCO_3$**		R-G-B 160-192-255 H-S-V 146-89-240	Transitional
B9				Mixed
B10				Basic
B11	**$Ca\text{-}SO_4$**		R-G-B 255-236-176 H-S-V 30-74-240	Transitional
B12				Mixed
B13				Basic
B14	**$Mg\text{-}SO_4$**		R-G-B 30-240-195 H-S-V 208-156-0	Transitional
B15				Mixed
B16				Basic
B17	**$Na\text{-}SO_4$**		R-G-B 255-208-255 H-S-V 200-44-240	Transitional
B18				Mixed
B19				Basic
B20	**Na-Cl**		R-G-B 192-192-0 H-S-V 40-239-180	Transitional
B21				Mixed

PIE CHART FOR THE PRESENTATION OF HYDROCHEMISTRY OF WATERS ADDITIONAL TO GROUNDWATER

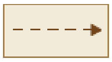
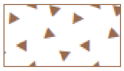
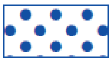


EXAMPLES OF REPRESENTATION OF DETAILED DATA

No. in library	Specification	Description
D1		Isosalinity in mg/l (contours of TDS)
D9		Area of groundwater with a high content of fluorides in orange colour (above the national standards)
D10		Dug well with a high content of nitrates (above the national standards)

APPENDIX 5
Symbology in geohazard map

The items of legend to the geological hazard maps include three main groups of graphical information: colour or raster of polygons, line element and symbols (indexes). Each item has a number, graphical expression and text description.

No. in library	Symbology	Geodynamical feature
1	Dark blue	Seismic hazard
2		Potential occurrence of ground fissures, subsidence of terrain and suffusion
3		Observed ground fissures
4		Pyroclastic falls
5		Limit of the possible extent of lava flows
6		Area prone to surface erosion
7		Landslide
8		Landslide escarpment
9		Rockfall
10		Trajectory of earth flows and debris flows
11		Area prone to rapid accumulation and aggradation of sediment
12		Inundation zone
13		Vent of the late Pleistocene to Holocene silicic volcano
14		Fumarole

APPENDIX 6
Recommended codes for the Reference Soil Groups

OVERVIEW OF KEY TO REFERENCE SOIL GROUPS

Acrisol	AC	Cryosol	CR	Leptosol	LP	Regosol	RG
Alisol	AL	Durisol	DU	Lixisol	LX	Solonchak	SC
Andosol	AN	Ferralsol	FR	Luvisol	LV	Solonetz	SN
Anthrosol	AT	Fluvisol	FL	Nitisol	NT	Stagnosol	ST
Arenosol	AR	Gleysol	GL	Phaeozem	PH	Technosol	TC
Calcisol	CL	Gypsisol	GY	Planosol	PL	Umbrisol	UM
Cambisol	CM	Histosol	HS	Plinthosol	PT	Vertisol	VR
Chernozem	CH	Kastanozem	KS	Podzol	PZ		