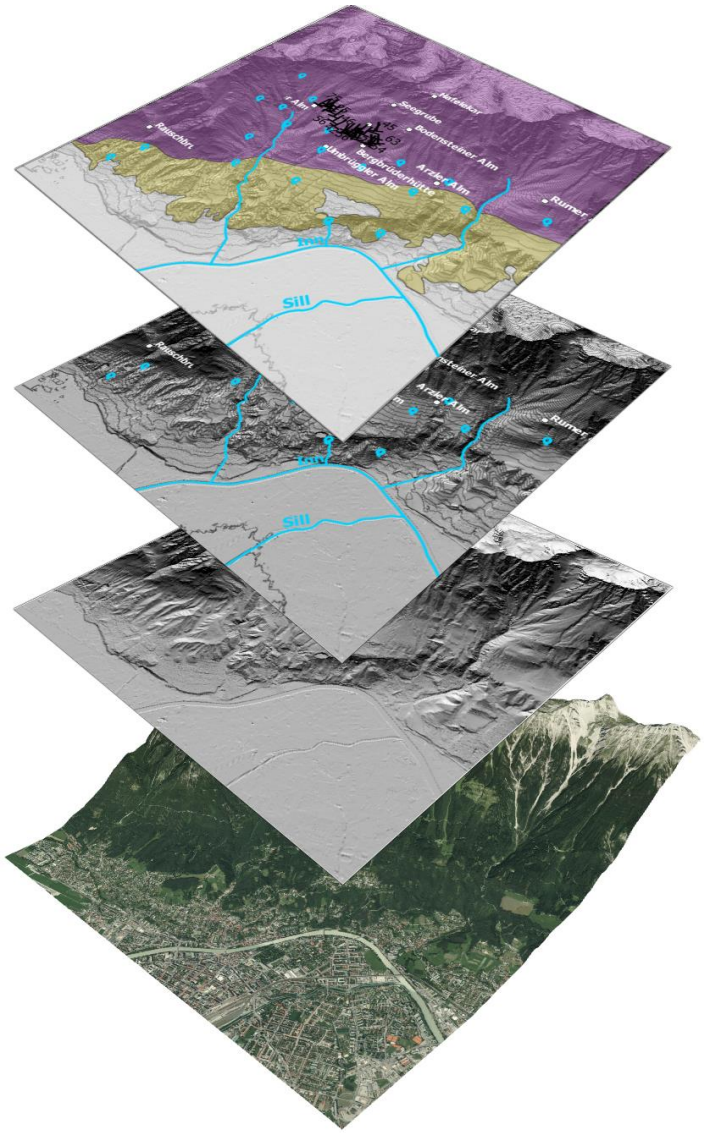
Geological Maps with QGIS 3.X



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Content

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Abstract

Within four steps: Start → Basemaps → Mapping → Layouts, this tutorial serves as a guide for geologists on how to create a digital, geological map with the open source GIS program QGIS 3. The tutorial is made for students and unexperienced users.

After a general overview, the first step gives instructions on the download and installation of the program and on coordinate reference systems. The second step explains how to implement different basemap layers as a mapping background. In the third step, the actual mapping is done by adding points, lines and polygons to the map. The last step shows how to create a printable map layout with elements like a coordinate grid, a north arrow, a scale bar etc.

The herein presented way of producing a geological map with QGIS is only one possibility and every user is encouraged to learn by exploring and playing with the numerous functions of the program!

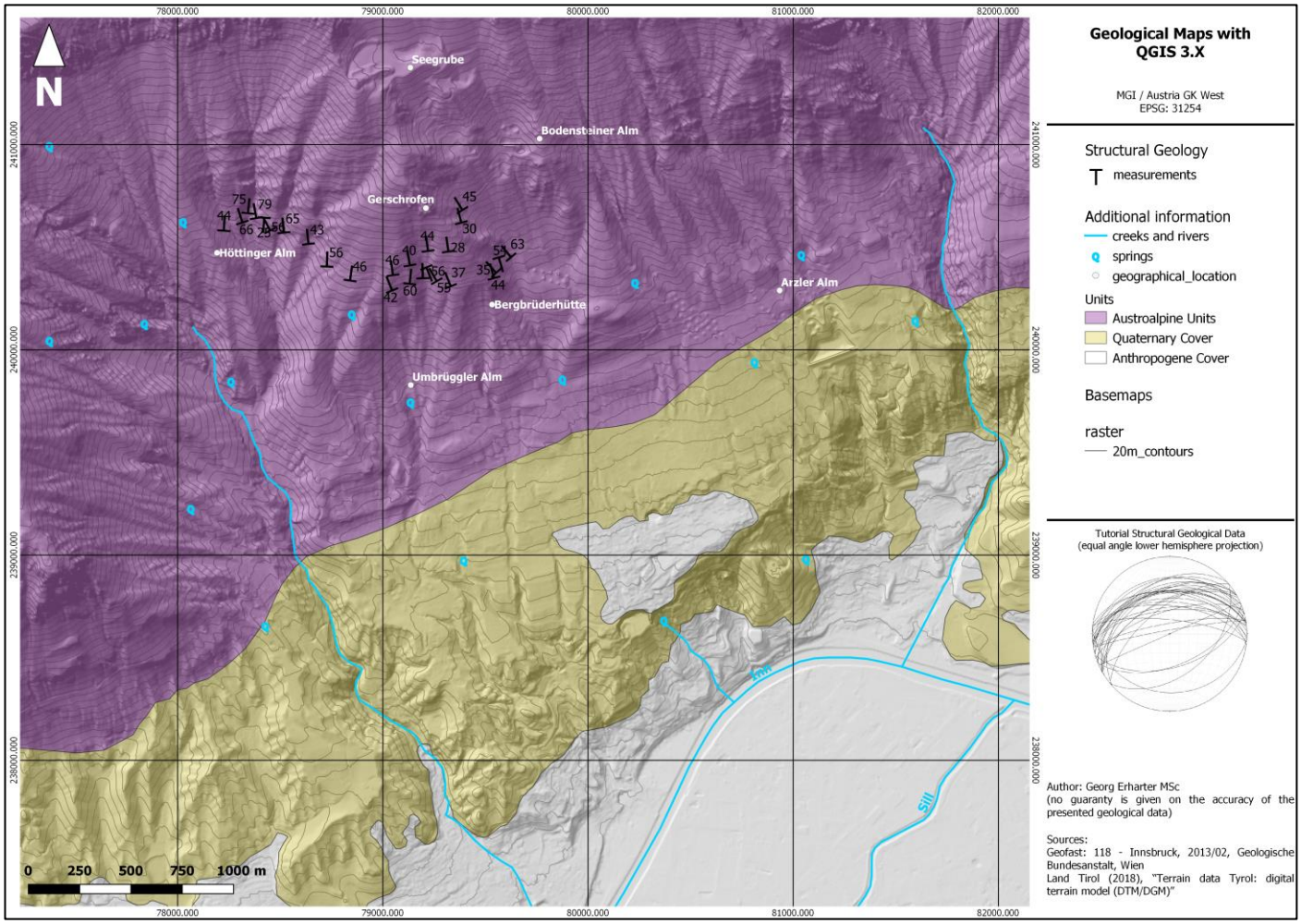

Figure 1, The final geological map as produced during the tutorial

Introduction

QGIS is an open source, freely available geographical information system (GIS) that is licensed under the Creative Commons Attribution-ShareAlike 3.0 license. It provides an ever-increasing number of tools to create, edit and visualize geospatial data (QGIS Development Team, 2018).

An in-depth description and further information about the program and its functions is given in the official QGIS documentation. Button icons were taken from there as well:

https://www.qgis.org/en/docs/index.html

This tutorial is a step by step instruction on how to create a geological map with QGIS. As an example for a mapping-project, a very simplified geological map of a small part of the Karwendel mountain range North of Innsbruck (Tyrol / Austria) will be created. **No geological research goal is pursued and the author does not guarantee for the correctness of the presented geological data.** The final map is given in Figure 1.

Additional background information to certain topics will be given between blue lines, in italic, blue letters like this sentence.

Useful tips will be given in italic, dark red letters like this sentence.

This tutorial is made for the windows based version of QGIS.

1. Step: Start

1.1. Download and Installation

The open source geographical information system QGIS can be downloaded for free from:

https://www.qgis.org → ***Download Now***.

On the following page you can choose the version that suits you best. This tutorial was designed for QGIS 3.0.1.

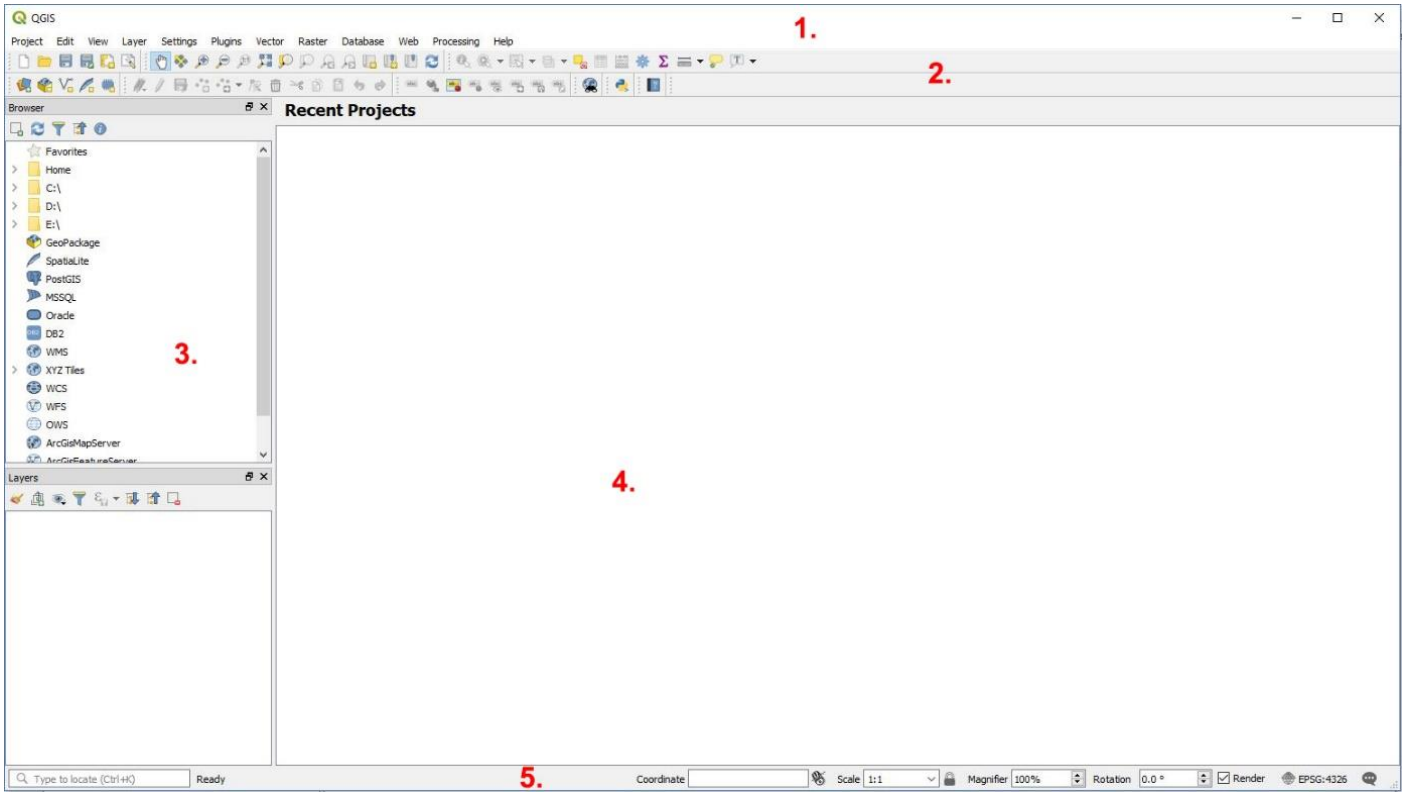

Figure 2; QGIS graphical user interface: 1. Menu bar, 2. Toolbars, 3. Panels, 4. Map window, 5. Status bar

Depending on your operating system (OS), you can choose the 32bit- or 64bit- version of the program *(usually you'd pick the 64bit version if you are using a 64bit OS, but some plugins are only working with the 32bit version of QGIS)*.

Follow the installation assistant step by step. At the end of the installation, a folder will be created on your desktop (or wherever you choose to save QGIS) which contains a link to the program "QGIS Desktop 3.0.1". → ***Double Click*** to launch.

1.2. Program Start – New Project

After initializing the program, you will see the QGIS graphical user interface (GUI) (Figure 2). The GUI is highly customizable. E.g.: by right clicking the toolbar, or via ***View → Toolbars,*** you can add additional tools and panels to the GUI. For this tutorial, it is recommended to add the "**Advanced Digitizing Toolbar**", the "**Manage Layers Toolbar**" and the "**Snapping Toolbar**".

To start a new project, press the ***New*** button  on the upper left side of the toolbars.

Generally, the mapping functionality of QGIS is based on a stack of layers with different kinds of data and information. Before starting a new project, you should give some thought to the order of these layers. This will help to keep your project neat and well organized! For this tutorial the data structure of Table 1 will be used.

Table 1; data-structure used in this tutorial

order	layer	datatype
TOP	point signatures (e.g. orientation data)	points (shapefiles)
	line signatures (e.g. faults)	lines (shapefiles)
	distribution of geologic units	polygons (shapefiles)
BOTTOM	basemaps (e.g.: pre-existing maps, terrain data)	rasters, web map servers…

It is recommended to store all files of the project in an organized folder structure. For this tutorial, the simple folder structure of Figure 3 will be used. The project itself is saved  into a designated folder which contains two separate folders for raster- and vector-data.

Well organized layer- and folder structures will save you lots of work (and headaches) later.

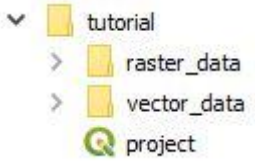

Figure 3; a simple folder structure for this tutorial

1.3. Coordinate Reference Systems

By default, the coordinate reference system (CRS) is set to WGS 84 (EPSG: 4326). The actual CRS can be seen on the right side of the **Status bar**. By clicking this CRS symbol or by ***Project → Project Properties → CRS*** you can switch between different CRSs. QGIS3 shows you a preview of the CRS boundaries. This allows you to check whether you have selected a valid system (Figure 4).

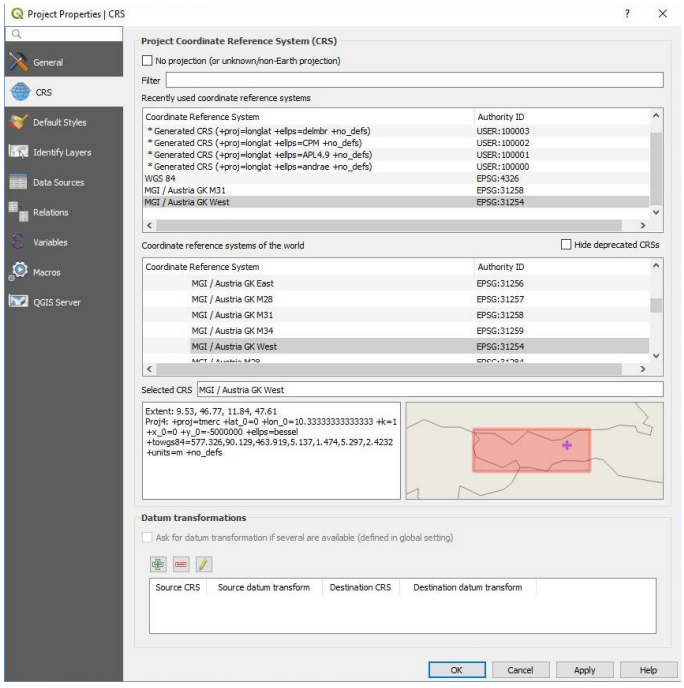

Figure 4; You can switch coordinate reference systems (CRS) easily within the Project Properties. As a new feature, QGIS3 gives you a preview of the CRS boundaries.

2. Step: Basemaps

The first step for the creation of a digital geological map by QGIS is to add a basemap to the project. It serves as the "background" on which new, individual information is presented. Basemaps can for example be scanned, old geological maps, digital geological maps, topographical maps, rasterized terrain data etc. Before adding data, ***Right Click*** into the **Layers Panel** and press ***Add Group***  . Call this group "basemaps" and insert all basemaps you want to use. *In case of numerous basemaps, subgroups may help to keep the project organized.* Data-sources of this tutorial can be found in Appendix 1.

2.1. Raster data

2.1.1. Adding raster data

The digital elevation model (DEM) of Tyrol with a 5m resolution (provided by Land Tirol (2018)- data.tirol.gv.at for free) will here be used as the main basemap (data source: Appendix 1) .

Clear definitions of digital terrain/elevation/surface model (DTM, DEM, DSM) are controversial (Li et al., 2005). An old definition of a DTM is given by Miller and Laflamme (1958):

"The digital terrain model (DTM) is simply a statistical representation of the continuous surface of the ground by a large number of selected points with known X, Y, Z coordinates in an arbitrary coordinate field."

In this tutorial DEM – in contrast to DSM - refers to raster data that represents the ground surface without vegetation and buildings.

The easiest way to add raster data, is to "drag and drop" the raster file from its folder into the map window. Alternatively, you can press the ***Add Raster Layer*** button  in the **Manage Layers Toolbar**. In the following window, choose the raster file's location on your computer and press ***Add***.

By adding raster files like the "DGM_Tirol_5m_epsg31254.tif", QGIS automatically switches the project CRS to the raster file's CRS which in this case is the "MGI / Austria GK West" (EPSG: 31254).

2.1.2. Clipping raster data

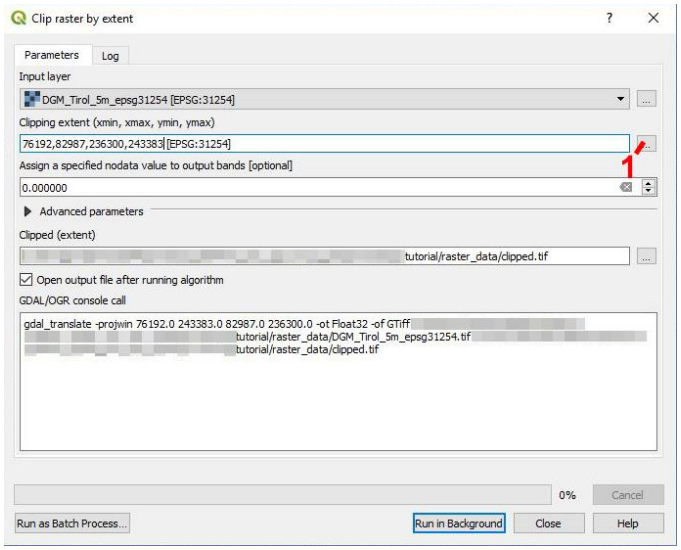

Figure 5; Settings for the "Clip raster by extent" tool

Due to the high resolution and size of the used raster file it is computationally very demanding. Therefore, the next step is to clip the part of the project area from the raster (i.e.: to crop all unnecessary parts of the raster file). In the **Menu bar** choose ***Raster → Extraction → Clip raster by extent***. In the following window, choose the correct "Input Layer" and the folder path where you want to save the clipped raster. Click the button next to the field "Clipping extent" (1 in Figure 5) and choose ***Select extent on canvas***. After you have chosen the desired extent on the map window by dragging a frame around it, click ***Run in Background.*** You will find the clipped part of the raster as a new layer "Clipped (extent)" in your layers panel. *The new layer is only a temporary layer. To save it permanently,* ***Right click*** *it and choose* ***Save as.*** *Within the* ***Save Raster Layer as… window*** *you can select different file types (choose the default GeoTIFF) and change the CRS of the new layer.*

2.1.3. Hillshade, slope, contour lines

By default, QGIS chooses a "singleband gray" rendering to display raster data. This style colorizes the raster layer with a black to white gradient from the lowest to the highest point which is sometimes not the graphically most appealing and informative style. By choosing ***Raster → Analysis → Hillshade*** from the **Menu bar** you can add

a raster layer with a shaded view of the terrain which is a more three-dimensionally looking style (Figure 7).

Apply different azimuths and altitudes of the light to your DEM and see how the visibility of morphologies changes under different light angles.

Another option is the "slope" view which assigns a (continuous) colorband or discrete colors to the raster layer depending on its steepness. ***Raster → Analysis → Slope***

Extracting contour lines is possible by clicking ***Raster → Extraction → Contour***. Choose the desired "Interval between contour lines".

*When using these raster tools, always check whether the correct raster layer is chosen in the **Input Layer** field. A wrong input can easily lead to weird output and extended computing time.*

Right click a new layer within the **layer panel** and select ***Properties***. Choose from a wide range of customization options for styling your layers.

By now, your project should look approximately like Figure 6.

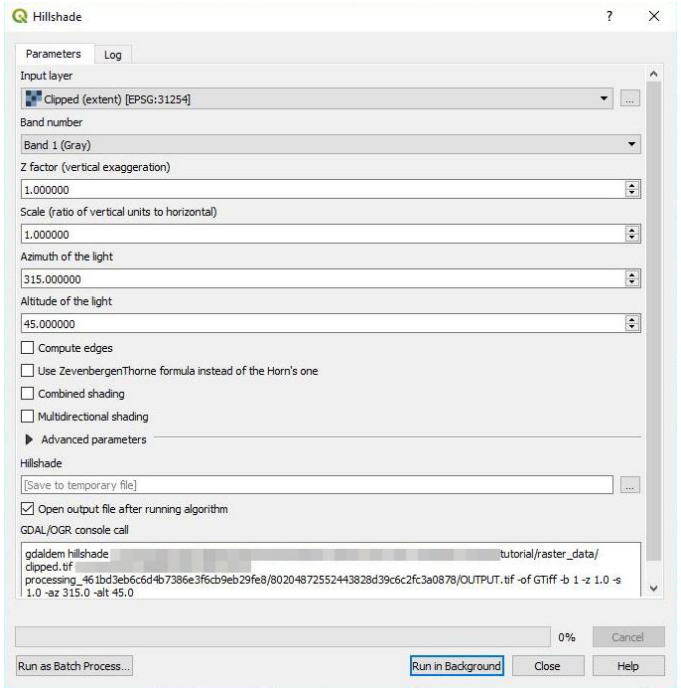

Figure 7; Calculating a Hillshade view from a DEM

2.2. Web Map Service

Web map service (WMS), web feature service (WFS) or web coverage service (WCS) are possibilities to access and implement layers of geographic information from remote servers, without the need of storing additional data on your computer.

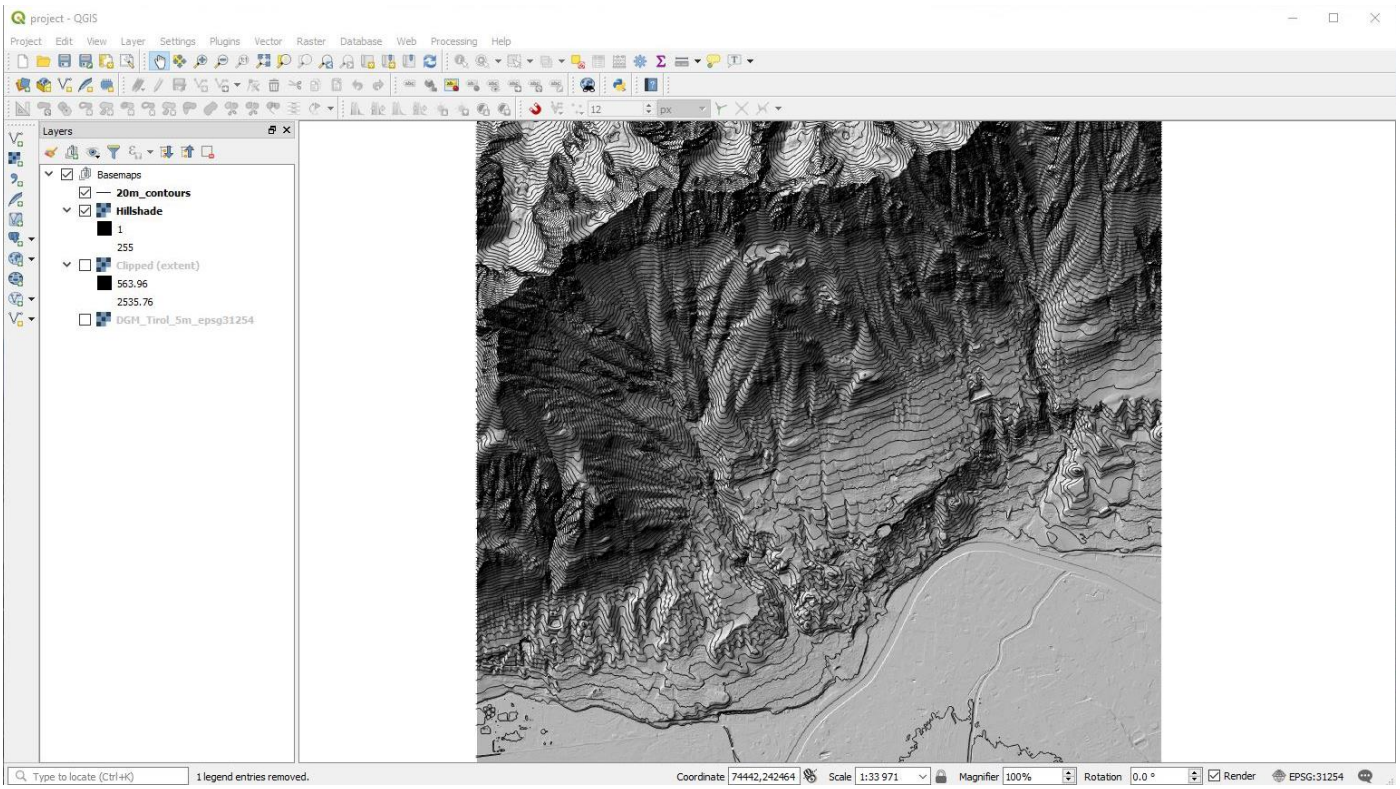

Figure 6; QGIS GUI with some toolbar - and panel customizations (compared to Figure 2). A DEM with "Hillshade" style has been added and contours with a spacing of 20m were extracted from the DEM.

Web Map Services (WMS) constitute an additional data-source. By pressing the ***Add WMS/WMTS Layer*** button  within the **Manage Layers Toolbar**, or by going ***Layer → Add Layer → Add WMS/WMTS Layer*** from the **Menu bar**, the **Data Source Manager** window pops up. Upon pressing ***New***, another window pops up where you can enter the desired name and URL of the WMS. Enter "Orthophoto Tirol" as "Name" in the "Connection Details**"** and the following URL: *"https://gis.tirol.gv.at/arcgis/services/Service_Public/orthofoto/MapServer/WMSServer?request=GetCapabilities&service=WMS"* and confirm by pressing ***OK***. Back in the **Data Source Manager**, press ***Connect***, select the layer with the title "Aktuell_RGB" and finish with ***Add*** (Figure 8).

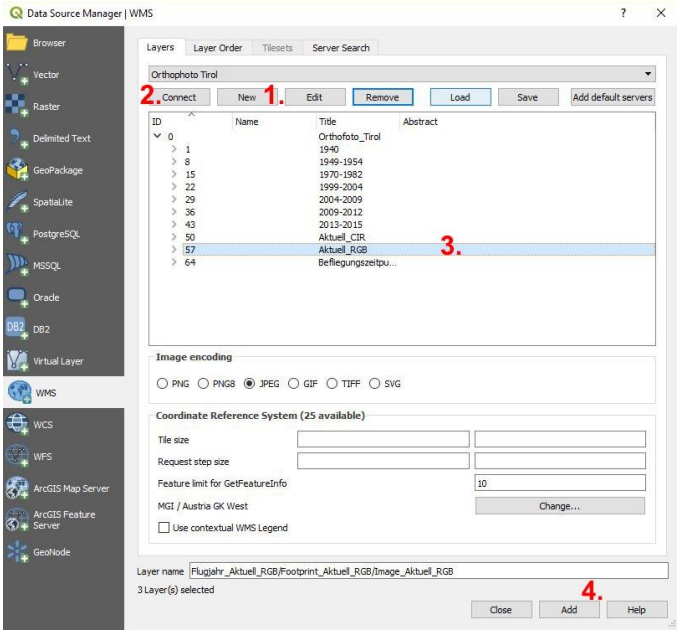

Figure 8; Workflow to add a WMS layer to the project: 1. add new WMS; 2. connect to the service; 3. select the desired layer; 4. add layer

Public institutions often provide a variety of geographic information via WMS. These include recent and historic orthophotos, hillshades, topographical maps and even geological maps! The URL to WMS from the Geological Survey of Austria can be found in Appendix 1. Despite the advantage of no additional consumption of computer storage, the drawback of WMS is that it is usually only a 2D layer without additional information. For example, you cannot create contour lines from a WMS hillshade.

2.3. Georeferencing

Georeferencing is the process of fitting (i.e. rotating, scaling and warping) maps to a CRS. This is done by marking points on the map where the coordinates are known and then transforming it accordingly.

Scans of field maps usually lack spatial information. To add spatial information, you have to georeference your map. Therefore, you have to define the coordinates of at least three points within that map. Alternatively, you can georeference a map onto an already georeferenced map of the same area.

As an example, a small, scanned field map with structural geological data of the project area will be georeferenced to the already existing layers of the project by "pinning" together known geographical locations. (The basemap for this field map was exported from tiris (2018))

Before georeferencing, the "Georeferencer GDAL" plugin (preinstalled in QGIS3) must be activated. From the **Menu bar**, select ***Plugins → Manage and Install Plugins***. Within the **Plugin Manager** either search for "Georeferencer GDAL" or look for it in the installed plugins. Check the checkbox besides the plugin and close the **Plugin Manager**. The **Georeferencer GDAL**  is now part of your **toolbar**, open it.

To start, press ***Open Raster***  , load the un-georeferenced map and select a CRS. The spatial information of your raster-file will be saved in that CRS. To add a new ground control point (GCP) (i.e.: point of known location) press ***Add Point***  and click on the first point of the un-georeferenced map of which you know the location. You can now either enter known coordinates or select a point  ***From Map Canvas***. Confirm and proceed to add some known points.

At least three known points (even more for some types of georeferencing are needed. Use distinctive points like crossroads, summits, churches, huts etc. for georeferencing, but be careful that the points are the same in both maps! A coordinate grid in the un-georeferenced map is usually the most reliable reference point.

After you have added some points (Figure 9), open the ***Transformation Settings***  , choose a Transformation type (e.g. "Linear" for very simple transformations), select the project CRS as "Target CRS", select a location where the georeferenced map is supposed to be stored and check the "Load in QGIS when done" checkbox.

QGIS offers several other (more sophisticated) Transformation Types that are worth checking out in case you deal with heavily distorted maps (e.g.: historical maps):

The small red lines at your GCPs will now give you a preview of the transformation. ***Start Georeferencing***  and feel free to save the GCPs (often not necessary). The scanned map will now appear in your map window and you can check whether or not it is in the correct place (Figure 10).

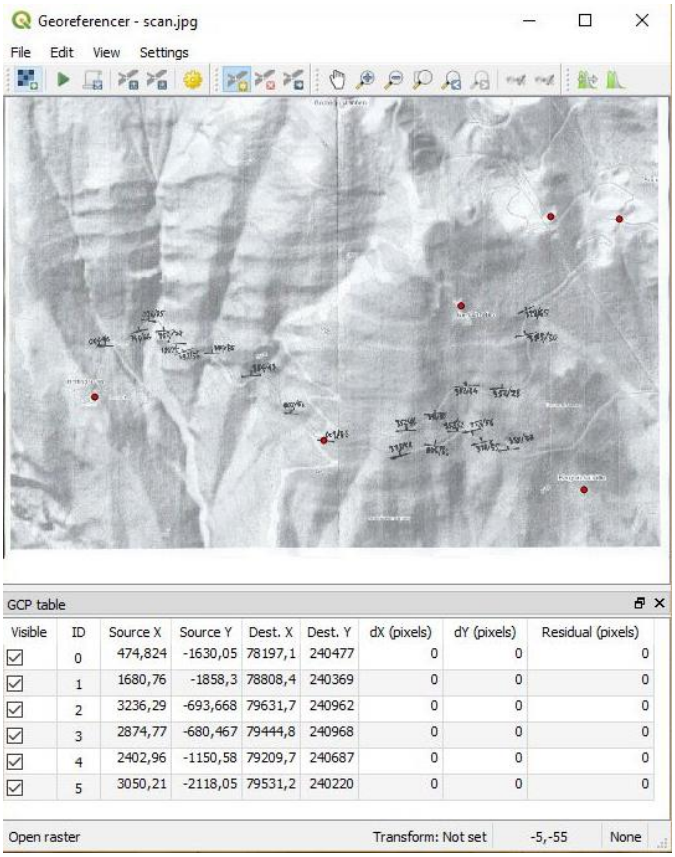

Figure 9; GCPs (red points) added to a scanned field map.

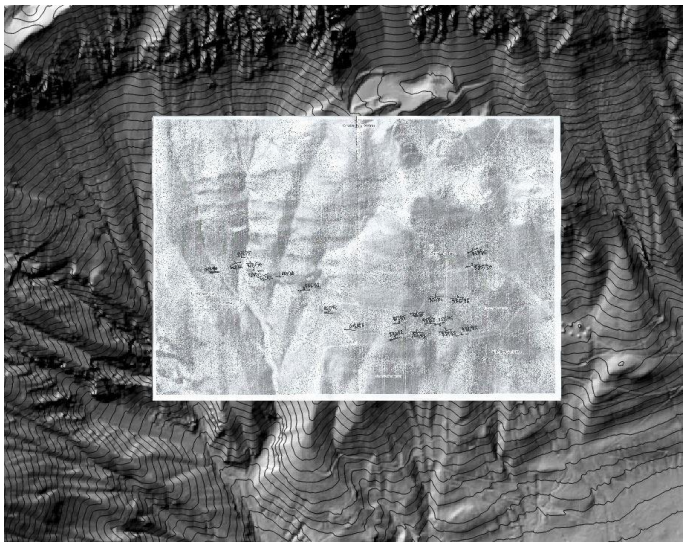

Figure 10; a georeferenced, scanned field map

3. Step: Mapping

On a geological map, information is presented with points, lines and polygons. A "shapefile" is a common way to save such geometries. Although the shapefile (.shp) is a well-established file type, it has several drawbacks. For example, at least three files are generated which must be stored together. The new main-file type in QGIS3 is the "geopackage" which offers the advantage that all information is stored in one file. Further on, it allows the storage of different feature-classes (point, line and polygon) together while shapefiles can only store one feature class per file.

For additional technical information on shapefiles, see ESRI (1998). For geopackages, the website *http://www.geopackage.org/* is recommended.

3.1. Points

Points like structural geological orientation data, springs, wells, geographical locations etc. can be defined directly within the project or added automatically from spreadsheets

3.1.1. Direct input

As an example, some geographical locations well visible in the previously added orthophoto WMS layer will be digitized. The goal is to create a point layer with the geographical locations and their respective names.

To create a new point layer, choose ***Layer → Create Layer → New Shapefile Layer.*** Call the new shapefile (or geopackage) "geographical_location", leave all other settings as they are and save the file to the vector data folder within your tutorial-folder (Figure 11).

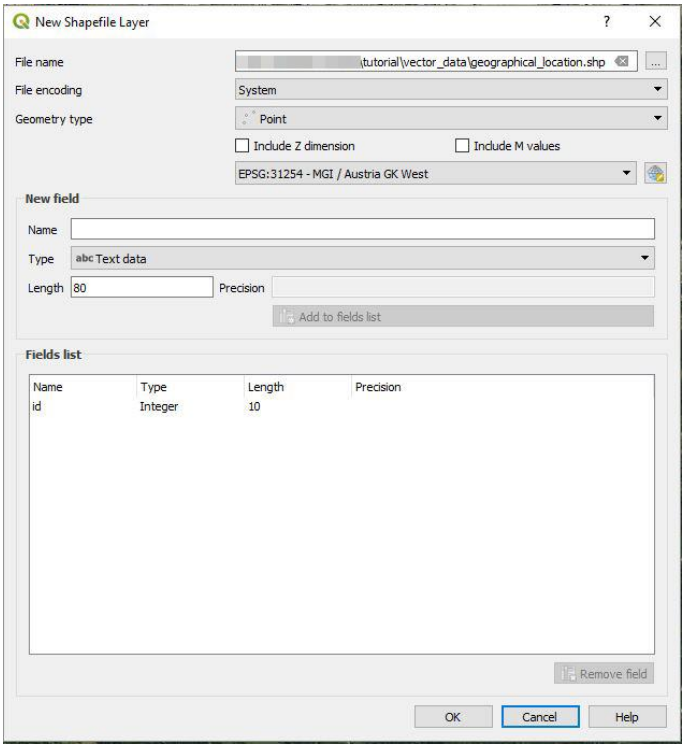

Figure 11; Creating a new Shapefile - point layer

Since at least three separate files are created for every shape file, you may consider to further subdivide your "vector_data" folder for bigger projects to keep it organized (or to use the geopackage-file instead).

Within the layers panel of your project, add a folder "Additional information" on top of everything else. Move the new "geographical_information" layer to this folder. By default, QGIS chooses a simple circle marker with an arbitrary color for newly added point layers. If you want to change the style, ***Right click → Properties → Symbology*** on that layer to enter the layer properties window.

To add a "name" attribute to the layer ***Right click*** it and select ***Open Attribute Table.*** In the new window ***Toggle editing mode*** and click ***New Field***. Within the "Add Field" window, enter a name for the new column, change the type to "text" and give a sufficiently high number as "Length" of the field (Figure 12).

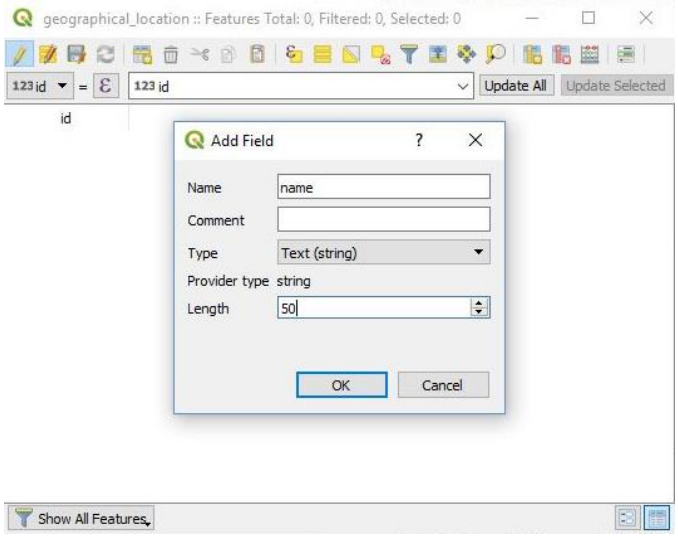

Figure 12; adding a new attribute

Safe layer edits regularly to avoid loss of progress.

For adding, removing, and general editing of shapefiles (or geopackages), the editing mode must be activated. To add a point to the map, press the ***Add Point Feature*** button within the digitizing toolbar. After clicking the desired location in the map window, a small window appears where you can assign attributes to that feature.

Add some geographical locations to the map (for example with the help of google maps or tiris (2018)) and add names to the features. Safe your edits and deactivate the layer's editing mode. To label the layer, ***Right click*** it and select ***Properties → Labels***. Change the selection to "Show labels for this layer". In the drop-down menu of "Label with", select the "name" attribute and press ***OK*** (Figure 13).

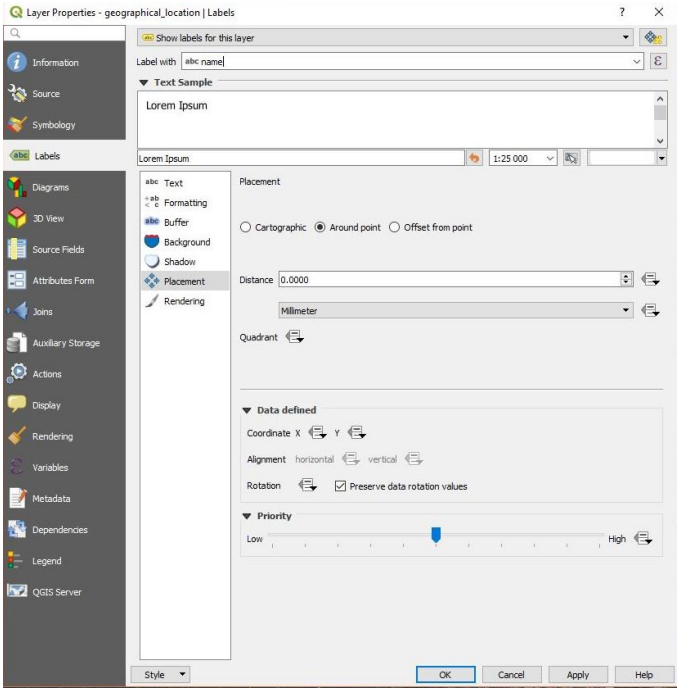

Figure 13; Adding labels to point layers

Again, it is highly recommended to play with all the possibilities for style and label customization to find an appealing design!

With this method, a variety of highly customizable point layers can be added to the map. As another example a layer with a font marker (instead of the simple marker) showing the location of springs in this area is added to the map.

By now your map should look similar to Figure 14.

3.1.2. Importing data from text files

Geolocated point data (e.g.: structural geological measurements, well locations etc.) is often stored as a text file which can be imported into QGIS. The advantage of using text files as data sources is that if the data source changes (e.g. new measurements are made), the point layer is updated within your project (when QGIS is restarted, or the layer is reloaded).

As an example, some structural geological measurements were taken on roadcuts in the area between Höttinger Alm and Bodensteiner Alm. (i.e.: two huts).

To show the orientation of planes with strike/dip symbols, a text file with at least four columns is needed. Usually an additional column with the type of the measurement (i.e.: bedding plane, joint, fault…) is given (see Table 2) and can be utilized for a classified symbology (see chapter 3.3 “polygons” for explanation on classified symbology)

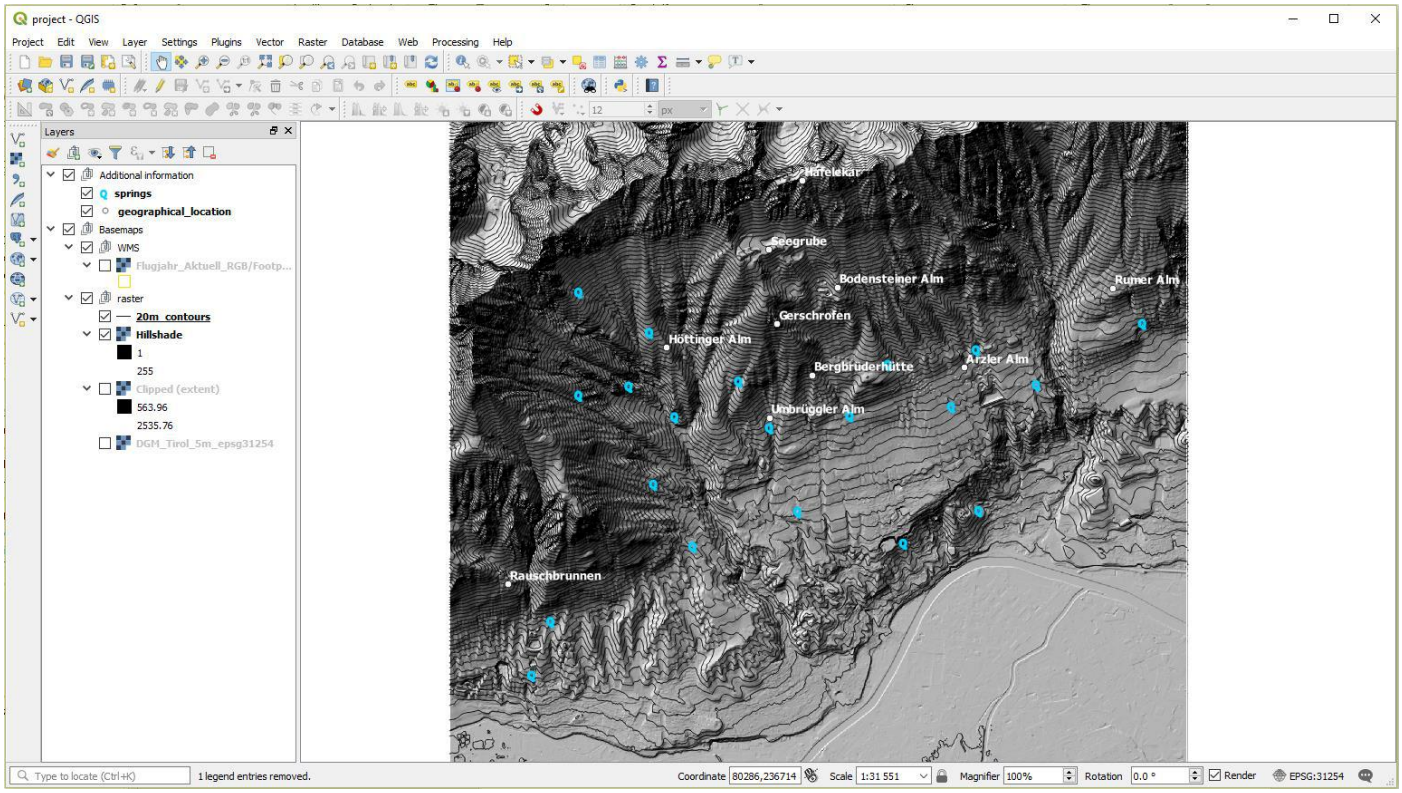

Figure 14; Map with two new point layers: geographical locations and springs

Table 2; example of a text-file with five columns, containing geolocated structural geological measurements

longitude	latitude	dip direction	dip	type
47.29701	11.38180	338	37	bedding
47.29752	11.38044	158	56	bedding
47.29739	11.38057	355	62	bedding
…	…	…	…	…

To add data from a text file either use ***Add Delimited Text Layer*** within the **Manage Layers Toolbar** or go to ***Layer → Add Layer → Add Delimited Text Layer …*** from the **Menu bar**. Adjust the settings of the ***Data Source Manager | Delimited Text*** window to match your file (Figure 15) and ***Add*** the points to the map.

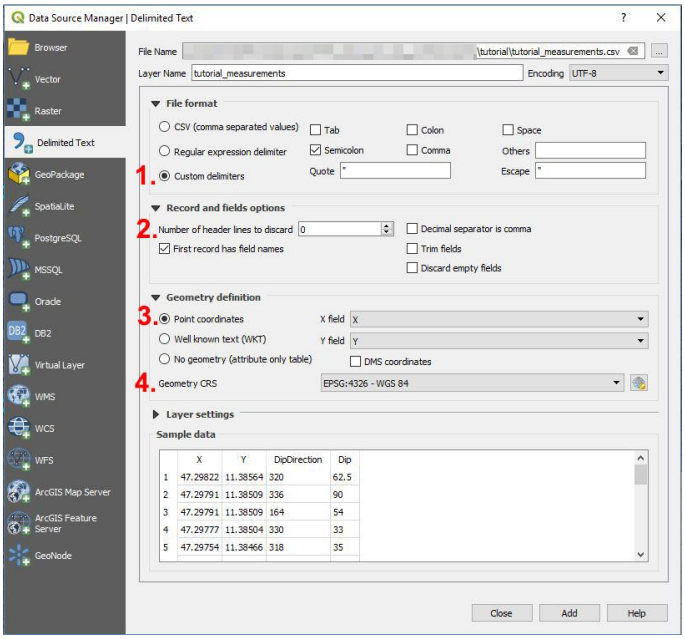

Figure 15; Adding a delimited text layer to the project; common error sources labelled 1.-4.

Common sources of confusion are (labeled 1-4 in Figure 15):

1. *unknown/wrong custom delimiters of the text file (in doubt: right click and open the text file with a text editor instead of spreadsheet applications to see what the delimiter between columns is)*
2. *number of header lines to discard is not correct*
3. *wrong columns for X- and Y- coordinates are selected, or X and Y coordinates are switched. If this happens, points will usually plot far away from their expected location and are 90° rotated. You can check if points are located far outside your basemap by **right clicking** the new layer and clicking **Zoom to Layer** .*
4. *wrong CRS is chosen for the geometry of the text file (this CRS does not necessarily have to fit your project CRS)*

As described above, the point layer's symbology can be changed for the layer with ***Right click → Properties → Symbology.*** To symbolize the dip direction of the measurements, choose a "Font marker" instead of the "simple marker". Change the "Fill"- and "Stroke color" to black, choose a visible size and select the letter "T" as symbol (Alternatively, look for a better symbol for the "strike/dip" symbol within your installed font-types or create a customized symbol) To rotate the symbol according to the dip direction, click the ***Data-defined override*** button beside the "Rotation" input field and choose the name of the dip direction – column of your dataset (Figure 16).

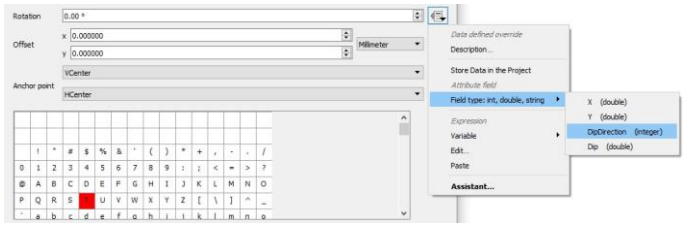

Figure 16; setting the symbol rotation according to the dip direction of the point

By clicking ***Apply***, your symbols are rotated, but 180° twisted. To correct this, choose ***Edit*** (Figure 17 (top)) and enter >180 + "DipDirection"< in the **Expression String Builder** (or whatever your dataset's column with the dip direction is called) (Figure 17 (bottom)). If you have chosen a letter that is already 180° rotated, this step is not necessary. As a last step, choose the "Dip" column as label for the structural geological measurements (***Right click*** on the layer, select ***Properties → Labels*** and change the selection to "Show labels for this layer".).

Instead of "font markers" also "SVG markers" can be used. Scalable Vector Graphics (SVG) can be created with different graphic programs and allow you to design your own markers from scratch.

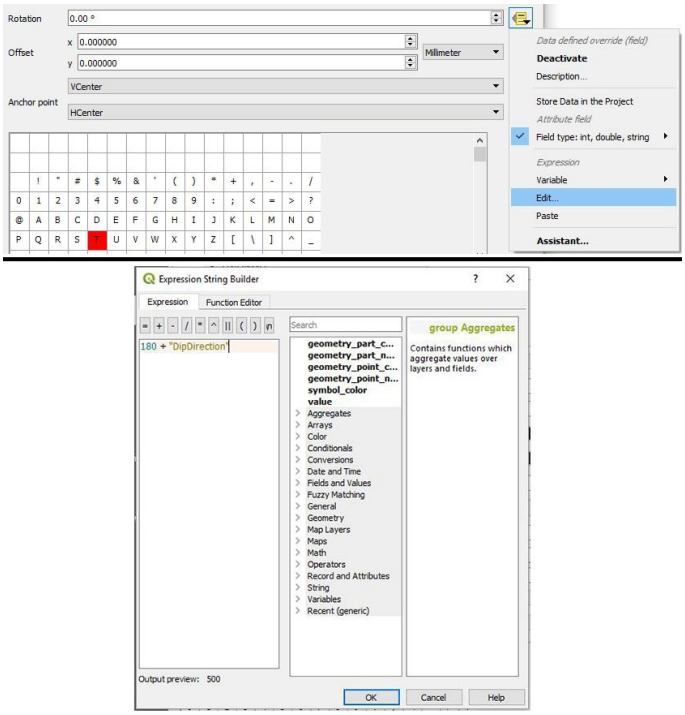

Figure 17; Workflow to twist point layer symbology by 180°

3.2. Lines

To create new lines (for features like rivers, fold hinge lines, crowns of landslides…) go to ***Layer → Create Layer → New Shapefile Layer*** and choose "Line" as the "Geometry Type" in the **New Shapefile Window**.

To demonstrate the functionality, rivers and creeks will be added to the map. ***Toggle Editing***  ***→ Add Line Feature***  and draw a new line by adding vertices to the map. ***Enable Snapping***  and adjust its functionality in the ***Advanced Configuration***  if you want to connect two lines (for example two creeks). To add labels to line features ***Right Click*** them and select ***Properties → Labels*** and change the selection to "Show labels for this layer". By default, QGIS adjusts labels parallel to the line. If inappropriate, this can be changed.

3.3. Polygons

One kind of geological maps is the lithological map, which aims to show the spatial distribution of different lithologies. Lithologies are usually presented by closed polygons with a uniform symbology (i.e. one color, or one signature). In this tutorial, three simple units will be differentiated: 1. Anthropogene Cover; 2. Quaternary Cover; 3. Austroalpine Units. The distribution of the geological units was simplified after the *Geofast* – geological map of Innsbruck and derived from the DEM and Orthophoto data.

To create new polygons, go to ***Layer → Create Layer → New Shapefile Layer.*** The "geometry type" in the ***New Shapefile Window*** has to be changed to "Polygon". Polygons should be placed above basemaps and below point- or line data.

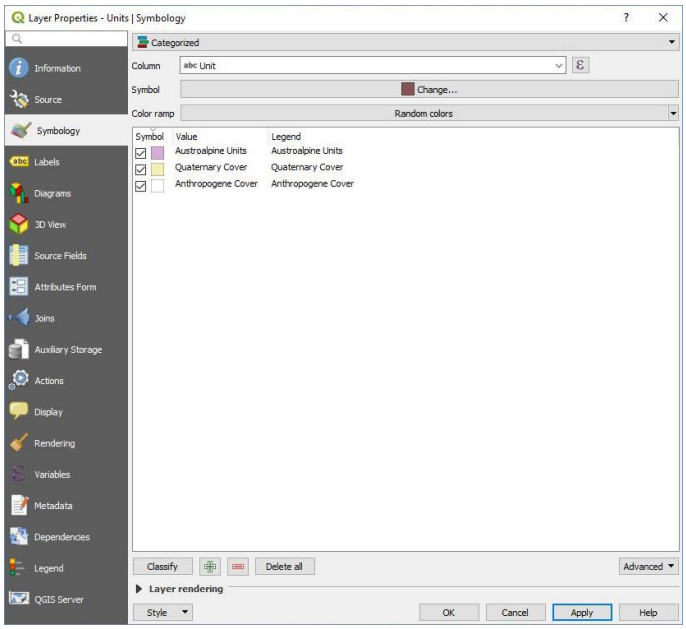

Figure 18; using a categorized symbology for displaying different geological units

Add a new text-column to the **Attribute Table** of the new polygon layer and term it "Geologic Unit". With that column you can name each polygon according to its respective geological unit. To classify the polygons (i.e.: assign individual symbols to each unit) ***Right Click*** the polygon layer and select ***Properties → Symbology*** and select "Categorized" instead of "Single Symbol" in the upper part of the **Layer Properties Window** (Figure 18). Press ***Classify*** and change the symbology.

Whatever color you may choose for your polygons, adding transparency to polygons is often a good idea because it allows the basemap- and polygon layers to be displayed simultaneously.

Add polygons to your map by ***Toggle Editing*** → ***Add Polygon Feature*** and start "drawing" by clicking the desired place on the map (Figure 20). Tools like **Add Ring** from the **Advanced Digitizing Toolbar** help to create more complex geometries.

When you are drawing and editing polygons, always keep in mind what the final scale of your map is supposed to be and create your polygons with enough nodes/vertices for a proper, smooth looking result.

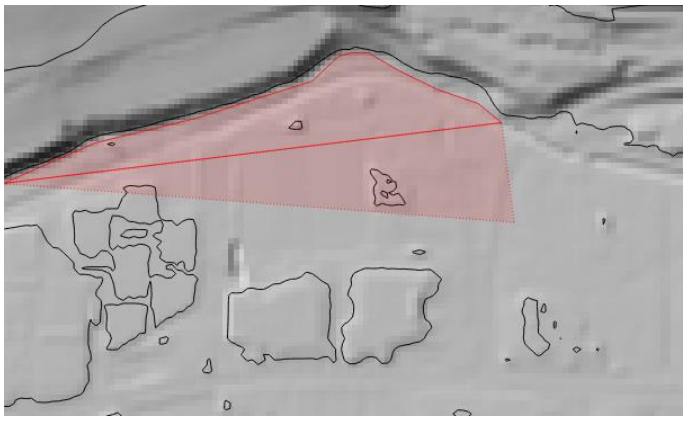

Figure 20; creating a new polygon

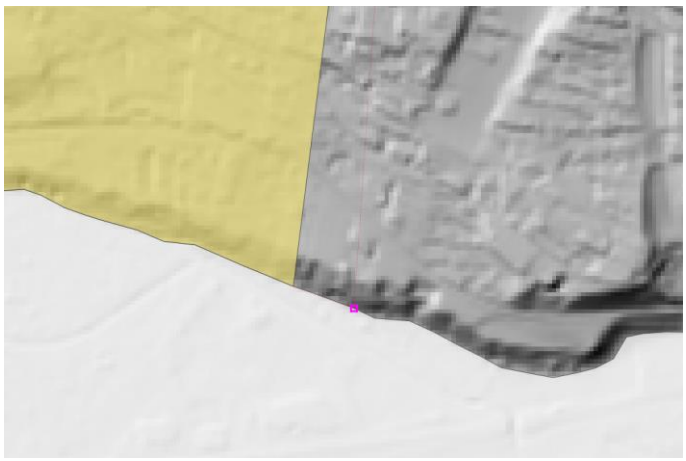

Figure 21; Snapping helps to fit one feature to another

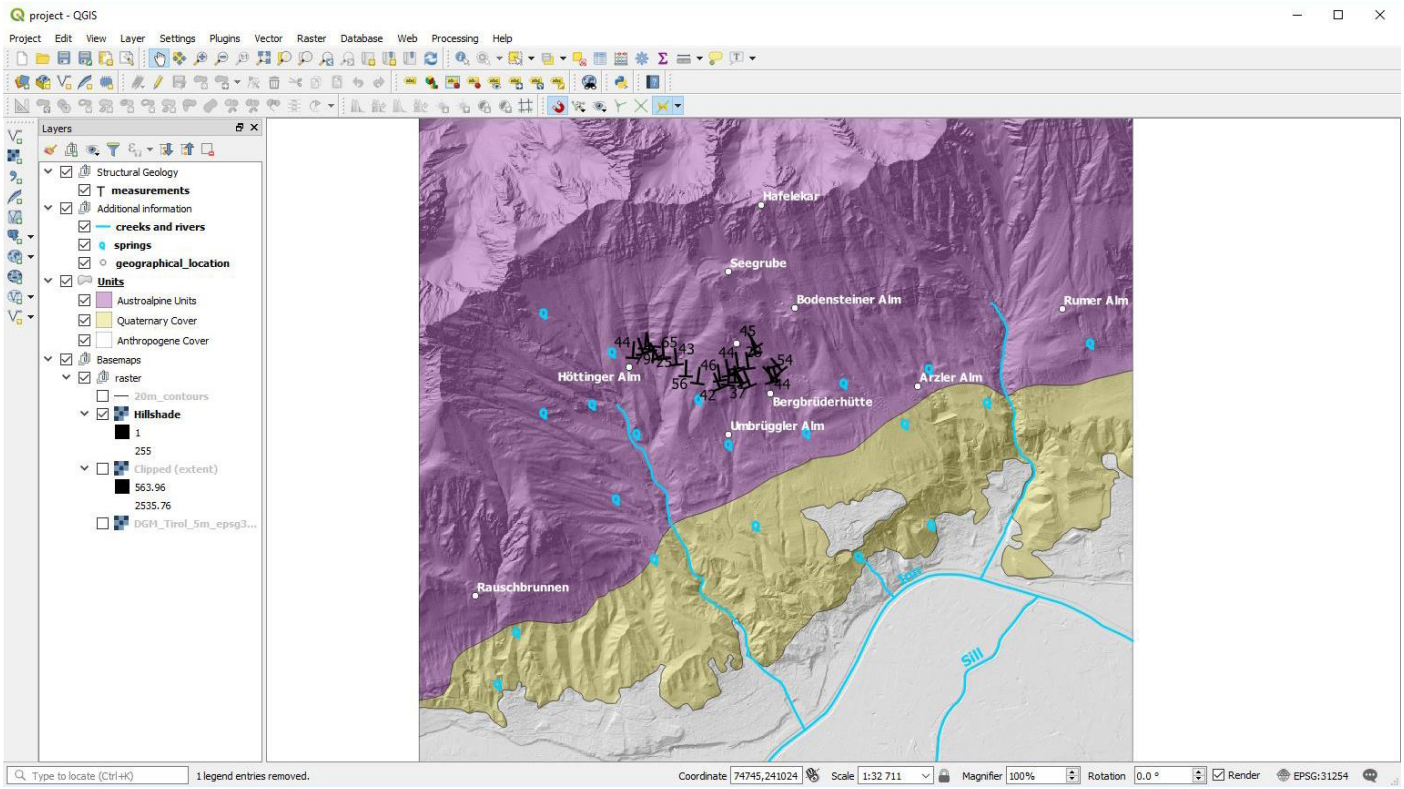

Figure 19; The map after adding point-, line- and polygon-layers.

Finish the new polygon by right clicking the map window and pressing ***OK*** in the small attribute window (like with points and lines you can add attributes to polygons).

Whenever you are creating polygons adjacent to each other, ***Enable Snapping*** and ***Tracing*** to speed up the process and to create borders without holes and intersections (Figure 21).

Avoid overlapping polygons or gaps in between. Such errors may cause problems later on.

By now your map should look like Figure 19.

4. Step: Layouts

A "quick and dirty" way of exporting maps from QGIS is ***Save Map as Image*** which can be found in ***Project.*** Do not forget to scale the resolution accordingly.

Anyway, a geological map needs a legend, a scale bar and a north arrow. To create such a map, select ***Project*** → ***New Print Layout*** in the **Menu bar** and name your map layout. Upon confirmation, the **Print Layout window** opens (Figure 22).

First, ***Right Click*** the empty page of the map window and select → ***Page Properties***. Within the **Item Properties panel**, you can change the overall properties (height, width, orientation…) of the page. To add a new map, choose the ***Add a new Map to the layout*** button within the toolbox and draw a boundary box onto the empty page. Your main map window (with all active layers) will now appear. The displayed map corresponds to the active layers in your main QGIS window. *Note that you can add more than one map to your layout.* Clicking ***Move item content*** in the **toolbox** allows you to zoom in and out by scrolling and to move the whole map content within the boundary box. *After you have found an appropriate scale and the right area of the map, it is recommended to lock the map item within the Items Panel to avoid accidental shifting of the map content.*

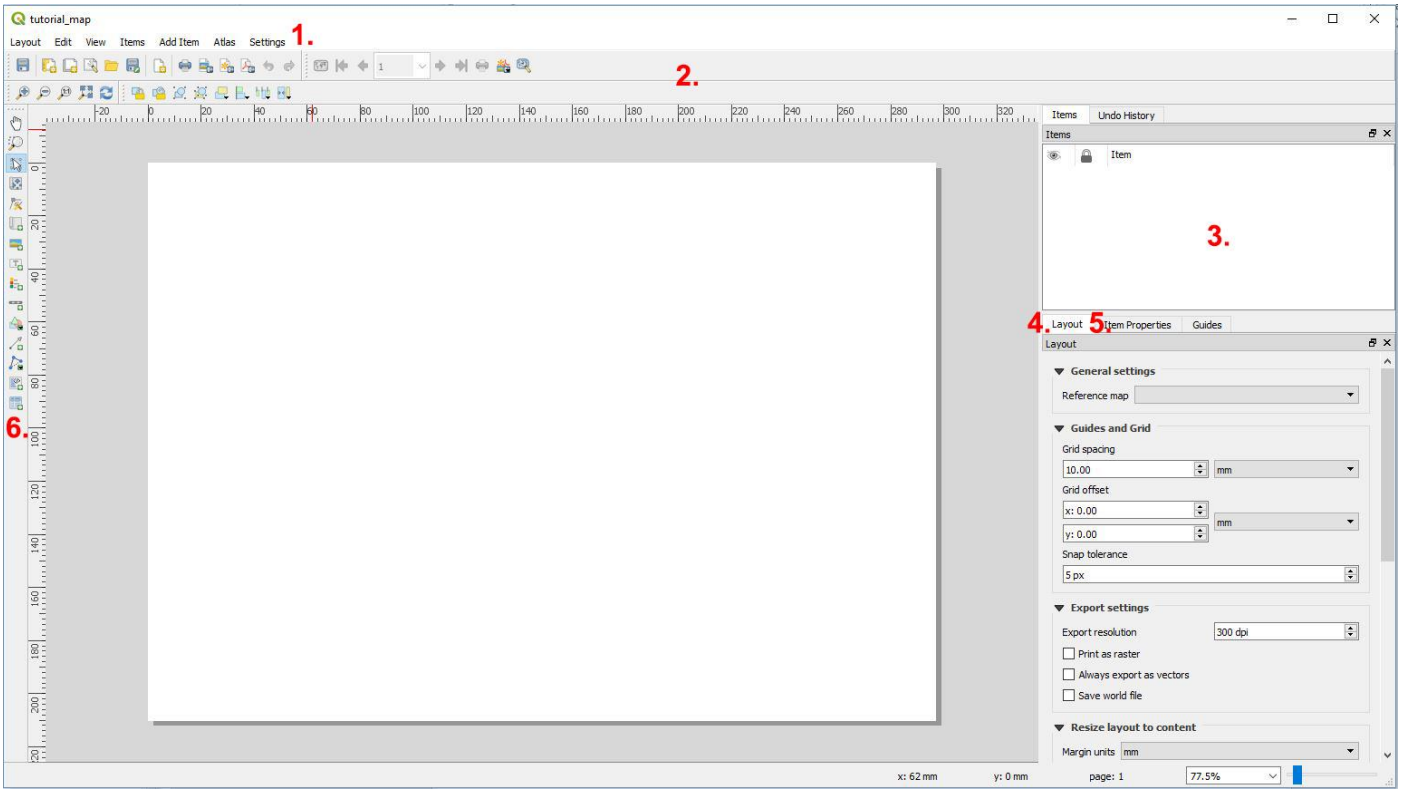

Figure 22; Print Layout window with several GUI elements: 1. Menu Bar; 2. Toolbars; 3. Items Panel; 4. Layout Panel (and other panels); 5. Item Properties Panel (and other panels); 6. Toolbox

Every item of the map has its own **Item Properties Panel** which can be used for manual customization. For example: You can choose your map's scale (e.g.: 1:15 000) or add features like a frame, background or coordinate grid. To add a grid, go to the "Grids" section of the **Item Properties Panel** of your map, click ***Add a new grid***, activate ***Draw "Grid 1" grid*** and click ***Modify grid…*** (Figure 23)

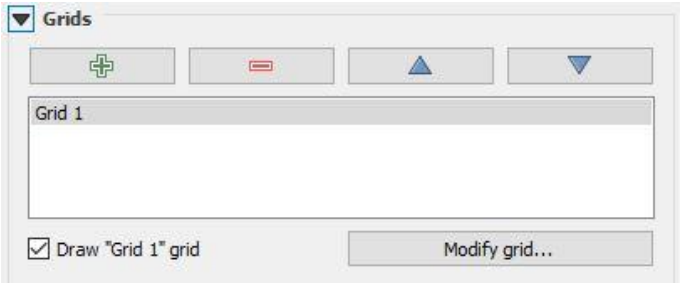

Figure 23; adding a grid to the map

Within the **Map Grid Properties**, the grid itself can be customized and for this tutorial's map the following parameters were chosen: Grid type: solid; CRS: EPSG:31254; Interval Units: Map Units; Interval (X,Y): 1000,00. *Do not forget to give the used CRS's name on your map.*

Click ***Add a new Scalebar to the layout*** and place it on the map. Modify the item properties to enhance visibility. A North arrow can either be added by combining a triangle shape (***Add Shape***) with the letter "**N**" (***Add Label***), or by inserting an image of a North arrow by clicking ***Add Picture***. ***Add a new Legend to the layout*** and place it accordingly. By unchecking "Auto update" within the **Item Properties panel** of the legend, you can manually edit the legend-content. By using the described tools of the **toolbox**, you can easily add additional information to your map and make it look more appealing. For demonstration, some additional labels and a stereonet (created with *Stereonet 10* by Rick Allmendinger (Allmendinger *et al.*, 2012; Cardozo and Allmendinger, 2013)) are added to the map.

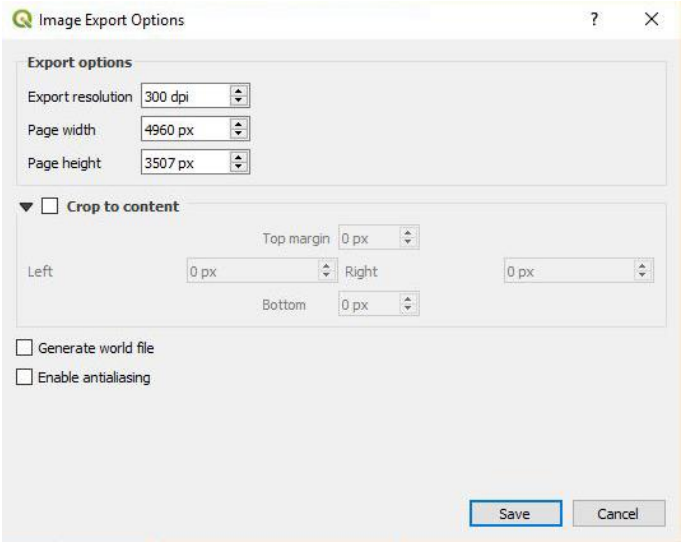

Figure 24; Image export options

By clicking ***Layout → Export as Image*** or ***Layout → Export as PDF*** you can export the map. In the **Image Export Options,** you can choose the export resolution, if you want to create a world file (for georeferencing of the map-image) and if you want to enable antialiasing (for smoother graphics) (Figure 24).

The final map is presented in Figure 1.

Congratulations, you have created a geological map with QGIS 3!

Acknowledgements

I want to thank the QGIS development team for their efforts of developing and constantly upgrading this tremendously handy piece of software. I also want to thank the Land Tirol for publicly offering the high resolution geospatial data that was used in this tutorial. Review and tips from Markus Palzer and Dominik Jaeger are greatly appreciated.

The work of the authors of the countless tutorials and guides that are freely available on the internet (e.g.: Lorscheid (2013)) is acknowledged.

Appendix

Appendix 1; Data sources used in this tutorial

Name	Type	Source
5m res. digital elevation model Tirol	raster data	https://www.data.gv.at/katalog/dataset/land-tirol_tirolgelnde
Orthophoto Tirol	WMS	https://www.data.gv.at/katalog/dataset/35691b6c-9ed7-4517-b4b3-688b0569729a
Geologische Bundesanstalt - Web Services	WMS	https://www.geologie.ac.at/services/web-services/?R=%252Fetc

References

Allmendinger, R.C., Cardozo, N. and Fisher, D.M. (2012), *Structural geology algorithms: Vectors and tensors,* 1. publ, Cambridge Univ. Press, Cambridge.

Cardozo, N. and Allmendinger, R.W. (2013), "Spherical projections with OSXStereonet", *Computers & Geosciences*, Vol. 51, pp. 193–205.

ESRI (1998), *ESRI Shapefile Technical Description*.

Geofast: 118 - Innsbruck, 2013/02, Geologische Bundesanstalt, Wien.

Land Tirol (2018), "Terrain data Tyrol: digital terrain model (DTM/DGM)".

Li, Z., Zhu, Q. and Gold, C. (2005), *Digital terrain modeling: Principles and methodology*, CRC Press, New York.

Lorscheid, T. (2013), "Anleitung zur Erstellung einer geologischen Karte mit QGIS 2.0", Stand: 18.10.2013, available at: https://www.steinmann.uni-bonn.de/studium-geowissenschaften/outdoor/nachbereitung/protokoll/gesamtanleitung-qgis-2.pdf.

Miller, C.L. and Laflamme, R.A. (1958), "The Digital Terrain Model. Theory & Application", *Photogrammetric Engineering*, No. 24, pp. 433–442.

QGIS Development Team (2018), "QGIS Geographic Information System", available at: https://www.qgis.org/en/site/ (accessed 6 May 2018).

tiris (2018), "Tiroler Rauminformationssystem", available at: https://www.tirol.gv.at/statistik-budget/tiris/ (accessed 10 May 2018).